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Carnegie Climate Governance Initiative

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CARNEGIE COUNCIL for Ethics in International Affairs

EVIDENCE BRIEF

Governing Marine Carbon Dioxide Removal and Solar Radiation Modification

This briefing summarises the latest evidence around Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM) techniques related to the marine environment. It describes a range of techniques currently under consideration, exploring their technical readiness, current research, applicable governance frameworks, and other socio-political considerations. It also provides an overview of key instruments relevant for the governance of marine CDR and SRM.

Introduction

Almost three years after the Paris Agreement on climate change, recognition is growing that without a rapid acceleration in action, limiting global average temperature rise to 1.5-2 degrees Celsius will not be achieved through emissions reductions or existing carbon removal practices alone. Scientists have begun exploring the additional use of large-scale CDR and SRM techniques to limit climate impacts, including keeping temperature rise down. These techniques are sometimes defined collectively as 'geoengineering' and can be sub-categorized as Nature Based Solutions (NBS), technology based or hybrid (NBS and technological combined).

This briefing focuses on CDR and SRM techniques related to the marine environment. It describes techniques currently under consideration and explores their relative strengths and weaknesses. Current applicable governance frameworks are examined and other social-political issues pertinent to large-scale interventions in the marine environment are discussed.

All the techniques discussed still require significant development, trialing and not least governance dialogue and decision making before they might ever be deployed. The Carnegie Climate Governance Inititative (C2G) has no position on the appropriateness of any of the techniques described here; we seek only to broaden the conversation about them and catalyse debate about the future of such techniques by providing this impartial overview.

This briefing explores interventions that would be in, on or directly above the marine environment. There may be other techniques that would be conducted in other domains that would have impacts upon the marine environment, but these are outside the scope of this briefing. The briefing is not an assessment of the techniques, rather it provides a description of each and a brief analysis of technical readiness, the research landscape, governance and socio-political issues associated with each (summarised in table 1). For a more comprehensive assessment, the review by the Joint Group on the Scientific Aspects of Marine Environmental Protection (GESAMP) (2018) is recommended. This briefing draws extensively on this report as part of its evidence base.

In the governance section a high-level overview of the relevant legal instruments including existing law and some key non-binding principles, or codes of conduct are offered.

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Background

Any discussion about the use of the marine environment as a location for CDR or SRM should be held in the context of its importance to planetary and human wellbeing. The oceans provide essential ecosystems services to Earth and humanity. Covering 71% of the planet's surface they support carbon storage, oxygen production, provide food and income generation and flood and storm protection. Human well-being is intrinsically intertwined with the oceans. 40% of global population resides in coastal communities and three-quarters of the world's mega-cities are by the sea.

The oceans already play a key role in the climate system (and mitigating climate change) acting as a major heat and carbon sink. The IPCC Fifth Assessment Report (IPCC, 2013) revealed that they have absorbed 93% of the extra energy from the enhanced greenhouse effect and ocean warming is now being observed at depths of 1,000 m. In the ten years to 2016 increased atmospheric CO 2 concentrations have led to a net uptake of 8.7 ± 2 Gt CO2 per annum (Royal Society 2018), a volume equivalent to 25% of human emissions. In addition, further carbon is taken up at the ocean surface by organic processes, especially photosynthesis by marine plants. Warming is leading to ice melting, coral bleaching and changes in fish migration patterns. Climate change is also changing the oceans' boundary with sea level rise drowning low lying land and wetlands and changing patterns of erosion and flooding on coastlines.

Physically, the marine environment and oceans in particular are a potentially useful host for CDR/SRM interventions. For example, their sheer size offers some potential for albedo modification, a form of SRM such as the use of reflective foams floating on the surface, which require a large area on which to sit. In addition, there are areas of the oceans which are nutrient poor and less biologically productive. Interventions to effect a positive change in these balances could enhance biological productivity – and carbon uptake. Further, the oceans' biological processes already capture and store carbon on a medium-long term basis. If these were enhanced, they could provide additional storage for anthropogenic carbon over timescales that are not possible in the atmosphere.

However, whilst there may be scale and other drivers that suggest the oceans might be an appropriate host for CDR/SRM techniques, there are multiple other factors to consider before any decisions are taken. Many proposed CDR techniques would perturb or place materials in the deep oceans. However, our understanding of the oceans, and especially the deep oceans are limited. Therefore, any discussions about new CDR techniques should be in the context of these uncertainties, particularly in relation to environmental impacts.

Perhaps the socio-political challenges will be the most testing. The oceans undoubtedly retain a special place in the environmental awareness of many societies, Greenpeace for example grew out of activities focussed on ocean protection issues. Processes that intentionally interfere with the oceans frequently meet with hostility. This coupled with important governance questions, such as: who would deploy, monitor, pay for and insure against harms of any interventions; how they would be governed; and, how might trade, food production and other resource extraction be affected create a considerably challenging environment.

Table 1. Traffic Light overview of Marine CDR/SRM Techniques

Techniques	Readiness	Active Research Area	Governance Framework	Social Acceptability
Iron Ocean Fertilisation	Technically feasible and the industrial Iinfrastructure required is well understood.	Yes. In particular environmental impacts and capacity to uptake CO_2.	Research addressed under the LP and UNCLOS.	Limited research suggests it is not welcomed.
Macro-nutrients, Nitrogen and Phosphorus Fertilisation	Modelling studies only to date.	Very limited theoretical and modelling research.	Research addressed under the LP.	Unlikely to be welcomed – see Iron Fertilisation.
Crop Residue Oceanic Carbon Sequestration	There are no technical constraints to deployment.	Not an active area of research. More evidence regarding environmental impact is required.	Covered by the LP.	It is uncertain how publics will respond to this technique.
Macroalgal Cultivation for Sequestration	Technologies are readily available. Further development may be required to maximise methane and CO_2 capture and use.	Yes. Limited research underway.	Dependent on the location of cultivation, which could be in nearshore or offshore waters.	As an extant farming method, a proliferation of the technique may pose insurmountable challenges.
Placing liquid CO_2 in the mid/deep oceans	No. Minimal theoretical development of the method only to date.	None.	Would be subject to UNCLOS and the LP.	It is uncertain how publics will respond to this technique.
Placing liquid CO_2 on the seabed	No. Minimal theoretical development of the method only to date.	None.	Would be subject to UNCLOS and the LP.	It is uncertain how publics will respond to this technique.
Placing liquid CO_2 in deep sea sediments	No. Minimal theoretical development of the method only to date.	None.	Would be subject to UNCLOS and the LP.	It is uncertain how publics will respond to this technique.
Mineralisation of injected CO_2 within geologic structures	Technologies are not to hand; work underway to develop the technologies for demonstration.	Research currently funded by the EU and the US Department of Energy.	Would be subject to UNCLOS and the LP.	There is no evidence to indicate the nature and scale of any responses.

Techniques	Readiness	Active Research Area	Governance Framework	Social Acceptability
Ocean Upwelling & Down Welling	Not currently practical, even in principle in engineering terms, to deliver cooling.	Very limited if any activity.	Unresolved.	Unknown.
Ocean Carbon Capture and Storage (OCCS)	The principles are well understood. Chemical engineering research is required before a viable technology becomes available for testing.	Mainly technical and economic modelling.	If conducted in exclusive economic zones, OCCS would be subject to nation state terms. On the high seas, the storage of CO_2 beneath the seabed would be covered by the LP.	There is no evidence to indicate the nature and scale of any responses.
Methane Capture and Processing	There is very limited information about how the methane might be captured.	None.	Unknown.	Unknown.
Enhancing Alkalinity	A major challenge remains to reduce the large carbon/ energy footprint of the manufacturing processes.	Very limited.	Would be subject to UNCLOS and the LP in the future, if named in Annex 4.	Limited research on broadly similar techniques suggests it is unlikely to be welcomed.
Enhancing Surface Albedo	Currently none of the potential technologies are ready. Some small-scale field trials are underway.	An area of active research.	Would be subject to the LP in the future, if named in Annex 4.	There is no evidence to indicate the nature and scale of any responses.
Marine Cloud Brightening (MCB)	The underlying principles are known. Which particles to use and how to consistently produce a supply of them of an appropriate diameter and quantity at sea is unresolved.	An area of active research.	Assuming sea water will be utilised, states would be free to conduct MCB on the high seas, provided that this is done with "due regard" for other states' interests.	Limited research evidence suggests perceived controllability of MCB may reduce citizens' concerns about governance of the technique.

Key: red=low; orange=medium; green=high

Marine CDR Techniques

Iron ocean fertilisation

The principle

Photosynthesis by, for example, plankton in the ocean removes around 40 Gt CO_2 from the ocean surface and transports it downward to the deep ocean (Royal Society 2018) this so called 'biological pump' is limited by the abundance of photosynthesising life which in turn is constrained by the supply of micronutrients such as iron (or macro nutrients including nitrates and phosphates). Iron ocean fertilisation seeks to address this shortfall by introducing additional micronutrients.

The technique and its readiness

Distributing iron into the oceans is technically feasible and the industrial infrastructure required is well understood. Some 12 experimental fertilisations have been carried out in several areas with variable results in terms of both the characteristics of the plankton blooms created, and the carbon sequestrated (Boyd et al., 2013). Modelling suggests that the subarctic Northern Pacific, Eastern Equatorial Pacific and Southern Ocean would be the most suitable locations for deployment, with the latter the most promising for net carbon sequestration (Bopp et al., 2013). Further research assessment of carbon transfer in large-scale experiments is required (Williamson 2012).

Estimates (Strong et al. 2009) suggest the maximum capacity for ocean iron fertilisation to capture CO_2 is no more than 1 Gt CO_2 per annum, giving a total ocean sequestration capacity until 2100 of 75 Gt CO_2, assuming continuous iron fertilisation of all suitable areas of the ocean from 2025. It is unlikely there will ever be the capacity to reduce mean surface temperature with iron fertilisation (Zhang et al., 2015).

Some potential side-effects have emerged during testing, including population increases of toxic species of diatoms (Silver et al., 2010 and Trick et al., 2010). There is also limited evidence of increased concentrations of methane and nitrous oxide during the decomposition of the sinking particles (Law, 2008).

Current research activity

Oceaneos, a marine research organization in the United States is currently taking forward research on nutrient enrichment technology in waters off Peru. The stated purpose of the work is to understand how to 'increase wild fish populations at a local scale, through targeted ocean fertilisation focused on rehabilitating the human-impacted marine ecosystem' (Oceaneos 2019). However, the project will also likely inform understanding of iron fertilisation.

Socio-political considerations

The Haida Gwaii 2012 project provides an example of how socio-political reactions to iron fertilisation can play out. The small remote community off Prince Rupert Columbia became subject to global news after the Guardian newspaper headlined a story 'World's Biggest Geoengineering Experiment 'Violates' UN Rules' (Lukacs, 2012). The Haida Salmon Restoration Corporation had released 120 tonnes of iron sulphate into an ocean eddy 400km offshore. This was flagged to the media when ETC Group alerted the press to the project. This coincided with the UN's Convention on Biological Diversity Conference of Parties in India (CBD COP 11), in which the ETC Group were presenting a case for a test ban on 'geoengineering' (ETC, 2012). Contiguous with the Haida experiment, the governing body of the London Protocol tasked its Ocean Fertilization Working Group to develop options for providing

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a control and regulatory mechanism for ocean fertilization and, on 18 October 2013 the Protocol Parties, added a new article (6bis), 2 new annexes and consequential amendments to Articles of the London Protocol (LC&P, 2015).

Research suggests that the public are broadly unaware of the technique, and when informed about it they view it negatively describing concerns about pollution and other deleterious environmental consequences (Corner et al. 2014)

Governance

The technique falls under Annex 4 of the London Protocol, which was accepted as an amendment to the Protocol on 18 October 2013 (IMO 2013) which is not yet in force. Other interested parties could include civil society and commercial interests.

Ocean fertilisation with macro-nutrients, nitrogen and phosphorus

The principle

The underlying principal of this technique is the same as for iron fertilisation, the enhancing of organisms that photosynthesise. It simply uses different substances.

The technique and its readiness

Nitrogen and/or phosphorus would be added to nutrient-impoverished waters. The evidence is based on both modelling studies and limited field work (GESAMP 2018a). It has been suggested that nitrogen fertilisation, when additional costs including manufacture, transport and distribution by vessels on the ocean are included, is potentially a more efficient means of sequestration than iron fertilization (Harrison 2017 and Matear and Elliot 2004). However, further research is required to clarify these claims in the light of new knowledge gained from further development of the techniques and their potential deployment mechanisms.

The CYCLOPS study which fertilised an area in the Eastern Mediterranean Sea with phosphorus demonstrated that half of the added phosphate was taken up biologically (Rees et al., 2006).

Research is still required to understand the biological processes further and the supply chain infrastructure and market mechanisms to underpin deployment. However, Harrison (2017) suggests that the technique has a theoretical capacity to offset up to 15% of annual global CO_2 emissions (as at 2017).

Current research activity

Academic research on macro-nutrients has declined in recent years, peaking in the period 2004-2008. However, in the commercial world, the Ocean Nourishment Corporation Pty Ltd ('ONC') (ONC 2019) is pursuing research to develop what it calls 'Ocean Nourishment' technology. Funded by the Ocean Nourishment Foundation, it works in partnership with academic institutions focussing on how carbon transfers to and is stored within the ocean.

Socio-political considerations

These are broadly the same as for iron fertilisation. An additional key challenge relates to the availability of phosphorus. It is not a renewable resource and stocks are in decline with concern about the future capacity to fertilise crops. The geo-politics of phosphorus are also important, it is not evenly distributed with large mines only in Morocco, Russia, China and the US. Prices are highly volatile leading to stockpiling. Its large-scale use for ocean fertilisation could then create significant tensions

competing with food production at the same time as population increase outstrips capacity to supply enough food.

Governance

The technique falls under Annex 4 of the London Protocol. Other interested parties would include intergovernmental or civil society organisations, and commercial interests, especially those associated with food production and mining/minerals.

Crop residue oceanic carbon sequestration

The principle

Ballasted bales of crop residue would be dumped into the deep ocean or off the deltas of large rivers. With suitable additional ballast, biochar, timber and other organic matter could also be deposited in the deep ocean seabed.

The technique and its readiness

Crop waste (and other material) would be secured, gathered centrally and taken to appropriate ports for transport to dumping sites and, having been suitably weighted, they would be dumped. There are no technological constraints to hinder the implementation of this technique.

Allowing for an average land transport distance of 200 km, and a combined average river and ocean shipping distance of 4,000km, Strand and Benford (2009) suggested that 30% of global annual crop residues of 2 Gt C could be available sustainably without harming soils. However, 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. Lenton and Vaughan (2009) suggest that an annual sequestration rate of up to 1 Gt C of material per annum, half the global annual crop residues, would only make a very modest contribution to slowing climate change.

The environmental impacts of depositing crop wastes in the deep ocean are uncertain and there is a dearth of knowledge about its impacts on ecosystem services. It is, though, known that, if deployed in shallow water (below 1,000m), its impacts on ecosystem services could be more significant, particularly on deep-sea fisheries. In addition, long-term oxygen depletion and deep-water acidification could be regionally significant given cumulative deposition in limited areas (GESAMP 2018).

Current research activity

This is not an area of considerable current research interest.

Socio-political considerations

It is uncertain how publics would respond to this technique. To deliver enough mass of material to the deep oceans to have a material effect a new, very large-scale infrastructure and market mechanism would need to be constructed. How much material would be taken, and from where would require monitoring and regulation to protect soils and crop productions as well as to inform the market mechanism. In addition, crop residues provide multiple services within agricultural systems. This technique could have important, unintended, and harmful consequences for those systems. Finally, monitoring of the nature of the material being dumped would also be necessary to protect against rogue or ‘fly-tipping’.

Governance

The technique may be permissible subject to assessment under the Organic Material of Natural Origin category in Annex 1 of the London Protocol and the Uncontaminated Organic Material of Natural Origin category in Annex I of the London Convention (IMO, 2016). The technique could potentially come under the purview of The International Convention for the Prevention of Pollution from Ships (MARPOL), Annex V, if the Convention were to be revised in the light of a conclusion that the crop residue constituted either food waste, or a noxious substance. More broadly, other interested parties would include those engaged in food production and supply and the governance of agriculture, CSO, FAO, civic society and agricultural interests.

Macroalgal cultivation for sequestration

The principle

Sometimes called 'ocean afforestation' (N'Yeurt 2012), macroalgal cultivation is the proposed large-scale farming at sea of macroalgae to capture carbon through photosynthesis. The biomass would subsequently be harvested either for sequestration or bio-fuel production (the lack of connection to the substrate would prevent the macroalgae being sequestrated in situ (Sondak et al 2017)). Large-scale macroalgae could potentially play a role in enhancing the biological pump.

The technique and its readiness

Nearshore macroalgal aquaculture is a well-established industry globally and in particular in China, Japan and South Korea (Pereira and Yarish, 2008). It may already account for the accumulation of ~0.8 Mt of organic carbon annually in the Asia-Pacific region (Sondak et al., 2017). Offshore macroalgal aquaculture has a far greater capacity. N'Yeurt (2012), for example, has demonstrated that if 9% of the oceans were converted to macroalgal aquaculture they would generate 12 Gt per annum of bio digested methane. This could be burned as a substitute for natural gas. The biomass involved would capture 19 Gt of CO_2 and an additional 34 Gt CO_2 could be captured, if the CO_2 produced by burning the methane was captured and sequestrated.

Current research activity

Research is underway in China, Denmark, the United Kingdom and the United States exploring the challenge of entrapping macroalgae in the seabed (Querios et al. 2019). Other work is exploring the effect of ocean acidification on microalgae growth, which may diminish the value of the technique if acidification continues.

Socio-political considerations

As an extant farming method, a proliferation of the technique in the Asia-Pacific region would not raise novel socio-economic challenges. Diversification to other regions is practical and commercial operations are functioning on the Atlantic coastline and elsewhere. In addition to environmental benefit, the technique has economic value from sale for nutrition, energy and fertiliser. In addition, GreenWave, Oceans 2050, ClimateWorks and 3Degrees are working with industry, scientists and NGOs to design and launch a kelp carbon credit protocol for certification by international carbon credit agencies. These potential economic returns may offset the capital investment need for large processing plants and aerobic combustion and CCS facilities. Its noteworthy that this technique would avoid the competition for land resources of other afforestation methods.

Governance

The regulation of nearshore waters is a matter for individual nation states to resolve. Regimes would include those relevant to environmental protection and food safety. For waters outside exclusive economic zones (EEZ), the technique would fall under customary international law, the London Protocol and the UN Convention of the Law of the Sea (UNCLOS).

Placing liquid CO_2 in the mid/deep oceans

The principle

Injecting liquid CO_2 at depth (below 2800m) would bypass the naturally slow adsorption and transport of CO_2 from the surface and add CO_2 directly at depth to dissolve into inorganic carbon. It would lead to increased acidification at these depths.

The technique and technological readiness

The technique was discussed in the Special Report on CO_2 and Storage (IPCC 2005). However, there has been minimal further research and no field tests have been undertaken, although some planned in-situ studies in Norway and Hawaii were cancelled in the light of negative public opinion (Adams et al., 2002, Gewin 2002). There are no estimates of this method's capacity to store carbon long term.

Current research activity

In light of the likely high cost, environmental impacts and questions of public acceptability, very limited research on this technique is underway (GESAMP 2018).

Socio-political considerations

The experience of previous planned trials in Norway and Hawaii suggests the technique would be socially problematic. Economic modelling of the costs suggests a range of between USD $5 and $25 per tonne of CO_2 (Anderson et al., 2005 and Livermont et al., 2011). If further research is conducted on this technique costing models will likely become more precise.

Governance

It is likely that the technique would fall under the London Convention and London Protocol. Other interested parties may include intergovernmental or civil society organisations and commercial interests.

Placing liquid CO_2 on the seabed

The principle

Liquid CO_2 would be injected directly onto the seabed (where deeper than 3,000m), using trenches and depressions to maximise capacity and limit lateral spread.

The technique and technological readiness

The technique was discussed in the Special Report on CO_2 and storage (IPCC 2005). However, there has been minimal further research and no field tests have been undertaken. Small scale field-based research (Brewer et al. 2005) suggests the sequestrated material would remain stable in situ. No technology is currently available, although, adaptation of current methods and techniques, drawing

on the offshore oil industry, suggest early adoption is possible.

The storage capacity of this technique is theoretically very large. Andersson et al. (2005) suggest it would be feasible for 4 bulk carriers to inject up to 0.02% of current global CO_2 emissions in 24 hours. Reservoir size on the ocean floor or isolated in trenches is not a limiting factor. However, how the CO_2 would be captured, and transported to the deposition sites is unresolved.

Current research activity

Currently very limited research investment.

Socio-political considerations

Goldthorpe (2017) suggests that the technique could be readily and cost-efficiently accomplished and Andersson et al (2005) have estimated a per tonne CO_2 cost of $25. Given the depth and good mapping, it is unlikely the stores would interfere with or be perturbed by human activity. There is no evidence to indicate the nature and scale of any socio-political responses.

Governance

It is likely that the technique would fall under the London Convention and London Protocol and UNCLOS. Other interested parties may include intergovernmental or civil society organisations and commercial interests.

Placing liquid CO_2 into deep-sea sediments

The principle

Liquid CO_2 would be injected several hundred metres into deep-sea sediments, where the seabed is deeper than 3,000m. House et al. (2006) demonstrated that the total storage capacity in these sediments is vast compared to current emissions and that the CO_2 would be stable in that environment.

The technique and its readiness

There is currently no direct evidence of the feasibility of this technique. However, it could be feasible as it can draw on the considerable experience gained from 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. An alternative approach has proposed using torpedo shapes of solid CO_2 being released at the sea surface, gaining sufficient velocity to penetrate some distance into deep-sea sediments (Murray et al. 1996). Currently there is no evidence of the feasibility of this technique.

Current research activity

No known on-going research on the technique.

Socio-political considerations

There is no evidence to indicate the nature and scale of any socio-political responses. Neither is any economic analysis available.

Governance

It is likely that the technique would fall under the London Convention and London Protocol and

UNCLOS. Other interested parties may include CSO, IGOs, civic society and big business interests.

Mineralisation of injected CO_2 within geologic structures

The principle

Carbon dioxide would be injected into appropriate host rocks beneath the seabed to react with the minerals and form stable minerals.

The technique and its readiness

Carbon injected into commonly found basalt and peridotite rocks would react with available magnesium and calcium ions to form stable carbonate minerals (Matter and Kelemen, 2009). The maximum theoretical storage capacity would be much greater than all the CO_2 that would be emitted by burning all the fossil fuels on earth (Goldberg et al., 2008). Work is underway to develop techniques supported by the US Department of Energy (see current research activity).

Current research activity

The EU funded CarbFix project has demonstrated a viable complete mineralisation process onshore and has secured funding until 2022 to continue its work. The Carbon Storage Assurance Facility Enterprise (CarbonSafe) project is conducting an onshore study to assess technical evaluations of collecting and storing 50 million tonnes of CO_2. Their objective is to have over 50 operative 50 million tonne facilities in operation by 2026.

Socio-political considerations

There is no evidence to indicate the nature and scale of any socio-political responses.

Governance

It is likely that the technique would fall under the London Convention and London Protocol and UNCLOS. Other interested parties may include intergovernmental or civil society organisations, and commercial interests related to mining and chemical engineering.

Artificial upwelling

The principle

Across much of the mid and low latitude oceans, nutrients are depleted in the surface waters, limiting biological production (Moore et al., 2013). Artificial upwelling would bring deeper, nutrient-rich waters up toward the surface stimulating phytoplankton growth and the absorption of carbon. In addition, upwelled waters would be cooler than surface waters, and therefore cool the surface waters increasing their capacity for heat absorption from the atmosphere at local scales (i.e., providing ‘air-conditioning’ for coastal cities nearby upwelling interventions). It has been estimated that the maximum carbon capture and storage of this technique would be less than 20 Gt C by 2100 (GESAMP 2018). Unlike fertilisation techniques, upwelling would not add any new nutrients to the oceans.

The technique and its readiness

There is no scalable technology available to date. Some modelling studies have demonstrated a limited potential for upwelling to draw down carbon from the atmosphere (Oschlies et al., 2010) and a number of small field trials have examined the technical feasibility of generating upwelling and

transporting nutrients (Pan et al., 2016 and White et al. 2010). There has not been any experimental measurement of achieved carbon sequestration.

The engineering challenges which must be surmounted to deliver meaningful carbon sequestration using this technique are substantial, including questions about the water transportation methods, and the design and construction of the tubes.If it were achieved, upwelling is likely to have a substantial termination effect. If the process were stopped, the heat stored at depth could return to the surface, leading to surface temperatures exceeding those previously experienced (Keller et al., 2014).

The potential extent of any environmental impacts of the technique are unknown but it is known that artificial upwelling would bring up high levels of dissolved CO_2 as well as nutrients which would have effects.

Current research activity

Research is limited to modelling and laboratory scale prototyping and a small scale project to test upwelling 'tubes' in the South China Sea. More research is required to better understand the feasibility of the large-scale engineering required and the associated economics.

Socio-political considerations

Issues to be addressed include: the economics of interventions; decisions regarding who would operate systems and why; where they would be located; monitoring and risk assessment; and, social acceptability.

Governance

Governance of upwelling interventions is unresolved; however, it would likely be within the scope of the London Protocol and UNCLOS.

Artificial downwelling

The principle

Engineering interventions would transport cold surface waters saturated in CO_2 into the deep ocean. At the surface, these 'down welled' waters would be replaced laterally by warmer surface waters. These would subsequently cool, taking up CO_2 because of enhanced solubility.

The technique and its readiness

No artificial downwelling ideas have been tested. There are no technologies available capable of creating oceanic downwelling. If it were to be introduced, the oceans would sequester carbon, but also be further acidified. Given the scale of the engineering challenge and the likely carbon uptake return, Zhou and Flyn (2005), for example estimated that increasing downwelling by 1 million cubic metres per second would only increase carbon uptake in the oceans by 0.01 Gt per annum, 360 million times less than annual human carbon emissions (IPCC, 2013), it is unlikely to be developed further.

Current research activity

The technique is not currently being researched in any detail, in part due to the scale of the engineering challenges involved, the high costs and low potential carbon uptake.

Socio-political considerations

Socio-political consideration has not been discussed given the low likelihood of the technique being developed.

Governance

How downwelling might be governed is uncertain; however, it would likely be under the scope of the London Protocol and UNCLOS.

Ocean carbon capture and storage (OCSS)

The principle

The oceans contain most of the carbon on the planet (Archer 2005). This technique would remove the dissolved inorganic carbon from the water to be taken to long term storage sites. This removal would increase the capacity of the oceans to absorb CO_2 from the atmosphere driven by a natural return to equilibrium.

The technique and its readiness

The principles underlying the technique are well understood and are used at small scale in laboratories during sea water analysis (Willauer et al., 2017). This would require scaling up, work on which is only at very early stages. OCSS would require a ready supply of energy. However, given the technique could be conducted at coastal locations, low carbon energy sources could be used to meet the energy demand. Estimates of the theoretical maximum efficiency of this technique are uncertain given the limited understanding of how scaling up would work.

Current research activity

Technical and economic modelling is underway (Eisaman et al., 2018) exploring cost and infrastructure challenges of OCSS. Many critical research issues remain, most importantly the feasibility of large-scale engineering development of OCCS and the associated costs and whether a scaled-up system would be suitable for climate mitigation. There have been no environmental impact studies. There is no co-ordinated programme of investment in this area.

Socio-political considerations

It is unclear what incentives would be required to encourage up-take were a technology proven. Which institutions would develop this and why is unknown. It is also unknown where the captured carbon would be stored and at what opportunity cost, nor whether the technique would be socially acceptable?

Governance

If conducted in nearshore waters, OCSS would be subject to nation state regulation, customary law and wider governance dialogue. In international waters, the governance frameworks are uncertain. Currently, it is unclear how sequestration and the rates of natural carbon up-take would be monitored.

Methane capture and processing

The principle

Methane is created in the seabed sediments in situ by decomposing organic matter. Some scientists are concerned, due to the far higher warming potential of methane, that the warming of the oceans will lead to large-scale releases of methane, in particular in the Arctic region (Shakhova et al., 2010; Whiteman et al., 2013). Hence there may be a need for methane capture in the future.

The technique and its readiness. There is very limited information about how the methane might be captured. Lockley (2012) and Stolaroff et al. (2012) have suggested covering kilometre-sized areas with plastic film and then either 'flaring off' the methane or recovering it to shore. An alternative suggestion is to reduce the size of the methane bubbles by sieving them though porous materials at the point of origin, causing them to dissolve into the water column before reaching the surface. Given this vagueness it has not been possible to estimate the potential scale of greenhouse gas capture.

Current research activity

None, other than theorising about the method.

Socio-political considerations

Unknown.

Governance

Whilst the technique is at a very early stage of theoretical consideration, if ever deployed it should be expected to come under the remit of UNCLOS. Other interested parties may include intergovernmental or civil society organisations, and commercial interests related to energy and chemical engineering.

Enhancing alkalinity

The principle

Alkalinity is the capacity of a solution to neutralise acid. Given the CO_2 absorbed in oceans is acidic (prominently in the form of carbonic acid) adding additional alkalinity to the surface of the ocean will decrease the relative pressure of CO_2 in the water and, as a result, increase the uptake of CO_2 by the ocean from the atmosphere. Enhancing alkalinity would also help reduce the effects of ocean acidification on the marine ecosystem.

The technique and its readiness

Lime, which readily dissolves in seawater would consume CO_2 in a well-known and understood process. Ocean liming would require no new technical developments prior to deployment. However, currently there is a major problem with this approach – there is a very large carbon and energy footprint in the current manufacturing processes of the material. If alternative methods could be developed, with a small footprint, liming may have potential as an effective CDR technique.

Other approaches include adding naturally occurring minerals to the oceans, or electrochemical enhancement of carbonate and silicate mineral weathering. These techniques can also be conducted on land, avoiding the costs of transport to and across the oceans. In addition, the impacts of introducing alien particles from these materials on the environment are unknown. However, mineral weathering is the primary way in which CO_2 is removed from the atmosphere over geologic timescales

and, if the materials could be processed, distributed and deployed at sufficient scale, the combined (on land and in the oceans) capacity of this process to contribute to CO_2 mitigation is theoretically unlimited (IPCC 2013). Resolving how the processes of alkalinity enhancement could be delivered safely, at acceptable environmental and economic cost could play an important role in humanity's response to climate change.

Current research activity

Insufficient research has been completed to properly inform decision making about enhancing alkalinity. Further research is required to develop understanding about which minerals or other materials would deliver the best net CO_2 return, the likely impacts on ocean ecosystems, the longevity of any sequestration, the economics and resource efficiency of the methods and how both deployment and its effects would be monitored.

Currently, multiple research projects are seeking to address these challenges, including a large interdisciplinary endeavour led by the University of Oxford in the United Kingdom that brings together five universities across six disciplines (Henderson 2019).

Socio-political considerations

There are questions about the public acceptability of the process. Research by Corner et al. (2014) suggests publics may not be supportive of ocean-based interventions of this nature. It is possible that the very large-scale of deployment that would be required by this technique may compound these concerns.

Governance

The technique could fall under Annex 4 of the London Convention and London Protocol and UNCLOS. Other interested parties may include intergovernmental or civil society organisations and commercial interests related to chemical engineering.

Marine SRM Techniques

Enhancing surface albedo

The principle

If the reflectivity, or albedo of the ocean surface is enhanced, additional radiation will return to space, altering the Earth's radiation balance and countering some of the effects of greenhouse warming. Only 2% of the total radiative forcing of the Sun would need to be redirected to counter the effects of the doubling of carbon dioxide concentrations in the atmosphere (Royal Society, 2009). Limited competition for space on the oceans, compared to on land makes locating an intervention potentially less politically challenging.

The technique and its readiness

Several approaches to enhancing albedo on the ocean surfaces are under consideration. Manufactured reflective floating silica spheres could be placed on sea ice to slow melting (Field et al. 2018); micro bubbles could be deployed using a bubble injection technology (Seitz 2011); stable reflective rafts of foam could be spread on the surface (Aziz et al., 2014); Arctic sea ice could be grown using wind power to cool the water in winter (Desch et al. 2016); and, bright calcifying phytoplankton blooms have been shown to increase the reflectivity of the ocean surface (Holligan et al., 1993) and could be created using the iron fertilisation techniques discussed above.

Simulations of microbubble deployment that increase ocean albedo by 0.05 suggested a potential decrease in global average surface temperatures by about 2.7 degrees Celsius (Seitz 2011). Gabriel et al. (2017) found that a decrease in temperature of 0.6 degrees Celsius could be achieved using foam to enhance the albedo in southern subtropical ocean gyres.

An important characteristic of these techniques is the likelihood of them being able to deliver local or regional cooling – shaving of heat during local temperature spikes. This could be a valuable characteristic, for example, by locally cooling waters over coral reefs, retarding coral bleaching.

Currently none of the proposed approaches described are available for deployment.

Current research activity

Work on developing spheres, bubbles, seas ice and foams are underway in small scale studies, including small scale field trials. For example, ICE911, a non-profit organisation based in California is testing and developing silicon dioxide microspheres for Arctic deployment (ICE911 2019) and small-scale field trials in Canada and the United States are underway.

Remaining research challenges include improving the longevity of bubbles and foam and enhancing their resilience to disturbance and breakdown by wave, rain, tide and shipping. The techniques could affect vertical mixing in the ocean, changes in ocean circulation, impacts on photosynthesis, and risks to the biosphere. To achieve the long durations required, surfactants may be required and the effects of these on the marine environment are unknown. Environmental impact research must then also be conducted in parallel with the technique's development. These should also consider effects of accumulations of materials on coastal zones, seabirds, fish, cetaceans etc.

Socio-political considerations

There is no in-situ market to support deployment. Carbon markets would be inappropriate for albedo, so value would likely need to be derived from levels of cooling achieved or net light reflected. The

economic effects on fisheries and effected coastal communities/economics are unknown.

Governance

The techniques discussed would require the deliberate placement of materials at sea and would therefore likely be subject to regulation by the London Protocol as a type of marine SRM, as well as the UNCLOS. Other interested parties would include CSO, IGOs, civic society and big business interests.

Marine cloud brightening (MCB)

The principle

The fundamental principle underlying MCB is the same as enhancing albedo. As with albedo enhancement MCB could deliver cooling. However, they would not address the cause of warming – concentrations of CO2 – raising questions of moral hazard (i.e., they may undermine the appetite for pressing on with mitigation) (Lin 2012).

The technique and its readiness

In relatively dust-free parts of the marine atmosphere, increasing the number of cloud-condensation nuclei (particles around which droplets of water coalesce to form clouds) would raise cloud albedo significantly and may also increase the cloud longevity (Albrecht 1989) and this has been demonstrated in situ by the E-PEACE project (Russell et al., 2013).

The scale of effect of this technique could be very large. For example, a doubling of the natural cloud-droplet concentration of the marine stratus clouds off western coasts of North and South America and the west coast of Africa would compensate for approximately a doubling of atmospheric CO2 (Latham et al. 2008). However, the potential to scale up MCB to regional scale is unclear.

Distribution mechanisms might be technically uncomplicated. It has, for example, been suggested that solar powered ships or aircraft could routinely deliver the required particles at precisely the location needed (Wood et al. 2017). However, a key remaining technical challenge is resolving which particles to use and how to consistently produce a supply of them of an appropriate diameter and quantity at sea. The most likely candidate base material is sea water.

As with albedo enhancement, MCB could also be deployed locally, securing regional benefits and such interventions are currently being researched at the Sydney Institute of Marine Science (Ellis-Jones 2017).

Current research activity

No programmes of field work that include small scale deployment are underway. However, the Marine Cloud Brightening Project, based at the University of Washington is leading research activity in the area and has described a research plan (Wood 2018) to help address some of the remaining challenges which include: MCB field experiments to provide better insight into cloud-aerosol interactions and the effect of MCB on cloud physics; how to generate, deliver and observe particles in an ecologically benign way; and, studying the regional climate implications.

Socio-political considerations

There is no established market to drive a move toward deployment. Infrastructure (deployment

vehicles) are currently not available. Public perceptions and likely responses to MCB are uncertain, although research in the UK suggests that a perceived controllability of MCB may reduce citizens' concerns about governance of the technique (Bellamy et al., 2017).

Governance

Assuming sea water spray is used for deployment, responsibilities under the UNCLOS and the London Protocol to protect against pollution of the marine environment would not constrain deployment, unless, as noted in section 24 of the GESAMP report (2018), the deposition of salt particles on the ocean surface were interpreted as the depositing of 'wastes or other matter' under the London Protocol. Otherwise, States would generally be free to conduct MCB on the high seas, provided that this is done with "due regard" for other States' interests.

Monitoring the effects of deployment would have governance connotations and how MCB might be monitored (both deployment and its effects) is not resolved.

Governance Instruments

C2G uses the IPCC's definition of governance in relation to CDR/SRM - 'A comprehensive and inclusive concept of the full range of means for deciding, managing, implementing and monitoring policies and measures. Whereas government is defined strictly in terms of the nation-state, the more inclusive concept of governance recognizes the contributions of various levels of government (global, international, regional, sub-national and local) and the contributing roles of the private sector, of nongovernmental actors, and of civil society to addressing the many types of issues facing the global community' (IPCC 2018).

There has been considerable generic debate about the governance of emerging climate techniques over the past 10-years. Of this, techniques that aim to have a global effect, and in particular stratospheric aerosol injection SRM have been a central topic, with considerably less attention being paid to CDR and other SRM techniques. This section, however, focuses on the marine environment and specifically on the existing law and some key non-binding principles or codes of conduct. The purpose of the section is to highlight the most important provisions, but not to analyse them in depth. Reynolds (2018), Scott (2013 and 2015), Redgwell (2011) and Ginzky (2018) have produced in-depth descriptions of international law relevant to CDR/SRM for those who wish to explore further.

The key international regulatory frameworks that are relevant to marine CDR/SRM are the:

- Convention on Biodiversity (CBD) (CBD 2008);
- London Convention 1972 and the 1996 London Protocol (IMO 2016);
- UN Convention on the Law of the Sea (UNCLOS) (UN 2009);
- UN Framework Convention on Climate Change (UNFCCC) (UN 1992); and,
- Paris Agreement 2015 (UNFCCC 2015);

The Convention on Biodiversity (CBD)

The 1993 CBD, with 168 signatories, has three main goals:

- to conserve biological diversity;
- the sustainable use of biodiversity, and,
- the fair and equitable sharing of benefits arising from genetic resources.

The CBD is one of the few conventions to have discussed 'geoengineering' directly. The initial focus was on ocean fertilisation activities when, at its 9th conference, it adopted decision IX/16 C that urged signatories 'to ensure that ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities, including assessing associated risks, and a global, transparent and effective control and regulatory mechanism is in place for these activities; with the exception of small scale scientific research studies within coastal waters'. (CBD, 2008, p.7).

In 2010, with a view to protecting biodiversity, the CBD went further when it invited Parties and other Governments, as well as relevant organisations and processes to note its decision (X/33(8)(w)) that 'no climate-related geo-engineering activities that may affect biodiversity take place, until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks for the environment and biodiversity and associated social, economic and cultural impacts.....' (CBD, 2010, p.5). It should be noted however that the CBD recommendation did not include small-scale scientific research studies undertaken in controlled settings that would help identify the potential impacts on the environment. Subsequently, the COPs XI and XIII reaffirmed this decision.

Whilst the CBD position appears strong, it is not binding. The language used is 'soft', only inviting parties rather than requiring parties to comply and it only extends under the CBD's mandate in relation to the conservation of biodiversity and the sustainable use of biological resources. The CBD evocation of the Precautionary Principle may, however, be an important demonstration of international law's willingness to take such measures in time. However, the limitations of the CBD also highlight that individual extant protocols and conventions as currently constructed could only form an incomplete basis for global regulation, which forms an important element of governance, because they each apply to discrete, specific topics and issues whereas some marine CDR/SRM interventions would operate at scale, across treaty boundaries.

London Convention 1972 and the 1996 London Protocol

Known as the London Convention, the Convention on the Prevention of Marine Pollution by Dumping of Wastes or Other Matter was adopted in 1972 and came into force in 1975. The London Protocol 1996 came into force in 2006. The two instruments operate in parallel and when the Protocol was adopted, parties agreed no further amendments would be made to the Convention. The Protocol directly addresses CRR/SRM and it is evolving in the context of the evolving debate about marine 'geoengineering'. The key article is Article 3.1 which requires parities to "…apply a precautionary approach to environmental protection from dumping of wastes or other matter…" and this article is amended by Annex 4 to include the placement of matter for marine 'geoengineering' activities.

The Parties first discussed CDR/SRM issues in June 2007 when an ocean fertilization experiment was being proposed (Brahic, 2007). Subsequently, in 2008, resolution LC-LP.1(1) decided that ocean fertilization activities other than legitimate scientific research were contrary to the aims of both instruments. In 2010, the Parties adopted an Assessment Framework for Scientific Research Involving Ocean Fertilization (OFAF) (resolution LC-LP.2(2)). Whilst neither resolutions were legally binding, in 2013 amendments to regulate ocean fertilization activities by resolution LP.4(8) were adopted. These amendments will give the Parties power to regulate CDR/SRM activities within the scope of the Protocol after two thirds of the Contracting Parties have deposited their instruments of acceptance. However, to date only the UK, the Netherlands and Finland have done so.

United Nations Convention on the Law of the Sea (UNCLOS)

UNCLOS was adopted in 1982 and amended in 1994 and 1995. Part XII - 'Protection and Preservation of the Marine Environment' and Part XIII 'Marine Scientific Research' cover the relevant environmental protection obligations under the Convention that apply to marine CDR/SRM activities. The key articles are:

- Article 192. States have a responsibility to protect and preserve the marine environment.
- Article 194 requires States to take measures to prevent, reduce and control pollution of the marine environment. This includes pollution from greenhouse gases and marine 'geoengineering' activities.
- Article 195 prohibits the transfer, directly or indirectly, of hazards or pollutants from one area into another.
- Article 204(2) requires States to monitor activities which they permit to determine if they may cause pollution.
- Article 206 requires States to assess potential effects of their activities if there are grounds to believe activities may cause pollution/harm.

- Article 210(6) requires compliance with the London Convention/Protocol regarding dumping.
- Article 240(d) requires States ensure that marine scientific research, whether conducted in or under their areas of jurisdiction or on the high seas complies with the marine environmental protection provisions of UNCLOS.
- Article 257 gives States and competent international organizations the right to conduct marine scientific research in seas beyond the limits of the exclusive economic zone (i.e., within the global commons).
- Article 263 makes States and competent international organizations responsible for ensuring research is conducted in accordance with the Convention.

Articles 257 and 263 raise interesting questions about: who decides what is and is not legitimate science; who and by what mechanisms do States keep control of science when equipment, funding and information is broadly available; and, how can deployment and research be disentangled for the purposes of the Convention, by whom and to what effect? The potential importance of UN negotiations for a new international agreement under UNCLOS is an evolving Convention and an intergovernmental process is in progress that will lead to an international legally binding instrument under the Convention on the conservation and sustainable use of marine biodiversity of areas beyond national jurisdiction. The third Intergovernmental Conference to discuss this important instrument, which could have important implications for parties interested in marine CDR/SRM, will take place in August 2019.

UN Framework Convention on Climate Change (UNFCCC)

Adopted in 1992 the UNFCCC provides an overarching framework to intergovernmental efforts to tackle climate change and it is likely that it will play a significant role in the global governance of marine and other CDR/SRM activities. However, what that role might be is unclear at this time. Three key elements of the Convention in this context are:

- Article 21 - "Affirming that responses to climate change should be coordinated with social and economic development in an integrated manner with a view to avoiding adverse impacts on the latter, taking into full account the legitimate priority needs of developing countries for the achievement of sustained economic growth and the eradication of poverty".
- Article 2 - "The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."
- Article 4(1)(d) - "Promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems".

The Paris Agreement 2015

Adopted in December 2015 the Paris Agreement is an agreement within the United Nations Framework Convention on Climate Change (UNFCCC). The key purpose of the Agreement is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit

the temperature increase even further to 1.5 degrees Celsius. In an analysis of the Agreement, Craik and Burns (2016) have identified four ways in which it is expected to influence the future direction of marine CDR/SRM, as detailed below. Craik and Burns also suggested that whilst SRM (albedo enhancement and MCB) would not come under the auspices of the Agreement, it could potentially provide procedural mechanisms to help satisfy demands for transparency and public debate about deployment.

- CDR/SRM are likely to arise directly out of the Agreement's objectives, building on the inclusion of 'removals' that have been present in the UNFCCC since 1992. The objectives are only achievable with recourse to 'climate engineering' (scenarios that deliver the 2 degrees Celsius limit are underpinned by a mixture of emission reductions and 'CDR technologies' (GESAMP 2018)).
- CDR techniques fall within the scope of Article 4, which includes CO 2 removals as a contribution to the mitigation commitments expected via the Parties' voluntary Nationally Determined Contributions (NDC)s.
- The inclusion of CDR techniques in NDCs will raise legal questions about technological readiness and equity implications.
- The Agreement's institutions and mechanisms provide a basis for future deliberations about market incentives which will be required to allow scaled-up deployment of CDR.

The International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978 (MARPOL)

Developed by the IMO to minimize pollution of the oceans and seas, the Convention focusses on dumping, oil and air pollution from ships. It came into force in 1983 and 156 states are party to the Convention. Reviews of international governance mechanisms pertinent to CDR/SRM have generally not discussed the Convention, although Talberg et al., (2017) does mention MARPOL in relation to ocean fertilization. Dependent on how food wastes and noxious liquid substances (under Annexes V and II respectively) are interpreted by the IMO and signatories in the future, the techniques discussed in this briefing could potentially become subject to the Convention. However, what that role might be is unclear.

Conclusions

The oceans play a key role in climate regulation. The marine environment has been considered by many interested and affected parties to be an appropriate location to develop novel CDR/SRM interventions in response to the climate change challenge. A wide range of potential techniques, ranging from scaling-up well understood technologies or practices, to mega-scale engineering projects have been subject to debate and research. Whilst none of these approaches is yet sufficiently developed or understood to deliver measurable climate-scale effects, the increasingly urgent need to address anthropogenic climate change is driving forward work that may, in the future, lead to regionally effective deployments.

In light of the growing debate about marine CDR/SRM governance, the regulatory mechanisms have been evolving. New instruments have been introduced to Conventions and Protocols aimed at both protecting the natural environment and providing new frameworks that allow for scientific and engineering progress, including field trials.

Moving forward, increasingly close cooperation between scientists, engineers, publics, governments, global institutions and civic bodies will be essential to deliver a safe, socially acceptable and environmentally appropriate future for the world's oceans and, in turn all life on Earth.

C2G

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Summarised information about the techniques and their governance is available in the

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This briefing is based on the latest literature and has been subject to independent external expert review. Please notify ***contact@c2g2.net*** *of any suggested corrections.* *Version 20190809.*