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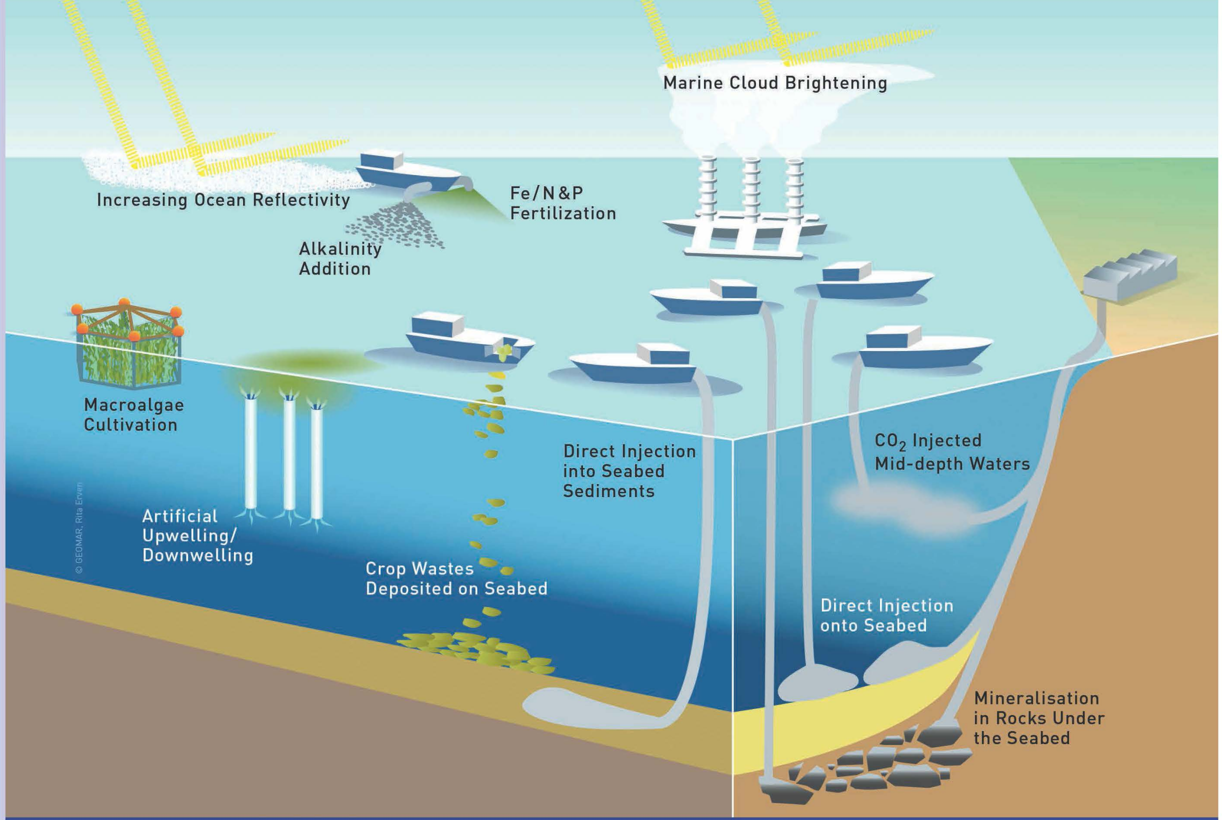
REPORTS AND STUDIES

GESAMP
Joint Group of Experts on the
Scientific Aspects of Marine
Environmental Protection

HIGH LEVEL REVIEW OF A WIDE RANGE OF PROPOSED MARINE GEOENGINEERING TECHNIQUES

GESAMP WORKING GROUP 41



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5 ASSESSMENT OF INDIVIDUAL MARINE GEOENGINEERING TECHNIQUES

In this section we present a description of some 27 techniques (including variations of approaches) which is designed to provide a comprehensive repository of all information, available at the time of writing the report, on each approach.

5.1 Ocean fertilization – iron

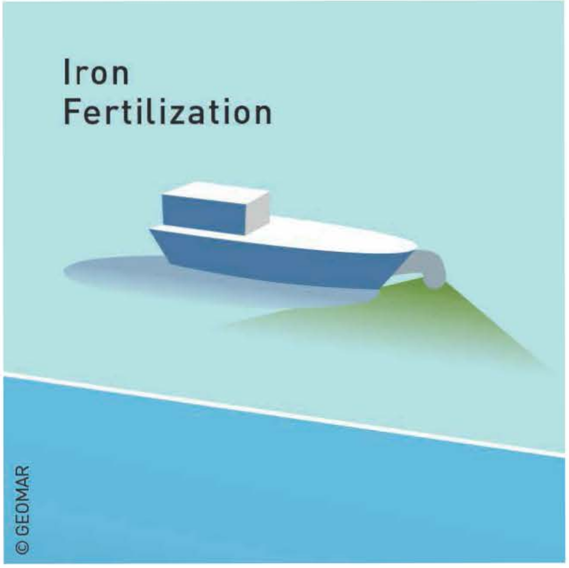


Figure 5.1 *Ocean iron fertilization*

Approach/rationale

Maps of the upper ocean macronutrient inventory for either Phosphorus (P) or Nitrogen (N) compounds reveal three conspicuous regions in which there is a perennial surplus of nutrients (termed HNLC – High Nutrient Low Chlorophyll) (Boyd *et al.*, 2007; Cullen, 1991). It is now established that the paradox of HNLC regions is due to iron limitation of primary producers in the Southern Ocean, subarctic North Pacific and Eastern Equatorial Pacific (Boyd *et al.*, 2007). The rationale for ocean iron fertilization is based on the purposeful addition of iron (Fe) to the ocean, such that it drives blooms in HNLC regions which can utilise the unused stocks of macronutrients which in turn results in enhanced carbon sequestration via the biological pump (see Figure 5.2), and hence carbon dioxide removal. The biological pump is the ocean's biologically driven sequestration of carbon from the atmosphere to the deep ocean and underlying sediments. It is the part of the oceanic carbon cycle responsible for the cycling of organic matter formed mainly by phytoplankton during photosynthesis. The biological pump removes 4-10 Gt C from surface waters annually, however, ≈ 90% of this C is released back into the atmosphere within a year.

Underlying principle(s) with citation and extent of knowledge

Iron is a trace element (sub-nanomolar, i.e., << ppb) required to catalyse key metabolic processes such as N-based physiology and C fixation (Morel and Price, 2011). Hence, the addition of a small amount of iron, in oceanic regions where it is lacking, results in a disproportionately large enhancement (on the order of 105) of C and N biogeochemistry. Therefore, the amount of iron that must be added to the ocean to drive phytoplankton blooms and their contribution to C sequestration is amenable to upscaling and large-scale delivery to the ocean. Laboratory phytoplankton experiments and sophisticated measurements of phytoplankton elemental composition have confirmed the stoichiometric relationship between iron and carbon (Sunda and Huntsman, 1995; Twining and Baines, 2013). In addition, 13 mesoscale iron enrichment studies, examining the role of iron supply in driving change in past climate and its function in the present ocean (i.e., not geoengineering studies) provided evidence on scales of up to 1000 km^2 of enriched HNLC ocean that addition of several metric tonnes of iron salt resulted in massive blooms over this region (Boyd *et al.*, 2007). Thus, these experiments demonstrated that iron limits phytoplankton production in the contemporary ocean and provided potential insights on past climate. However, there were significant differences in the ratio of iron added to carbon fixed photosynthetically, and in the ratio of iron added to carbon sequestered across these 12 studies (H. J. W. de Baar *et al.*, 2008). This wide range of ratios has implication both for the success of this strategy, and its cost (de Baar *et al.*, 2008). A similarly wide range of ratios was reported from studies of naturally-driven iron-stimulated blooms at sites such as Crozet and Kerguelen in the Southern

Indian Ocean (Blain *et al.*, 2008; Pollard *et al.*, 2009; Trull *et al.*, 2015). It appears that subtle differences in the bloom initial condition and or in its evolution can result in differing degrees of C sequestration: from a relatively small effect (~15% higher than ambient) of iron supply in the North-East Pacific experiment SERIES (Boyd *et al.*, 2004) to a pronounced effect (200-300%) in the polar Southern Ocean experiment EIFEX (Smetacek *et al.*, 2012).

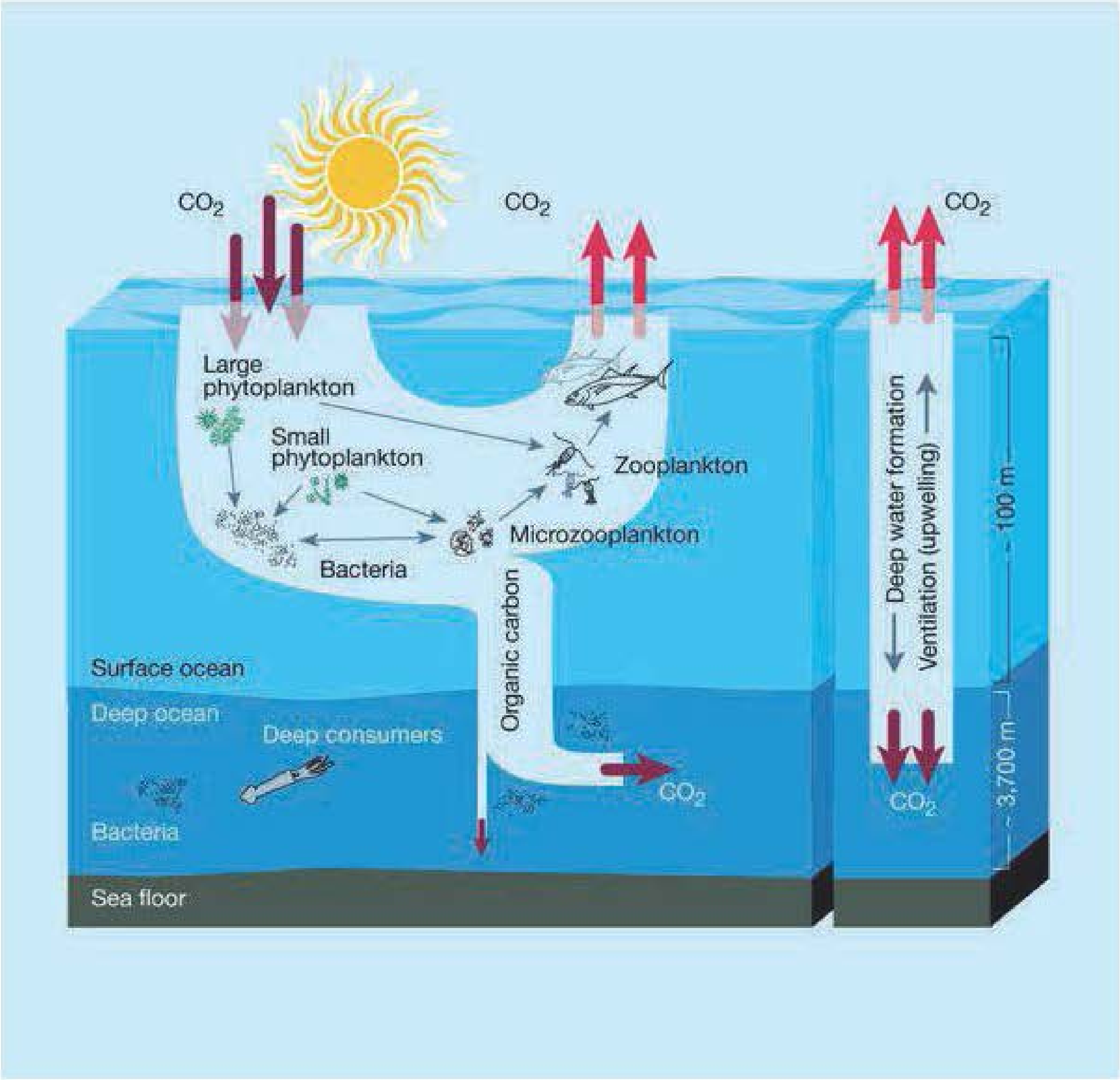


Figure 5.2 *The Biological Pump is a collective property of a complex phytoplankton–based foodweb. Together with the solubility pump (right), which is driven by chemical and physical processes, it maintains a sharp gradient of CO_2 between the atmosphere and the deep ocean carbon reservoir (Reprinted by permission from Nature, © 2000, S.W. Chisholm (2000) 'Stirring times in the Southern Ocean', Nature 298, 685–687).*

Evidence of concept from the natural world

In nature there is evidence of iron-stimulated blooms that occur each year (Blain *et al.*, 2008; Pollard *et al.*, 2009; Trull *et al.*, 2015). along with those driven by episodic iron supply such as volcanic eruptions (Achterberg *et al.*, 2013, 2018; Hamme *et al.*, 2010) and dust supply (Bishop *et al.*, 2004). In some of these events the extent of observations ranges from CO_2 drawdown from the atmosphere through to downward particle flux of organic carbon (Trull *et al.*, 2015) and in others the evidence base is less detailed (Bishop *et al.*, 2004). There is also compelling evidence in the geological past that changes in iron supply (thought to be associated with alteration of aerosols dust supply) play a major contribution to changes in atmospheric CO_2 concentrations via alteration of the biological pump largely driven by the Southern Ocean (Jaccard et *al.*, 2013; Martin 1990, Martinez-Garcia *et al.*, 2014). It is estimated that altered iron supply in the deep past could be responsible for up to 1/3 of the 80-90 ppmv CO_2 decrease during the glacial terminations (Sigman and Boyle, 2000; Sigman et *al.*, 2010). Based on these contemporary and paleoceanographic observations, it has been proposed that iron fertilization could be used to enhance the productivity of HNLC waters (in particular of the Southern Ocean) resulting on enhanced carbon sequestration and hence a drawdown of significant amounts of atmospheric CO_2.

Direct/indirect sequestration

Carbon sequestration would be direct via an enhanced biological pump, as reported for some mesoscale iron enrichment studies (Smetacek *et al.*, 2012) and for natural iron-enriched events (Blain *et al.*, 2008). However, the degree of enhancement of the biological pump varied considerably between experiments, with the upper bound (i.e., 50% or more of the iron-mediated bloom sank to 1000 m depth) reported from the EIFEX study in the Southern Ocean (Smetacek *et al.*, 2012) and the lower bound (8% of the bloom was exported to the depth of the permanent pycnocline) from the SERIES experiment in the subarctic Pacific (Boyd *et al.*, 2004).

Proposed deployment zone(s) and potential scale of use

Proposed zone includes the 3 main HNLC regions (subarctic Northern Pacific, Eastern Equatorial pacific, Southern Ocean), with modelling studies suggesting that the latter is the most promising for net carbon sequestration (Bopp *et al.*, 2013; Keller *et al.*, 2014; Robinson *et al.*, 2014; Sarmiento and Orr, 1991). Modelling also reveals that the scale of use would require the entire Southern Ocean to obtain a large enough enhancement of export flux (Oschlies *et al.*, 2010a)

Duration of deployment

Multiple year to multiple decades based on modelling studies (Oschlies *et al.*, 2010a).

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

There is a broad base of evidence for the feasibility and efficacy of this approach ranging from laboratory culture studies (Sunda and Huntsman, 1995) to >ten scientific mesoscale iron enrichment research (Boyd *et al.*, 2007; de Baar *et al.*, 2005; Lampitt *et al.*, 2008). A major uncertainty from field studies that remains is how wide-ranging bloom characteristics lead to different C sequestration patterns (Boyd, 2013). Modelling studies have been able to provide upscaling of such findings from each of the three HNLC regions (Subarctic Pacific, Equatorial Pacific and the Southern Ocean) to the regional and global ocean (Gnanadesikan *et al.*, 2003, Sarmiento and Orr 1991). Subsequent modelling projections revealed that iron-mediated increases in particle export alone were insufficient to drawdown more carbon, and that ocean circulation, stoichiometric ratios (carbon and nutrients) and gas exchange were also highly influential in setting the efficacy of ocean iron fertilisation (Gnanadesikan and Marinov, 2008).

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

Several potential side-effects have emerged from mesoscale scientific iron enrichment experiments, including the emergence of stocks of potential toxic species of diatoms during the development of several of the mesoscale iron enrichment experiments (Silver *et al.*, 2010; Trick *et al.*, 2010). There is also limited evidence of increased concentrations of other GHG's such as methane and nitrous oxide during the subsurface decomposition of the sinking particles from iron-stimulated blooms (Law, 2008). These GHG's are more potent than CO_2, and hence the release of even small amounts of them – eventually into the atmosphere – could have a disproportionately large effect in offsetting any additional drawdown of CO_2 into the ocean that was mediated by ocean iron fertilisation.

5.2 Ocean fertilization – macro-nutrients – nitrogen and phosphorus

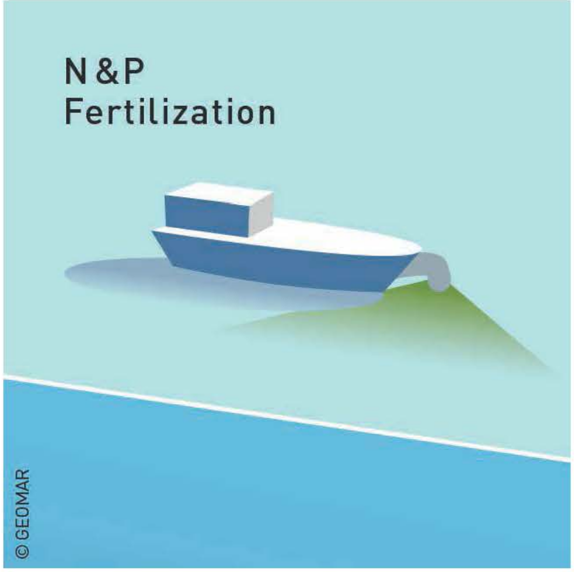


Figure 5.3 *Ocean nitrogen and phosphorus fertilization*

Approach/rationale

Much of the global ocean in the low latitudes, comprising the tropics and sub-tropics, is characterised by nutrient-impoverished waters where either N or P limit primary productivity and hence the export of carbon to the oceans interior (Moore *et al.*, 2013). It has been proposed that these so-called LNLC (Low Nutrient Low Chlorophyll) waters could be fertilised with N and/or P (Jones and Young, 1997) to boost fisheries productivity and/or sequester carbon.

Underlying principle(s) with citation and extent of knowledge

The oceans biological pump is projected, across a suite of Earth system models, to export 4-10 Gt C out of the surface layer each year (Bopp *et al.*, 2013), resulting in the removal to vanishingly low levels of N and/or P in the surface ocean (Martinez-Garcia *et al.*, 2014). Hence, fertilization of these LNLC waters with N and/or P would likely result in a further enhancement of the oceans' biological pump. However, ≈ 90% of the 4-10 Gt C is re-released into the atmosphere within a year.

Evidence of concept from the natural world

Evidence comes from the role of the oceans' biological pump discussed above, and the resulting low inventories of N and P in the upper ocean. Further evidence comes from a number of shipboard experiments that show that N and/or P addition causes an increase in phytoplankton productivity and biomass (Moore *et al.*, 2013).

Direct/indirect sequestration

The sequestration of carbon would be direct via an enhanced biological pump. However, if such a nutrient enrichment approach was also used concurrently to boost fisheries productivity this could offset the magnitude of the carbon sequestration, as the carbon flowing through enhanced fisheries would ultimately be released into the atmosphere (Young, 2007).

Proposed deployment zone(s) and potential scale of use

Three options have been proposed by Harrison (2017): addition of N to waters with excess P (relative to N, termed P*, (see Deutsch *et al.*, 2007) for the conceptual background for P*) which are mainly located in the low latitude oceans; continuous fertilization with only N; and continuous enrichment with both N and P (both of the latter options would avoid low iron HNLC waters) and hence would not be global deployments.

Duration of deployment

Both one-off (in regions with positive P*) and continuous deployments have been discussed (Harrison, 2017).

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

The evidence is based on both modelling studies (Harrison, 2017; Lawrence, 2014; Matear and Elliott, 2004) and mesoscale P addition field experiments (Dixon, 2008; Thingstad *et al.*, 2005). However, there is no acknowledgement of the findings from the research on mesoscale P addition by researchers examining modelling simulations e.g. Harrison (2017).

Lawrence (2014) reported a 75% sequestration efficiency of global N enrichment, with some variation evident dependent on the chemical form in which the N was added. His study took into consideration additional costs such as manufacture of the fertilizer and its transport and distribution by vessels on the ocean. He defined this efficiency as the percentage of additional C fixed photosynthetically, following N enrichment (i.e. sequestered carbon per atom of added nutrient), that could potentially be transported into the ocean's interior – i.e. long-term sequestration. Lawrence speculated that N enrichment is potentially a more efficient means of sequestration than that projected for iron fertilization. Estimates from Harrison (2017) and Matear and Elliott (2004) were 78% and 80% efficiencies, respectively.

Thingstad *et al.* (2005) added phosphate during the CYCLOPS study to a mesoscale (sulphur hexafluoride labelled) patch of LNLC ocean in the Eastern Mediterranean Sea using a scientific research approach successfully used for mesoscale iron enrichment studies (Law *et al.*, 2005). Half of the added phosphate was taken up biologically, and the remainder was 'lost' laterally from the P-enriched path as the added P was diluted by mixing with the surrounding low P waters (Law *et al.*, 2005). Thingstad *et al.* (2005) reported a decrease in chlorophyll stocks following P enrichment and provided a putative explanation that much of the added P was taken up by heterotrophic bacteria and removed into the upper foodweb via 'ecological tunnelling'. An increase of 50% in nitrogen fixation (relative to the surrounding 'control' waters) was reported from this P-enrichment in the Eastern Mediterranean Sea (Rees *et al.*, 2006).

In a further P mesoscale enrichment experiment – called FeeP – in May 2004, in the subtropical N Atlantic, 20 tonnes of anhydrous monosodium phosphate was added at 10 metres depth over ~25 km^2, and in a further patch experiment a similar amount of P was added over the same area but with the addition of 5 tonnes of an acidified iron salt (Dixon, 2008). These additions raised phosphate from 9.6 ± 4.9 nM to 163 ± 18 nM (for P patch) and 200 ± 13 nM (for P + Fe patch) within ~12–16 h after enrichment(s) (Dixon, 2008).

Neither community primary production or and chlorophyll concentrations exhibited any increases in situ during either P or P/Fe enrichment, relative to the natural variability for rates and stocks of phytoplankton at all control sites samples outside of the P and P/Fe enriched mesoscale patches (Dixon, 2008). There appears to be a disjoint between global model projections (see above) and the outcomes of these two mesoscale scientific research P enrichment studies.

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

There is indirect evidence of detrimental side effects of N and/or P enrichment via agricultural runoff, resulting in both dead-zones (Diaz and Rosenberg, 2008) and in increased incidents of harmful algal blooms in the coastal zone (Gilbert *et al.*, 2008; Gilbert *et al.*, 2014). However, the magnitude of nutrient enrichment that results in either dead-zones or harmful algal blooms, may differ from that employed using this approach.

Enhancing Dissolved Refractive Carbon in the Deep Ocean

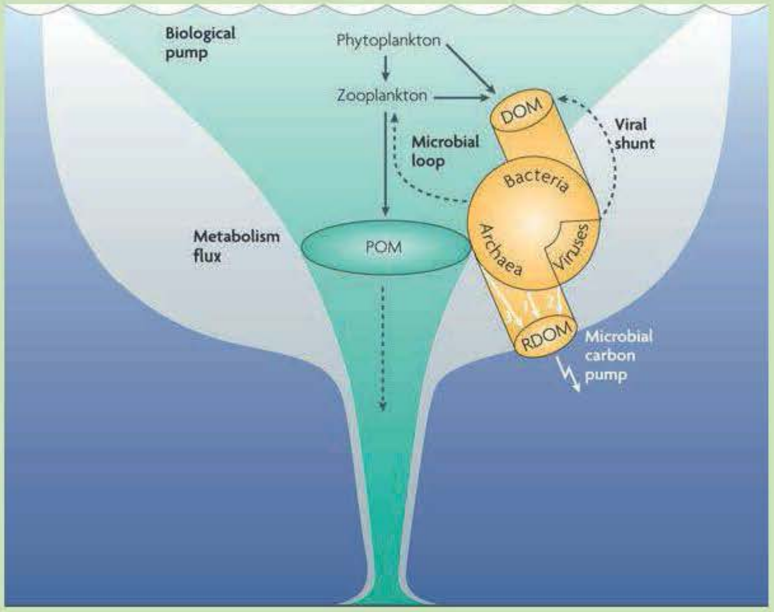
Another proposed, but as yet untested, technique that has parallels with sections 5.1 and 5.2 on the enhancement of the biological pump based on increasing the export of sinking particles is presented in Box 3. In this case, the concept of boosting the stocks of refractive dissolved organic carbon in the deep ocean is explored.

Box 3

Enhancing refractive carbon in the deep ocean: an untested concept

Approach/rationale

The current estimate of dissolved organic carbon (DOC) stocks in the ocean is comparable to the inventory of atmospheric CO_2 (Hansell *et al.*, 2009). Furthermore, changes in oceanic DOC stocks affect carbon partitioning among different carbon pools both in the ocean and atmosphere. The proposed concept of a microbial carbon pump (MCP) hypothesizes a DOC sequestration mechanism based on the microbial generation of refractory dissolved organic carbon (RDOC), which is resistant to biological decomposition and assimilation, and thus persists and accumulates in the water column (Box 3 Figure below). The average age of RDOC in the ocean is ~5000 years pointing to sequestration of carbon for millennia.



Box 3 Figure The Microbial Carbon Pump (MCP) and its putative relationship with the biological pump. Most primary production is in the form of Particulate Organic Matter (POM), but a portion of this fixed carbon is released as dissolved organic matter (DOM) into the ocean. This DOM together with DOM from other sources can be partially transformed by the MCP into RDOM (Jiao and Azam, 2011). (Reprinted by permission from Nature, © 2010 Jiao et al. 'Microbial production of recalcitrant dissolved organic matter: long-term carbon storage in the global ocean'. Nature Reviews Microbiology 8(8), 593-599.)

Underlying principle(s) with citation and extent of knowledge

The MCP describes the ecological processes and chemical mechanisms that produce RDOC. A modelling study reports that >50% of POC may be transformed into DOC via biological processes (Anderson and Tang, 2010). Marine microbes readily utilize most of this DOC, producing CO_2 but also transform some DOC to RDOC (Koch *et al.*, 2014). Sinks for the RDOC pool are unclear, but may include UV oxidation in surface waters (Mopper and Kieber, 2002), and scavenging onto particles (Hansell and Carlson, 2013).

The MCP hypothesis has not been explicitly included in the ocean carbon cycle framework. It is argued that the MCP is a quantitatively significant biogeochemical pathway for RDOC generation and carbon sequestration that should be specified in ocean carbon models (Jiao *et al.*, 2010; Sexton *et al.*, 2011).

Box 3 *(Cont.)*

Evidence of concept from the natural world

Observations and experiments have shown that there are large amounts of RDOC in the oceans, but identifying the mechanisms affecting the production of RDOC and its fate are still largely unknown. This is mainly due to the long-life span of RDOC in the oceans, and the lack of methodologies to study this new hypothesis.

Direct/indirect sequestration

MCP is a direct form of sequestration.

Proposed deployment zone(s) and potential scale of use

Not applicable at present.

Duration of deployment

Not applicable at present.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

At present, none of the hypotheses concerning the MCP has been tested experimentally because of lack of appropriate facilities, and hence modelling has been used to study the MCP. For example, the MCP was were simulated in the South China Sea using a physical-biogeochemical coupled model (Lu *et al.*, 2018).

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

There is currently no information and evidence about MCP as a method to enhance RDOC on the potential impacts on the marine environment.

5.3 Ocean fertilization – fertilization for fish stock enhancement

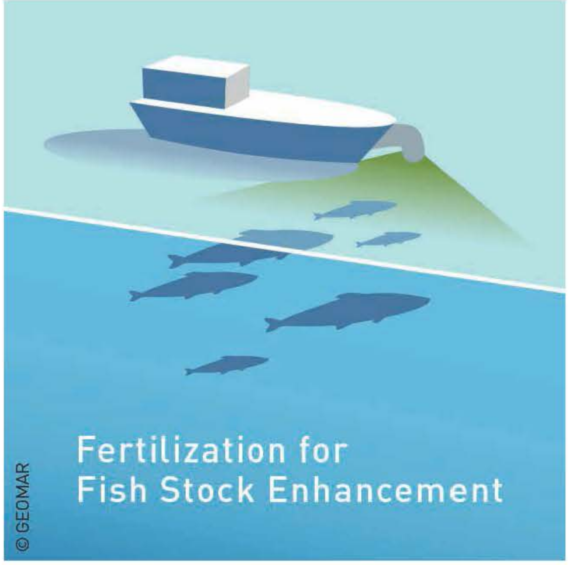


Figure 5.4 *Ocean fertilization for fish stock enhancement*

Approach/rationale

Overfishing along with other anthropogenic pressures in nearshore waters, allied with growing populations and demand for protein has led to chronic undersupply. This had led to proposals that large regions of offshore waters (such as eddies, ~100 km in diameter) be fertilised with nutrients (such as iron, see section 5.1 and macronutrients, see section 5.2) to increase the areal extent for fisheries, in particular for pelagic species. This approach differs from fish-farms in marine and freshwater systems which are contained within pens or enclosures.

Underlying principle(s) with citation and extent of knowledge

Stock enhancement, using nutrient fertilization, is routinely used in freshwater and marine aquaculture on 'farm-scales'[21] and has been used (with little success) to boost demersal fish stocks by releasing eggs and (yolk-sac) larvae in nursery grounds in European waters (Blaxter, 2000). The underlying principles of commercial stock enhancement have been applied to the open ocean. Commercially-based proposers of this approach have proposed using the principles that underlie mesoscale ocean iron fertilization as applied to scientific research studies (see examples in Boyd *et al.* (2007). In this approach, it is proposed that the iron fertilization will boost phytoplankton stocks in the upper ocean which will subsequently be consumed by larval and/or juvenile fish residing in surface waters of the iron-enriched region. As these fish often have complex life-cycles, for example if they are migratory (such as salmon) of fast-swimming pelagic species (such as jack mackerel) they may only be in this fertilised region for a short time period (weeks) during their much longer life history.

Evidence of concept from the natural world

Distinctive oceanographic features such as fronts and some types of eddies (anti-cyclonic, (Godø *et al.*, 2012)) have been reported to be characterised by enhanced productivity that is reflected across multiple trophic levels. The underlying physical oceanography boosts nutrient supply to the surface waters of these features. There has also been debate over whether episodic natural events can bolster regional fish stocks. For example, in the HNLC low iron waters of the North-East subarctic Pacific, a range of interpretations have been put forward on the veracity of a linkage between the episodic supply of iron to the upper ocean during volcanic eruptions and the subsequent enhancement of fish stocks (McKinnell, 2013; Olgun *et al.*, 2013; Parsons and Whitney, 2014).

Direct/indirect sequestration

In the cases proposed to date, the sequestration of carbon is not targeted, and instead the enhancement of the biomass of higher trophic levels is targeted (which support the fishery that the proposers wish to enhance). This proposed 're-routing' of the carbon through food webs in the upper ocean rather than via fast-sinking plankton blooms, if upscaled sufficiently could result in a net source of C to the atmosphere (The extra C passing up the food chain is largely respired).

Proposed deployment zone(s) and potential scale of use

Proposed deployment zones, to date, range from the HNLC waters off the Gulf of Alaska to the mesoscale eddy field associated with the Humboldt Current off Chile. In the former case, in which salmon enhancement was targeted via ocean iron fertilization (i.e. contrary to CBD non-binding decision - see Tollefson, 2012), the scale of use was 10's of km (Batten and Gower, 2014; Xiu *et al.*, 2014). In the latter case, iron-poor eddies of typically 100 km diameter were proposed as the site for fertilization (Tollefson, 2017) to stimulate fast-swimming pelagic species such as jack mackerel (Vásquez *et al.*, 2013).

Duration of deployment

In the North-East Pacific the duration of deployment was weeks (i.e., the duration of a typical diatom bloom) as evidenced by post-hoc analysis of satellite remote-sensing (Batten and Gower, 2014; Xiu *et al.*, 2014).

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

The iron fertilization of waters west of Haida Gwaii (North-East Pacific) in 2012 was conducted ostensibly to enhance the salmon fishery (and thus may be equated with a pilot study (albeit a controversial one, see Tollefson (2012)). No published (i.e., peer-reviewed) information is available in the permanent record from the team who conducted this research. After this event was reported (Tollefson, 2012), analysis of remote-sensing archives suggested that iron fertilization did apparently stimulate a large bloom (Batten and Gower, 2014; Xiu *et al.*, 2014), However, linking this bloom event to fisheries enhancement was not trivial due to four reasons: the required transfer of carbon through the micro- and meso-zooplankton (Batten and Gower, 2014); the migratory pathways of the salmon over large distances (McKinnell, 2013); and issues linking much larger episodic natural iron enrichments (from a volcanic eruption) to fisheries enhancement (McKinnell, 2013; Xiu *et al.*, 2014).

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate).

In the case of the fishery enhancement study in the North-East Pacific no published (i.e., peer-reviewed) information is available on the potential impacts of this approach in the permanent record from the team who conducted this research.

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[21] http://www.fao.org/docrep/008/ae932e/ae932e09.htm

5.4 Carbon storage in the ocean – liquid CO_2 placed in mid/deep ocean depths

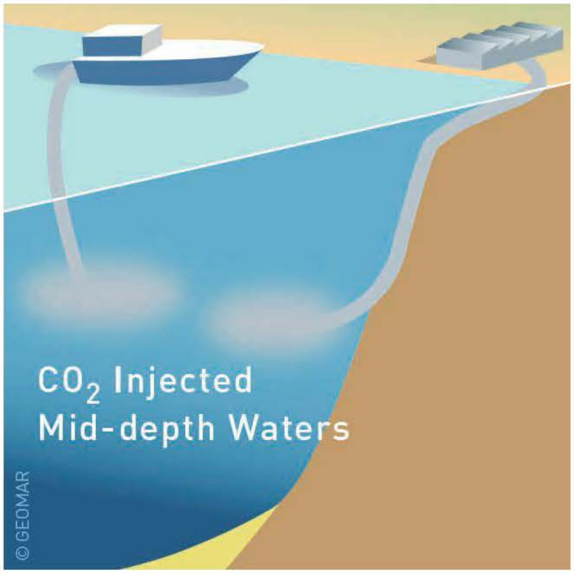

Figure 5.5 *Liquid CO_2 placed in mid/deep ocean depths*

Approach/rationale

The deep ocean (≈> 2,800 m) contains about 70 Tera tonnes (1 T tonne =1012 tonnes) of carbon dioxide or 50 % of the semi-labile carbon in the global carbon system comprised of the terrestrial, atmospheric and oceanic carbon pools (Sarmiento and Gruber, 2002). Due to its size and buffering capacity, the deep ocean will, in time, sequester over 85 % of the excess carbon produced by fossil fuel burning (Orr *et al.*, 2001). However, the rate of carbon uptake at the ocean surface is limited by the speed that the ocean circulates which is on the order of 200-1000 years (IPCC, 2005). Injection of liquid CO_2 at depth is a means of bypassing the natural bottleneck at the surface by adding CO_2 directly to the deep ocean where it can dissolve and dissociate into carbonate and bicarbonate ions and decrease the pH. It will increase the dissolved inorganic carbon (DIC) pool and lead to increased ocean acidification at these depths. The DIC will remain isolated from the atmosphere for centuries or longer depending on ocean circulation/ventilation at the location of injection. Once the water parcel with elevated CO_2 reaches the surface part of it will outgas some of the CO_2 decreasing the overall efficiency of storage (Reith *et al.*, 2016).

Injection of CO_2 into the deep ocean was first suggested by Marchetti (1977) and was subsequently detailed in Chapter 6 of the special IPCC report on carbon dioxide and storage (IPCC, 2005). Little ground-breaking research and no field tests have been performed since then.

Injection of liquid CO_2 in the ocean addresses the storage component of bio-energy capture and storage (BECCS), direct air capture and storage (DACS), and other carbon capture and storage (CCS) technologies, but not the capture. The capture and transformation of gaseous CO_2 into liquid CO_2 is the challenging and costly part, such that disposal has received comparatively less attention. As dissolution of CO_2 in the ocean will alter ocean chemistry with likely impacts on deep ocean ecosystems, alternatives storage location such placing CO_2 in depleted hydrocarbon reservoirs or saline aquifers on land are the primary options for geological sequestration of CO_2 (National Research Council, 2015a).

Underlying principle(s) with citation and extent of knowledge

At depths greater than 2,800 m (28 MPa) and colder than 5 °C the liquid form of CO_2 is the stable phase and at these pressures and temperatures it is denser than seawater. CO_2 injected to those or greater depths will sink to the bottom and dissolve during sinking if suitably dispersed. Small droplets could dissolve completely unless they become coated with hydrates that are a snow-like crystalline substance composed of water ice and carbon dioxide (Yamane *et al.*, 2006). When the liquid CO_2 dissolves it forms carbonic acid that will rapidly dissociated to bicarbonate and carbonate and in the process release hydrogen ions. It becomes part of the inorganic carbon pool of the ocean, and with appropriate means of injection and dispersion will over time it can dilute to close to background values. However, near injection sites there will be hotspots of elevated CO_2 and low pH leading to increased undersaturation with respect to carbonate minerals. Aside that the CO_2 needs to be injected at depth, the sequestration efficiency will be dependent on the location of injection with the least ventilated (isolated) parts of the ocean showing greatest efficiency (Ridgwell *et al.*, 2011).

Evidence of concept from the natural world

There are a limited number of studies and many unknowns about how liquid CO_2 can be injected and dissolve in a natural seawater environment (see IPCC, 2005) and Goldthorpe (2017) is a recent example that does address this issue conceptually. Proposed field studies off Hawaii and Norway in the late 1990s and early 2000s were abandoned due to negative public opinion[22] (Adams *et al.*, 2002; Gewin, 2002; Giles, 2002; Gough *et al.*, 2002). The regulation of this means of disposal would likely fall under The London Convention and London Protocol – see section 2.4. Treating CO_2 storage as pollution can seem inappropriate given that the majority of the anthropogenic carbon emitted to the atmosphere will eventually be stored in the ocean. However, the general definition of pollution covers "deliberate placement of matter or energy" and so does not apply to the passive ocean uptake of anthropogenic CO_2.

Direct/indirect sequestration

The approach is a direct sequestration of liquid CO_2 and subsequent dissolution to become part of the marine inorganic carbon pool. Of note is that once liquid CO_2 turns into DIC it will follow same pathways and have same effect as other methods that have DIC as final product. (e.g. enhancements of the biological pump and subsequent remineralization).

Proposed deployment zone(s) and potential scale of use

The storage capacity of the ocean for inorganic carbon is huge with over half the ocean volumes being at depths greater than 2800 m. Since the deep ocean is generally distant from land, deployment from ships or deep-sea platforms are the most viable options. From a dissolution and impact perspective it is desirable to disperse the injection plume which can be best accomplished by injection from a moving ship (Nakashiki and Hikita, 1995; Ozaki, 1998). Disposal can probably be done with modified current technology and should be readily upscaled. Mid-depth injection also means that the time of isolation to the atmosphere is limited by the characteristic ventilation time of the water at depth. Waters at mid-depth in the North Pacific have the oldest ventilation ages. Most deep waters removed from the ventilation areas on the North Atlantic and Southern Ocean have residence times of centuries up to a millennium (DeVries and Primeau, 2011; IPCC, 2005; Ridgwell *et al.*, 2011).

Duration of deployment

Deployment would be a sustained operation to offset CO_2 increases in the atmosphere. Moreover, as the CO_2 would re-enter the atmosphere on the order of centuries, the efficiency of capture will decrease over time. Reservoir size is not a limiting factor. Upscaling the disposal through utilization of more bulk carriers or open ocean dispersing pipes is technically and operationally feasible.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

Limited field and theoretical studies have been done to date in large part, because other means and locations of storage have lower perceived risk, do not impact unique and largely unexplored environments, and have proven feasibility. Models have determined the efficacy from a global carbon budget and residence time perspective (DeVries and Primeau, 2011; Reith *et al.*, 2016; Ridgwell *et al.*, 2011). Studies on the feasibility from a geochemical/environmental perspective are focussed on the engineering feasibility and cost. The cost estimates range widely from \$5 (Livermont *et al.*, 2011) to \$25 (Andersson *et al.*, 2005) per tonne CO_2 with most costs estimates focused on transport and disposal that can be compared with the cost of CO_2 acquired for enhanced oil recovery of \$40 to \$50 per tonne CO_2. These costs are higher than geological storage (Adams and Caldeira, 2008). The true cost of this mitigation approach that would have to include liquification and capture would be significantly higher. Also, modelling efforts by Adams and Caldeira (2008) and Reith *et al.* (2016) show a 16–30 % decrease of efficiency over time as a result of carbon cycle feedbacks and back fluxes in both land and ocean. However, the natural partitioning of CO_2 favouring the ocean reservoir will mean that much of the CO_2 dissolved will remain in the ocean.

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

The ocean has unique commercial, environmental, economic and cultural values. Moreover, the areas where mid-depth injection would take place are largely unexplored. These factors raise concerns to implementing this storage approach. However, an advantage over liquid storage in geological formations is that the CO_2 in stored in its natural state, and if properly dispersed, with only limited increase of background values. If a total estimated fossil fuel reserve of 5,000 Gt (=109 tonne) CO_2 was uniformly absorbed in the deep ocean (> 2800 m), that contains approximately 70,000 Gt CO_2 of DIC, the DIC would increase by about 7 %. This can be compared to the natural gradient with depth in which total DIC increases about 10 % from surface to mid-depth. The depths of injection have low temperature, no light and are below the saturation depth of calcite minerals such that it already is inhospitable to much biota. Small-scale and short duration studies suggest that the biota at depth is not unduly impacted and bacterial stocks actually increased near dissolving liquid CO_2 (Takeuchi *et al.*, 1997). Of note is that addition of liquid CO_2 and subsequent dissolution in deep water will have amplified effects on ocean acidification compared to surface water as the deep waters are less buffered and close to, or below, conditions at which calcium carbonate particles dissolve.

Using the example above, a 7 % increase in DIC would decrease saturation state at depth by over 50 % and in many cases make the waters corrosive. Thus, injection and dissolution at depth could cause a wholesale change in fragile deep ocean ecosystems. Deep ocean ecosystems are unique, with very low metabolic rates and likely very sensitive to small changes in environmental conditions over long periods of time. Thurber *et al.*, 2014) considered the ecosystem function and services provided by the deep-sea and summarized the important role of the deep-sea in society. These would need to be taken into account in such a disposal

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[22] https://dspace.mit.edu/handle/1721.1/16929

option. More recently, Folkerson *et al.* (2018) carried out a systematic review and meta-analysis of the economic value of the deep-sea. This revealed a lack of sufficient data to accurately estimate the economic value of the deep-sea, emphasized the need for future research into economic value-aspects of the deep-sea and revealed an urgent need for further scientific research into the deep-sea's ecosystem in order to ensure the resource is managed sustainably in the long-term.

Taken in sum, due to the potential biological impacts, high cost, and public acceptance concerns (Gough *et al.,* 2002; Kamishiro and Sato, 2009), little research is currently being conducted in disposal and subsequent dissolution of liquid CO_2 into the deep sea.

5.5 Carbon storage in the ocean – liquid CO_2 placed on the seabed

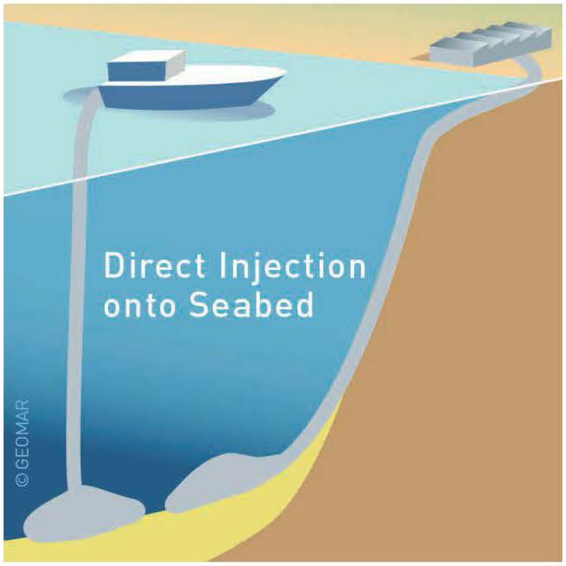

Figure 5.6 *Liquid CO_2 placed on the seabed*

Approach/rationale

Storage schemes of liquid CO_2 on the seabed are generally in the form of lakes of liquid CO_2 in depressions and trenches to maximize storage capacity while minimizing the footprint. It addresses the storage component of carbon capture and storage (CCS) technologies, but not the capture. Alternative storage locations such placing CO_2 in depleted hydrocarbon reservoirs or saline aquifers on land are the primary options for geological sequestration of CO_2 (National Research Council, 2015a). Injection of CO_2 onto the seabed of the deep ocean was detailed in Chapter 6 of the special IPCC report on carbon dioxide and storage (IPCC, 2005). Little ground-breaking research and no field tests appear to have been performed since then.

Underlying principle(s) with citation and extent of knowledge

At depths greater than 2,800m (28 MPa) and 5 °C the liquid form of CO_2 is the stable phase. Based on the physical properties of CO_2 as shown in a gravity diagram (Figure 5.7), liquid CO_2 is denser than seawater at pressures greater than 28 MPa such that CO_2 injected to those depth or greater will remain on the bottom. There are few studies and many unknowns regarding how a liquid CO_2 pool will behave in a natural seawater environment and only a limited number of small-scale in situ studies have verified the stability of liquid CO_2 on the ocean floor of the deep ocean (see Brewer *et al.* 2005 and chapter 6 of IPCC, 2005).

Capron *et al.,* (2013) proposed using geosynthetic containers to securely store CO_2 on the seabed in 2 different ways:

- As solid CO_2 hydrate in geosynthetic containers at depths over 500 metres. This option allows many more sites closer to shore and thus would have lower costs than the other option; and
- As liquid CO_2 in geosynthetic containers at depths below 3,000 metres.

It was claimed that this storage method would become similar to geologic storage over millennia due to gradual burial by deposited detritus and would achieve better than 99.9 % storage permanency. Capron *et al.* (2013) concluded that it was likely that CO_2 could be stored as a hydrate in geosynthetic containers for less than $16 per ton CO_2 for stored volumes of 100,000 tons CO_2. He also proposed that effective real-time monitoring of these geosynthetic containers could provide reliable verification and accounting of stored CO_2.

Caserini *et al.* (2017) described a new process for the storage of liquid CO_2 in glass capsules on the deep seabed. It was claimed to be a safe option to store CO_2 by separating the CO_2 from seawater and thus reducing the risks associated with open disposal of CO_2 on the seabed.

Evidence of concept from the natural world

Liquid CO_2 has been observed on the seabed, likely originating from hydrothermal fluids leaked from a nearby fracture zone (Inagaki *et al.*, 2006). The pool was found at Yonaguni Knoll in the Okinawa Trough at a depth of ≈1,400 m which is striking because liquid CO_2 at this depth is less dense than water (Figure 5.7) and should not remain on the seabed. It appears to be stabilized by a CO_2 hydrate.

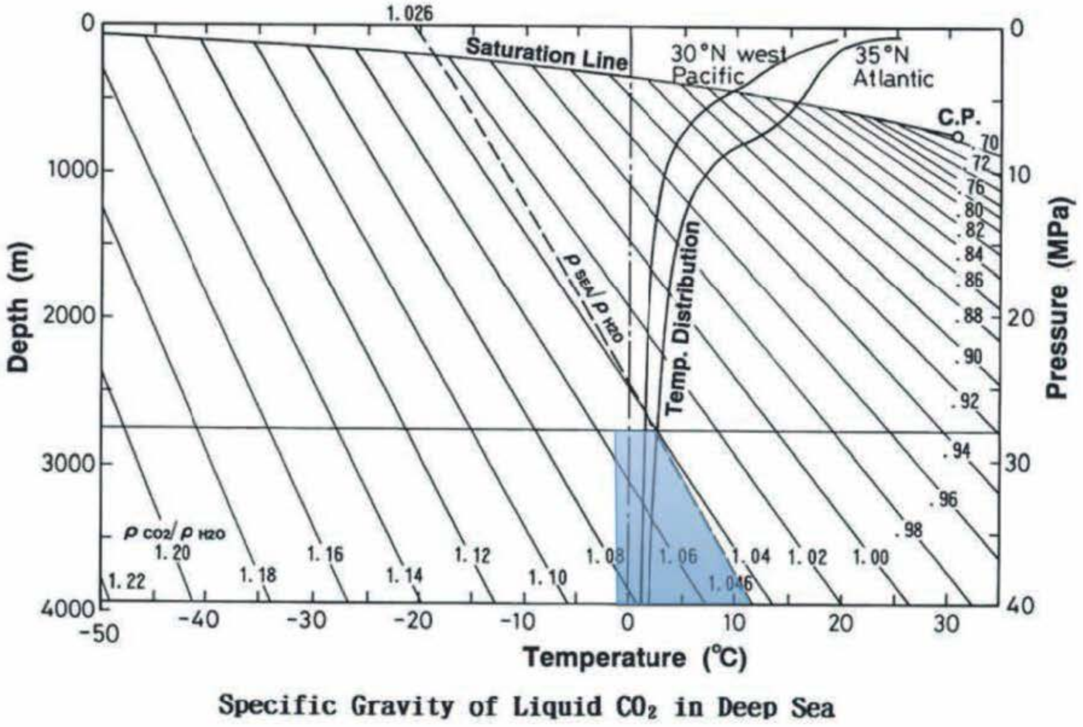

Figure 5.7 *The specific gravity of liquid CO_2 compared to basic ocean water properties (temperature, density, and pressure). The high compressibility of liquid CO_2, and low temperature in the deep-sea, result in gravitational stability of liquid CO_2 at depths ≈>2800 m (blue shaded area). Seawater temperature profiles in the North Pacific and North Atlantic are indicative that for most of the deep ocean liquid CO_2 is the stable phase. Adapted from (Brewer* et al.*, 2005). Reproduced with permission from P.G. Brewer.*

Direct/indirect sequestration

The approach is direct sequestration of CO_2 in its liquid form.

Proposed deployment zone(s) and potential scale of use

The storage capacity of the ocean is large. The global storage potential of the ocean has been estimated in excess of 5,000 Gt of CO_2 by (Haugen and Eide, 1996), which is of the same order as the fossil fuel reserves. Storage capacity of liquid CO_2 in contained environments such as trenches is more limited but still ample to sequester 100's of Gt CO_2 below their sill depths. There are several depression and trenches near major fossil fuel emission sources such that liquid CO_2 storage could be readily and cost-efficiently accomplished (Goldthorpe, 2017; Livermont *et al.*, 2011). Disposal could be done by adaptation of current methods and technologies, largely available from the oil industry, either through pipes from shore or by dedicated ships. In particular, nearshore trenches near industrial regions have been proposed (Goldthorpe, 2017). Trenches have the advantage of containing the liquid well isolated from the atmosphere and with finite surface area inhibiting dissolution thereby increasing storage time and limiting ocean acidification and other possible adverse effects of surrounding waters (Goldthorpe, 2017). Deployment zones for the geosynthetic containers could be almost anywhere that meets the relevant depth criteria, although the design and cost of the containers would vary according to the depth and environments of the selected deposit sites, but for the shallower locations they would need to be located away from any human activities that might impact on the containers e.g. deep-sea fishing. Potential capacity would be very large – trillions of tonnes according to (Capron *et al.*, 2013).

Duration of deployment

Deployment would be a sustained operation to offset CO_2 increases in the atmosphere. Theoretical studies show that sustained injection rates of 20,000 tonne CO_2/day (≈0.02 % of current global CO_2 emissions) in the form of CO_2-hydrates can be achieved with 4 bulk carriers (Andersson *et al.*, 2005). Reservoir size on the ocean floor or isolated in trenches is not a limiting factor. Moreover, upscaling the disposal through pipelines or more bulk carriers would be technically and operationally feasible.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes – modelling, lab, pilot experiments

Small controlled injections of liquid CO_2 have been performed on the seafloor at 4 km depth (e.g. Brewer *et al.*, 2005 and see chapter 6 in IPCC, 2005). These short duration studies were documented with video and in situ probes. The study results suggested that covering the seafloor with liquid CO_2 made it uninhabitable, but there seemed to be no direct short-term and acute impact on nearby fauna. at depth despite high total CO_2 and lower pH near the pool due to dissolution of the liquid CO_2 and transformation to bicarbonate and hydrogen ions in seawater. The illustrative studies were performed by placing a small flume filled with liquid CO_2 on the ocean bottom. A stabilizing hydrate skin formed at the liquid CO_2-seawater interface that was not uniform but had imperfections in the lattice where increased CO_2 loss occurred. This CO_2-water hydrate is expected based on thermodynamics of the interface of the liquid CO_2 and seawater. However, the basic properties and stability of the hydrates in seawater are not well known (Andersson *et al.*, 2005). While a fully formed hydrate will be denser than seawater, any gaps in the CO_2-H_2O matrix will lead to metastable intermediates of lesser density. Also, in the flume study referenced above, surface tension kept the hydrate on the liquid CO_2 surface rather than sinking through the liquid CO_2 pool thereby acting as a partial barrier to dissolution.

Aside from the observations of a natural CO_2 pool by Inagaki *et al.* (2006), and the CO_2 in a flume at 4 km depth (Brewer *et al.*, 2005), limited field and theoretical studies have been done to date – see chapter 6 of IPCC (2005). This is in large part because other means and location of storage have lower perceived risk, do not impact unique and largely unexplored environments, and have proven feasibility. Models have determined the efficacy from a global carbon budget perspective (Reith *et al.*, 2016). Studies on the feasibility from a geochemical/environmental perspective are mostly focused on the engineering feasibility and cost. The cost estimates range from \$5 (Livermont *et al.*, 2011) to \$25 (Andersson *et al.*, 2005) per tonne CO_2 with most costs estimates focused on transport and disposal that can be compared with the cost of CO_2 acquired for enhanced oil recovery of \$40 to \$50 per tonne CO_2. The true cost of this mitigation approach that would have to include capture, liquification and transport would be significantly higher. In general, transport costs for disposal on the deep seabed will be greater than storage on land.

The stability of a lake of CO_2 on the ocean floor is unknown and would be a function of environmental conditions, in particular seawater flow over the surface of liquid CO_2 (Enstad *et al.*, 2008). However, these lakes would be at least partially stabilized by the formation of a surface skin of hydrates at the CO_2/ water interface (Adams and Caldeira, 2008; Brewer *et al.*, 2005; Inagaki *et al.*, 2006; IPCC, 2005) that would slow the dissolution of CO_2 into the water column above. Once dissolved, the CO_2 becomes part of the inorganic carbon pool seawater and its storage time would be a function of the ventilation rate of the water parcel that for deep-water ranges from centuries to millennia (see carbon storage in the ocean, section 5.4 – Reith *et al.*, 2016; Ridgwell *et al.*, 2011).

There does not appears to have been any further research into the use of geosynthetic containers, so their feasibility is unknown. There is much experience with using geosynthetic containers for landfill lining, for encapsulating hazardous materials and in the marine environment for coastal protection purposes and for managing contaminated sediments, but this proposal is very different.

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

The areas where ocean floor disposal would take place are largely unexplored. Lakes of liquid CO_2 on the ocean floor would eliminate established life on and in the immediately underlying sediments. While total biomass at depth is low, the unique and fragile ecosystems are largely unexplored and would likely be significantly impacted by changes in CO_2 (and pH) levels in the waters near a lake of CO_2. (Adams and Caldeira, 2008; Barry *et al.*, 2004; Inagaki *et al.*, 2006; IPCC, 2005; Kita and Ohsumi, 2004; Seibel and Walsh, 2001; Williamson *et al.*, 2012). Thurber *et al.* (2014) considered the ecosystem function and services provided by the deep-sea and summarized the important role of the deep-sea in society and these would need to be taken into account in such a disposal option. See also the paper by Folkerson *et al.* (2018) mentioned in section 5.4 above.

Low probability but large impact events could take place such as displacement of the CO_2 pools into lower pressure higher temperature environments (see Figure 5.7) causing rapid expansion into CO_2 gas that along with positive feedbacks could have negative consequences; there have been reports of CO_2 ebullitions (i.e., bubbling from high CO_2 bottom waters) such as in Lake Nyos in 1986 (Socolow, 2005), but it is uncertain how robust an analogue this event is for liquid CO_2 placed on the seabed at great depth.

However, an advantage over storage in geological formations on land is that there is "secondary containment". Any dissolution of liquid CO_2 into its aqueous forms in the ocean would be absorbed by the surrounding seawater. This would lead to acidification of the water surrounding the pool but at a depth that is already corrosive to marine life (Feely *et al.*, 2004). Once dissolved into seawater, the ventilation timescales will determine the eventual release of CO_2 to the atmosphere, which based on modelling would be on the order of multi-century to millennial timescales depending on location (Reith *et al.*, 2016; Ridgwell *et al.*, 2011).

The physical impact of depositing large numbers of geosynthetic containers on the sea floor would have some similarities to the impact described for the depositing of crop wastes in the deep ocean (see section 5.8). Any impacts arising from leakage from the containers are likely to be similar to those adjacent to lakes of liquid CO_2 on the sea floor (see section 5.4) but of a much smaller scale.

The potential biological impacts, high cost, and public acceptance concerns (e.g. Kamishiro and Sato, 2009) are viewed as significant detriments and little research is currently being conducted on sequestering of liquid CO_2 on the ocean bottom ocean although the concept has been raised by Goldthorpe (2017).

5.6 Carbon storage in the ocean – liquid/solid CO_2 placed into unconsolidated deep-sea sediments

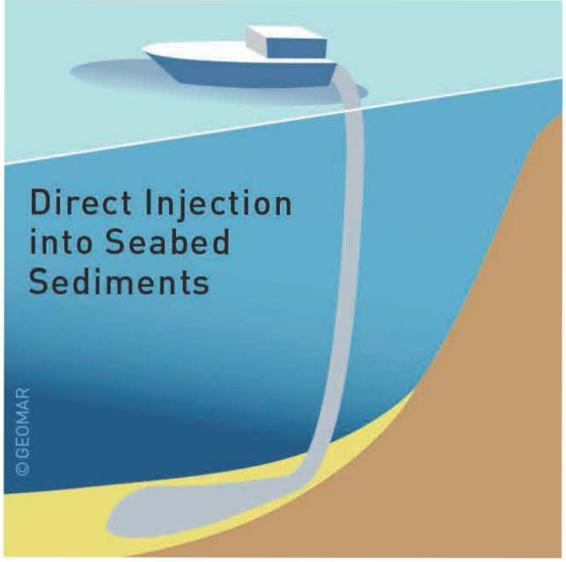

Figure 5.8 *Liquid/Solid CO_2 placed into unconsolidated deep-sea sediments*

Approach/rationale

Carbon dioxide storage in unconsolidated deep-sea sediments was first suggested by (Koide *et al.*, 1997). The technique involves the injection of liquid CO_2 into deep-sea sediments at depths greater than 3,000 metres where it would be stable for very long periods of time.

It should be noted that there have been proposals to extract the methane in deep-sea methane hydrate deposits by replacing the methane with CO_2, thus simultaneously storing the CO_2 and recovering the methane for use as a fuel or feed stock (Babu *et al.*, 2014; Ersland *et al.*, 2009; Goel, 2006; Park *et al.*, 2006). A small-scale deep-sea field test was carried out by Brewer *et al.* (2014). However, concerns have been raised about the risks of massive methane releases from such activities (Marshall, 2009; Zhang and Zhai, 2015).

Underlying principle(s) with citation and extent of knowledge

Liquid CO_2 injected a few hundred metres into deep-sea sediments at greater than 3,000 m depth is stable due to the high pressures and low temperatures in such locations (House *et al.*, 2006; Koide *et al.*, 1997a; Koide *et al.*, 1997b; Qanbari *et al.*, 2011) - see Figure 5.7 in section 5.5 above. Also, at these depths the liquid CO_2 will be denser than the ambient pore fluid, so that it is gravitationally stable (Levine *et al.*, 2007) i.e. the lower density pore fluid acts as a buoyancy cap. In addition, the CO_2 injected into deep-sea sediments will slowly dissolve in the pore fluid and form a solution that is slightly denser than the surrounding pore fluid (House *et al.*, 2006). House *et al.* (2006) state that "The key aspect of our study is to inject pure $CO_2(l)$ (i.e. liquid) below the sediment layer where CO_2 hydrates form and below the sediment layer of less dense pore fluid". In addition, CO_2 hydrate formation at the interface between the liquid CO_2 and pore waters will impede any flow of the liquid CO_2 (House *et al.*, 2006; Koide *et al.*, 1997a; Koide *et al.*, 1997b; Qanbari *et al.*, 2011).

However, House *et al.* (2006) and Qanbari *et al.* (2011) pointed out that with increased depth below the ocean floor and as a result of increased temperature with depth in the sediment, the density of CO_2 reduces faster than that of water such that at some depth below the ocean floor, CO_2 will be lighter than the surrounding water.

Murray *et al.* (1996) proposed to form torpedo shapes in solid CO_2 (dry ice) that when released at the sea surface would gain sufficient velocity to penetrate some distance into deep-sea sediments. It was suggested that this would "...provide permanent storage as the emplaced carbon dioxide will be chemically sequestered by the sediments (via the formation of an intermediate clathrate [=hydrate])".

Evidence of concept from the natural world

None.

Direct/Indirect Sequestration

These techniques would all be direct sequestration.

Proposed deployment zone(s) and potential scale of use

Deployment zones for liquid CO_2 storage in deep-sea sediments, would be areas of the ocean within depths greater than 3,000 m and unconsolidated deep-sea sediments deeper than a few hundred metres above bedrock. The total storage capacity in deep-sea sediments is vast compared to current CO_2 emissions House *et al.*, 2006; Schrag, 2009).

Deployment zones for the solid CO_2 torpedoes would be similar to the zones for liquid CO_2 in deep-sea sediments but would not require such a depth of deep-sea sediments above bedrock. Potential capacity would be very large.

Duration of deployment

This could be for decades or more if required for all these techniques.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

Liquid CO_2 storage in deep-sea sediments - There is currently no direct evidence of the feasibility of this technique. However, this technique could be feasible as it can draw on much experience with drilling for oil and gas in similar depth waters, as well as the more limited experience with projects exploring the potential to extract methane from methane hydrates in the deep-sea – see above. Qanbari *et al.* (2011) carried out modelling to simulate fluid flow and heat transfer when liquid CO_2 is injected into deep-sea sediments. Teng and Zhang (2018) investigated the short-term and long-term fate of injected CO_2 and analysed the viability of CO_2 storage in deep-sea sediments under different geologic and operational conditions. They claimed that under a deep-sea setting, CO_2 sequestration in intact marine sediment is generally safe and permanent.

Solid CO_2 torpedoes – there does not appear to have been any further research on this suggestion since 1997 perhaps because the energy requirements to make solid CO_2 torpedoes and keep them in that state until disposal would be very high. If it were feasible to make and deploy such solid CO_2 torpedoes, then it might be a secure storage technique.

If the techniques work as described, then they should be secure storage techniques. However, much further research would be needed to establish whether that was the case.

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

Liquid CO_2 storage in deep-sea sediments – Provided the CO_2 remained at its initial depth in the sediments and reacted with surrounding sediments and pore waters as described, there should be little impact on the chemistry and biology of the seabed and overlying waters. However, any biota, probably limited to microbiota and bacteria, at and close to the location of the injected liquid CO_2 is likely to be significantly impacted.

Solid CO_2 torpedoes – While the impacts of this technique may have some similarities with those for liquid CO_2 storage in deep-sea sediments, the risks of impacts on the chemistry and biology of the seabed and overlying waters would be likely to be somewhat higher as the emplaced CO_2 torpedoes would be likely to be closer to the sea floor and thus have a thinner sediment cover. However, those risks would be significantly less than from CO_2 lakes on the sea floor due to the attenuation provided by the overlying sediments and to the formation of CO_2 hydrate around the body of the torpedoes.

5.7 Carbon storage in the ocean - mineralisation of CO_2 in geologic structures beneath the seabed[23]

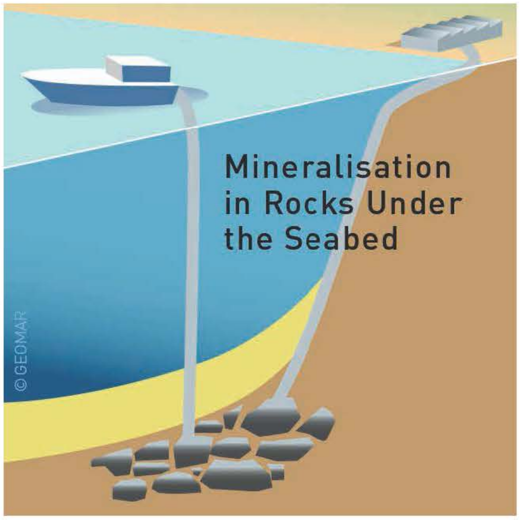

Figure 5.9 *Mineralisation of CO_2 in rocks beneath the seabed*

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[23] i.e. in geological structures beneath unconsolidated seabed sediments.

Approach/rationale

Using mineral silicates to form carbonates in an engineering context was first mentioned by Seifritz (1990) and studied in detail in by Lackner *et al.* (1995). Carbon dioxide can be injected into basalt and peridotite rocks where it reacts with the calcium and magnesium ions in silicate minerals to form stable carbonate minerals (Matter and Kelemen, 2009; McGrail *et al.*, 2006). Basalt rocks are commonly found beneath the oceanic seabed where they may be suitable to sequester CO_2 (Goldberg *et al.*, 2010; Goldberg *et al.*, 2008; Goldberg and Slagle, 2009). Goldberg *et al.* (2018) described the CarbonSAFE Cascadia project that is conducting a pre-feasibility study to evaluate technical and non-technical aspects of collecting and storing 50 million tonnes of CO_2 in an ocean basalt reservoir offshore from Washington State and British Columbia.

Note that unlike the storage of CO_2 in unconsolidated deep-sea sediments covered in section 5.6 above, this technique may be able to be carried out at much shallower depths since the CO_2 is not stored in liquid form but reacts with the minerals in the rocks to form new minerals.

This technique is not the same as carbon capture and storage (CCS) where the CO_2 is physically stored in the pore space of the rock formations. While this mineralisation activity may be thought of as a form of CCS and so be covered by the London Protocol under the 2006 amendments to Annex 1 (IMO, 2016a), the London Protocol's CCS Specific Guidelines and associated Risk Assessment and Management Framework were not written with this activity in mind and are thus unlikely to be appropriate for it in their current forms.

Underlying principle(s) with citation and extent of knowledge

Injected CO_2 mixes reacts with basalt and the subsequent release of Ca^{2+} and Mg^{2+} ions from basalt forms stable carbonate minerals as reaction products. This is well documented (Goldberg *et al.*, 2008).

Evidence of concept from the natural world

In nature, mineral carbonation of host rocks occurs in in a variety of well documented settings, such as hydrothermal alteration at volcanic springs, through surface weathering, and in deep ocean vent systems (Goldberg *et al.*, 2008). Also, volcanic geothermal systems store CO_2 derived from magma as calcite within basaltic rocks (Snæbjörnsdóttir *et al.*, 2014).

Direct/indirect – sequestration

This is direct sequestration.

Proposed deployment zone(s) and potential scale of use

This means of CO_2 sequestration utilises basaltic rocks that are very common on the earth's surface (Snæbjörnsdóttir *et al.*, 2014) and also under the ocean (Goldberg *et al.*, 2008; Goldberg and Slagle, 2009). The capacity of these rocks to store CO_2 is potentially orders of magnitude greater than the release of CO_2 by burning all the fossil fuels on earth (Goldberg *et al.*, 2008; Goldberg and Slagle, 2009; Snæbjörnsdóttir *et al.*, 2014).

Duration of deployment

Given the vast storage capacity referred to above, the duration of deployment could be decades to centuries.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

CarbFix is a project that aimed at developing safe, simple and economical methods and technology for permanent CO_2 mineral storage in basalts (https://www.or.is/carbfix). In 2011-2014, the CarbFix project received funding through the European Commission's 7th framework programme for research and technological development. During that time, the project developed the technology and expertise to capture, transport and geologically store CO_2 as carbonate minerals through in situ carbonation in the subsurface. This knowledge has furthermore been demonstrated at the pilot scale at Hellisheidi power plant, SW-Iceland, where a pilot gas separation station, pipes for transport and injection and monitoring infrastructure was successfully built and operated (European Commission, 2015; Matter *et al.*, 2016; Gislason *et al.* 2018, Gunnarsson *et al.*, 2018). The project found that over 95% of the CO_2 injected into the CarbFix site was mineralized to carbonate minerals in less than 2 years (Matter *et al.*, 2016).

A follow-on project, CarbFix2, aims on moving the demonstrated CarbFix technology from the demonstration phase to a general and economically viable complete CCS chain that can be used through Europe and throughout the world. CarbFix2 has received funding from the European Union's Horizon 2020 research and innovation programme (https://www.or.is/carbfix2).

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

There is no information about the potential environmental impacts of this technique were it to take place in the marine environment. The only large-scale experiment to date – CARBFIX – occurred on land. (Trias *et al.*, 2017) have shown that the microbial populations living in deep in basalts are affected by injected acidic CO_2-charged groundwater.

5.8 Carbon storage in the ocean – depositing crop wastes in the deep ocean

Figure 5.10 *Depositing crop wastes in the deep ocean*

Approach/rationale

Metzger and Benford (2001) suggested that the sequestration of weighted bales of crop residues (corn, wheat and soybeans) by their disposal in the deep ocean or off the deltas of major rivers could capture 12% of the U.S. atmospheric carbon emissions at that time. They also suggested that the bales could be shaped to allow penetration of several metres into the soft sediments in the deep ocean and that this would provide more secure sequestration. This concept was further developed by Strand and Benford (2009) who referred to it as 'Crop Residue Oceanic Permanent Sequestration' (CROPS). They suggested ballasting the bales of crop residue with stone. They projected that up to 0.6 Gt C (30% of global annual crop residues of 2 Gt C) could be available sustainably i.e. not cause unacceptable harm to soils and could be deposited in an annual layer 4m deep in an area of seabed of ~1,000 km² at greater than 1,000-1,500 metres depth. Potentially, charcoal (biochar), timber or other organic remains could also be deposited on the deep ocean seabed, if suitably ballasted.

It should be noted that this technique would appear to be covered by the existing category of wastes "Organic material of natural origin" in Annex I of the London Protocol and "Uncontaminated organic material of natural origin" in Annex I of the London Convention (IMO, 2016a). If that is the case, it means that disposal of such material at sea may be permitted subject to satisfactory assessments; although the existing guidance for this category of wastes would need to be reviewed/amended to ensure it was appropriate for such disposals.

Underlying principle(s) and extent of knowledge

The principle of this technique is to sequester significant amounts of carbon in the deep ocean with a slow return to the atmosphere over some hundreds to several thousands of years.

There are large unknowns due to the limited knowledge about this technique. Only a few peer-reviewed papers on the proposed technique have been published including one laboratory study. Furthermore, while there is a large body of knowledge about the impact of the deposit of organic material on continental shelf sediments e.g. sewage sludge (Pearson and Rosenberg, 1977), it is unclear whether this is readily translated into the very different deep-sea environment.

Burdige (2005) suggested that the remineralisation of terrestrial organic matter in the oceans was much less efficient than that of marine organic matter. Keil *et al.*, (2010) found in a laboratory experiment using deep-sea sediments that overall, the weight-averaged degradation rate constant for the agricultural crops is more than two orders of magnitude slower than the weight-averaged value for plankton. It seems likely that studies of locations where there is rapid export of terrestrial organic matter into the deep-sea could provide useful information about the degradation of crop wastes in the deep ocean. An example of such a location is off Taiwan where extreme river flood discharges due to typhoons rapidly export organic matter into the deep-sea (Kao *et al.*, 2014; Selvaraj *et al.*, 2015).

Evidence of concept from the natural world

See sub-section above.

Direct/indirect sequestration

This would be direct sequestration but there would be some leakage back to the atmosphere over the long-term i.e. over hundreds to thousands of years.

Proposed deployment zone(s) and potential scale of use

The proposed deployment locations are areas of the deep ocean greater than 1,000-1,500 metres deep and potentially off the deltas of major rivers carrying substantial sediment loads where the crop residues would be rapidly buried by newly deposited sediments. Strand and Benford (2009) allowed for an average trucking distance of 200 km, an average river shipping distance of 3,000 km and an average shipping distance to deep ocean deposition sites of 1,000 km. They suggested that up to 0.6 Gt C (30% of global annual crop residues of 2 Gt C) could be available sustainably i.e. not cause unacceptable harm to soils. They estimated that if 30% of the U.S. crop residues were sequestered, 0.15 Gt crop residue per year could be deposited on the ocean floor; a volume of ~1 x 109 m^3/year. If this was deposited in an annual layer 4 m deep, it would cover an area of 260 km^2.

Duration of deployment

This technique could potentially be utilised on a continuous basis over very long periods of decades or more.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

In their proposal, (Strand and Benford, 2009) took into account the carbon emitted per ton of crop residues processed for nutrient replacement, baling, transportation and ballast.

Keith (2001) suggested that the use of such biomass to produce electricity in a power plant that captures the CO_2 and sequesters it in geological formations would be a more effective option. Keith and Rhodes (2002) and Metzger *et al.*, (2002) further discussed the merits of crop sequestration in the deep ocean versus its use to produce electricity with carbon capture and storage.

Karlen *et al.*, (2000) pointed out that crop residues provide many services within sustainable and well-functioning agricultural systems and raised concerns that CROPS may have important, unintended, and harmful consequences for those systems. They state that "Crop residues have multiple biological, chemical, and physical roles that are crucial for sustaining the soil resources upon which humans depend for food, feed, fibre, and, most recently, feedstocks for biofuel. Crop residues protect soil resources from wind and water erosion, serve as food sources for micro- and macro-organisms, and enhance nutrient cycling, water relationships (infiltration, retention, and release), and soil structure". They also challenged the economics of the proposal.

Keil *et al.* (2010) evaluated the potential of crop residue sequestration in deep-sea sediments through a controlled 700-day incubation experiment where crop residues (soy stalk, maize stover, and alder wood chips) were added to deep-sea hemipelagic sediments in the laboratory. The degradation rate constants for the agricultural crops were more than two orders of magnitude slower than for plankton. Modelling of the remineralization data indicated that after 2 years more than 92% of the crop residue remained and out to 100 years suggested that more than 75% of the crop residue would likely remain in the sediment.

An annual sequestration rate < 1 Gt C/yr (< 3.7 Gt CO_2/yr) would only make a modest contribution to slowing climate change (Lenton and Vaughan, 2009).

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

Where crop residues are deposited as ballasted bales in bulk, it is certain that there will be significant physical impact on the seabed due to the sheer mass of the material covering the seabed. In addition, there may be wider chemical and biological impacts through reductions in oxygen and potential increases in hydrogen sulphide, methane, nitrous oxide and nutrients (nitrogen and phosphorus compounds) arising from the degradation of the organic matter.

The degradation of crop residue bales is likely to be slow due to the ambient conditions of low temperature and limited oxygen availability; the apparent lack of a marine mechanism for the breakdown of lignocellulose material; and the anaerobic conditions within the bales (Strand and Benford, 2009) as confirmed by Keil *et al.* (2010). While it can be argued that potential impacts could be reduced if deposition occurred in areas of naturally high sedimentation, such as off the mouths of major rivers e.g., the Mississippi (Strand and Benford, 2009), many such areas are already susceptible to eutrophication and anoxia from existing anthropogenic, land-derived nutrient inputs. These effects are likely to be worsened if increased use of inorganic fertilizer were needed to replace the nutrients removed in the crop residues.

The type of packaging would also be significant when assessing potential impacts as its permeability to water and gases would influence the flux of substances into near-seabed waters. If the bales were buried within the sediment, then such impacts are likely to be significantly reduced due to slower release rates into near-seabed waters. Geosynthetic containers, as suggested by Capron *et al.* (2013) for storing CO_2 on the seabed (see section 5.6), could also be used to contain crop wastes. Additional manipulations or packaging would, however, almost certainly have significant cost implications.

If organic matter leaked out from the packages in significant amounts, this addition of organic matter to the deep-sea seabed and near bottom waters could lead to reduced oxygen levels and to greater density and biomass of benthic organisms over a long period in the locations where the crop residues are deposited: a perturbation from the natural state.

The limited knowledge of ecosystem services from the deep-sea combined with limited understanding of the impacts of depositing crop wastes on the deep ocean seabed, lead to a lack of understanding about its impacts on ecosystem services. However, if done in the shallower end of the water depths suggested (1000–1500 m), its impacts on ecosystem services could be more significant since this is now within the range of deep-sea fisheries. Whilst the area directly affected could be relatively restricted (on a global scale), larger-scale and longer-term indirect effects of oxygen depletion and deep-water acidification could be regionally significant if there is cumulative deposition of many gigatonnes of organic carbon to the seafloor, and most of this is eventually decomposed.

5.9 Carbon storage in the ocean – macroalgal cultivation for sequestration and/or biofuels

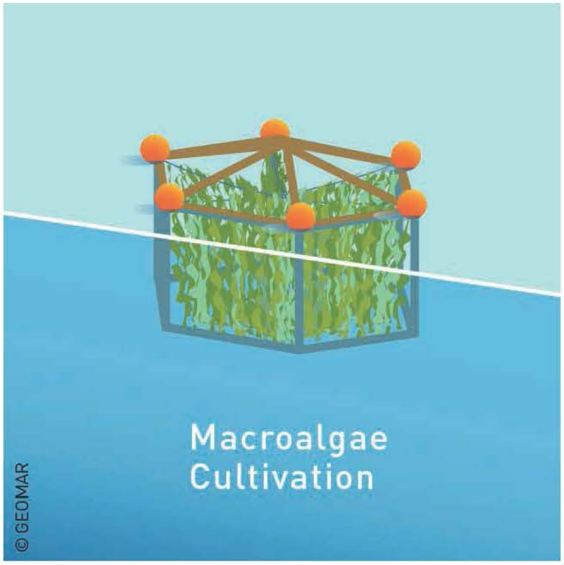

Figure 5.11 *Macroalgal cultivation for sequestration and/or biofuels*

Approach/rationale

Macroalgal aquaculture in the nearshore environment, to supply a range of products from food to nutraceuticals, is a well-established industry globally (Pereira and Yarish, 2008), and in particular in China, Japan and S. Korea (Chung *et al.,* 2011). In this Asia-Pacific region, macroalgal cultivation already may account for ~0.8 Mt organic carbon accumulated annually (Sondak *et al.,* 2017), this compares with estimates of the natural and ongoing sequestration of macroalgae in the deep ocean and sediments of ~170 Mt C per year (Krause-Jensen and Duarte, 2016). There has been debate about whether this aquacultural approach can be extended onto larger scales to produce biomass that could potentially be sequestered (Chung *et al.,* 2011; Duarte *et al.,* 2017; Moreira and Pires, 2016; Raven, 2017). Macroalgal material could be stored in containers placed on the deep ocean seabed e.g. the geosynthetic containers referred to in section 5.6, but the costs of such an approach may make it impractical. Sondak *et al.* (2017) advocated that cultivated macroalgae could mainly play a key role as a 'carbon donor' for biomass conversion into biogases and/or biofuels.

Underlying principle(s) with citation and extent of knowledge

The large amount of carbon biomass that is harvested from macroalgal cultivation in nearshore waters (Sondak *et al.,* 2017) has been used to demonstrate the potential of this approach for CDR geoengineering (Chung *et al.,* 2013). The term 'ocean afforestation' was introduced by N'Yeurt *et al.* (2012) and this led to discussion about the role of macroalgae as 'blue carbon' (usually associated with sediment-linked biota such as sea-grasses, mangroves and saltmarshes). Chung *et al.* (2013) pointed out that the lack of a sediment-substratum link for kelp would probably prevent macroalgal carbon being sequestered on long timescales and that their potential role lay in bio-fuels. Sondak *et al.* (2017) reached a similar conclusion with respect to their main role being "carbon donors'.

Evidence of concept from the natural world

A recent study has highlighted the potential of macroalgae to currently play a significant role in the oceans biological pump (Krause-Jensen and Duarte, 2016) and hence challenges the above assertion by Chung *et al.* (2013). The authors collate reports of the sequestration of macroalgae in the deep ocean and also marine sediments and use this as the basis to develop a global budget for macroalgal carbon sequestration, along with propagation of error analysis. Krause-Jensen and Duarte (2016) report that macroalgae have the potential (without enhanced cultivation) to sequester ~170 Mt C annually (c.f. 5-10 Gt C per year by the phytoplankton-driven oceanic biological pump). Most of the macroalgal sequestration is through export to the deep-sea (90%) with the remainder buried in coastal sediments.

Direct/indirect sequestration

Direct C sequestration via burial in sediments and export to the deep ocean (Krause-Jensen and Duarte, 2016), and indirect sequestration if used for bio-fuels (Chung *et al.,* 2013; Sondak *et al.,* 2017).

Proposed deployment zone(s) and potential scale of use

Current deployment zones are in the coastal ocean (Pereira and Yarish, 2008) and based on the natural C sequestration budget of (Krause-Jensen and Duarte, 2016) and/or the estimates from intensive aquaculture (Sondak *et al.,* 2017) would have to be expanded into more nearshore areas and/or moved offshore (Buck *et al.,* 2004) to achieve a significant scale of additional sequestration. There has also been debate about using hybrid approaches such as permaculture[24] (Flannery, 2017) in which macroalgal cultivation takes place alongside other forms of aquaculture within 1 km length scale submerged to 25 m depth, to avoid navigational issues. This approach is also termed IMTA (Integrated Multi-Trophic Aquaculture[25]), (Troell *et al.,* 2009; Buck *et al.,* 2018). Other hybrid approaches (proposed for offshore waters) include macroalgal farms in conjunction with wind farms (Buck *et al.,* 2004).

Duration of deployment

The deployment(s) would likely be long-term (years, sustained, ongoing) as this approach is CDR geoengineering (see National Research Council, 2015a).

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

There has been a range of pilot studies, perhaps best exemplified by the CCRB (Coastal CO_2 Removal Belt) off South Korea (Chung *et al.,* 2013). The 0.5 ha CCRB pilot farm (with perennial brown macroalgae on a mid-water rope-culture framework for grazer avoidance) has removed 10 t CO_2 ha-1 y-1 as measured using net community production and time-series of dissolved inorganic carbon (Chung *et al.,* 2013). Prospects for the use of macroalgae for fuel in Ireland and the UK have been evaluated, informed by stakeholder interviews (Roberts and Upham, 2012). They found considerable practical obstacles to the technology, amplified as operations move offshore, leading to scepticism among stakeholders that an offshore industry could develop. However, a Norwegian study on the opportunities and risks of seaweed biofuels in aviation indicated large coastal area potentially available for seaweed production (Andersen, 2017).

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

There is little evidence, so far, of assessment of side-effects from either macroalgal cultivation or IMTA pilot studies (such as Chung *et al.,* 2013). There is also little discussion of the need for, and implications of, upscaling cultivation, either in nearshore and/or offshore waters, to increase the magnitude of C sequestration, or how to detect and attribute sequestration. Clearly, modelling simulations could be used to further develop this debate.

Several studies have recently examined the wider ecological or societal implications of macroalgal cultivation for geoengineering (Aldridge *et al.,* 2012; Cottier-Cook *et al.,* 2016; Wood *et al.,* 2017). Cottier-Cook *et al.* (2016) produced a policy brief which considers and debates "how the production of seaweed affects and impacts our alternate source of safe food and nutrition supplement or our surrounding environment, with respect to pollution of coasts, our indigenous biodiversity, disease outbreak (food safety standard -pet food, chocolate and toothpaste), climate change mitigation, fair trade and blue economy". Wood *et al.* (2017) have recently raised a range of policy-relevant issues around the licensing of further work into this potential marine geoengineering approach.

5.10 Ocean pumping – artificial upwelling

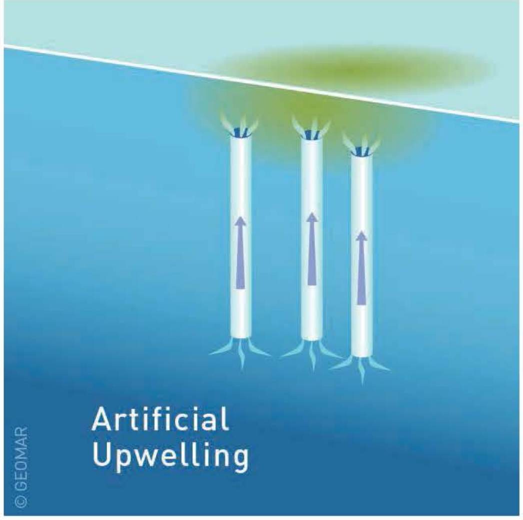

Figure 5.12 *Artificial upwelling*

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[24] http://theconversation.com/how-farming-giant-seaweed-can-feed-fish-and-fix-the-climate-81761

[25] http://www.dfo-mpo.gc.ca/aquaculture/sci-res/imta-amti/imta-amti-eng.htm

Approach/rationale

Over vast areas of the mid- and low-latitude oceans, nutrients are depleted in the surface waters, limiting biological production (Cullen, 1995; Karl *et al.*, 1997; Moore *et al.*, 2013). Artificial upwelling has been suggested as a fertilization measure by bringing deeper, nutrient-rich waters to the sunlit surface ocean, where they can stimulate phytoplankton growth and subsequently export of organic carbon to depth. Artificial upwelling has also been discussed for enhancing fish production or cooling coral reefs (Kirke, 2003). Deeper waters are generally enriched in nutrients relative to surface waters due to the remineralization of organic matter exported from the surface to the ocean interior. For the same reason, deeper waters generally hold more dissolved inorganic carbon. In contrast to iron fertilization, artificial upwelling does not introduce new nutrients, but merely redistributes nutrients within the ocean. A second effect of artificial upwelling is that upwelled deeper waters are generally colder than ambient surface waters, thereby cooling the ocean's surface and, eventually, the overlying air, thus helping counter global warming at least at local/regional scales.

Underlying principle(s) with citation and extent of knowledge

Lovelock and Rapley (2007) suggested in a short note that artificial upwelling could "...stimulate the Earth's capacity to cure itself...". Oschlies *et al.*, (2010b) and Yool *et al.* (2009) essentially refuted the concept that fertilization by artificial upwelling could lead to a significant drawdown of CO_2 because upwelled nutrients are accompanied by a stoichiometric equivalent of respired carbon. Artificial upwelling can, however, induce some net marine CO_2 uptake in regions where upwelled waters have a particularly low CO_2 content. Integrated until year 2100 in a business as usual emission scenario, the oceanic uptake is estimated as less than 20 Gt C (Oschlies *et al.* (2010). That is equivalent to a 10-ppm atmospheric drawdown, which is appreciable compared to capacity some of the other techniques mentioned. Colder upwelling waters lead to lower sea surface temperatures and a number of dominant effects:

(i) surface air temperatures are reduced, which if conducted at a large enough scale cools the land. In the models, this reduces respiration and thereby enhances terrestrial carbon sequestration (up to 100 Gt C in the model experiments of Oschlies *et al.* (2010). The cooling also helps counter, at least at some spatial and temporal scale, ongoing GHG-driven surface warming;

(ii) Lower sea surface temperatures reduce outgoing long-wave radiation of the planet. As a result, Earth accumulated more energy during the operation of artificial upwelling. The additional energy is stored as heat in the subsurface waters that are displaced downward by the overlying upwelled waters. This disturbs the thermocline and, on centennial timescales, leads to higher global mean temperatures (Kwiatkowski *et al.*, 2015); and

(iii) Artificial upwelling can have substantial termination effect. Once artificial upwelling stops, the additional heat can make it back to the surface and lead to surface temperatures that exceed those of a planet that had never experienced artificial upwelling (Keller *et al.*, 2014; Oschlies *et al.*, 2010).

Evidence of concept from the natural world

Because of the enhanced supply of nutrients from a few hundred meters depth to the sea surface, regions of natural upwelling, in particular eastern boundary upwelling regions off Namibia, California and Peru, but open-ocean upwelling regions along the equator and in the Arabian Sea, are the most productive regions in the World Ocean (Chavez and Messié, 2009). Temperatures of the surface waters are lower than ambient temperatures by several degrees. However, because of the high amounts of respiratory carbon in the nutrient-rich upwelled waters, upwelling regions are usually areas where CO_2 outgasses from the ocean to the atmosphere (Takahashi *et al.*, 2009). From the natural world, there is thus strong evidence that upwelling enhances biological production, phytoplankton growth and export. There is also strong evidence that upwelling cools the ocean surface and overlying atmosphere. However, there is no evidence that upwelling leads to local [net] uptake of CO_2 from the atmosphere.

Direct/indirect sequestration

Direct sequestration is thought to be small (< 20 Gt C until year 2100). Indirect sequestration is estimated several times larger and related to reduced soil respiration at lower atmospheric temperatures that follow colder sea surface temperatures.

Proposed deployment zone(s) and potential scale of use

Deployment zones are the vast areas of the mid- and low-latitude oceans where nutrients are depleted in the surface waters, limiting biological production. Since, the power of hurricanes/cyclones are strongly affected by the sea surface temperature (Murakami *et al.* 2018;), artificial upwelling has also been proposed as a measure to weaken hurricanes by bringing cooler water to the surface, with model studies showing some potential for artificial upwelling reducing hurricane-induced damages on land (Klima *et al.*, 2012; Launder, 2017).

Duration of deployment

Different durations of deployment are discussed for different applications. Ocean carbon sequestration is discussed in terms multi-decadal operation of artificial upwelling, possibly with seasonal modulation to maximize CO_2 drawdown (Pan *et al.*, 2016). Deployment would be much shorter (days) for a potential mitigation of hurricanes.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

A number of modelling studies have shown that there is limited potential in artificial upwelling drawing down carbon from the atmosphere (Oschlies *et al.*, 2010). Artificial upwelling devices have been tested in the field (White *et al.*, 2010). A number of short-term field trials focused mainly on the technical feasibility of generating upward transport and on the supply of nutrients (Pan *et al.*, 2016). Casareto *et al.* (2017) described enhanced phytoplankton production in a small-scale upwelling field experiment. They did not report measurements on carbon sequestration.

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

Giraud *et al.* (2016) studied the potential impact of artificial upwelling on plankton ecosystems and found substantial changes in species composition.

Enhanced biological production at the scale required for climatic benefits is likely to lead to enhanced remineralization of organic material in the water column and thus significantly deplete mid-water oxygen levels and increase methane and nitrous oxide release (Williamson *et al.*, 2012a and 2012b) .

5.11 Ocean pumping – ocean carbon capture and storage

Approach/rationale

The vast majority of available inorganic carbon of the planet is dissolved in the oceans in various chemical forms (Archer, 2005; Sarmiento and Gruber, 2002). Almost all of this is in the dissolved inorganic form (DIC) and is the sum of the carbon in carbon dioxide, carbonic acid, bicarbonate and carbonate. This DIC reservoir in the ocean exchanges naturally with the atmosphere, being taken up in some regions and released in others (Takahashi *et al.*, 2009) according to the air-water CO_2 concentration gradient. The approach of OCCS is to remove DIC from the ocean and to transport it to sites of long-term storage as for other carbon capture and storage (CCS) schemes. The subsequent return to equilibrium between the ocean and the atmosphere will involve absorption of CO_2 from the atmosphere.

OTEC (Ocean Thermal Energy Conversion) is a potential approach which could be applied in parallel both to provide deep water which has high DIC concentration and to provide (locally) the energy required for the entire process.

Underlying principle(s) with citation and extent of knowledge.

The principle of removing DIC from seawater is not new and is an inherent part of some types of seawater analysis. Bipolar Membrane Electrodialysis (BPMED) has been recently developed to perform this task (Eisaman *et al.*, 2012; Willauer *et al.*, 2017) and could be the basis of a development in OCCS. The principle is that seawater is pumped through a BPMED system and results in two output streams: acidified and basified seawater. In the acidified stream, the HCO_3^- and CO_3^{2-} ions in the input seawater are converted into dissolved CO_2, which is subsequently vacuum stripped, producing a stream of pure CO_2 gas. The CO_2-depleted acidified solution is then combined with the basified solution, creating a neutral-pH solution that can be returned to the ocean. The laboratory-based technique has achieved 59% extraction of DIC as CO_2 gas with an energy consumption of 242 kJ/mol (CO_2) (Eisaman *et al.*, 2012). de Lannoy *et al.* (2017) reported the construction and assessment of a prototype system based on the laboratory scale system of Eisaman *et al.* (2012). The paper by de Lannoy *et al.* (2017) reported similar extraction efficiencies and it presents the design, experimental characterization, analysis of the closed-loop acid process efficiency, identification of the most cost-sensitive parameters, and recommendations for future optimization. The data from this study were fed into a techno-economic model (Eisaman *et al.*, 2018) which identifies the most cost-sensitive aspect. The model and accompanying analysis (Eisaman *et al.*, 2018) highlight the current cost challenges and identifies some critical R&D requirements. More work is also required to explore the feasibility of large-scale engineering development of OCCS and the associated costs.

At a more advanced stage of development is research into the practicalities of OTEC. The broader environmental consequences of OTEC have been addressed by Fujita *et al.* (2012) and Grandelli *et al.*, (2012) and see section 5.17 below.

The deployment of an OCCS system within an OTEC plant has major benefits in that deep DIC-rich seawater is supplied to the surface by OTEC and furthermore there is a local energy supply which could be used to support the entire process including the energy-demanding process of DIC extraction. An alternative, negative-emissions OTEC has also been proposed (Rau and Baird, 2018).

Evidence of concept from the natural world

Conceptually this is one of the simplest CDR techniques which have been suggested for the ocean, stimulating a process, outgassing, which already occurs but capturing the CO_2 released rather than allowing it to escape to the atmosphere.

Direct/indirect - sequestration

As OCCS extracts CO_2, it has the potential to directly sequester carbon.

Proposed deployment zone(s) and potential scale of use

One proposal has been to combine this with OTEC so that the locations suitable for OTEC would determine suitable locations for OCCS i.e. the tropics. If alternative sources of low-carbon energy are used such nuclear power, a wide variety of coastal locations could be considered.

Duration of deployment

Once developed, this technique would continue to run indefinitely.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

As stated above, this proposed technique is in its early stages and would require massive development from the current prototype method to one involving large flow rates of hundreds of tonnes per second. Consequently, significant theoretical work is required to determine if it is feasible as a technique for climate mitigation followed by major engineering development if OCCS is to be developed. A very significant issue is the supply of energy required to pump water into the system and extract the CO_2. One proposal has been to combine this with OTEC – see section 5.17 below. Cost issues and energy requirements would seem the main constraints on this approach.

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

There have been no impact studies to date on OCCS but clearly the manipulation of large volumes of seawater in this way could have a deleterious effect on oceanic biota. The effect on the atmosphere would simply be to enhance ocean uptake of CO_2 as a result of the increased concentration gradient between the atmosphere and the ocean.

There have however been studies on the OTEC system which may be associated with OCCS in order to provide the required energy source. (Grandelli *et al.*, 2012) modelled the effect of a 100MW OTEC plant off Hawaii discharging effluent seawater at 70m depth at 750 tonnes/second. The 70 m depth was selected in order to reduce adverse effects on the euphotic zone where primary production occurs. The effects on nutrients, primary production and lower trophic groups were apparently modest and within the envelope of natural variability, although the long-term consequences of this artificial upwelling of deep water require additional research. However, the productive layer in this area extends well below 70 m depth.

5.12 Ocean pumping – artificial downwelling

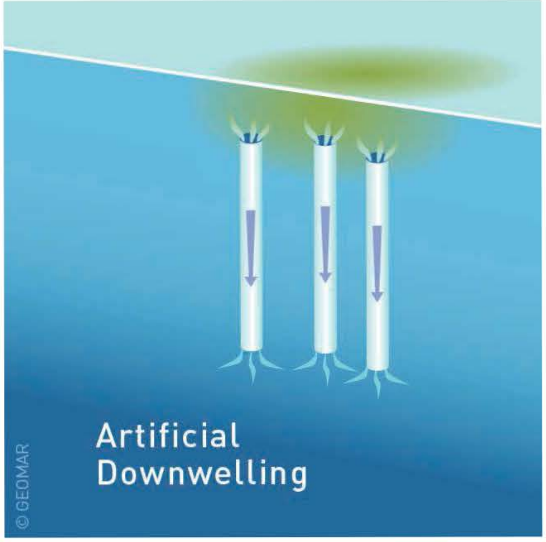

Figure 5.13 *Artificial downwelling*

Approach/rationale

Artificial downwelling has been suggested to enhance the solubility pump of carbon, by downwelling cold surface waters saturated in CO_2 into the ocean interior (Zhou and Flynn, 2005). At the sea surface, downwelled waters would be laterally replaced by warmer surface waters that subsequently cool and, in this process, take up CO_2 via cooling-enhanced solubility. Artificially enhancing the formation of sea ice could help to induce downwelling via the release of salty brine from the forming sea ice. As CO_2 concentrations in the brine would be elevated, addition of CO_2 would be difficult. The main approach considered is therefore the enhancement of downwelling and associated transport of CO_2-saturated waters to depth. Artificial downwelling has also been proposed to weaken hurricanes (Intellectual Ventures, 2009; Salter, 2009).

Underlying principle(s) with citation and extent of knowledge

Artificial downwelling was first proposed by Zhou and Flynn (2005). Lenton and Vaughan (2009) estimated that by continuously cooling surface waters by 1 °C in the downwelling region forming North Atlantic Deep Water, less than 1 Gt C could be sequestered until the year 2100, at high costs. Storage would also not be permanent, as the additional carbon downwelled would eventually upwell on centennial to millennial timescales.

Zhou and Flynn (2005) estimated the energy production required to cool 1 Sv (Sverdrup = 1,000,000 m^3/sec) of seawater from 6 °C to 0 °C as 25 TW and arrived at cost estimates between 4,000 and 20,000 USD per tonne of CO_2, with lower cost estimates (177 USD per tonne CO_2) for a speculative thickening of sea ice by spraying salty seawater on floating ice and expecting that melting of the thickened ice in spring would release more salt, enhance the density of surface waters and subsequent downwelling. None of these ideas have been tested in ocean circulation models nor in the field. Because of the low sequestration potential and high costs, artificial downwelling has, until now, not been considered further in recent assessments of climate engineering proposals.

Evidence of concept from the natural world

The oceans solubility pump is thought responsible for about a quarter to a third of the vertical gradient of dissolved inorganic carbon in the global ocean. The residence time of deep waters is hundreds to a few thousands of years. So even though sequestration would not be permanent, it could help to "shave the peak" of atmospheric CO_2 concentrations.

Direct/Indirect Sequestration

So far, only direct effects have been estimated. Changes in ocean overturning will likely induce indirect effects.

Proposed deployment zone(s) and potential scale of use

Arctic Ocean near regions of North Atlantic Deep Water formation (and its precursors) has been suggested. Some ideas involve artificial thickening of sea ice.

Duration of deployment

Seasonal to permanent. Deemed to be stoppable without termination effects.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

None available.

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

None available.

5.13 Enhancing ocean alkalinity

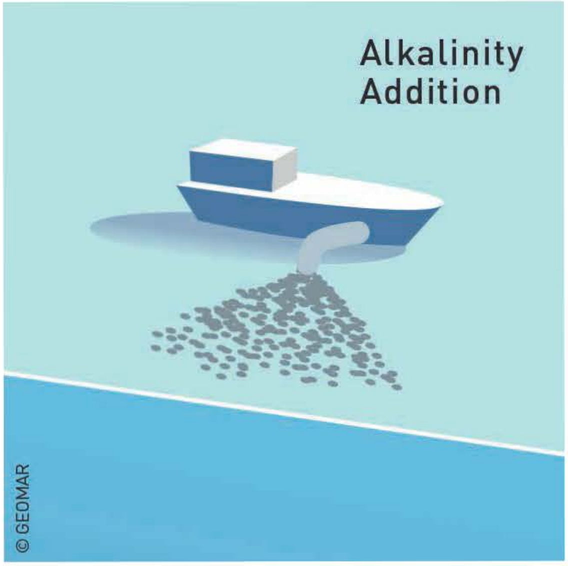

Figure 5.14 *Enhancing Ocean Alkalinity*

Rationale and principle

Alkalinity is the capacity of a solution to neutralize acid. Seawater alkalinity is predominantly composed of bicarbonate (HCO_3^-), carbonate (CO_3^{2-}) and to a much smaller extent hydroxide (OH^-) anions that are charge-balanced by cations other than H+. The preceding chemical bases then constitute nearly all of seawater's alkalinity.

CO_2 dissolved in water readily forms carbonic acid, $H_2CO_3^-$, which in the case of the ocean is ≥99% dissociated and transformed to more stable forms via reactions and equilibria with the preceding seawater carbonate and hydroxide bases. It therefore follows that adding additional chemical base (alkalinity) to seawater can be useful in helping: (i) decrease surface water partial pressure of CO_2 (pCO_2) thereby increasing CO_2 uptake by the ocean, (ii) counter seawater acidity such as that generated by excess CO_2, and/or (iii) provide a vast and relatively stable storage medium for anthropogenic CO_2 in the form of mineral bicarbonate and carbonate ions (alkalinity) in seawater. Note that these 3 benefits are not independent but are interlinked and concurrent.

Enhanced ocean alkalinity also raises the carbonate saturation state of the oceans, which can help reverse the effects of ocean acidification, in particular countering its effects on calcifying organisms (e.g. corals and shellfish) that are central to marine biodiversity (e.g. (Albright *et al.*, 2016; Marubini and Thake, 1999; Renforth and Henderson, 2017).

A source of inspiration for marine geoengineering through enhanced ocean alkalinity comes from the natural weathering process, in which globally abundant silicate (e.g. Eqn 1) and carbonate minerals (e.g. Eqn 2) naturally react with atmospheric CO_2 and water to consume and store excess CO_2 as stable, dissolved or solid alkaline compounds (Berner, 2004).

Eqn 1 $CaSiO_3 + 2CO_2 + 3H_2O\ Ca^{2+} + 2HCO_3^- + H4SiO_4 \rightarrow 3H_2O + CO_2 + CaCO_3 + SiO_2$

Eqn 2 $CaCO_3 + H_2O + CO_2 \rightarrow Ca^{2+} + 2HCO_3^- \rightarrow H_2O + CO_2 + CaCO_3$

This can be compared with reactions involving synthetic bases/alkalinity e.g.:

Eqn 3 $Ca(OH)_2 + 2CO_2 \rightarrow Ca^{2+} + 2HCO_3^- \rightarrow H_2O + CO_2 + CaCO_3$

In each case, the first step of the reaction (first arrow) indicates dissolution and reaction with CO_2. Note that some CO_3^{2-} is also formed via equilibrium reactions. The second step of the reaction (second arrow) indicates carbonate precipitation. If, after dissolution, the aqueous constituents remain in or are delivered to the ocean, ocean C storage and alkalinity is increased. However, if carbonate precipitation occurs, CO_2 is re-released such that approximately half the CO_2 initially consumed and stored via silicate weathering is lost (Eqn 1) and all the CO_2 captured and the alkalinity generated by carbonate weathering is lost (Eqn 2).

The idea of emulating the natural weathering process to drawdown atmospheric CO_2 was first proposed by Seifritz (1990), and first studied in detail by Lackner *et al.* (1995). They suggested that ultramafic igneous rocks could be reacted with atmospheric CO_2 to produce calcium and/or magnesium carbonates, supported by the results of preliminary experimental work (see also Figure 5.7). Because more than 90% of the Earth's crust is composed of alkaline minerals and mineral weathering is the primary way excess CO_2 is consumed on geologic time scales (Archer *et al.*, 2009), the capacity of such processes to contribute to excess global CO_2 mitigation is thought to have no known physical limit (IPCC, 2013). Determining cost-effective and safe ways of accelerating such weathering and alkalinity generation could therefore play a major role in reducing CO_2 and ocean acidity on human time scales.

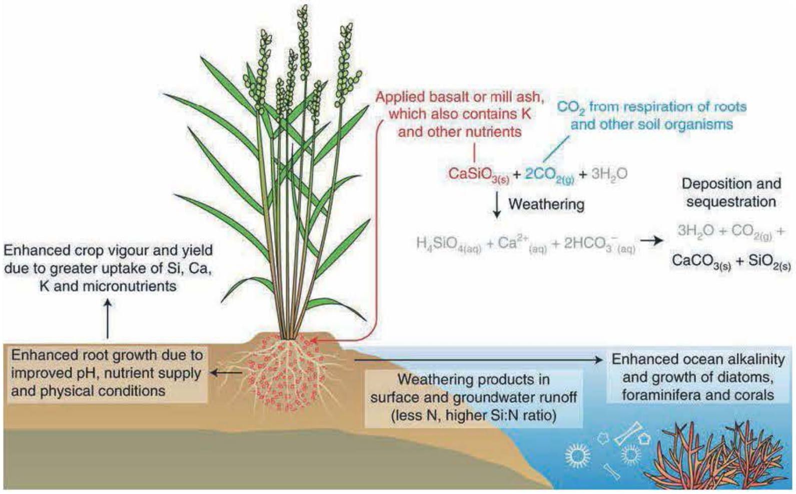

Figure 5.15 *Summary of the potential effects of weathering of crushed basalt or silicate-rich wastes, such as sugarcane mill ash, applied to croplands. As silicate rocks weather, they release nutrients that can improve soil conditions and support crop production, and also generate alkaline leachate, ultimately leading to export of dissolved inorganic carbon forms to the oceans. Reprinted by permission from Nature, © 2018, D Beerling et al. (2018) 'Farming with crops and rocks to address global climate, food and soil security', Nature Plants, 4, 138-147.*

Extent of knowledge and potential feasibility and efficacy of techniques

Adding lime directly to the ocean

This is also known as "ocean liming" and is achieved by the calcination of limestone to produce lime (calcium oxide - CaO) or portlandite (calcium hydroxide - $Ca(OH)_2$) to bypass the slow dissolution rate of natural carbonate minerals (Henderson and Rickaby, 2008; Kheshgi, 1995, Renforth and Henderson, 2017). Lime readily dissolves in the ocean and consumes ocean and air CO_2 (see Eqn 3 above). The chemistry of this is well understood, but a major negative is the large energy and carbon footprint of conventional of conventional calcination. Nevertheless, alternative methods of generating hydroxide using non-fossil energy could avoid this problem (e.g. "Electrochemical enhancement..." below).

Adding carbonate minerals to the ocean

While the surface ocean is supersaturated with respect to $CaCO_3$ and therefore any added $CaCO_3(s)$ will not dissolve to form alkalinity, such carbonate can dissolve in undersaturated subsurface waters (Harvey, 2008). By choosing locations where undersaturated water is present at shallow depths and where vertical advection of such water is relatively rapid (100's of years) the addition of $CaCO_3(s)$ here can eventually affect surface ocean alkalinity addition and CO_2 sequestration, though on timescales likely irrelevant to mitigating more urgent excess CO_2 and surface ocean acidification problems.

Accelerated weathering of limestone (AWL)

Dissolution of carbonate minerals (e.g. $CaCO_3$(s)) can be achieved by reacting them with waste flue gas CO_2 and seawater (Caldeira and Rau, 2000; Chou *et al.*, 2015; Langer *et al.*, 2009; Rau, 2011; Rau and Caldeira, 1999; Rau *et al.*, 2007). This raises seawater pCO_2 to >0.51 kPa and lowers pH and $CaCO_3$(aq) saturation state such that when contacted with solid calcium carbonate, reaction with CO_2 spontaneously occurs (Eqn 2 step 1). The resulting alkalinity is discharged to the ocean. The technique does require that thousands of tonnes of seawater be used per tonne of CO_2 sequestered. The downstream use of pumped seawater that is commonly employed as cooling water in coastal power stations could be used for this. In the context of stable C storage, environmental impacts of AWL would seem favoured over direct injection of CO_2 into the ocean, though further research on environmental desirability, cost effectiveness and global capacity is needed.

Electrochemical enhancement of carbonate and silicate mineral weathering

During the course of the electrolysis of saline solutions (such as seawater) to produce hydrogen (H_2), acids that are produced in these processes can be neutralized with carbonate or silicate minerals, which leaves un-neutralized OH^- that is co-produced in electrolysis, balanced by cations such as Mg^{2+}, Ca^{2+} or Na+. As in the case of ocean liming, these dissolved mineral hydroxides are highly reactive with CO_2 and when exposed to air remove atmospheric CO_2, forming stable, bicarbonate-rich solutions (Eqn 3; (House *et al.*,air → ocean2007; Lu *et al.*, 2015; Rau, 2008; Rau *et al.*, 2013).) The air contacting and bicarbonate formation can occur away from the ocean or can occur after the hydroxide is added to the ocean, in the latter case increasing air → ocean CO_2 flux. In either case, the surface ocean is the recipient of the resulting (bi)carbonate alkalinity and is the medium for the ensuing carbon storage. To effect maximum CO_2-emissions negativity such systems must be powered by non-fossil electricity, yet at least some of this energy can be recovered from the H_2 produced (e.g. via the use of fuel cells). Limited experimental work has been conducted on this process. An evaluation of global capacity of such methods suggests that 100's of Gt CO_2 removal and 1000's of EJ of energy generation per year might be technically possible (Rau *et al.*, 2018).

Brine thermal decomposition (BTD) of desalination reject brine

Desalination reject brine contains magnesium salts including magnesium chloride ($MgCl_2$), thermal decomposition of which produces magnesium oxide (MgO). MgO added to the ocean would draw down CO_2 through conversion to bicarbonate (Davies *et al.*, 2018). This is similar in theory to the schemes proposed by Kheshgi (1995), essentially a variant on the ocean liming process (see above). $MgCl_2$ decomposition was shown to be achievable at temperatures <600 oC, well within the capabilities of solar energy receivers. This process has advantages over ocean liming because reject brine is potentially a logistically better raw feedstock than limestone. The total electrical requirements of the desalination plant increase by ~50% due to the dewatering of reject brine by nanofiltration, but this is offset by absorptive capacity of MgO produced through BTD.

Open ocean dissolution of olivine

Olivine or other silicate mineral particles can be added to the surface ocean (Köhler *et al.*, 2013; Köhler *et al.*, 2010) to effect CO_2 removal, analogous to Eqn 1. However, because of very low dissolution rates per unit surface area, silicate minerals need to be ground to ≤1μm to dissolve on relevant time scales (elevated ambient ocean pH slows dissolution rates). The energy and CO_2 footprint of crushing such volumes of olivine required may be significant with additional contributions from mineral extraction and transport. For example, Hangx and Spiers (2009) estimated that a total of >60 kWh of energy would be consumed and >30 kg CO_2 emitted when finely ground olivine was used to consume 1 tonne of CO_2.

Soluble silicon (Si) derived from silicate minerals could increase diatom growth (biogeochemical models exist simulating this), and there could be additional Fe fertilization effects for silicates containing iron. (see also "Appraisal of the potential impacts..." below.) The proposed concentration of 1 μm olivine particles (1011 m^{-3}) is similar to that of the most abundant phytoplankton in the ocean, Prochlorococcus. Potential influences of these alien particles on food-web interactions (grazing) were not considered and are unknown. The biochemical effects and fate of other metal impurities released from silicate minerals are also concerns and require further study.

Coastal spreading of olivine

An alternative to open ocean addition of olivine is its amendment within coastal and shelf environments where wave action and biological activity can accelerate dissolution (Montserrat *et al.*, 2017; Schuiling and de Boer, 2011). Such methods could be incorporated into existing coastal management projects e.g. dredging operations, land reclamation, beach nourishment. Small-scale experiments have effectiveness; however, they also indicate problems such as nonstoichiometric dissolution, potential pore water saturation in the seabed, and the potential occurrence of secondary reactions which may limit the CO_2 sequestration potential.

Enhanced weathering of mine waste

Silicate and carbonate mine waste (already crushed into small particles) could be treated with microbes or spread over agricultural land to accelerate natural weathering process, and via downstream transport ultimately add to the surface ocean (Renforth and Henderson, 2017;). Use of fine particulate mine waste avoids the extra energy and cost of mineral crushing/grinding. To involve the use of the ocean, waste mineral dissolution needs to be done near the site of surface ocean addition to prevent in situ precipitation of minerals re-releasing CO_2. Mine waste is currently not well-characterised, and could contain major/trace elements, e.g. metals which would affect ocean biogeochemistry.

Amending cropland soils with crushed reactive silicates

Soil pore waters are naturally corrosive, allowing in situ acceleration of dissolution kinetics and CO_2 removal (Beerling *et al.*, 2018; Hartmann *et al.*, 2013; Manning, 2008; Manning, Renforth et al, 2013; Taylor et al, 2017). Products of dissolution (including increased alkalinity of rainwater) are transported to the ocean via runoff, rivers and groundwater. Slow dissolution rates at ambient temperature and pressure, combined with solubility limits of naturally occurring minerals, hamper this process. Soil pore water aqueous chemistry could enhance precipitation of carbonate minerals, which has been widely observed in anthropogenic soils. Adding crushed reactive silicates however accelerates the natural chemical breakdown of soils which enhances CO_2 drawdown and the aqueous products are then transported to the oceans, raising alkalinity. This has the advantage that the reactions taking place can facilitate further fertilization of crops, both lowering levels the need for pesticides and potentially delivering better food security. Single column reactor experiments and several large-scale trials are taking place in the USA, Australia and Malaysian Borneo.

Potential scale of use

As explained under 'Rationale and principle', precipitation of carbonate minerals decreases the efficacy of all these techniques. Modern day surface oceans are supersaturated in calcite by ~4 times, because other ions present in seawater inhibit inorganic precipitation (Renforth and Henderson, 2017). The concentration of these ions is such that abiotic precipitation from seawater will not occur until about 20-fold saturation is achieved, meaning seawater's ability to accommodate additional carbon storage in the form of bicarbonate and carbonate alkalinity is quite significant. Nevertheless, care would be needed to stay below such limits, especially during the initial addition of alkalinity prior to subsequent ocean mixing and dilution. It is likely that the first applications of alkalinity addition would be local and coastal because this would be logistically much simpler to achieve, and because of the desire to alleviate the stress on coastal resources affected by ocean acidification e.g. shellfish/corals (Albright *et al.*, 2016). Local addition of alkalinity could pass the inorganic precipitation threshold if addition occurs faster than the mineral dilution rate (Henderson and Rickaby, 2008), which merits further research via laboratory saturation experiments and calculations. In any case, the duration of deployment of enhanced ocean alkalinity would need to be continuous if sustained carbon dioxide removal and/or ocean acidification mitigation are required.

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate

All of the preceding enhanced marine and land mineral weathering and alkalinity generation adding the surface ocean (in particular the divalent cations Mg^{2+} and Ca^{2+}). While such ion input is part of natural mineral weathering, both the benefits and impacts of increased addition require further study. As stated above, abiotic carbonate precipitation is strongly inhibited in seawater yet biologically-mediated precipitation of $CaCO_3$ could be enhanced, possibly beyond that which can be viewed as restoration of present ocean-acidity-depressed calcification. Such bio precipitation would also release CO_2 (eqns 1-3), reducing the efficacy the original carbon storage in dissolve alkaline form. Other ions (e.g. derived from the silicon, nickel , lead, zinc and chromium contained in carbonate and silicate minerals) introduced by these techniques could also either impede or enhance carbon fixation and other biogeochemical processes, potentially affecting marine ecosystems (Renforth and Henderson, 2017). Therefore, the marine biogeochemical and ecological response to alkalinity addition and impurities therein must be investigated before any of these approaches are implemented. This includes consideration of the ocean in the vicinity of river mouths where land-derived alkalinity would be delivered prior to dilution. In the coastal ocean, it is also possible that any change in the deposition of anthropogenic sulphate and nitrate aerosols could have significant influence on ocean alkalinity (Hunter *et al.*, 2011).

Conclusions for enhancing ocean alkalinity

Insufficient research and testing has been done on these topics to allow informed decision-making on large-scale deployment. Enhancing ocean alkalinity in this way would help draw down atmospheric carbon dioxide and reverse ocean acidification. The key unknowns which require further research are:

(i) the characterisation of the minerals or other alkalinity to be used, including specific ions and materials that would accompany alkalinity addition to the ocean;

(ii) the marine biological response to these additions;

(iii) determination of the response and effects of biotic and abiotic carbonate precipitation under alkalinity addition, in particular. their impact on net C storage and lifetimes;

(iv) public acceptability;

(v) economics and cost effectiveness; and

(vi) monitoring and verification.

5.14 Methane capture and destruction/degradation

Approach/Rationale

Methane gas hydrates are stable at the high pressures and low temperatures found in sediment beneath the sea. They form naturally in sediments where adequate supplies of methane and seawater can combine in a location with both high pressure and relatively low temperature. The methane is created in situ by the decomposition of organic carbon, and then the methane generally migrates upward through water-laden sediment. Under the right conditions, the methane combines with water to form gas hydrate. Most sedimentary marine gas hydrate deposits found so far have been in continental margin and slope sediments. The global inventory of gas hydrates appears to be very large. Recent estimates of the total amount of methane contained in the world's gas hydrates range from 1500 to 15,000 gigatonnes of carbon (Beaudoin *et al.*, 2014).

Some scientists (e.g. Shakhova *et al.*, 2010; Whiteman *et al.*, 2013 and Glikson, 2018) and groups (e.g. the Arctic Methane Emergency Group[26]) have raised serious concerns, due to the much higher global warming potential of methane, about the potential release of vast amounts of methane from the Arctic, particularly the seabed, as the Arctic warms. Hence, there is the potential need for methane capture and/or degradation (such as by 'flaring' with concomitant CO_2 release) to minimise the additional warming of the atmosphere via methane release. However, most scientists working on this matter have discounted the likelihood of significant large-scale methane releases from Arctic sediments driven by warming (e.g. Archer *et al.*, 2009; Pohlman *et al.*, 2017; Ruppel and Kessler, 2017).

It should be noted that there have been proposals to extract the methane in hydrate deposits by replacing the methane with CO_2, thus simultaneously storing the CO_2 and recovering the methane for use as a fuel or feed stock (Babu *et al.*, 2014; Ersland *et al.*, 2009; Goel, 2006; Park *et al.*, 2006). As noted in section 5.6 above, a small-scale deep-sea field test was carried out by Brewer *et al.* (2014). However, concerns have been raised about the risks of massive methane releases caused by destabilizing the hydrates during the process of injecting the CO_2 and recovering the methane (Marshall, 2009; Zhang and Zhai, 2015).

Underlying principle(s) with citation and extent of knowledge

The first published information suggesting a means to capture methane released from seabed sediments was by Salter (2011). Subsequently, a very limited amount of information has been published about mitigation and capture methods for methane i.e. that by Lockley (2012) and Stolaroff *et al.* (2012). Salter (2011) proposed a method to physically capture methane being released from the Arctic seabed by covering kilometre-sized areas with plastic film and then either 'flaring off' the methane or recovering it to shore.

Stolaroff *et al.* (2012) also considered capturing methane and flaring it off or recovering it. However, they also considered laying porous material on the seabed to reduce the size of bubbles causing them to dissolve before reaching the sea surface. This should enhance the breakdown of methane by methanotrophic bacteria in the water column (they metabolize methane as their only source of carbon and energy). Lockley (2012) suggested that mixing of water masses "may promote bubble dissolution by extending mean bubble path and altering methane partial pressure of surrounding water".

Evidence of concept from the natural world

Techniques to enhance natural degradation are utilising the natural processes.

Direct/indirect – sequestration

It appears that the current main options are physical capture followed by flaring off or recovery for use or alternatively methods encouraging methane breakdown in the water column. However, given the limited information currently available, it is too early to have clarity about the options that may be available for methane capture or mitigation.

Proposed deployment zone(s) and potential scale of use

The main areas for initial deployment of techniques to capture methane are likely to be around the Arctic Ocean where rapidly rising temperatures may release methane from the large deposits of methane hydrates found in sediments in that area (Shakhova *et al.*, 2010; Whiteman *et al.*, 2013). However, methane hydrate deposits are found worldwide (Beaudoin *et al.*, 2014).

Duration of deployment

This is currently unclear but could be necessary for a considerable period of decades to centuries depending on the development of climate change.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

There does not appear to be any information currently on the feasibility or efficacy of the proposed techniques.

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

There does not appear to be any information currently on the potential impacts on the marine environment of the proposed techniques.

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[26] http://www.ameg.me/

5.15 Increasing ocean albedo – reflective particles, microbubbles, foams, ice and reflective algal blooms

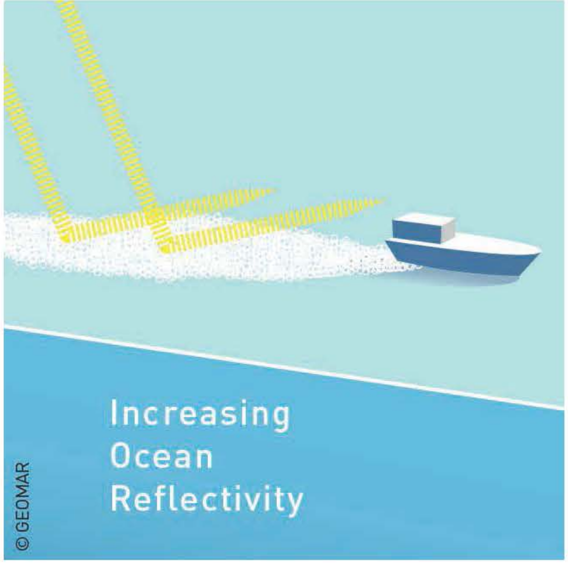

Figure 5.16 *Increasing ocean albedo*

Approach/rationale

Approximately 5% of the sunlight impinging on the world's oceans is redirected upwards through surface reflection and scattering from the interior. The proportion is referred to as albedo or reflectivity. If the albedo of the surface ocean were increased, more sunlight would escape into space, thereby counteracting some effects of greenhouse warming by altering the Earth's radiation balance (National Research Council, 2015a). Warming of surface waters would also be reduced. Strategies to increase the reflectivity of the surface ocean include the following types - microbubbles, foams, ice, reflective algal blooms and other reflective materials.

In 1965, an early report of scientific advisors to the President of the U.S. recognized that increased carbon dioxide in the atmosphere might produce climatic changes that could be deleterious from the point of view of human beings, and they recommended thorough exploration of "The possibilities of deliberately bringing about countervailing climatic changes" (PSAC, 1965). The report included a brief discussion of spreading of very small reflecting particles over large oceanic areas and also suggested its potential for inhibiting the formation of hurricanes. The idea resurfaced in 1977 in a report from the U.S. National Academy of Science (National Research Council, 1977) but possibly insuperable disadvantages were mentioned such as piling up of material on coastlines and potentially disastrous effects on fisheries. They stated that "The disadvantages of such a scheme [reflective particles] are obvious and may be insuperable". Since those short discussions, there has been little evidence to suggest that the manufacture and distribution long-lived reflective particles over broad expanses of the ocean is being considered seriously as a marine geoengineering option. This situation is unlikely to change, now that it is recognized the plastics and particularly micro-plastics are a major threat in the marine environment (GESAMP, 2015, 2016; UNEP, 2016).

Microbubbles in the top few metres – Recognizing that small bubbles (micron sized) brighten water by reflecting light, Seitz (2011) suggested that bubble injection could be used to increase the reflectivity of oceans and inland waters to help to stabilize climate, effectively offsetting CO_2 emissions while avoiding identifiable risks from introducing reflective materials into the stratosphere. In particular, it was claimed that activities could be localized to where it would be most beneficial (e.g., cooling surface waters in storm tracks to reduce cyclone intensity), no potentially harmful materials are emitted to the atmosphere, and bubble production could be modulated on the time scale of days in response to unfavourable conditions or unforeseen ecological stresses. Commenting on Seitz's paper, (Robock, 2011) agreed that the topic should be included in the list of albedo modification options being considered as a part of geoengineering, adding that its rigorous evaluation should be conducted in a broader framework of governance and ethical decision-making.

Reflective foams[27] on the ocean surface – Reviewing strategies for reflecting sunlight away from the earth, (Evans *et al.*, 2010) argued that the production of reflective foams represented a relatively simple, environmentally-acceptable mechanisms for increasing the albedo of the ocean. Two approaches were identified:

i) the manufacture of rafts of short-lived bubbles that would reflect light, and their bursting could potentially increase the number of reflective cloud droplets in the marine boundary layer; and

ii) widespread production of stable foams that would reflect sunlight directly from the ocean surface. As indicated by subsequent research, the latter pro-

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[27] Note that foam bubbles are likely to be larger than the microbubbles discussed above.

posal is attracting more attention, including research on the production and stabilization of foams (Aziz *et al.*, 2014) and simulations of climate responses to large-scale alterations of ocean albedo (Crook *et al.*, 2016; Gabriel *et al.*, 2017).

Ice - Desch *et al.* (2016) have proposed to enhance Arctic sea ice formation by using wind power during the Arctic winter to pump water to the surface to increase ice thickness by about 1 m over a winter. A non-profit organization, Ice911, is developing plans to deploy manufactured reflective floating silica spheres to preserve Arctic ice from melting (Field *et al.* 2018).

Reflective algal blooms - There has been considerable discussion about stimulating phytoplankton blooms via fertilization with either iron or macronutrients (see Sections 5.1 and 5.2) as a viable CDR technique. The large areal extent of blooms along with the increase in phytoplankton stocks can have a warming effect on the upper ocean heat budget (Frouin and Iacobellis, 2002). However, in the case of calcifying phytoplankton called coccolithophores (typically <10-micron diameter cells with distinctive plates composed of calcium carbonate - known as 'liths'), their blooms have been observed to increase the reflectance of the surface ocean via light scattering (Holligan *et al.*, 1993). The blooms also are a source of dimethyl sulphide (DMS) to the atmosphere which has been linked theoretically to alteration of cloud reflectance (see Charlson *et al.*, 1987 but c.f. Quinn and Bates, 2011). Hence, stimulation of coccolithophore blooms could potentially be a means to modify the albedo of both surface waters, and the overlying clouds, in open ocean regions.

Underlying principle(s) with citation and extent of knowledge

The direct effects of increasing the albedo of the surface ocean include the intended alteration of the Earth's energy balance, a reduction of light in the ocean interior corresponding to that which is reflected, and — if the reflective materials are not confined to the surface interface — a redistribution of energy closer to the surface due to enhanced light scattering. The studies by Crook *et al.* (2016) and Gabriel *et al.* (2017) demonstrate how the direct effects of these changes on the physical system can be simulated; the former also examines effects of what amounts to shading on primary production in the water column.

At the fundamental level, the principles are straightforward. Materials that reflect light — bubbles, foams, reflective particles — are introduced in the surface layer of the ocean, and more of the solar radiation impinging on the ocean surface is reflected away. Modelling experiments (e.g. Gabriel *et al.*, 2017) that take into account interactions of the reflected radiation with clouds and atmospheric circulation suggests that a net cooling of the surface can result. The Earth absorbs less solar energy than it would otherwise, counteracting the retention of energy by greenhouse gases. Albedo is a measure of the proportion of sunlight reflected, i.e., reflectivity; it varies with the angle of sun and sea-state, with an estimated daily average for the ocean of 0.06 (Jin *et al.*, 2002) — that is, 6% of sunlight is reflected away. This includes the contribution of natural foams, with albedos of about 0.4–0.6 (Evans *et al.*, 2010) but limited spatial coverage.

Seitz (2011) presents a global simulation of an increase in ocean albedo of 0.05 from the production of microbubbles: the resulting increase in energy escaping the Earth was enough to decrease global average surface temperatures by about 2.7 °C. Subsequent to Seitz's publication, two modelling efforts explored the consequences of intentionally increasing the ocean's albedo. Exploring microbubbles as an agent, Crook *et al.* (2016) estimated that a 0.5 °C reduction in global mean temperature could be achieved if the lifetime of bubbles in wakes of global shipping traffic were increased to 6–13 days from the typical 7–15 minutes, requiring the use of surfactants. Considering the production of long-lasting foams as described by Aziz *et al.* (2014), Gabriel *et al.* (2017) found that a relative decrease in global temperature of 0.6 °C could be achieved by increasing the albedo of the three subtropical ocean gyres of the Southern Hemisphere by 0.1.

The reflectance of the surface ocean is enhanced by high concentrations of coccolithophores, and as the bloom declines by the detached liths. A number of bio-optical studies have specifically targeted coccolithophore reflectance and attempted to model the relationship between coccoliths and coccolithophores and albedo modification (Tyrrell *et al.*, 1999). The model revealed that the detached liths boost the water-leaving radiance (i.e., enhanced reflectance), and also influence the degree of solar heating of the upper ocean, with less heating at depth. There is no evidence in the permanent record of advocacy of this approach by either geoengineering researchers or proposers, and hence the link between increased reflectance observed in coccolithophore blooms (Tyrrell *et al.*, 1999), and other approaches that have been advocated to alter albedo (see Russell *et al.*, 2012) appear tenuous.

Evidence of concept from the natural world

Setting aside questions about how ocean albedo might be modified, the relationships between reflectivity of the ocean and the global distribution of heating follow mechanistic relationships, the details of which can be complicated. Changes in the Arctic and farther afield associated with shrinking ice cover and the resulting decreased ocean albedo are an example (Perovich and Richter-Menge, 2009).

Seitz (2011) reported that measurements and satellite observations both confirm that ambient microbubbles do measurably alter the ocean's return of solar energy to space and that while natural microbubbles typically occupy only a minute volume fraction of near-surface ocean water—a part per million or less, they provide up to a part per thousand of the Earth's albedo.

Persistent foams are sometimes produced in nature. For example, the nuisance alga, Phaeocystis globosa produces foams that pile up on beaches, harm tourism, interfere with aquaculture, and clog fishing nets (Blauw *et al.*, 2010).

The biogeochemical imprint of coccolithophore blooms has been studied in detail in regions such as the subpolar North-East Atlantic (Holligan *et al.*, 1993). This bloom was ~250,000 km^2 (based on satellite imagery) and had a duration of around three weeks. Surface ocean albedo was enhanced across an area that corresponded to the coccolithophore bloom, as was DMS production. More recently, Southern Ocean blooms with similar properties have been investigated in detail (Balch *et al.*, 2014). More recent studies in the Southern Ocean (McCoy *et al.*, 2015) have pointed to the complex relationship between phytoplankton (using chlorophyll as a proxy, and not assessing coccolithophores) sulphate aerosol, organic matter in sea spray and cloud droplet concentration. Other confounding issues include the potential effect of ocean acidification on DMS production (Archer *et al.*, 2018).

Direct/indirect sequestration

These techniques do not sequester carbon.

Proposed deployment zone(s) and potential scale of use

It has been suggested that long-lived microbubbles could be produced by suitably equipped commercial ships, for-purpose ships, or by bubble generators (Crook *et al.*, 2016; Evans *et al.*, 2010; Seitz, 2011). If commercial shipping were used (about 30,000 vessels at sea at any one time), much of the northern hemisphere oceans would be influenced, as simulated in a model that reduced global temperatures by 0.5 °C (Crook *et al.*, 2016). The scale required for proof of concept is unknown, but it would have to be large enough to test for persistence of reflective materials for many weeks to months. It would have to be larger in areal extent than for any ocean fertilization experiment to date, for example see, Wallace *et al.* (2010).

The proposers of studying stable foam production have already identified potential deployment zones. Implicitly recognizing that an "ocean mirror" would have environmental impacts, (Aziz *et al.*, 2014) identified high-nutrient low-chlorophyll (HNLC) regions of the ocean as being most suitable for deployment because they support low levels of marine life due to iron deficiency. Gabriel *et al.* (2017) highlighted this as an attractive attribute, suggesting that the foam technique be deployed exclusively in the "20% of the ocean that is not biologically active…and therefore have little impact on the biosphere". However, this is a totally incorrect view of HNLC areas as it is well-established that they can have significant productivity (e.g. Arrigo *et al.*, 2008; Conway *et al.* 2018).

Desch *et al.* (2016) and Field *et al.* (2018) have proposed to enhance Arctic sea ice reflectivity by pumping seawater onto the surface and by deploying manufactured reflective floating silica spheres respectively.

There is no evidence of any specific proposals for enhancing reflective algal blooms in the permanent record. Coccolithophore blooms are regularly detected from satellite in specific oceanic locales of the Northern and Southern Hemisphere (Brown and Yoder, 2012), suggesting that only a specific set of environmental conditions can initiate such blooms (see discussion in Boyd *et al.*, 1997 and Holligan *et al.*, 1993).

Duration of deployment

Deployments could be continuous for many of these techniques, but could be stopped when warranted (Seitz, 2011). Algal blooms typically last for around 3 weeks (Holligan *et al.*, 1993) and often take place under low macronutrient conditions later in the phytoplankton growth season (Boyd *et al.*, 1997; Lessard *et al.*, 2005). Hence, enhancement of blooms would require detailed knowledge of the environmental triggers to initiate and to terminate coccolithophore blooms and monitoring of environmental conditions to be able to determine when to initiate any enhancement.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

The production of long-lived microbubbles was recognized as a challenge in the ocean-albedo strategy (Seitz, 2011); surfactants are required to extend bubble lifetimes. The study by (Crook *et al.*, 2016) provided important initial estimates on how long the bubbles would have to persist: days to weeks, or about 10,000 times, or more, longer than bubbles in ship wakes. Independent of benefit/risk assessment, the feasibility of ocean brightening depends on the demonstration that such lifetimes could be achieved in a wide-scale deployment scenario. For further consideration, the chemical nature and amount of added surfactant would have to be specified.

Stable foams with an albedo of 0.5 or more have been manufactured in the laboratory using non-toxic materials, making "the prospect for enhancing oceanic albedo feasible" (Aziz *et al.*, 2014) and providing Gabriel *et al.* (2017) with an impetus to model the effects of deploying this technology, which they characterized as plausible. However, it should be noted that the foams, which performed best when their upper surfaces were dry, were made with reconstituted sea water and kept in dishes in the laboratory for three months, with no exposure to wind, waves, rain, or marine microbes. The effects of these natural influences, along with the inevitable concentration of such floating materials at fronts and other surface convergences, is untested (Gabriel *et al.* 2017). It can therefore be argued that at present there is no direct evidence that an "ocean mirror" (Aziz *et al.*, 2014) could be deployed effectively in nature.

Field *et al.* (2018) reported that the concept to deploy manufactured reflective floating silica spheres to preserve Arctic ice from melting had been subjected to a number of small-scale field-testing experiments on lakes in Canada and the USA and at pilot scale on a lake in northern Alaska (17,500 and 15,000 m^2 in 2017 and 2018 respectively[28]) in with, it is claimed in the latter case, no adverse impact on wildlife. The website states that "In our most recent 2018 testing season, analysis of treated versus untreated areas showed higher reflectivity in treated areas, as well as higher thickness when observed empirically." If this proposed technique were used on sea ice to enhance its albedo, then it would appear to constitute deliberate placement at sea and thus potentially be subject to regulation by the London Protocol as a type of marine geoengineering.

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[28] http://www.ice911.org/arctic-testing/

Cvijanovic *et al.* (2015) and Mengis *et al.* (2016) have assessed the climate impacts and risks of ocean albedo modification in the Arctic through modelling. Recently, Moore *et al.* (2018) and Wolovick and Moore (2018) have suggested geoengineering glaciers to slow sea level rise by a) blocking warm water from getting to the base of glaciers, b) pinning ice shelves in front of glaciers by constructing berms or islands and c) removing or freezing sub-glacial water to reduce its lubricant effect. However, Moon (2018) suggested that the consequences of such technology could be even more serious than in its absence.

The most pertinent research to date on reflective algal blooms is from bio-optical modelling by Tyrrell *et al.* (1999). They project the present-day contribution of coccolithophores to Earth's annual mean planetary albedo (up to ~0.13% via light scattering). This equates to a globally-averaged radiative forcing of ~0.22 W m–2, which is relatively small (c.f. the contribution of biogenic sources over productive regions of the Southern Ocean which may increase summertime mean reflectance by 10 W m–2 or more, McCoy *et al.*, 2015).

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

Initial modelling efforts have provided indications of the impacts of ocean albedo modification on the marine environment and on global climate, constrained by the structure and assumptions of the simulation models (Crook *et al.*, 2016; Gabriel *et al.*, 2017). As with other sunlight reflection schemes (see section 5.16 on marine cloud brightening), there are a great number of indirect effects on the climate system, including altered distributions of temperature and precipitation, and the potential for biologically mediated changes in the ocean sink for atmospheric carbon. Modelling has started to constrain what the effects might be, but many uncertainties exist.

Seitz (2011) recognized the need to understand the environmental and other impacts of introducing microbubbles into the ocean but there does not appear to have been any such assessment made to date. Robock (2011) pointed out that the efficacy of this technique could affect vertical mixing in the ocean, changes in ocean circulation, impacts on photosynthesis, and risks to the biosphere.

There is essentially no expert assessment in the permanent public record of the potential effects of bubble rafts, foams, and the introduced chemicals that must stabilize them on the marine biota, ecosystem function, fisheries (including artisanal), or social and economic activities in coastal environments. By far, the greater uncertainties when adding materials to the ocean to produce long-lasting bubbles or foams relate to the potential for indirect effects on the marine environment, due to the need to use surfactants or other stabilizing materials. These include:

1 Retardation by added surfactants on air-sea exchange of gases, including carbon dioxide (Tsai and Liu, 2003) and includes aerosol precursors such as DiMethyl Sulphide (DMS). This combined with a net decrease in DMS resulting from the reduction in irradiance in the surface ocean and so lower phytoplankton production of DMS, may reduce the natural oceanic source of planetary albedo;

2 Complex influences on carbon cycling expected from interactions of bubbles, foams and surfactants with existing organic constituents of surface waters (Mari *et al.*, 2017);

3 Impacts on ocean chemistry;

4 Cooler surface waters will absorb CO_2 to a greater extent, enhancing ocean acidification;

5 Chemical interactions with micro-plastics, and how this might affect the biota (Law and Thompson, 2014; UNEP, 2016);

6 Interactions between surfactants, bubbles and foams with the sea-surface ecosystem, including microbes, larvae, turtles, marine mammals and seabirds;

7 Interference with fisheries and fishing; and

8 Economic/ecological consequences of foams accumulating in coastal areas, in aquaculture sites and on beaches.

Gabriel *et al.* (2017) say that "Evaluating the changes in the ocean, especially changes in its circulation that are caused by the surface albedo modification, is one of the next issues to explore. The ocean regions we propose to brighten have low biological productivity and weak currents, but the possibility of remote impacts, due to changes in circulation having negative impacts on important ocean regions, is worth considering".

Informed assessments of these potential environmental effects, and others that might emerge during their consideration, are essential to a basic evaluation of feasibility. Experts in appropriate fields could provide these assessments, but to date this has not happened.

As indicated above, Cvijanovic *et al.* (2015) and Mengis *et al.* (2016) have assessed the climate impacts and risks of ocean albedo modification in the Arctic in general through modelling. However, there do not appear to be any specific assessments of the ice techniques mentioned in this section. Field *et al.* (2018) state "While testing of the materials on fish and birds has shown no ill effects, evaluation of potential impacts by the materials on some further key species, such as marine mammals, needs to be done".

There is no direct evidence, but observations of ecosystem effects in the vicinity of a coccolithophore bloom (potentially initiated by anomalous weather conditions), point to a sea-bird mass mortality event in the SE Bering Sea (Baduini *et al.*, 2008).

5.16 Increasing ocean albedo – marine cloud brightening

Figure 5.17 *Marine cloud brightening*

Approach/rationale

Clouds form when water droplets gather on dust or other particles in the air. The idea behind the marine cloud brightening (MCB) technique is that seeding marine stratocumulus clouds with sub-micrometre sea water particles might significantly enhance the cloud albedo through the formation of more of these water droplets, making the clouds denser and therefore more reflective. It might also possibly enhance the longevity of the clouds. Latham (1990) was the first to suggest that this could be done using small boats to introduce sea water particles to the marine boundary layer.

Implemented at a large enough scale MCB could conceivably offset a large fraction of, or even all, anthropogenic warming (National Research Council, 2015b). If effective, this would reduce impacts of global warming, while not addressing its root cause. Because this type of radiation management can only be implemented over oceans it will have direct effects on the marine boundary layer as well as indirect effects on the underlying waters (see below), it can be considered a type of marine geoengineering.

It has also been suggested by Latham *et al.* (2012) and Latham *et al.* (2014) that MCB could prove capable of significantly lowering sea surface temperatures and hence reducing the energy available to tropical cyclones, so reducing their power or intensity.

Underlying principle(s) and extent of knowledge

The principle is to cool the surface temperatures of the planet thereby reducing negative impacts associated with climate change. The technique exploits the Twomey effect, whereby more and smaller cloud droplets reflect more sunlight away from the surface more effectively than fewer, larger droplets do. While numerous modelling experiments have demonstrated that enhancing cloud reflectivity over the ocean would cool the planet (Jones *et al.*, 2011; Kravitz *et al.*, 2013; National Research Council, 2015b), the efficacy of marine cloud seeding to actually increase albedo over large areas and extended periods of time is much more uncertain.

There is a large body of observational analysis demonstrating cloud brightening along ship tracks (Hobbs *et al.*, 2000). In 2011, the E-PEACE experiment demonstrated in situ that deliberate introduction of cloud condensation nuclei (CCN) into the boundary layer can modify cloud albedo (Russell *et al.*, 2013). Battlefield smoke generators were used to vaporize paraffin-type oil to produce the CCN. A number of other such experiments also support that deliberate introduction of particles into the marine boundary layer influences cloud properties including albedo (National Research Council, 2015b). However, the potential to extrapolate such small-scale studies to regional-scale radiative forcing perturbations remains unclear. A process-based modelling study that simulated net albedo effects of MCB implemented through release of particles by ships, showed that when clouds were seeded and brightened along one to three ship tracks, clouds in areas adjacent to the brightened tracks became dimmer offsetting the albedo modification effects (Wang *et al.*, 2011).

Latham *et al.* (2008) and Salter *et al.* (2008) concluded that sea-level injection of microdroplets of sea water would be as effective as injection from aircraft flying below the bases of the marine clouds to be brightened, while offering major environmental and cost-saving benefits. While the spraying equipment could be installed on regular cargo vessels, Salter *et al.* (2008) concluded that it was better to have a fleet of vessels dedicated to the task of cloud seeding and described the design and operation of such a type of vessel.

Evidence of concept from the natural world

While not exactly the natural world, proof of the concept of the effective introduction of cloud-brightening particles artificially has been observed from ship tracks (Hobbs *et al.*, 2000).

Direct/indirect sequestration

This technology does not sequester carbon; however, a cooler surface ocean absorbs more carbon dioxide and therefore MCB may lead to indirect sequestration.

Proposed deployment zone(s) and potential scale of use

While the technology could conceivably be deployed nearly anywhere over the ocean, there are certain regions that are considered more amenable to effective deployment, in particular, the north-eastern or south-eastern tropical Pacific (Latham *et al.*, 2012) due to the frequent occurrence of marine stratocumulus clouds. In order to offset the warming associated with a typical anthropogenic climate change scenario, one study showed that regional perturbations of more than 30 W/m^2 would be required (Jones *et al.*, 2011).

Duration of deployment

This technique could be used indefinitely to cool surface temperatures. If it is deployed to mask a significant amount of greenhouse gas-driven warming, any abrupt termination before greenhouse gas concentrations are reduced could result in rapid warming (Jones *et al.*, 2011).

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

As discussed above, there is observational analysis demonstrating cloud brightening along ship tracks as well as experimental evidence supporting that deliberate introduction of particles into the marine boundary layer influences cloud albedo (National Research Council, 2015b). However, practicalities of MCB require much more consideration, for example demonstration that fine sprays can be produced routinely in the ocean… and an appropriate environmental impact assessment for paraffin-type oil dispersed over large expanses of ocean, if they were proposed to be used.

MCB could, in theory, be used to counteract all of the global radiative forcing changes associated with all anthropogenic climate change (Lenton and Vaughan, 2009). Like other proposed forms of solar geoengineering, implementation would have different effects on regional temperatures and hydrological cycles over land (Alterskjær *et al.*, 2013). Modelling studies suggest it would not be possible to simultaneously stabilize both greenhouse gas-driven warming and changes in hydrology (Bala *et al.*, 2011). More so than other forms of solar geoengineering, MCB would alter the land-sea temperature gradient, influencing regional climatology (Kravitz et al., 2013). Model-based impacts assessments suggest that MCB could reduce some negative impacts of climate change, such as crop failures (Parkes et al, 2015) and coral bleaching events (Latham et al., 2013). Impacts on tropical rainforests could be positive or negative (Muri et al., 2015).

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

Despite a number of studies examining the terrestrial impacts of MCB, comparatively little work has been done to quantify the marine ecosystem impacts. Implementing MCB at scale would require very large perturbations to the surface energy budget in the selected areas where MCB would be expected to be effective: perhaps 30-50 W/m^2 (Jones et al., 2011). Because of these large regional perturbations, the technique could be expected to have large effects on marine ecosystems in vicinity of the area of implementation, through significant reductions in sea surface temperatures and photosynthetically active radiation. Sea surface temperature reductions could in turn lead to changes in upwelling and mixing, and effects on ecosystem services (National Research Council, 2015b).

MCB implemented using sea salt as the CCN could possibly increase the salinity of the ocean surface layer as the emitted particles would result in increased salt deposition in the regions in and surrounding which MCB is deployed (NRC, 2015b), with the sea surface microlayer presumably likely to be most affected. However, by reducing the amount of sunlight reaching the sea surface, MCB would influence primary productivity, alter vertical structure of the water column and modify both food webs and biogeochemical cycling, with influences on carbon sequestration that are not readily predicted (Baughman et al., 2012; Hardman-Mountford et al., 2013; Kravitz et al., 2013; Lauvset *et al.* 2017; Partanen et al., 2012 and 2016). As pointed out by Russell *et al.* (2013), the vaporized paraffin-type oil used for their MCB experiment is deployed in similar amounts for skywriting, an activity that is considered environmentally safe. But the authors did not consider the environmental effects of such oil on marine ecosystems, including alteration of the sea surface microlayer and direct influences on the biota, nor its large-scale use.

5.17 Other techniques – Ocean thermal energy conversion (OTEC)

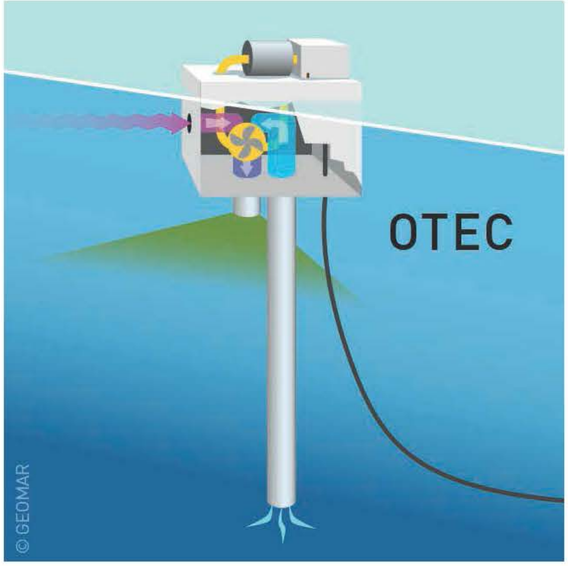

Figure 5.18 *Ocean thermal energy conversion*

Approach/rationale

Ocean Thermal Energy Conversion, or OTEC, is a process proposed 140 years ago (Jules Verne in 'Twenty Thousand Leagues Under the Sea'). OTEC exploits the difference in temperature between the surface and deep layers of the ocean to generate electrical power. Warm surface water is employed to vaporize a working fluid with a low boiling point, such as ammonia, and then the vapour is used to drive a turbine and generator. Cold water pumped from the deep ocean is then used to re-condense the working fluid. The temperature differential must be greater than about 20 °C for net power generation. Such differentials exist between latitudes 20 and 24 degrees north and south of the equator e.g. tropical zones of the Caribbean and the Pacific (Fujita et al., 2012). It involves moving large volumes of water, of the order of 50,000 m^3 per minute for a 100MW power plant[29]. Energy is captured using facilities located at sea, near-shore or on land.

The electricity generated could be used directly to power an electrical grid or to produce hydrogen fuel (Rau and Baird, 2018)[30]. While the technology was not developed for geoengineering purposes, the physical principles and engineering approaches could be adapted and applied as thermodynamic or heat pipe geoengineering (effectively a gigantic heat pipe used to transfer heat into deep waters) to cool ocean surface waters as a by-product of OTEC or without generating electricity[31].

Underlying principle(s) with citation and extent of knowledge

According to the second law of thermodynamics, heat flows from warmer to cooler bodies. In the case of OTEC, the temperature differential between the surface and deep ocean drives a heat engine and electricity is generated. The basic theory underlying OTEC or thermodynamic geoengineering is very robust (Liu, 2014). However, its engineering application in the marine environment has only been demonstrated at a pilot scale: successful projects in Japan[32] and Hawaii[33] have produced net power but several orders of magnitude less than a typical power plant.

Evidence of concept from the natural world

None.

Direct/indirect sequestration

Depending on the scale of implementation, OTEC could indirectly sequester carbon by altering the surface temperature and circulation of the ocean. It may also indirectly increase uptake of CO_2 from the atmosphere by bringing nutrient-rich deep water to the surface of the ocean, increasing primary production (Yool et al., 2009 and see section 3.16 Artificial Upwelling above). However, deep water containing elevated levels of nutrients will also contain elevated CO_2, so decreasing the surface air-sea CO_2 gradient and thus reducing ocean CO_2 uptake. Rau and Baird (2018) propose using OTEC-generated electricity onsite to power a process (Rau et al., 2013) that electrolytically consumes and stores CO_2 while producing H_2 that facilitates the transport of energy onshore.

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[29] tps://en.wikipedia.org/wiki/Ocean_thermal_energy_conversion

[30] https://en.wikipedia.org/wiki/Ocean_thermal_energy_conversion

[31] https://www.climatecolab.org/contests/2015/geoengineering-workspace/c/proposal/1315102

[32] http://otecokinawa.com/en/Project/index.html

[33] https://www.makai.com/ocean-thermal-energy-conversion/

Proposed deployment zone(s) and potential scale of use

OTEC has the highest potential effectiveness in the tropics where thermocline gradient is steepest. The best sites for deployment will also be in areas where deep ocean water can be found close to land. OTEC has been tested in:

- Hawaii[34];
- Okinawa, Japan[35]; and
- Tamil Nadu, India[36]

But many additional regions have suitable geographic properties for OTEC, including those bordering the Gulf of Mexico, Caribbean Sea, Gulf of Guinea, Northern Indian Ocean, northern coast of Australia and islands in the South China Sea (Muralidharan, 2012).

Duration of deployment

This activity could be deployed continuously on an almost indefinite basis.

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

OTEC would contribute directly to climate change mitigation in producing carbon-neutral or carbon-negative energy (Rau and Baird, 2018). Theoretically, OTEC could replace most fossil-fuel based energy (Muralidharan, 2012). However, after more than four decades of research and development, OTEC has still not been deployed at scale. A pilot project produces net 105 kilowatts is operational in Hawaii[37].

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

OTEC presents the possibility of introducing multiple ecological stressors in the vicinity of its deployment (Hammar and Gullström, 2011). The technique could potentially contribute to the climate problem by discharging at the surface sea water with elevated levels of carbon and nutrients that could potentially shift community species composition, enhance phytoplankton growth or cause algal blooms (Fujita et al., 2012; Knight, 2014). Modelling studies suggest that by discharging the return OTEC flows downwards at a depth below 70 metres, the dilution is such that a 100 MW power plant can operate continuously with temperature and nutrient perturbations that are within naturally-occurring levels (Grandelli et al., 2012; Rocheleau and Grandelli, 2011). Grandelli *et al.* (2012) reported that their modelling showed no perturbation occurring in the upper 40 metres of the ocean's surface and in the 70-110 metres depth range the picoplankton response was approximately a 10-25% increase that was said to be within naturally occurring variability, a negligible nanoplankton response and a small enhancement of the productivity of diatoms. Nonetheless, a factor not apparent taken into consideration in these or other studies, is the potential for cumulative impacts if multiple OTEC plants are operating in close proximity.

Impingement of fish and entrainment of plankton and other small organisms can occur at both surface and deep-water inflow points of an OTEC system. The physical presence of OTEC pipes and the noise and vibrations generated by their operation may have uncertain physical and biological effects on fish and other species, for example, by interfering with predator/prey dynamics or communication (Muralidharan, 2012). Structures in the ocean usually get covered in fouling organisms and so effectively act as artificial reefs that attract fish. This could lead to ecosystem changes if the scale of deployment of structures was large.

Heat pipe OTEC (also called 'Thermodynamic geoengineering') to cool surface waters could effectively reduce warming associated with climate change but implemented at a large scale such effects would be temporary, regionally heterogeneous and present the type of termination risks usually associated with solar geoengineering approaches (Kwiatkowski et al., 2015). Large scale deployment of OTEC heat pipes for purposes of thermodynamic geoengineering would be potentially disruptive to the marine environment considering that, by definition, it would significantly reduce sea surface temperatures on a regional scale while having all the same localized environmental impacts as conventional OTEC.

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[34] https://www.makai.com/ocean-thermal-energy-conversion/

[35] http://otecokinawa.com/en/index.html

[36] https://www.niot.res.in/index.php/node/index/163/

[37] https://techxplore.com/news/2015-08-celebrating-hawaii-ocean-thermal-energy.html

5.18 Other techniques – deep water source cooling / sea water air conditioning

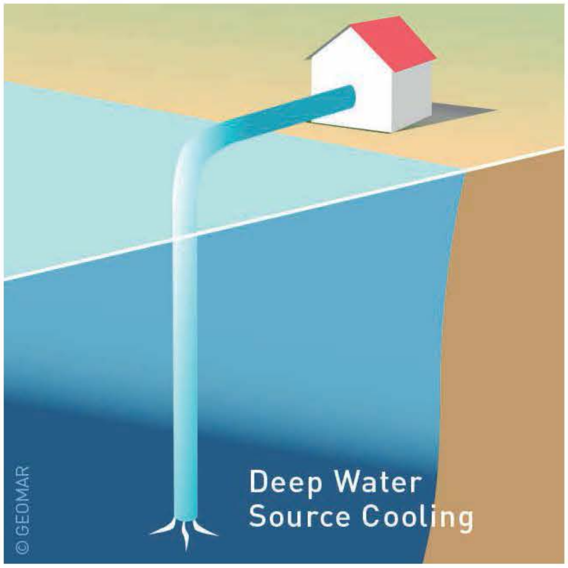

Figure 5.19 *Deep water source cooling / sea water air conditioning*

Approach/rationale

Deep ocean water is pumped up to cool buildings, particularly in tropical areas[38] (Elsafty et al., 2009; Kobayashi, 2015; Pala, 2010; Sant et al., 2014; Surroop and Abhishekanand, 2013; Zhen et al., 2007,). It is referred to as' Deep Water Source Cooling' or 'Seawater Air Conditioning' (DWSC or SWAC).

Underlying principle(s) with citation and extent of knowledge

The technique takes advantage of cold sea water from depths down to around 1,000 metres to replace energy-intensive central air conditioning systems[39] (Hou et al., 2010). It is said to save more than 90% of the energy cost of a conventional air conditioning system. Given the extent of deployment of the technique (see below), it would appear to be reasonably well understood. The technique has also been used with deep lake water for locations in Toronto, Stockholm and at Cornell University in Ithaca, New York[40] (Looney and Oney, 2007; Newman and Herbert, 2009).

Evidence of concept from the natural world

None.

Direct/indirect sequestration

This technique does not sequester carbon but does use much less energy than conventional air conditioning. However, as with OTEC, deep water will also contain elevated levels of CO_2 and nutrients, so potentially leading to losses of CO_2 to the atmosphere and increased nutrient levels in surface waters.

Proposed deployment zone(s) and potential scale of use

This technique requires access to deep cold seawater reasonable close to shore so suitable locations are where the continental shelf is very narrow or non-existent. Many oceanic islands meet this requirement, as do mainland locations[41]. Examples of locations where this technique has been deployed include:

- Halifax, Canada[42];
- Hawaii[43];
- Bora Bora[44];
- Reunion Island, Indian Ocean[45];
- Pyeongchang, Republic of Korea for cooling the ice rink at the 2018 Winter Olympics[46];
- Hong Kong[47]; and
- Curacao[48]

Duration of deployment

This activity could be deployed continuously on an almost indefinite basis.

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[38] http://en.wikipedia.org/wiki/Deep_water_source_cooling

[39] http://www.makai.com/brochures/SWAC_Brochure_3_2012.pdf

[40] http://www.makai.com/p-swac.htm

[41] https://www.bardotocean.com/pages/swac-sea-water-air-conditioning-by-bardot-group

[42] https://crcresearch.org/case-studies/case-studies-sustainable-infrastructure/energy/deep-water-cooling

[43] http://www.makai.com/p-swac.htm and http://honolulus-wac.com/

[44] http://www.makai.com/p-swac.htm

[45] http://www.makai.com/p-swac.htm

[46] http://english.chosun.com/site/data/html_dir/2011/12/13/2011121301347.html

[47] https://en.wikipedia.org/wiki/The_Excelsior_(Hong_Kong) https://en.wikipedia.org/wiki/HSBC_Building_(Hong_Kong)

[48] http://www.makai.com/brochures/SWAC_Brochure_3_2012.pdf

Evidence of feasibility and efficacy of the techniques for climate mitigation or other purposes - modelling, lab, pilot experiments

The technique does not address climate mitigation but does appear effective for its designed use.

Appraisal of the potential impacts of the techniques on the marine environment (and the atmosphere where appropriate)

The technique can potentially contribute to the climate problem for the same reasons as for artificial upwelling and OTEC i.e. by discharging at the surface sea water with elevated levels of carbon and nutrients that could potentially shift community species composition, enhance phytoplankton growth or cause algal blooms (Fujita et al., 2012; Knight, 2014). The websites for DWSC/SWAC referred to above indicate that the return flows back to the ocean will likely occur at shallow depths such that environmental effects due to temperature differences are eliminated. They do not appear to address the elevated levels of carbon and nutrients in these waters. However, in the case of OTEC, modelling studies suggest that by discharging the return OTEC flows downwards at a depth below 70 metres, the dilution is such that a 100 MW power plant can operate continuously with temperature and nutrient perturbations that are within naturally-occurring levels (Grandelli et al., 2012; Rocheleau and Grandelli, 2011). Grandelli *et al.* (2012) reported that their modelling showed no perturbation occurring in the upper 40 metres of the ocean's surface and in the 70-110 metres depth range the picoplankton response was approximately a 10-25% increase that was said to be within naturally occurring variability, a negligible nanoplankton response and a minor enhancement of the productivity of diatoms. Nonetheless, a factor not apparent taken into consideration in these or other studies, is the potential for cumulative impacts if multiple OTEC or DWSC/SWAC plants being operated in close proximity.

6 REVISITING THE ASSESSMENT FRAMEWORK

6.1 Suitability of the application of the LC/LP Ocean Fertilization Assessment Framework to other methods

At present the LC/LP Ocean Fertilisation Assessment Framework (OFAF)[49] only applies to research projects and their governance. Consequently, any proposals for deployment of ocean fertilisation (OF) geoengineering, beyond research, would require a bespoke OFAF to be developed so that such proposals could be effectively assessed.

At present, the parties to the LC are being proactive in wishing to know what marine geoengineering approaches may arise and might be advocated in the near future, so they can be prepared when and if this scenario takes place. This will enable the LP to obtain a general overview of what approaches, and their characteristics relative to those of OF, and what impacts they may have, to get a head start if regulation becomes necessary. Table 6.1 (an abbreviated version of Table 4.4) cross compares the research governance needs of each illustrative approach and then cross-reference to OF. For example, three distinct categories of scale are evident from Table 6.1: 10% (or more of the global ocean) for OF, ocean alkalinity and artificial upwelling; ~1% of the global ocean for liquid CO_2, foams and MCB (using sea water); and 2 approaches about which little is known regarding spatial scales for implementation (macroalgae and fertilization for fish stock enhancement). A key component of the OFAF deals with the characterization of risk (characterization and management) which relates directly to two of the criteria in the Table 6.1 (consequences and co-benefits; socio-political risks). So, on the basis of one of the eight criteria we can see convergences and departures from OF, and hence the potential need for different categories of regulatory framework. A summary of the convergences and divergences, across all eight criteria, of other approaches relative to OF is presented in Table 6.1. A key point from Table 6.1 is that in many cases differentiation of the degree of convergence or divergence across the characteristics of each marine geoengineering approach are hindered by a lack of fundamental knowledge – a recurring theme in this report.

Which of the approaches in the Table 6.1 is closest to a constrained or an unconstrained field trial or pilot study (see Figure 4.1)? These methods are the ones that the LC/LP needs to be alerted about. Moreover, the methods may reveal key pointers as to what triggers the readiness of an approach to deployment. Of the eight approaches, only three have had field trials, based on information in the permanent public record:

- OF (unconstrained field trials) (e.g. Markels and Barber, 2001; Tollefson, 2012);
- liquid CO_2 on the seabed in a very small-scale constrained field trials (e.g. Brewer et al., 2005); and
- artificial upwelling (unconstrained field trials) (e.g. Maruyama et al., 2011; Maruyama et al., 2004; White et al., 2010).

Of these three, the OFAF is in place for the initial assessment of OF pilot or trial studies. Placement of liquid CO_2 in the sea, on the seabed or in deep-sea sediments may be classed as dumping under the LC and would be classed as dumping under the LP (see section 2.4) and thus banned. The future for artificial upwelling is unclear following the catastrophic failure of the device after < 1 day (White et al., 2010) and recent

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[49] http://www.imo.org/en/OurWork/Environment/LCLP/EmergingIssues/geoengineering/Documents/OFassessmentResolution.pdf