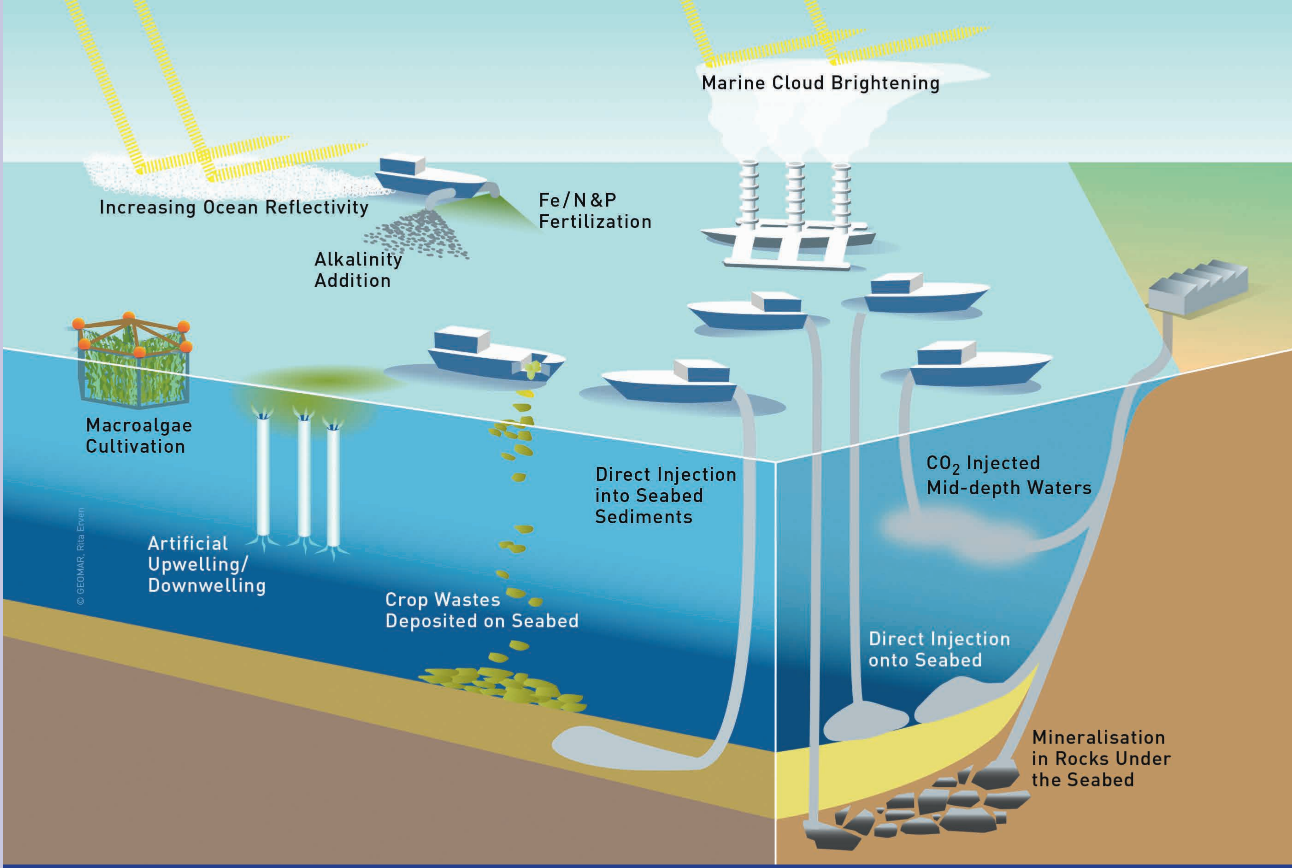
98

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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EXECUTIVE SUMMARY

Background

‘Geoengineering’ has been put forward as a potential tool for countering climate change and was defined by the UK Royal Society in 2009 as: *the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change.* Proposed approaches are often divided into two groups: those intended to remove carbon dioxide from the atmosphere and those intended to reduce the amount of solar energy that is absorbed by the Earth’s surface. Although the term ‘geoengineering’ in relation to mitigating climate change had first been used in the peer-reviewed literature in 1977 (Marchetti, 1977), in 1965 President Johnson’s Science Advisory Committee gave an example of an approach to address the impact of increasing atmospheric CO_2 concentrations: by spreading small reflective particles over large oceanic areas to increase the albedo. Individual geoengineering techniques were subsequently addressed in a number of papers and reports over the following decades. Geoengineering in the atmosphere first gained significant widespread attention across the scientific community and beyond in 2006 when Nobel laureate Paul Crutzen drew parallels between the global cooling effects of sunlight-reflecting aerosols in the upper atmosphere (stratosphere) from a volcanic eruption, and the potential to purposefully increase the stratosphere’s ability to reflect incoming solar radiation using aerosol injection (Albedo Modification). Subsequently, comprehensive assessments of geoengineering techniques have been published by national academies (UK, USA) and intergovernmental bodies (Intergovernmental Panel on Climate Change, Convention on Biological Diversity), but their focus has been generic with generally little emphasis on marine geoengineering techniques.

While Marchetti (1977) was the first to propose using ocean density currents to transport and store anthropogenic carbon dioxide in the deep ocean, “marine geoengineering” first came to widespread public attention in 1990 when global headlines announced US ocean scientist John Martin idea that ocean fertilization could be used to enhance biological carbon dioxide uptake and storage to counteract carbon dioxide induced global warming. It came to widespread public attention again in 2007 due to a proposed ocean iron fertilization activity, planned as a commercial venture by Planktos Inc., off the Galapagos Islands. Such ventures have since taken place in the North-East Pacific off Canada and have been planned for the western seaboard of South America off Chile. The Contracting Parties to the London Convention and London Protocol (LC/LP) expressed concern about the marine environmental impacts of the proposed activity off the Galapagos. In 2008 the Parties adopted a resolution deciding that ocean fertilization activities other than legitimate scientific research should be considered as contrary to the aims of both instruments. Subsequently, due to ongoing interest in marine geoengineering, the LP was amended in 2013 to regulate ocean fertilization activities. These amendments also enable the Parties to regulate other marine geoengineering activities within the scope of the LP by listing them in the new Annex 4 of the Protocol. Thus, the LP has a governance framework that potentially can be applied to newly emerging marine geoengineering technologies.

Objectives

In the light of the growing interest in marine geoengineering techniques and the LP amendment, GESAMP decided that a Working Group (WG) was needed to:

1 Better understand the potential environmental (and socio-economic) impacts of different marine geoengineering approaches; and

2 Provide advice to the London Protocol Parties to assist them in identifying those marine geoengineering techniques that it might be sensible to consider for listing in the new Annex 4 of the Protocol.

Establishment of WG 41

The WG was established and comprised mainly natural scientists with wide-ranging expertise relevant to marine geoengineering, along with a smaller group of experts from economics and political sciences. The preliminary and main findings are reported here.

Findings

- This is the first dedicated assessment of the wide range of proposed marine geoengineering approaches. It catalogues 27 approaches (including variations of approaches) and details 8 illustrative examples from the categories spanning Carbon Dioxide Removal (CDR), Albedo Modification (AM), and hybrid (i.e., for purposes extending beyond CDR or AM) technologies.
- The information available on proposed marine geoengineering techniques varies widely, ranging from the promotion of initial concepts on web sites to theoretical examinations of potential efficacy and risks in the peer-reviewed literature, supported by some basic descriptions of matching technology. Techniques have been proposed by scientists and by the private sector.
- Descriptions are provided for >20 techniques and are structured to include: approach/rationale; underlying principle(s); extent of knowledge; evidence of concept; proposed deployment zone(s); potential scale of use; duration of deployment; evidence of feasibility; and appraisal of potential impacts.
- Detailed information and evidence are essential to assess the efficacy and the potential long-term benefits and risks of a marine geoengineering approach. It was agreed that if there is no substantive science behind a proposal, it is not possible to provide a scientific review of it nor to provide solid policy recommendations beyond providing guidelines as to how to proceed.

- For each and every technique, information on marine geoengineering approaches available in the permanent public record, and/or as peer-reviewed documents, is inadequate to permit a robust scientific assessment, much less one that can be readily intercompared with other approaches to climate intervention.
- Although decisions on policy formulation or governance often have to be based on incomplete information, for many of the marine geoengineering approaches examined the knowledge available was viewed to be insufficient for evidence-based decision-making. These major gaps also raise issues regarding the ability to effectively communicate the many aspects of geoengineering to the general public. In the report we have attempted to provide guidelines for proponents on the series of steps needed to support an evidence-based assessment.
- Despite the widespread knowledge gaps, it was possible to provide an evaluation of eight illustrative marine geoengineering approaches using the most applicable and pertinent criteria from prior reports (NAS, CBD) bolstered with additional essential criteria (Summary Table). The most important of these criteria is the availability of information on the performance and impacts of these approaches as attained by scientific testing and experimentation.

Summary Table. Examples of geoengineering approaches in eight categories.

Category	Prominent Example	Sources of evidence-based knowledge	Nature of field studies	Knowledge gaps	Wider applicability of OF regulations[§]
Carbon Dioxide (CO_2) Removal – biology	Ocean Iron Fertilization (OIF)	Theory[*], natural analogues[†], modelling (~10% of current CO_2 emissions), field studies[‡]	Unconstrained, transient, 100 km scale, not legal	Detection, attribution, upscaling issues, side-effects	Regulated by the LC/LP[‖]
Food Security – Fertilization	Fish Stock Enhancement	Theory, natural analogues, field studies	Unconstrained, transient, 100 km scale, not legal	Detection, attribution, upscaling issues, side-effects	Parallels, Large scale fertilization
Carbon Dioxide Removal – physical transport	Liquid CO_2 on the Seabed	Theory, natural analogues, field studies	Unconstrained, transient, m scale	Upscaling issues, side-effects	Not applicable Banned by the LP but LC position uncertain,
Hybrid technologies for Carbon Dioxide Removal/ food security	Macroalgal Cultivation	Theory, natural analogues, modelling (<<10% of current CO_2 emissions), field studies	Unconstrained, transient, < 5 km	Upscaling issues, side-effects	Many differences from OIF, coastal
Carbon Dioxide Removal – physical transport and biogeochemistry	Artificial Upwelling	Theory, natural analogues, modelling (<10% of current CO_2 emissions), field studies	Tests - from catastrophic failure (< 1 day) to 35 days	Detection, attribution, upscaling issues, side-effects	Parallels, Large scale transboundary issues
Carbon Dioxide Removal – geochemical	Ocean Alkalinization	Theory, natural analogues, modelling (~10% of current CO_2 emissions), lab tests, field studies	Unconstrained, transient, 10 km scale	Detection, attribution, upscaling issues, side-effects	Parallels, Large scale transboundary issues
Albedo Modification – ocean surface	Reflective Foams	Theory, natural analogues, modelling	None for marine-based foams, lab-based trials	Many major unknowns, foam performance, side-effects, detection, attribution, upscaling	Not Carbon Dioxide Removal
Albedo Modification – lower atmosphere	Marine Cloud Brightening (using seawater spray)	Theory, natural analogues, indirect evidence from ship emissions, modelling	None. Lab-based proof of concept for droplet formation	Many major unknowns including feasibility of producing sub-micron salt water droplets	Not Carbon Dioxide Removal

[*] Theory refers to scientific principles that can be applied to make a prediction of effects.

[†] Natural analogues are parallel examples from the natural world, for example enhanced carbon sequestration in the geological past driven by increased iron supply from dust.

[‡] the majority of field studies occurred before the LC/LP amendment and the CBD (2008) decision.

[§] Denotes the relevance of the LC/LP agreements on OF to other marine geoengineering techniques.

[‖] Not yet in force

LC – London Convention 1972

LP – London Protocol 1996

Analysis of the summary table

- Those with untested potential for climate mitigation purposes, such as reflective foams, require more detailed evaluation. A wide range of knowledge gaps currently exist, ranging from testing of underlying principles, side-effects, to practical challenges and uncertainties for upscaling.
- The dearth of evidence on some approaches might hinder their consideration for inclusion in Annex 4 of the LP. However, these major knowledge gaps need not preclude development of an initial assessment framework for each of the techniques. Critically, some of these information gaps could be addressed in the laboratory, or with constrained field studies, and hence within existing legislation and/or codes of conduct within institutions or nations.
- For example, in cases such as marine cloud brightening using seawater sprays, approaches have been examined theoretically and experimentally to varying degrees, but there is little or no information on the testing beyond the laboratory.
- The gradualist approach, of building a portfolio of detailed evidence using lab and constrained field studies, may be contrasted with a tendency in some cases to plan large scale (unconstrained (i.e., unbounded) trials on the high seas) studies which may require new or amended legislation.
- Based on the collective knowledge across the WG membership, and the information currently available on marine geoengineering in the permanent public record, WG 41 could not make authoritative statements about the likelihood that individual geoengineering approaches can mitigate climate change, and with what risks.
- Several approaches, such as artificial upwelling, share common features for implementation with ocean iron fertilization, leading to similar issues (e.g. transboundary effects) and hence the potential for a common governance framework.
- In other cases, such as macroalgal cultivation or fisheries enhancement, amended or additional governance regulations may be required.
- On the basis of the reported rationale, principles, and estimates of efficacy from available models, several of the eight marine geoengineering approaches in the summary table (e.g., ocean alkalinisation), together with some others that we assessed, potentially could be considered for listing in the new Annex 4 of the London Protocol after more detailed assessment.
- It is presently difficult to advise on which of the different categories of geoengineering will advance (i.e., requests for unconstrained pilot studies) in the coming years, as approaches can emerge without a conspicuous footprint in the scientific literature, for example the proposed fisheries enhancement off Chile.

A key recommendation from this report is that:

A coordinated framework for proposing marine geoengineering activities, submitting supporting evidence, and integrating independent expert assessment must be developed.

It is essential that the process of evidence-based assessment takes place in parallel with ongoing efforts to devise research governance structures, since both are inextricably linked in the marine geoengineering debate and the development of policy. Together, they can ensure that any future multi-faceted exploration of the merits and challenges of a range of marine geoengineering approaches is built on a firm foundation. This will provide the platform needed to assess and compare marine with atmospheric and terrestrial geoengineering approaches with a view to common assessment frameworks and to take into account the interplay of these approaches across the Earth System.

Recommendations for future work:

1 Additional steps are required to address more completely parts of Terms of Reference 2 (i.e., a detailed focused review of a limited number of proposed marine geoengineering techniques that are likely to have some potential for climate mitigation purposes) that the WG was not able to fully attend to in this report.

2 The findings of the WG evaluation provide an important starting point for the next phase of assessment by presenting a major challenge *to develop a streamlined, robust framework for scientific assessment that engages proposers of individual techniques and provides the opportunity for effective, transparent scientific review;* and

3 This framework is essential to promote a transition towards a more holistic assessment that includes social, political, economic, ecological, ethical and other societal dimensions. Marine geoengineering approaches must be grounded in strong underpinning science, and then explored, and potentially developed, in a manner that is useful and acceptable to society.

1 BACKGROUND TO THE GESAMP WG REVIEW

The primary background to this report is the issue of climate change and how to address it. This background section briefly covers the issue of climate change, particularly as it affects the oceans, and why in turn geoengineering the ocean is being considered, with a wide number of methods being put forward. These in turn inform the need for frameworks such as that of the London Convention/London Protocol, and the Paris Agreement 2015.

1.1 Climate change and the ocean

“Oceans and climate are inextricably linked and oceans play a fundamental role in mitigating climate change by serving as a major heat and carbon sink. As concerns about climate change increase, the interrelationship between oceans and climate change must be recognized, understood, and incorporated into climate change policies.”

The ocean plays a central role in regulating the Earth’s climate. The Fifth Assessment Report published by the Intergovernmental Panel on Climate Change in 2013 (IPCC, 2013) revealed that it has thus far absorbed 93% of the extra energy from the enhanced greenhouse effect, with warming now being observed at depths of 1,000 m.

Carbon dioxide and other greenhouse gas emissions are giving rise to changes in the ocean including:

1 Temperature rise – effects include polar ice melting, coral bleaching and fish migration;

2 Ocean acidification – Ocean acidification reduces the ability of marine organisms, such as corals, plankton and shellfish, to build their shells and skeletal structures. It also exacerbates existing physiological stresses and reduces growth and survival rates during the early life stages of some species;

3 Sea level rise – effects include drowning wetlands and increased coastal erosion/flooding; and

4 Expanding of oxygen minimum zones as an indirect effect of increased stratification.

1.2 The ocean – why it is important

The ocean and coasts provide critical ecosystem services such as carbon storage, oxygen generation, food and income generation.

Coastal ecosystems like mangroves, salt marshes and seagrasses play a vital role in carbon storage and sequestration. Per unit of area, they sequester carbon faster and far more efficiently than terrestrial forests. When these ecosystems are degraded, lost or converted, massive amounts of CO_2 – an estimated 0.15-1.02 billion tons every year (Pendleton *et al.* 2012) – are released into the atmosphere or ocean, accounting for up to 19% of global carbon emissions from deforestation. The ecosystem services such as flood and storm protection that they provide are also lost.

The impacts of ocean warming and acidification on coastal and marine species and ecosystems are already observable. For example, the current amount of CO_2 in the atmosphere is already too high for coral reefs to thrive, putting at risk food provision, flood protection and other services corals provide. Moreover, increased greenhouse gas (GHG) emissions exacerbate the impact of already existing stressors on coastal and marine environments from land-based activities (e.g. urban discharges, agricultural runoff and plastic waste) and the ongoing, unsustainable exploitation of these systems (e.g. overfishing, deep-sea mining and coastal development). These cumulative impacts weaken the ability of the ocean and coasts to continue to perform critical ecosystem services.

The degradation of coastal and marine ecosystems threatens the physical, economic and food security of coastal communities – around 40% of the world population. Local fishermen, indigenous and other coastal communities, international business organisations and the tourism industry are already seeing the effects of climate change particularly in Small Island Developing States (SIDS) and many of the Least Developed Countries (LDCs).

Weakened or even lost ecosystems increase human vulnerability in the face of climate change and undermine the ability of countries to implement climate change adaptation and disaster risk reduction measures, including those provided for in Nationally Determined Contributions (NDCs) under the Paris Agreement[1].

1.3 The suitability of the ocean for geoengineering

The unprecedented scale and rapidity of climate change (IPCC, 2013) mean that climate intervention approaches must be correspondingly large and rapid if offsetting these changes is a desirable. The ocean covers three quarters of Earths’ surface area, and hence this areal coverage offers some potential for Albedo Modification (AM) for example using foams. The ocean is also characterised by diverse biogeochemical cycles such as for carbon and trace elements, and ocean circulation has much longer timescales than the atmosphere, meaning that additional anthropogenic carbon could be potentially stored, in the deep ocean or on the sea floor. The productivity of the ocean is limited in large areas of the ocean by iron or phosphorus. So, there is some potential in attempting to boost productivity through intentional nutrient enrichment, as a means to enhance the oceans biological pump.

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[1] https://www.iucn.org/resources/issues-briefs/ocean-and-climate-change

1.4 London Convention/ London Protocol policy involvement with climate change

The first significant policy-related discussions on climate change in the London Convention started in 2004 when the UK submitted document LC 26/6/1 to the 26th Consultative Meeting, which briefly described the issue of carbon capture and sequestration in the marine environment and the related discussions in other fora. The UK delegation suggested that, among other things, the meeting should consider the need, if any, to regulate CO_2 under a clear legal regime consistent with the aims of the Convention and Protocol, in the light of a full assessment of the environmental risks. The Meeting agreed that the issue of CO_2 sequestration should be included in its work programme with a focus on sequestration of CO_2 in geological structures. This led ultimately to the adoption of an amendment to Annex 1 of the London Protocol (which came into force on 24 March 2006) at the Governing Bodies meeting in December 2006 to permit CO_2 sequestration in sub-seabed geological formations. Earlier that year, an intersessional technical working group of the London Convention Scientific Group had developed a Risk Assessment and Management Framework for 'CO_2 sequestration in sub-seabed geological formations' (CS-SSGF) and, based on that document, subsequently developed specific guidelines for CS-SSGF that were adopted by the Governing Bodies of the London Convention and London Protocol in December 2007.

In 2007 the London Convention and London Protocol began to discuss the issue of geoengineering in the marine environment as a climate mitigation measure and this is described in section 2.4 below.

1.5 The Paris Agreement 2015

The Paris Agreement 2015 was adopted at the December 2015 meeting of the Parties to the UNFCCC. Its central aim 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. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change. See section 8.1.3 for further details of the Paris Agreement.

Prior to the Paris meeting that adopted the 2015 Paris Agreement, nearly all countries submitted 'intended national determined contributions' to show their national strategies for addressing climate change. These become 'National Determined Contributions' (NDCs) when countries join the Paris Agreement and they have to be revised and updated every 5 years. However, current mitigation efforts and existing future commitments are inadequate to meet the Paris Agreement temperature goals (Lawrence *et al.,* 2018).

2 GEOENGINEERING AND THE OCEANS

2.1 What is geoengineering?

Geoengineering[2, 3] has been suggested as a potential tool for addressing climate change and the Royal Society's definition has been widely accepted:

> "The deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change" (Royal Society, 2009).

However, a number of alternative definitions have been proposed, for example, Williamson *et al.* (2012a) listed 9 other definitions (see Annex I of their report) and used a slightly different formulation themselves:

> "deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and its impacts".

Williamson *et al.* (2012a) and Williamson and Bodle (2016) also provided additional information on options for definitions of climate-related geoengineering.

A number of other terms have been used in the scientific and other literature to refer to these techniques collectively including 'climate engineering', 'climate-related geoengineering', 'climate intervention' and 'climate remediation'. These terms will only be utilised in this report when referring to publications that employed those terms.

The Royal Society report classified geoengineering methods into two categories:

- Carbon Dioxide Removal (CDR) methods: which reduce the levels of carbon dioxide (CO_2) in the atmosphere, allowing outgoing long-wave (thermal infra-red) heat radiation to escape more easily; and
- Solar Radiation Management (SRM) (also known as Albedo Modification (AM)[4]) methods: which reduce the net incoming short-wave (ultra-violet and visible) solar radiation received, by deflecting sunlight, or by increasing the reflectivity (albedo) of the atmosphere, clouds or the Earth's surface.

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[2] Note that "geoengineering" has other meanings and has been used by the geotechnical engineering community for many decades – see http://www.geoengineeringfederation.org/ and http://www.geoengineer.org/about-us.

[3] Carbon capture and storage (CCS) where carbon dioxide is captured before it is released into the atmosphere is not usually considered to be a type of geoengineering. See Williamson *et al.* (2012a) Annex II and the footnote to paragraph 8 (w) of CBD of decision X/33 given in Bodle *et al.* (2012). (Bodle, Homan, Schiele, & Tedsen, 2012)

[4] Through the rest of this report the term Albedo Modification (AM) will be used rather than Solar Radiation Management (SRM) except where quoting from a publication that uses the term SRM.

It should be noted that the fundamental difference between albedo modification (AM) and carbon dioxide removal (CDR) is that the former deals with the “symptoms” while the latter is the “cure”. AM does not deal with atmospheric CO_2 levels and resulting surface ocean acidification. A number of authors have suggested that the term ‘geoengineering’ is not helpful as it lumps together techniques that are very different in their modes of action. Consequently, they have suggested that it is preferable to refer to CDR or AM as such and not use the umbrella term ‘geoengineering’ (National Research Council 2015a, 2015b).

Subsequent to the publication of the 2009 Royal Society report, the terms Negative Emissions Technologies (NETs) and Greenhouse Gas Removal (GGR) technologies have come into common use. These terms can include techniques addressing other greenhouse gas emissions such as methane and nitrous oxide, as well as carbon dioxide. However, it should be noted that geoengineering methods to remove greenhouse gases other than CO_2 from the atmosphere (e.g. methane and nitrous oxide) have received little attention so far (National Research Council, 2015a), although terrestrial mitigation measures have been addressed (UNEP and WMO, 2011; and de Richter *et al.* 2017). There are only a few publications that have addressed removal of methane from the marine environment (e.g. Salter, 2011 and Stolaroff *et al.,* 2012).

As pointed out by Meadowcroft (2013), “CDR (NETs/GGR) approaches vary widely. As a group they share a capacity to remove CO_2 from the atmosphere, but not a lot more. The CO_2 is captured and stored by varied mechanisms, involving different natural processes and forms of human activity. The approaches present varied profiles of costs and benefits, potential side effects and risks, and limiting factors”. These techniques have very little in common with AM techniques whereas they generally have much more in common with mitigation approaches (Boucher *et al.,* 2014; Heyward, 2013; Lomax *et al.,* 2015a). Many of these techniques involve the enhancement of natural sinks that are included within the IPCC definition of mitigation[5]. Heyward (2013) thus considered CDR as a subset of mitigation. Heyward (2013) came up with a new scheme to categorise responses to climate change that limited mitigation to reducing GHG emissions and covered all enhancement of sinks as CDR. Boucher *et al.* (2014) asserted that “… current definitions of mitigation, adaptation, and climate engineering are ambiguous, overlap with each other and thus contribute to confusing the discourse on how to tackle anthropogenic climate change.” Lomax *et al.* (2015a) stated that “… the distinction between GGR and emissions reductions is in many ways artificial and is an unconstructive basis for developing effective policy”. However, these views on categorising CDR are not generally accepted but are part of an ongoing semantic debate around definitions.

2.2 Geoengineering – an issue of international concern

Although the term ‘geoengineering’ in relation to mitigating climate change had first been used in the peer-reviewed literature in 1977 (Marchetti, 1977), in 1965 President Johnson’s Science Advisory Committee gave an example of an approach to address the impact of increasing atmospheric CO_2 concentrations: by spreading small reflective particles over large oceanic areas to increase the albedo (PSAC, 1965). Geoengineering *per se* was subsequently addressed in a number of publications over the next 20 years (e.g. Dyson, 1977; Keith, 2000; Keith and Dowlatabadi, 1992; National Research Council, 1992) and papers/reports/comments on individual geoengineering techniques were also published (e.g. Chisholm and Morel, 1991, Chisholm *et al.* 2001; Dyson, 1977; Gao and McKinley, 1994; IPCC, 2005; Kheshgi, 1995; *Lackner et al.,* 1995; Latham, 1990). However, geoengineering first came to significant attention across the wider scientific community and beyond with an editorial by the Nobel Laureate Paul Crutzen (Crutzen, 2006). The paper, which drew parallels between the global stratospheric effects of the Pinatubo eruption and what he called “the stratospheric albedo modification scheme”, suggested that the usefulness of artificially enhancing earth’s albedo and thereby cooling the climate by adding sunlight reflecting aerosol in the stratosphere might be explored and debated. The paper generated much controversy and stimulated the publication of many papers and postings of blogs on the internet. Results of bibliometric studies on published geoengineering research showed an exponential increase in the total number of scientific publications on this subject since 2000 (Belter and Seidel, 2013; Linnér and Wibeck, 2015; Oldham *et al.* 2014).

Subsequently, the Royal Society decided to study the issue and published the report ‘Geoengineering the climate: Science, governance and uncertainty’ (Royal Society, 2009). The report provided ratings for effectiveness, affordability, timeliness and safety of 12 geoengineering techniques, only one of which was a marine approach – ocean fertilization. However, in the discussion of ocean ecosystems methods, the report also commented on ocean upwelling/downwelling.

The Royal Society report stated that the governance challenges posed by geoengineering should be explored in more detail by an international body. Also, they advocated that relevant international scientific organisations should coordinate an international programme of research on geoengineering methods with the aim of providing an adequate evidence base with which to assess their technical feasibility and risks and reducing uncertainties within ten years.

One of the report’s key recommendations was:

> *“Further research and development of geoengineering options should be undertaken to investigate whether low risk methods can be made available if it becomes necessary to reduce the rate of warming this century. This should include appropriate observations, the development and use of climate models, and carefully planned and executed experiments.”*

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[5] A human intervention to reduce the sources or enhance the sinks of greenhouse gases (GHGs) – IPCC AR5 Synthesis Report (IPCC, 2014c)

Further details about the Royal Society report are given in Annex III.

A number of other assessments/reviews of geoengineering techniques have been published in recent years and these are summarised in Table 2.1 with more details given in Annex III. Those assessments varied in the number of geoengineering techniques assessed from five up to thirty and only a limited number assessed more than a few marine geoengineering techniques. Also, Working Groups I, II, and III (WGI, WGII, and WGIII) of the IPCC held a joint Expert Meeting on Geoengineering in Lima, Peru, from 20 to 22 June 2011 (IPCC, 2012) in preparation for the assessment of the scientific basis of geoengineering options, risks, and impacts in the IPCC's Fifth Assessment Report (AR5). It discussed terminology, clarified concepts and definitions and considered emerging issues. In addition, Williamson (2016) briefly describe several CO_2 removal methods.

Table 2.1 Assessments/reviews of geoengineering techniques.

Authors	**AM Techniques**	**CDR Techniques**
Boyd, (2008)	2 (1)	3 (1)
CBD (2009)	–	1
Keller (2018)	2 (2)	9 (6)
McCormack *et al.* (2016)	3	9 (3)
McGlashan *et al.* (2012)	–	5
McLaren (2012)	–	30(2)
National Research Council (2015a)	–	10 (4)
National Research Council (2015b)	6 (2)	–
Rickels *et al.* (2011)	5 (1)	9 (6)
Schafer *et al.* (2015)	1	2 (1)
UNEP (2017)	–	9 (1)
US GAO (2011)	4	6 (2)
Vaughan and Lenton (2011)	9	10 (6)
Williamson *et al.* (2012a)	4 (1)	14 (5)
Williamson and Bodle (2016)	4(1)	7(2)

Values in brackets are the number of marine-based techniques

It is worth noting the key findings obtained by the interdisciplinary Priority Program on the Assessment of Climate Engineering funded by the German Research Foundation (Oschlies and Klepper, 2017) that were in summary:

> "… compared to earlier assessments such as the 2009 Royal Society report, more detailed investigations tend to indicate less efficiency, lower effectiveness, and often lower safety. Emerging research trends are discussed in the context of the recent Paris agreement to limit global warming to less than two degrees and the associated increasing reliance on negative emission technologies. Our results show then when deployed at scales large enough to have a significant impact on atmospheric CO_2, even CDR methods such as afforestation - often perceived as "benign" - can have substantial side effects and may raise severe ethical, legal, and governance issues."

It should also be noted that atmospheric AM geoengineering techniques will have an impact on the ocean, but that impact will depend on the approach used (Hardman-Mountford *et al.* 2013; Lauvset *et al.,* 2017) - see also section 3.1.

Note that the following papers/reports on geoengineering came out after this GESAMP report had been drafted and so were not considered within it:

Minx *et al.* (2018) Negative emissions—Part 1: Research landscape and synthesis. Environmental Research Letters 13 63001;

Fuss *et al.* (2018) Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters 13 63002;

Nemet *et al.* (2018) Negative emissions—Part 3: Innovation and upscaling. Environmental Research Letters 13 63003;

National Academies of Sciences Engineering and Medicine and National Academies of Sciences and Medicine (2018) Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. The National Academies Press, DOI: 10.17226/25259;

Gattuso *et al.* (2018) Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. Frontiers in Marine Science 5: 337; and

Royal Society/Royal Academy of Engineering (2018) Greenhouse gas removal. Royal Society/Royal Academy of Engineering, London.

2.3 Why we are likely to need geoengineering to counter climate change

The international climate context has changed with the implicit acceptance of negative emission requirements in the 2015 Paris agreement (Gasser *et al.*, 2015; Geden and Schäfer, 2016; Shepherd, 2016). Most of the climate models analysed by the IPCC that limit the global atmospheric temperature increase to 2 °C require NETs to achieve that goal (Fuss *et al.,* 2016; Rogelj *et al.,* 2015, 2016; Smith *et al.,* 2016). The Summary for Policymakers of the IPCC AR5 Synthesis Report (IPCC, 2014c) makes clear that CDR is very likely to be necessary to meet agreed upper limits for climate change (in section SPM 3.4). The Summary for Policymakers of the IPCC Special Report on Global Warming of 1.5 °C (IPCC, 2018) (IPCC, 2018) states in paragraph C3:

> "All pathways that limit global warming to 1.5 °C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 Gt CO_2 over the 21st century. CDR would be used to compensate for residual emissions and, in most cases, achieve net negative emissions to return global warming to 1.5°C following a peak (high confidence). CDR deployment of several hundreds of Gt CO_2 is subject to multiple feasibility and sustainability constraints (high confidence). Significant near-term emissions reductions and measures to lower energy and land demand can limit CDR deployment to a few hundred Gt CO_2 without reliance on bioenergy with carbon capture and storage (BECCS) (high confidence)."

The United Nations Environment Programme 2017 Emissions Gap Report (UNEP, 2017) stated that "In order to achieve the goals of the Paris Agreement, carbon dioxide removal is likely a necessary step". The National Academy of Sciences CDR report (National Research Council, 2015a) comments in the 'Way Forward' chapter that CDR deployment would be necessary to achieve climatic stability for IPCC scenarios that involve a 'temporary overshoot' in atmospheric CO_2 concentrations.

A growing number of scientific studies and reports are concluding that NETS are or are likely to be necessary to achieve the Paris Agreements targets (e.g. Alcalde *et al.* 2018; ; Craik and Burns (2016;Fuss *et al.,* 2016; Gasser *et al.,* 2015; Jackson *et al.,* 2017; Kriegler *et al.,* 2018; Lomax *et al.,* 2015a; Peters and Geden, 2017; Psarras *et al.,* 2017; Rickels *et al.,* 2018; Van Vuuren *et al.,* 2017; Xu and Ramanathan, 2017;) and in editorials in scientific journals (Nature Climate Change Editorial, 2017). An exploration of alternative pathways (including lifestyle change, additional reduction of non-CO_2 greenhouse gases and more rapid electrification of energy demand based on renewable energy) to the 1.5 °C target by van Vuuren *et al.* (2018) found "Although these alternatives also face specific difficulties, they are found to significantly reduce the need for CDR but not fully eliminate it". The American Geophysical Union has issued a statement about climate intervention saying that it requires enhanced research, consideration of societal and environmental impacts and policy development (AGU, 2018).

A number of authors have suggested that methods of removing CO_2 from the atmosphere need to be brought into mainstream climate policy so that they can get the incentives to research and develop the technologies to discover which techniques may work at scale (Bellamy, 2018; Brent *et al.,* 2018; Honneger, 2018; Lomax *et al.* 2015b; Peters and Geden, 2017).

The IPCC Representative Concentration Pathway 2.6 (RCP2.6) climate change projection, the only RCP that has some likelihood of limiting global temperature rise to 2 °C above the pre-industrial level, relies upon significant carbon removal using a specific geoengineering approach, assumed to be in the form of Bio-Energy with Carbon Capture and Storage (BECCS) – see Figure 2.1. A recent study (Magnan *et al.,* 2016) indicated that for RCP 2.6 to be achieved, the best-case scenario required the removal of 0.5 – 3.0 Gt C per year and in the worst case 7-11 Gt C per year. Even if the global temperature rise is kept to 2 °C above the pre-industrial level, ocean pH will continue to decline for a considerable time (at least several decades) since the ocean will continue to take up CO_2, but at a decreasing rate, until the ocean and the atmosphere, are in equilibrium (Magnan *et al.,* 2016). Thus, geoengineering techniques that specifically address ocean alkalinity may merit consideration.

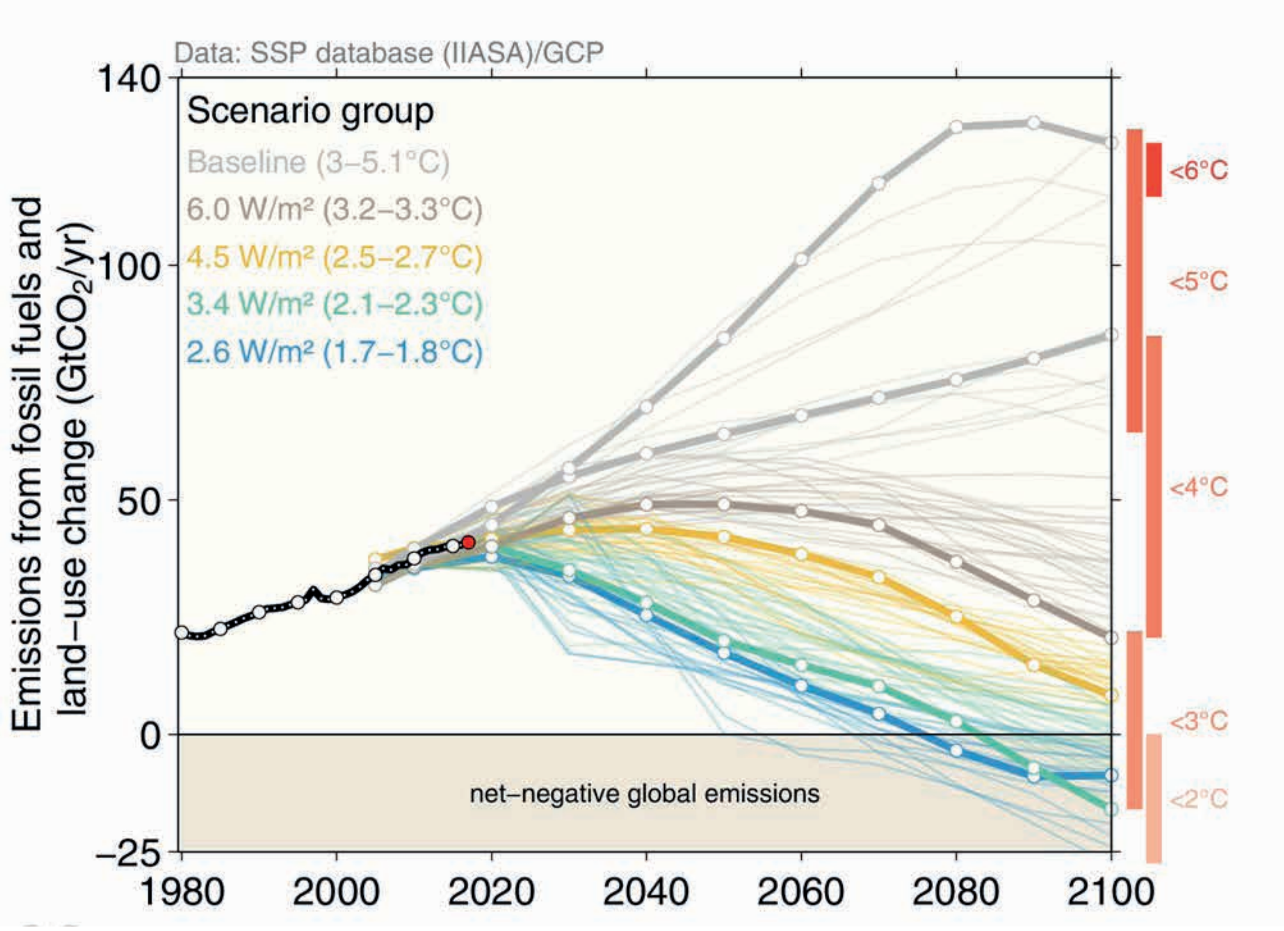

Figure 2.1 *Five Shared Socioeconomic Pathways (SSPs) developed to explore challenges to adaptation and mitigation. Source: Riahi* et al. *(2017); Global Carbon Budget 2017[6]. This work is licensed under a Creative Commons Attribution 4.0 International License[7].*

In a modelling study, Tokarska and Zickfield (2015) explored whether negative emissions would be effective in reversing climate change on human timescales, in particular, sea level rise, given the potentially counteracting effect of natural carbon sinks and the inertia of the climate system. Their study suggested that sea level would continue to rise for at least several centuries despite large amounts of CO_2 removed from the atmosphere. Ehlert and Zickfeld (2018) studied the response of sea level rise due to thermal expansion to a 1% yearly increase of atmospheric CO_2 up to a quadrupling of the pre-industrial concentration followed by a 1% yearly decline back to the pre-industrial CO_2 concentration. They concluded that "…sea level rise from thermal expansion is not reversible even under strong decreases in atmospheric CO_2 on timescales (1,000 years) relevant to human civilization".

Nichols *et al.* (2018) examined the effectiveness of stringent climate stabilization scenarios for coastal areas in terms of reduction of impacts/adaptation. They calculated global SLR and ocean pH projections to 2300 for 1.5 °C and 2.0 °C stabilization scenarios and a reference unmitigated RCP 8.5 scenario. They stated that "Under both stabilization scenarios, global mean ocean pH (and temperature) stabilize within a century. This implies significant ecosystem impacts are avoided, but detailed quantification is lacking, reflecting scientific uncertainty. By contrast, SLR is only slowed and continues to 2300 (and beyond). Hence, while coastal impacts due to SLR are reduced significantly by climate stabilization, especially after 2100, potential impacts continue to grow for centuries. SLR in 2300 under both stabilization scenarios exceeds unmitigated SLR in 2100. Therefore, adaptation remains essential in densely populated and economically important coastal areas under climate stabilization."

Mengel *et al.* (2018) quantified the effect of the Paris Agreement constraints on global sea level rise until 2300. They stated that "We estimate median sea-level rise between 0.7 and 1.2 m, if net-zero greenhouse gas emissions are sustained until 2300, varying with the pathway of emissions during this century. Temperature stabilization below 2 °C is insufficient to hold median sea-level rise until 2300 below 1.5 m. We find that each 5- year delay in near-term peaking of CO_2 emissions increases median year 2300 sea-level rise estimates by ca. 0.2 m, and extreme sea-level rise estimates at the 95th percentile by up to 1 m. Our results underline the importance of near-term mitigation action for limiting long-term sea-level rise risks".

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[6] http://www.globalcarbonproject.org/carbonbudget/archive/2017/GCP_CarbonBudget_2017.pptx

[7] https://creativecommons.org/licenses/by/4.0/

However, the utility of NETs for countering climate change has been contested by some authors e.g. Anderson and Peters (2016a and 2016b), Nature Editorial (2018), European Academies' Science Advisory Council (2018). Anderson and Peters (2016a) said "Negative-emission technologies are not an insurance policy, but rather an unjust and high-stakes gamble. There is a real risk they will be unable to deliver on the scale of their promise". The European Academies Science Advisory Council concluded "…that these technologies offer only limited realistic potential to remove carbon from the atmosphere and not at the scale envisaged in some climate scenarios (as much as several gigatonnes (one billion or 109 tonnes) of carbon each year post-2050). Negative emission technologies may have a useful role to play but, on the basis of current information, not at the levels required to compensate for inadequate mitigation measures". These arguments have not gone unchallenged. Lackner *et al.,* (2016) responded to Anderson and Peters "This characterization would sideline negative emissions technologies and remove potentially important options from the portfolio for mitigating and ameliorating climate change". Grubler et al. (2018) developed a scenario that would avoid the use of NETs, however, it involved a projected global energy demand in 2050 that would be 40% lower than current demand. That would seem to be a somewhat unrealistic scenario. Lawrence *et al.* (2018) evaluated climate geoengineering proposals in the context of the Paris Agreement temperature goals and stated that "Based on present knowledge, climate geoengineering techniques cannot be relied on to significantly contribute to the Paris agreement temperature goals".

In addition, there are claims that there are existing 'natural' solutions (some of which might be classified as CDR) that if implemented could avoid the need for geoengineering, including for example:

- 'Natural climate solutions' – 20 land management actions that increase carbon storage or avoid greenhouse gas emissions (Griscom *et al.,* 2017; Turner, 2018). Examples include reforestation, biochar addition to soil, peat restoration and coastal wetland restoration; and
- Drawdown[8] – a project that identified, researched and modelled 100 existing solutions to collectively address climate change.

It is also worth noting that there is on-going research into techniques that generate energy but are also carbon negative e.g. de Lannoy *et al.,* (2017); Hanak *et al.* (2017); Lu *et al.,* (2015) Note that the Hanak *et al.* proposal has recently received £1 million from the UK Government to build a 400kW prototype plant[9].

2.4 Marine geoengineering

In July 1988 at the Woods Hole Oceanographic Institution, oceanographer John Martin commented, partly in jest, "Give me a half tanker of iron, and I will give you an ice age." (Chisholm and Morel, 1991). His idea that ocean fertilization might counteract climate change was highlighted in global headlines in 1990, but marine geoengineering did not again come to widespread public attention until early 2007 when Planktos Inc. (Brahic, 2007) proposed and prepared for ocean fertilization activities initially off the Galapagos Islands and later in the North Atlantic off the Canaries (Courtland, 2008). The Contracting Parties to the London Convention and London Protocol (LC/LP) expressed concern about the marine environmental impacts of this proposed activity at their meeting in late 2007. Various environmental NGOs also expressed concerns about the proposed activity.

In 2008, the Parties to the LC/LP adopted Resolution LC-LP.1(1)[10] deciding ocean fertilization activities other than legitimate scientific research should be considered as contrary to the aims of both instruments. In 2010, by Resolution LC-LP.2(2)[11], the Parties adopted an Assessment Framework for Scientific Research Involving Ocean Fertilization. However, whilst these Resolutions set out political commitments, they were not legally binding.

Furthermore, in the absence of appropriate international mechanisms, Parties to the Convention on Biological Diversity (CBD) adopted Decisions IX/16 (2008) and X/33 (2010) which some such as the ETC Group[12] view as a de facto moratorium on deployment and on most forms of research into ocean fertilization and other forms of geoengineering *"in the absence of science-based, global, transparent and effective control and regulatory mechanisms for geoengineering".* These decisions are not legally binding, and others do not view the CBD decisions as a moratorium e.g. Galaz (2011), Horton (2010), Reynolds *et al.* (2016) and Sugiyama and Sugiyama (2010).

The London Protocol was amended in October 2013 to regulate ocean fertilization activities and these amendments also enable the Parties to regulate other marine geoengineering activities within the scope of the Protocol, in future (IMO, 2013) – see Box 1 for details of the amendments. The amendments need to be ratified by two thirds of the Contracting Parties to come into force (34 out of 51 Parties as at September 2018). To date, only the UK, Finland and The Netherlands have accepted the amendments. It took 10 years for the London Protocol itself to come into force and it seems likely that it will take a similar period for these amendments to come into force. However, Parties usually accept that when they have ratified/acceded to an international treaty or amendments to one, they are bound by its provisions. Note that the London Protocol definition of marine geoengineering can cover activities beyond just climate mitigation ones. This was a deliberate decision by the Parties to the London Protocol in order to be able to potentially control activities such as fisheries enhancement that would not be covered by a purely climate mitigation-based definition.

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[8] http://www.drawdown.org/

[9] https://www.innovatorsmag.com/1m-for-greenhouse-gas-removal-tech/

[10] http://www.imo.org/en/OurWork/Environment/LCLP/EmergingIssues/geoengineering/Documents/2008resolutionOF.doc

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

[12] http://www.etcgroup.org/content/news-release-geoengineering-moratorium-un-ministerial-japan

Box 1
2013 Amendments to the London Protocol 1996 (Resolution LP.4(8))

The amendments include:

1. A definition of "marine geoengineering" in Article 5bis: used to determine what activities might be listed in new Annex 4 and regulated under new Article 6bis:

   "Marine geo-engineering" means a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe;"

2. A new Article 6bis in "Marine Geoengineering Activities" that sets out the regulatory controls for activities listed on new Annex 4. It provides that Parties shall not allow placement of matter into the sea for a marine geoengineering activity listed in new Annex 4 except where the listing provides for the activity or sub-category of the activity to be authorised under a permit. Activities not listed in Annex 4 would not be regulated by the new Article 6bis;

3. A new Annex 4 to list types of marine geoengineering activities regulated under new Article 6bis. Annex 4 currently contains just one listing, namely ocean fertilization, but could be amended in the future to list further activities, as appropriate. The definition of ocean fertilization in Annex 4 is taken from the definition agreed by the Contracting Parties in resolution LC- LP.1 (2008). The listing provides that an ocean fertilization activity assessed as constituting legitimate scientific research is permissible. All other ocean fertilization activities are prohibited;

4. A new Annex 5 'Assessment Framework for Matter that may be Considered for Placement under Annex 4' that contains a generic assessment framework, which Parties must use before issuing permits pursuant to new Article 6bis; and

5. Consequential amendments to the London Protocol needed to take into account the above modifications.

This definition can potentially encompass manipulations of the marine environment for other reasons than solely for climate mitigation e.g. fisheries enhancement. The LP definition was inclusive enough to accommodate the examples of marine geoengineering approaches that WG members raised and it was therefore agreed that the WG would use the LP definition.

A wide variety of marine geoengineering techniques have been proposed (Vivian, 2013) that involve either adding substances to the ocean or placing structures into the ocean, primarily for climate mitigation purposes, but also for other intentions such as enhancing fisheries or Ocean Thermal Energy Conversion (OTEC). These proposed techniques are often little more than concepts but most of them, if implemented at large-scale, involve potentially large-scale responses in the ocean with the potential for significant impacts on the marine environment (Boyd, 2008a). In addition, many of these activities may take place on the high seas outside national jurisdictions so that they will raise international concerns. While all the marine CDR geoengineering techniques are designed to reduce CO_2 levels in the atmosphere by capturing and storing CO_2, this is achieved by various means, utilising diverse natural processes and types of human activity.

While a number of reviews of geoengineering per se have considered a small number of marine geoengineering techniques, mainly for their efficacy, none have reviewed a wide range of marine geoengineering techniques for their marine environmental impacts. The Scientific Groups of the London Convention and the London Protocol held a Science Day Symposium on 'Marine Geoengineering' on 23rd April 2015 that covered a range of marine techniques (IMO, 2016b).

At their annual meeting in September 2014, GESAMP (the United Nations Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection[13]) discussed a proposal for a study of marine geoengineering. It was considered that a GESAMP study could provide a better understanding of the potential ecological and social impacts of different marine geoengineering approaches on the marine environment. In addition, it was agreed that a GESAMP working group could provide information that could assist London Protocol Parties to identify those marine geoengineering techniques that might be sensible to consider for listing in the new Annex 4 of the London Protocol. The members of Working Group 41 on Marine Geoengineering are listed in Annex I and the Terms of Reference agreed by GESAMP for Working Group 41 on Marine Geoengineering are in Annex II.

GESAMP noted that the topic was both immense and of immediate importance to several of the Sponsoring Organizations, and IOC (International Oceanographic Organisation) and WMO indicated their willingness to contribute to the WG by each sponsoring one member.

On the subject of direct injection of CO_2 into the ocean, the WG noted that following much interest in the 1980's through to the mid-2000's, covered comprehensively in the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005), research had slowed thereafter although a number of papers have been published since the IPCC report (e.g. Goldthorpe 2017; Nealson, 2006; Reith *et al.,* 2016; Ridgwell *et al.,* 2011).

At present, it is not clear whether direct CO_2 injection from vessels or platforms would be banned under the London Convention. In order to be banned under the London Convention, CO_2 would have to be classed as an industrial waste and then it would be banned as it is not listed as one of the exceptions in paragraph 11 of Annex I of the Convention. During their Consultative Meeting in November 1999, the Parties to the London Convention discussed the conclusion of the Scientific

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[13] www.gesamp.org

Group that "…fossil fuel derived CO_2 was considered an industrial waste…" but no agreement could be reached on the Scientific Group's conclusion. Thus, the status of direct CO_2 injection from vessels or platforms under the London Convention is unclear. However, direct CO_2 injection from vessels or platforms is currently clearly banned under the London Protocol[14] as it is not listed in Annex 1 of the Protocol as a waste or other matter that may be considered for dumping. The WG decided not to exclude this technique since it could be a short- (years) to medium-term (decades or longer) solution having noted that injected carbon would eventually return to the atmosphere - within a few 100s or 1000s of years. Hence, it might be possible for this technique to be used in the short term at scale as a last resort or in an emergency e.g. following a significant climatic tipping point.

It is possible that marine cloud brightening (MCB) could be regulated by the LP (amongst others) due to the deposition of salt particles on the ocean surface from the activity constituting a deposit of 'wastes or other matter' under the LP. There is a precedent for such regulation as the London Convention (and also the Oslo Convention 1972) regulated incineration at sea that took place from the late 1960s to early 1990s due to the deposition of the products of combustion.

Mid 2017 saw the first major attempt to conduct a relatively large field trial (> 10 km length-scale) in the ocean since the 2012 unauthorized iron fertilization off Haida Gwaii in the Eastern Pacific off Canada (Tollefson, 2012). The planned pilot study was not referred to as geoengineering, but as eco-engineering or ocean restoration, even though it planned to fertilize a nearshore eddy feature off the coast of Chile with iron (Tollefson, 2017). It did not take place but the proponents are apparently still interested in such an experiment, potentially off Peru. There are many similarities between the planned approach and that of prior geoengineering pilot studies (Schiermeier, 2003). They include: a lack of detailed information on the permanent public record about the scientific basis for the proposed trial, side effects, risk assessment, and detection and attribution. Hence, the introduction of suitable governance frameworks for such approaches should be largely similar to that needed for ocean iron fertilization. One major distinction between marine geoengineering and 'ocean restoration' trials is the enhanced degree of difficulty in detection and attribution of purposeful fisheries enhancement (McKinnell, 2013).

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[14] Note that only the Parties who have ratified/acceded to an international treaty are bound by its provisions.

3 MARINE GEOENGINEERING TECHNIQUES – ISSUES FOR THEIR ASSESSMENT

3.1 Range of marine geoengineering techniques

Proposed marine geoengineering techniques vary widely from initial concepts to proposals backed up by peer-reviewed papers with some basic description of the matching technology. There are many concepts hosted on websites on the internet that have little or no additional documentation or supporting evidence. In particular, since 2009 the MIT Climate CoLab contests[15] have outlined several marine geoengineering concepts as has the Paul G. Allen Ocean Challenge for Mitigating Acidification Impacts[16]. Few of the geoengineering proposals in those events had a well-developed evidence base.

The WG discussed whether it would only focus on techniques that directly affect the marine environment, given that some models indicate that AM methods will have a large effect on the carbon cycle with major indirect effects on oceans (Cao, 2018; Cao *et al.,* 2015; Keller *et al.,* 2014; Tjiputra *et al.,* 2015; Xia *et al.,* 2016). The WG recognized that AM, over both land and sea, could have significant direct influences on the marine environment, e.g., on ocean circulation and productivity, and indirect effects on ocean acidification. The WG decided to primarily focus on methods which have direct impacts on the marine environment i.e. ocean plus the marine boundary layer (the well-mixed atmospheric layer in direct contact with the ocean) but would also consider some of those which may have significant indirect impacts. Thus, the Group agreed that marine cloud brightening (MCB) would be included in their assessment as it will have direct effects on the marine boundary layer as well as indirect effects on the underlying waters (e.g. altered underwater light for primary producers) (Baughman *et al.,* 2012; Kravitz, *et al.,* 2013; Partanen *et al.,* 2012 and 2016). It was also agreed that the implications of different marine geoengineering approaches for ocean acidification (Raven *et al.,* 2005; Williamson and Turley, 2012) should be considered in addition to temperature and precipitation effects.

A number of marine technologies have been proposed for a variety of purposes that do not fall under the broad geoengineering categories of CDR or AM but have "the potential to result in deleterious effects, especially where those effects may be widespread, long-lasting or severe" i.e. they fall within the LP definition of "marine geoengineering".

An example of such technologies is artificial upwelling. Some companies are considering it for non-climate geoengineering related purposes – such as energy and fish production (across a range of scales from eddies upwards) (Hou *et al.,* 2010; Jones, 2011; Kirke, 2003; Maruyama *et al.,* 2011), or to cool coral reefs (Hollier *et al.,* 2011). Other potential approaches that have been mooted include artificial downwelling given its potential

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[15] https://www.climatecolab.org/?isSigningIn=true&signinRegError=CREDENTIALS#

[16] http://www.pgaphilanthropies.org/oceanchallenge/TemplateHome.aspx?contentId=1

to "divert" hurricanes[17] (Intellectual Ventures, 2009; Mims, 2009; Salter, 2009). These additional technological approaches to modifying oceanic services have geo-political implications, which are related to where they might be deployed and the scale of the proposed operations (Boyd, 2016). How they would intersect with present day oceanic resource extraction (e.g. fisheries) or proposed marine geoengineering approaches is not known. There is a widespread lack of information for most of these methods, which at present are at the 'drawing board' stage of an initial idea underpinned with some technological R&D.

Artificial upwelling techniques such as Ocean Thermal Energy Conversion (OTEC) involve moving large volumes of water to the surface and could also potentially be used for ocean carbon capture and storage (see section 5.11 below). Again, the scale of the proposed intervention is important. Given that the definition of marine geoengineering under the London Protocol does not only cover techniques aimed at amelioration of climate change and since the WG will be appraising artificial upwelling, OTEC, or at least the potential effects of large-scale OTEC, have been included in this assessment.

While legal status of the direct injection of CO_2 into the ocean would appear to be unclear under the LC but banned under the LP (see section 2.4 above), the WG decided not to exclude this technique since it could be a short- (years) to medium-term (decades or longer) solution having noted that injected carbon would eventually return to the atmosphere - within a few 100s or 1000s of years. Hence, it might be possible for this technique to be used in the short term at scale as a last resort or in an emergency e.g. following a significant climatic tipping point.

3.2 Scale of research

The scale of research into geoengineering requires detailed consideration, particularly in relation to potential impacts. Some scientists have advocated a threshold beneath which small-scale research may proceed with modest regulatory oversight as they would have trivial environmental impacts, e.g. (Parson and Keith, 2013). The London Protocol definition of marine geoengineering is derived in part from the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques (ENMOD)18 and it refers to scale as follows: large scale, long term, severe interventions. But what exactly this scaling means is unclear and it was left to the Group to decide how to interpret it, on a case-by-case basis. For example, some might consider that a method only affecting a few square kilometres would not be considered to be marine geoengineering, particularly if it was a one-off activity. However, multiple instances of the same activity in time and space, would likely to be viewed differently. In contrast, adding alkalinity to a very large area e.g. the 344,400 km^2 of the waters overlying the Great Barrier Reef[19] to protect corals would very likely be considered as marine geoengineering. However, research into any environmental manipulation that could ultimately be deployed at a large scale e.g. ocean alkalinization, may be regarded as geoengineering and thus considered for regulation under the London Protocol following the example of ocean fertilization. Thus, in deliberations regarding the need to regulate a particular research activity, its scaling as a trial or pilot study may well be less important (but it will differ on a case-by-case basis) than the ultimate scale of its potential deployment as a geoengineering approach.

When considering scaling up from small-scale (km length scales) field experiments, the WG concluded that proposers should first use numerical models to provide appropriate information to evaluate potential efficacy and impacts as large-scale in situ experiments (e.g. >10 km length scales) have the potential for widespread impacts (Watson *et al.,* 2008). In addition, it should be borne in mind that small-scale experiments could potentially explore the uses/benefits of marine geoengineering to mitigate impacts of climate change or other activities on discrete areas of the marine environment - e.g. protecting the Great Barrier Reef (Albright *et al.,* 2016).

3.3 Knowledge to permit scientific assessment of marine geoengineering techniques

Proposed marine geoengineering techniques vary widely from initial concepts to ideas backed up by some basic description of the matching technology. The WG consequently discussed the level of knowledge needed to permit the assessment of proposed technologies. In many cases, little knowledge is available to make an individual scientific assessment, much less one that can be readily intercompared with other approaches. A significant amount of this knowledge appears to be 'transient' i.e., there is not a permanent public record of the basis for the proposed activity, as it resides on internet websites that may not available for the long term.

The WG agreed that if there is no substantive science behind a proposal, it is not possible to provide a scientific review of it. The WG agreed that where possible it would focus on proposals that have been through a peer review process so that it can make some robust appraisals on the techniques. Where sufficient information is available, modelling could provide assessments of the merits of individual approaches e.g. Keller *et al.* (2014) and especially within a model intercomparison framework such as the Carbon Dioxide Removal Model Intercomparison Project[20] (CDRMIP) - see Box 2 below. The WG terms of reference state that we should identify techniques that appear unlikely to have the potential for marine geoengineering. The WG will also identify techniques that we have not assessed because of the lack of information. The 'lack of knowledge' issue was raised many times during the WG's work, as was the mismatch between what is required to conduct

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[17] http://www.nextbigfuture.com/2011/04/hurricane--suppression-system-salter.html , https://climateviewer.com/2013/11/08/hurricane-hacking-the-department-of--homeland-security-enters-the-weather-modification--business/ and http://eureka.intven.com/stories/suppressing--a-hurricane

[18] http://un-documents.net/enmod.htm

[19] http://www.gbrmpa.gov.au/about-the-reef/facts-about-the-great-barrier-reef

[20] http://www.kiel-earth-institute.de/CDR_Model_Intercomparison_Project.html

an assessment and what is provided by proposers of marine geoengineering approaches (internet, publications, patents). The WG speculated whether there were any incentives for proposers of marine geoengineering to provide a peer reviewed version (or other imprints in the permanent record) of their proposed methods? It was considered unlikely that there is at present an incentive for those with commercial ideas, proprietary rights, etc. to write peer reviewed papers/proposals. However, can incentives be provided to progress an idea to peer reviewed papers through to a pilot study?

It was suggested that as part of Terms of Reference 2 (ToR 2), we should be very clear about the steps that need to be taken to achieve the knowledge threshold that would lead to a scientific assessment.

Box 2
Marine geoengineering – the utility of modelling simulations - CDRMIP

Another major recent advance in geoengineering research, that is particularly pertinent to marine approaches, is the Carbon Dioxide Removal Model Intercomparison Project (CDRMIP) – see Keller *et al.* (2018) and http://www.kiel-earth-institute.de/CDR_Model_Intercomparison_Project.html

Until recently, the only consensus-based approach to modelling geoengineering scenarios was GeoMIP based in the US (http://climate.envsci.rutgers.edu/GeoMIP/) which focussed solely on SRM approaches such as solar dimming, stratospheric sulfate aerosols, marine cloud brightening, and cirrus cloud thinning.

CDRMIP employs both Earth System Models (ESMs) and Earth System Models of Intermediate Complexity (EMICs) to better understand a range of CDR approaches. The project is particularly interested in better understanding:

> "1) Climate "reversibility", in the context of using CDR to return high future atmospheric CO_2 concentrations to a lower (e.g. present day or pre-industrial) level.
>
> 2) Potential efficacy, feedbacks, time scales, and side effects of different CDR methods"

CDRMIP will conduct simulations of approaches such as DAC (Direct Air Capture), afforestation, BECCS (Bioenergy with Carbon Capture and Storage), and also marine geoengineering including artificial upwelling and ocean fertilization. This research may then lead into collaborative modelling with GeoMIP to target jointly SRM and CDR simulations.

An example of one of their approaches is for:

> "C4) Ocean alkalinization: Under the high SSP (Shared Socioeconomic Pathway) emissions (driven from the pre-industrial with observed emissions) starting in 2020, add 0.25 Pmol yr-1 of alkalinity to the ocean for an 80-year period. The control simulations would follow high SSP emissions until 2100. In 2070 the alkalinity addition would cease, and the simulations would continue for another 30 years until 2100.".unt the above modifications.

Fully assessing the array of marine geoengineering approaches requires detailed, technical expertise across many disciplines to assess the risk/benefit/feasibility of the wide range of techniques. This presents a major challenge for assessment.

3.4 Modes of assessment of marine geoengineering approaches

Scientific assessments are used commonly to provide technical advice for the regulation of emerging technologies and/or their environmental application (Morgan, 2012). In this report, our Term of Reference 1 dictates that we synthesise scientific information based on "published information".

In the internet age, 'published information' can take many forms, many of which are impermanent — i.e., subject to deletion or undocumented revision. By convention, "published" connotes being recorded on the permanent record, a criterion that is not met by many presentations on marine geoengineering. For example, the www sites for ocean fertilization companies Plankton and Climos no longer exist. Moreover, of the 61 web documents cited by Strong *et al.* (2009) only 24 could be found at the published links (as of October 2018).

By convention a lasting assessment based on published information must rely upon a stepwise progression towards building a portfolio of evidence, the accumulation of which determine the scope of the scientific assessment that can be conducted (Figure 3.1). Progress in understanding the characteristics of a geoengineering approach can be gauged by whether synthetic activities such as modelling can take place (Figure 3.1).

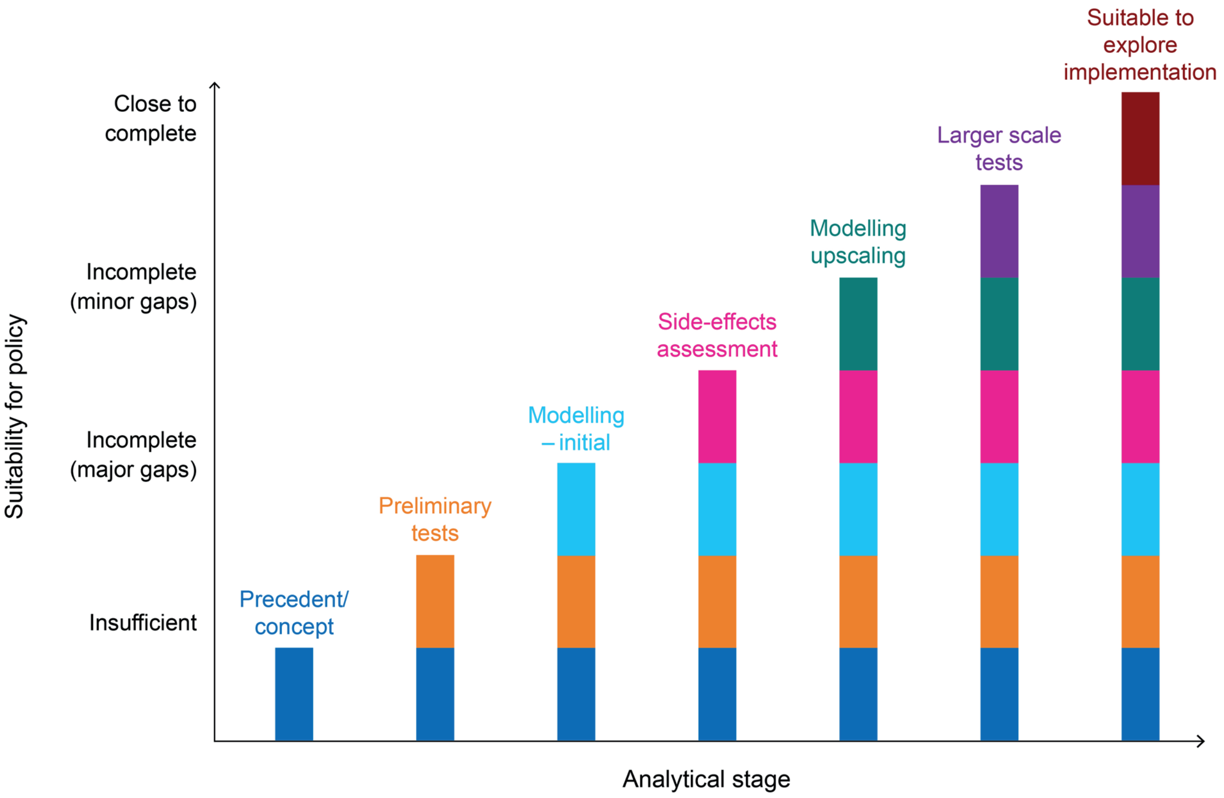


Figure 3.1 *Hypothetical plot to explore in detail the relationship between suitability for policy (from insufficient to near-complete) in relation to stage of the analysis. The graduations across "Analysis Stage" are based largely on the evolution of research into OIF. Provided by Philip Boyd ©.*

The progress in understanding different geoengineering techniques can be contrasted and compared using this approach (Figure 3.2). Note, in Figure 3.2 in the case of MCB and foams, large scale modelling took place before any robust demonstration of practicality and/or testing for side-effects (Figure 3.2). In the case of OIF, the sequence from precedent to large-scale (i.e., 1000 km^2 areal extent, see Strong *et al.,* 2009) tests (albeit, too small for assessment of OIF, see Watson *et al.,* 2007), followed by large scale modelling (Aumont and Bopp, 2006; Jin *et al.,* 2008) represented a much more comprehensive and complete assessment. Significantly, even though OIF does not fit the ideal sequence, the LC/LP did establish some policy using it (IMO, 2013).

In these cases, differences in the ability to scientifically assess techniques are conspicuous, with ramifications for how usefully their assessment can contribute to policy formulation (Figure 3.2).

In some cases, there may be insufficient information in the peer-reviewed and/or the permanent record (for example, IMO documents are reputable and useful.) literature to make a scientific assessment. However, policy-related decision-making (for example risk management) must often take place based on incomplete knowledge and uncertainty (Morgan, 2012). Under such circumstances, expert judgement is often used in conjunction with whatever is accessible in the peer-reviewed literature to compensate for the lack of information. In the case of this assessment of marine geoengineering, we argue that such expert assessment should be based only on material in the permanent record (not necessarily peer-reviewed). There are many examples of information on geoengineering methods being posted on websites (examples), and hence not in the permanent record.

3.5 The need for a holistic assessment of marine geoengineering methods

The scale of deployment of these techniques will potentially be enormous if they are to have a climatically significant effect. Furthermore, as many of the proposed techniques will influence and/or alter different aspects of marine ecosystems, it would appear prudent to assess them, to the extent possible, from a holistic environmental, economic and social perspective on a technique-by-technique basis.

While the precautionary principle does need to be fully taken into account (it is fundamental to the London Protocol), we also need to consider the balance of harms. We are already conducting a global climate intervention in the Anthropocene through the rapid and sustained release of anthropogenic CO_2 into the atmosphere. Hence, we need to consider the potential detrimental effects of these marine geoengineering measures, and any potential benefits of such interventions, against the potential harms from 'climate change' that will come from greenhouse gas emissions in the absence of marine geoengineering. Earth's environment has changed, and is changing, which needs to be taken into consideration, since any geoengineering measures would be taking place in an already altered, dynamic planet. The CBD report on assessing geoengineering in relation to biodiversity (Williamson *et al.,* 2012a) evaluated the potential for both positive and negative effects of geoengineering techniques on biodiversity in the context of climate changes that were already occurring and their projected trajectories.

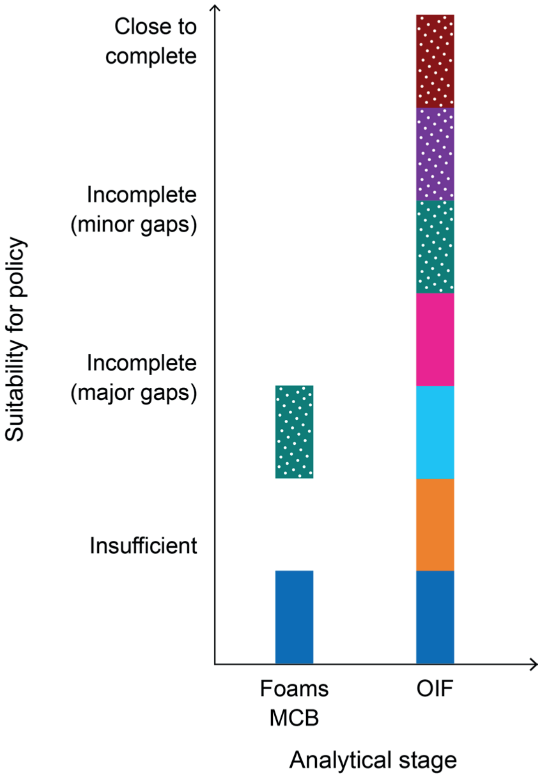


Figure 3.2 *Examples from a range of geoengineering approaches of the evolution of their stages of analysis. Stippled boxes denote incomplete analysis, colours are as for Figure 3.1. In the case of MCB and foams, several stages were overlooked, indication of approaches for which there is insufficient information for the formulation of policy. Note, in the case of MCB, we do not consider the results of the E-PEACE experiment (using paraffin-type oils to produce CCN) as a relevant preliminary test, see Section 5.16). Provided by Philip Boyd ©.*

An illustrative example of the need for a widespread and holistic assessment is enhancement of ocean alkalinity. While the WG considers that this approach merits more research, profound challenges exist, such as the mass of geochemical material required to make a significant local or regional effect on climate. This approach has other potential uses apart from carbon removal e.g. protecting aquaculture and marine protected areas, including the Great Barrier Reef. In the case of using olivine for enhancement of ocean alkalinity, one published study (Köhler *et al.,* 2013) uses an established marine ecosystem model to predict changes in biogeochemical fluxes, plankton species composition and marine food webs due to the addition introduction of 1 µm olivine particles to the surface layer of the ocean; neither that model nor others in general use are designed to account for the effects of alien inorganic particles on grazing interactions when they are added at about the same concentration and size as the most prevalent food source (pico-cyanobacteria) in the ocean. Another example discussed was that of MCB to increase marine cloud albedo, that is anticipated to have to overcome jurisdictional issues, uncertainties about regional effects, influence on ocean temperature, ecological effects, efficacy etc. Scaling issues, such as these, need to be communicated effectively to enable them to be understood by a broader community of scientists, social scientists, policy makers and the public.

In some cases, there has been little consideration of the wider-scale biological consequences, e.g. making aerosols out of paraffin-type oil for use in MCB, as employed during the E-PEACE project (Russell *et al.,* 2013). Previous environmental assessments, e.g., for sky-writing (using a small aircraft to expel special smoke during flight while flying in patterns that create writing readable by someone on the ground), did not encompass deployments on the scale of geoengineering. In another approach to increasing albedo using surface foams, if they can be stabilized, the ocean could be made more reflective. However, anything floating on the surface of the ocean tends to collect in 'windrows' - streaks of foam and floating debris on the sea surface aligned with the wind due to wind effects and Langmuir circulation of surface waters (Thorpe, 2004), or due to convergences such as at fronts over internal waves or associated with eddies. Free-drifting plastic waste also accumulates in these areas; their interactions with large accumulations of foams merit consideration. Blocking the penetration of sunlight into the ocean will clearly have significant ecological effects as will the physical presence of the foams. It has been suggested that due to their reduced biological activity, iron-limited, less productive open ocean regions could be used for such a technique (Aziz *et al.,* 2017). However, the suggestion that certain oceanic biomes can be targeted because their productivity is lower than others fails to consider biodiversity and the sustainability of fisheries (and the socio-economic implications) , and therefore must be explored further.

It was recognized that test cases can be used to explore the nature of these broader ecological and societal issues – for example the relatively well publicised unauthorised Haida Gwaii iron fertilization event off the west coast of Canada in 2012 (Service, 2012; Tollefson, 2012).

Earth System Modelling has great potential to help illuminate the many issues that must be considered in developing a holistic comparative assessment of geoengineering approaches. Sonntag *et al.* (2018) assessed atmosphere-, ocean-, and land-based climate engineering (CE) measures with respect to Earth system effects using the Max Planck Institute Earth System Model (MPI-ESM) model with prognostic carbon cycle to compare solar radiation management (SRM) by stratospheric sulfur injection and two carbon dioxide removal methods: afforestation and ocean alkalinization. The model experiments were designed to offset the effect of fossil-fuel burning on global mean surface air temperature under the RCP8.5 scenario to follow or get closer to the RCP4.5 scenario. Their results showed the importance of feedbacks in the CE effects and that normalizations allowed for a better comparability of different CE methods. For example, they found that due to compensating processes such as biogeophysical effects of afforestation more carbon needs to be removed from the atmosphere by afforestation than by alkalinisation to reach the same global warming reduction. Critically, they illustrated how different CE methods affect the components of the Earth system; identified challenges arising in a CE comparison, and thereby contributed to developing a framework for a comparative assessment of CE.

3.6 Interactions between marine geoengineering techniques

Most classifications/discussions of marine geoengineering methods look at individual methods in isolation and often there is no discussion of any potential effects of interactions between methods (Boyd, 2009) nor between multiple instances of the same techniques. If different marine geoengineering techniques or multiple instances of the same techniques are implemented in concert, then the potential interactive (cumulative) effects needed to be considered. This is especially the case for marine geoengineering field research experiments to ensure that results of an experiment are not misattributed to another study. An example of where an interaction between 2 AM techniques is mentioned, was given by Gabriel *et al.* (2017) who stated:

> "Whether or not a concurrent deployment of stratospheric geoengineering and ocean albedo modification could cool the entire planet while maintaining or enhancing the hydrological cycle, particularly in the tropics, is the next natural step in this research. Such research is motivated by the need to determine whether some combination of geoengineering techniques can be used to offset regional climate disparities that using one method of geoengineering alone could induce."

Potential interactions between marine geoengineering techniques are also important for governance considerations. Different types of bodies may be responsible for diverse types of techniques and there may be a need for partnerships e.g. between the UNFCCC and the London Protocol to govern any deployment of marine techniques.

4 METHODOLOGY FOR RANKING MARINE GEOENGINEERING TECHNIQUES

The comparative evaluation of a broad range of marine geoengineering approaches requires scoring or ranking based on evaluation criteria. It was recognized that, besides measures of potential efficacy and environmental risk, policy-focussed evaluation of marine geoengineering approaches would require consideration of factors such as economics (including effects on fishing and tourism) and health (ecosystem and human) effects. As many marine experiments may take place 100's of km offshore in the deep ocean, some experiments may therefore not have direct impacts on coastal societies. Other assessment criteria such as effectiveness could be difficult to score as they depend highly on a wide range of the perspectives. Although it may be possible to get widespread agreement that many techniques are likely to be ineffective, such agreement may not be universal, as some parties may consider them to be effective e.g. as occurs with weather modification activities where the efficacy of methods is disputed (World Meteorological Organization, 2010).

Political and socio-economic evaluation criteria to derive predictions/hypotheses based on accepted principles, probably would not be used in this initial assessment round. Also, ethical considerations would not be addressed in the WG's assessment as this was considered to be beyond the group's remit.

The WG considered who might use the evaluation criteria that might be developed by this WG. Besides proposers of a marine geoengineering technique, the criteria are likely to be primarily used by those who will be involved in governance – from initial research governance (including field experiments) through to the governance of the deployment of marine geoengineering approaches, and the need for adaptive governance, thereafter - and those who will select topics for research funding. Governance of research would need to take into account that marine geoengineering research could go through several different phases including for example conceptualisation, modelling, small-scale field experiments and larger scale field experiments. Foley *et al.* (2018) have suggested that anticipatory governance should be utilised for geoengineering. They describe it as “a vision for dealing with emerging technologies by building the capacity to manage them while management remains possible”. The 2012 Global Risk Report of the World Economic Forum (WEF, 2012) contrasts it with precaution: “More promising is the approach of ‘anticipatory governance.’ In this model, regulators accept the impossibility of anticipating the potential trajectory of innovations based only on past experience. They embrace the need for dynamic safeguards that can evolve with the system they are safeguarding. Anticipatory governance implies close, real-time monitoring in the direction in which innovations evolve, and involves defining safeguards flexible enough to be continually tightened or adapted in response to emerging risks and opportunities. The model of anticipatory governance is attracting attention in fields ranging from climate change to personalized medicine.”

4.1 Criteria to be used to assess the proposed techniques

The WG considered what criteria should be used to assess the proposed techniques and thus select those that should be considered further under ToR 2. The first phase assessment (i.e. ToR 1) was envisaged to be more about filtering out methods and a qualitative assessment, as there was often little published information about many of the techniques. It was anticipated that the second step (ToR 2) would involve more specific consideration of effects and might involve using modelling methodology etc. to evaluate measures.

The WG agreed to develop a ranking of expert viewpoints of the environmental impacts of marine geoengineering approaches which were to be summarised in a spreadsheet format. While the use of aggregating scores (e.g. McCormack *et al.,* 2016) is a powerful approach, it is a much more detailed assessment technique than could be used in the first round of assessment. However, such an approach could potentially be employed in the second round. The aggregating score approach involves a large amount of detail but comes up with very robust results if there is: a) adequate information on which to base the assessments; b) sufficient depth and breadth in the panel; and c) if the panel can commit the time required to complete the job effectively.

A multi-faceted approach to assessment was considered essential, as was the need to include political and socio-economic assessment criteria, to the extent possible, in a comprehensive analysis, especially given the potential governance/policy relevance of the report. To have a broad-based assessment of these criteria, we need to involve more social/economic scientists for ToR 2. However, it was pointed out that current literature on potential political implications of marine geoengineering is very limited (Boyd, 2016) although there is a chapter ‘Social, Economic, Cultural and Ethical Considerations of Climate-Related Geoengineering’ in Williamson *et al.* (2012). Annex V contains a broader discussion about criteria to be used to assess the marine geoengineering techniques and describes the development of assessment criteria by the WG.

4.2 Marine geoengineering techniques to include in an assessment

The WG agreed to assess a wide-range of marine geoengineering techniques based on those listed in Vivian (2013). This includes several techniques where there was very limited information that were included here to illustrate the range of information available for marine geoengineering techniques. Most of the marine geoengineering techniques fall into the CDR category with the remaining techniques designed to increase ocean albedo i.e. the reflectivity of the ocean. The WG decided to assess some additional techniques that either had potentially significant indirect effects on the ocean or were designed for other purposes and that, if deployed at a large-scale, could potentially have similar side-effects to marine geoengineering techniques. These were:

- Land-based enhanced weathering due to its potentially significant impacts, in coastal waters;
- Weakening of hurricanes - included in artificial upwelling and downwelling;
- Ocean Thermal Energy Conversion (OTEC); and
- Deep Water Source Cooling.

While there are just a few publications that have addressed the capture or destruction/degradation of methane in the marine environment (Salter, 2011; Stolaroff *et al.,* 2012), it was decided to include them in the assessment for completeness. It has been suggested that tractable levels of methane mitigation can make a substantial difference to the feasibility of achieving the Paris climate targets (Collins *et al.,* 2018) so this may be subject that could become an area of increased research.

The WG agreed at their initial meeting that they would not address any techniques related to enhancing blue carbon ecosystems i.e. storage of carbon in mangroves, salt marshes and sea grass beds, as it was unclear at that time whether these sinks could be significantly enhanced through deliberate human interventions i.e. marine geoengineering. Also, the scale of these ecosystems suggested a limited capacity to contribute to global climate mitigation and uncertainty whether they would be considered to be marine geoengineering. These ecosystems store very significant amounts of carbon (Alongi, 2012); Chmura *et al.,* 2003; Donato *et al.,* 2011; Nelleman *et al.* 2009; Fourqurean *et al.,* 2012; Pendleton *et al.* 2012; Siikamaki *et al.,* 2017) although there have been some challenges to the scale of their significance (e.g. Johannessen and Macdonald, 2016; Howard *et al.,* 2017). However, these ecosystems are under threat from anthropogenic conversion and degradation and are being lost at rates between 0.7% and 7% per annum with consequent carbon dioxide emissions (Howard *et al.* 2017, Hopkinson *et al.,* 2012; Nelleman *et al.* 2009; Pendleton *et al.* 2012; McLeod *et al.* 2011). Protecting these habitats from further destruction and allowing them to re-establish where possible will be important to preserve these carbon sinks. Siikamaki *et al.* (2017) concluded that “Under a broad range of assumptions, we find that the majority of potential emissions from mangroves could be avoided at less than \$10 per ton of CO_2". This cost is less than the current price for carbon in the EU Emissions Trading System. A number of authors have recently suggested that it might be possible to manage these coastal ecosystems to sequester more blue carbon (Griscom *et al.,* 2017; Howard *et al.,* 2017; Macreadie *et al.,* 2017;). In addition, Chung *et al.* (2017) suggest that seaweed aquaculture beds have considerable potential to contribute to blue carbon sequestration but that its effectiveness will depend on the fate of the resulting biomass. Consequently, it would probably be sensible for the WG to consider the potential enhancement of carbon in these coastal ecosystems in any future work.

It should be noted that there has been an increasing tendency in recent years for hybrid techniques to be proposed with either other climate engineering techniques e.g. Ocean Carbon Capture and Storage (de Lannoy *et al.,* 2017; Eisaman *et al.,* 2018) or with techniques with other purposes e.g. wind farms (Buck *et al.,* 2004).

Agreed list of marine geoengineering techniques for assessment

The techniques to be included in the assessment were grouped into categories of related techniques and are shown in Table 4.1 below.

Table 4.1 Marine geoengineering techniques for assessment together with other techniques with potentially similar side-effects.

Categories	Techniques
Ocean Fertilisation	Iron
	Macro-nutrients – Nitrogen and Phosphorus
	Fertilisation for fish stock enhancement
Carbon Storage in the Ocean	Liquid CO_2 placed in mid/deep ocean water depths
	Liquid CO_2 placed on the seabed
	Liquid/Solid CO_2 placed into unconsolidated deep-sea sediments
	Mineralisation of CO_2 in rocks beneath the seabed
	Depositing crop wastes in the deep ocean
	Macroalgae cultivation for sequestration
Ocean pumping	Artificial upwelling
	Ocean Carbon Capture and Storage
	Artificial downwelling
Enhancing ocean alkalinity	Adding lime directly to the ocean
	Adding carbonate minerals to the ocean
	Accelerated weathering of Limestone to produce alkalinity
	Electrochemical enhancement of carbonate and silicate mineral weathering
	Brine Thermal Decomposition (BTD) of desalination reject brine
	Open ocean dissolution of olivine
	Coastal spreading of olivine
	Enhanced weathering of mine waste
	Amending soils of managed croplands with crushed reactive silicates
Methane	Methane capture and destruction/degradation
Increasing Ocean Albedo/Reflectivity	Microbubbles
	Foams
	Ice
	Reflective particles/material e.g. small beads
	Marine cloud brightening
Other techniques with potentially similar side-effects to marine geoengineering	Ocean Thermal Energy Conversion (OTEC)
	Deep water source cooling

4.3 Assessment of a wide range of marine geoengineering techniques

The WG members found the task of appraising the diverse range of potential marine geoengineering approaches using 17 assessment criteria (see Annex V Table 2 in Annex V) extremely challenging. The main difficulty was the lack of fundamental knowledge in the permanent public record, whether in the peer-reviewed scientific literature or elsewhere, as already indicated in section 4.2. In many cases, little knowledge is available to make an individual scientific assessment, much less one that can be readily intercompared with other marine geoengineering approaches (see Figs. 3.1 and 3.2). A significant amount of this information appears to be 'transient' i.e., there is not a permanent public record of the knowledge, as it resides on internet websites that are not available for the long term and of uncertain quality.

Without this knowledge it is difficult to evaluate, many of the other assessment criteria, such as those that focus on more applied characteristics that relate to knowledge about the marine geoengineering method (such as climate/environmental/social benefits or negative socio-political and environmental issues) (see section 4.11 and Figure 4.2 below). However, the WG membership thought it was useful to be as expansive and hence as inclusive as possible in this initial appraisal. It was also thought to be beneficial to detail the process of developing these assessment criteria, as this process may assist to guide people conducting future appraisals in this rapidly emerging field.

Individual WG members were only able to score a small proportion of the techniques listed in Table 4.1 (between 6 and 25%) and often with a low degree of confidence. Consequently, the WG agreed that a change of tack in the WG's approach to their tasks was necessary and this is covered in section 4.4 below.

However, it was thought worthwhile to at least provide the WG's assessment of the knowledge base available for the marine geoengineering techniques shown in Table 4.1 above. this assessment was based on expert judgement and is given in Table 4.2 below. Note that assessments for techniques in the Enhancing Ocean Alkalinity and Increasing Ocean Albedo/Reflectivity (apart from MCB) categories were grouped together in one sub-section.

Table 4.2 Assessment of the knowledge base for marine geoengineering techniques

Categories	Techniques	Assessment
Ocean Fertilisation	Iron	3
	Macro-nutrients - Nitrogen and Phosphorus	2
	Fertilisation for fish stock enhancement	1
Carbon Storage in the Ocean	Liquid CO_2 placed in mid-deep water	1
	Liquid CO_2 placed on the seabed	1
	Liquid/Solid CO_2 placed into the seabed	2
	Mineralisation in rocks under the seabed	2
	Depositing crop wastes or biochar in deep ocean	0
	Macroalgae cultivation for sequestration	2
Ocean pumping	Artificial upwelling	2
	Ocean Carbon Capture and Storage	1
	Artificially enhanced downwelling	1
Enhancing ocean alkalinity	Adding lime directly to the ocean	2
	Adding carbonate minerals to the ocean	1
	Accelerated Weathering of Limestone to produce alkalinity	1
	Electrochemical enhancement of carbonate and silicate mineral weathering	1
	Brine Thermal Decomposition (BTD) of desalination reject brine	1
	Open ocean dissolution of olivine	1
	Coastal spreading of olivine	2
	Enhanced weathering of mine waste	2
	Amending soils of managed croplands with crushed reactive silicates	1
Methane	Methane capture and destruction/degradation	1
Increasing Ocean Albedo/ Reflectivity	Microbubbles	1
	Foams	1
	Ice	1
	Reflective particles/material	1
	Enhance reflective blooms to increase albedo	1
	Marine cloud brightening	2

Categories	Techniques	Assessment
Others with potentially similar side-effects to marine geoengineering	Ocean Thermal Energy Conversion (OTEC)	2
	Deep water source cooling	1
Key: 0 - Inadequate information to make a judgement i.e. techniques without quantitative estimates 1 - techniques with information from thought experiments or numerical modelling 2 - techniques with information from modelling studies and lab or natural / field experiments not primarily targeted at geoengineering 3 - techniques where dedicated field studies have been carried out		

4.4 Transitioning towards a detailed assessment of a subset of approaches

The task of appraising a diverse range of 27 potential marine geoengineering approaches using 17 assessment criteria was viewed as problematic by all assessors. We found that all techniques considered had either incomplete or insufficient information in the permanent public record to permit full scientific assessment of their merits. Consequently, it was not possible to meet all aspects of ToR 2, which specifies:

“Providing a detailed focused review of a limited number of proposed marine geoengineering techniques that are likely to have some potential for climate mitigation purposes addressing:

- The potential environmental and social/economic impacts of those marine geoengineering approaches on the marine environment and the atmosphere where appropriate.
- An outline of the issues that would need to be addressed in an assessment framework for each of those techniques, using the London Protocol Assessment Framework for Scientific Research Involving Ocean Fertilization as a template.
- Their potential scientific practicality and efficacy for climate mitigation purposes.
- An assessment of monitoring and verification issues for each of those marine geoengineering techniques.
- Identification of significant gaps in knowledge and uncertainties that would require to be addressed to fully assess implications of those techniques for the marine environment and the atmosphere where appropriate.”

Thus, an alternative pathway that best addressed the points within ToR 2 was needed. Therefore, the WG changed its approach from attempting to assess a wide range of marine geoengineering approaches to one assessing a subset of illustrative examples from each of the categories that describe the 27 approaches in the original assessment table. We first present the rationale for the selection of these 8 illustrative approaches that are representative of the techniques considered, followed by their detailed assessment. The assessment of the 27 techniques follows later in the report (section 5) and is designed to provide a comprehensive repository of all information, available at the time of writing the report, on each approach. Note that the 27 approaches include variations of some approaches, in particular of enhancing ocean alkalinity and increasing ocean albedo.

4.5 Pitfalls of selection of a subset of approaches based on incomplete knowledge

Due to the lack of information available (for example, the feasibility of filtering large volumes of seawater to provide a large reservoir of sub-micron droplets needed for some proposed forms of marine cloud brightening (see Latham, 2002)), the WG assessment cannot be completely comprehensive or authoritative. Put simply, we are currently not capable of doing an all-inclusive assessment of the technologies in our initial assessment, and hence of which approaches should be eliminated or retained and examined in more detail. We can attempt a high-level assessment that highlights where there are knowledge gaps that need to be bridged before a comprehensive assessment can be undertaken (see Figure 3.2). This appraisal will enable recommendations to be made on what type of information is needed to be able to complete a comprehensive and authoritative assessment.

For practical reasons we must reduce the number of techniques appraised, in order to conduct an effective detailed assessment. Without enough information to select “winners and losers” from the range of approaches collated, we can surmount this limited knowledge base by choosing illustrative examples from the categories that describe the 27 diverse approaches in the original assessment table.

It is evident from this initial assessment that some flexibility is required in the development of a research governance framework because we do not know what all the approaches are going to be since there are new ones emerging, for example hybrid approaches may be developed (see section 4.2). We need to be aware of this evolving landscape of approaches when developing adaptive governance frameworks. In our new focus on illustrative examples, we must be cognisant that some outside those selected are likely to be developed further in the coming years. We must, as far as possible pinpoint which of the techniques may be developed or tested in the next few years, as this will be of interest for the LP Parties. Fortunately, as there is already a research governance framework (LP/LC) in place for one of the categories of marine geoengineering approaches – ocean fertilization – we can cross-reference this approach to the other illustrative examples from each category to provide preliminary guidelines on what other forms of regulation might be required for other marine geoengineering approaches. This will help to address other bullets within ToR 2 including:

- An outline of the issues that would need to be addressed in an assessment framework for each of those techniques, using the London Protocol Assessment Framework for Scientific Research Involving Ocean Fertilization as a template.
- Their potential scientific practicality and efficacy for climate mitigation purposes.
- An assessment of monitoring and verification issues for each of those marine geoengineering techniques.
- The potential environmental and social/economic impacts of those marine geoengineering approaches on the marine environment and the atmosphere where appropriate.

4.6 Surmounting the knowledge gaps: employing illustrative examples across categories

The 27 marine geoengineering approaches, originally considered by the WG, sit within 7 broad categories. These categories capture the diverse underlying principles across techniques, such as those that purposefully alter ocean properties to remove carbon (ocean nutrient addition), or those that alter surface ocean albedo to increase reflectance (foams). Several other categories were chosen as they provide examples of other approaches to ocean modification (fisheries enhancement or a hybrid approach such as macroalgal cultivation).

Our approach is to take an example from each category to elaborate on, as opposed to selecting approaches that we view (based on often very little knowledge) as being more likely to have potential for climate mitigation. To select an illustrative approach for each category we first used our new metric which indicated the level/lack of fundamental knowledge on a marine geoengineering method to eliminate approaches we have little knowledge on, then ranking the approaches within each category to select a suitable example.

The illustrative examples will help to demonstrate where we have enough information to assess these approaches, and critically will also reveal what type of information/criteria would be needed to be able to assess the methods eliminated from this detailed assessment. Furthermore, in this report we will report on how this dearth of knowledge can be overcome. Potential ways ahead include an iterative questionnaire, or a table structured to seek the key strands of information that those planning an experiment would have to provide and detail for an assessment regulatory body.

4.7 Rationale for selecting illustrative examples

The rationale for the selection of illustrative approaches, summarised in Table 4.3, is based in pragmatism, since there is a wide range of knowledge bases across the categories, and also distinctions between them with respect to the degree to which they are currently regulated by governance frameworks. Some are AM, others are CDR marine geoengineering approaches, one is a hybrid approach (CDR with deliberate environmental co-benefits, and one is large scale environmental engineering (fish stock enhancement). Despite, our detailed consideration of only eight approaches, there is still a wide range of permutations with which to compare and contrast these methods that will enhance this assessment.

Table 4.3 Illustrative examples from each category represented in the initial assessment of approaches, and the rationale for selection. Each approach was subjected to more detailed assessment using 8 criteria (knowledge base; efficacy (for the purpose the approach is intended); scale (geographical and temporal); feasibility of implementation; environmental consequences and co-benefits; attribution (confidence that the effects can be attributed; socio-political risks; challenges for governance)

Category	Approach	Rationale
Ocean fertilization	Iron fertilization	High level of knowledge, still under consideration as a marine geoengineering approach
Ocean fertilization	Fertilization for fish stock enhancement	Low level of knowledge, different route for carbon than sequestration, transboundary effects between national jurisdictions
CO_2 Storage in the Ocean	Liquid stored on the seabed	Low level of knowledge, no longer considered (not allowed under London Protocol but unclear position under London Convention – see section 2.4)
CO_2 Storage in the Ocean	Macroalgal cultivation for carbon sequestration	Intermediate level of knowledge, hybrid approach, untested technical challenges.
Ocean pumping	Artificial upwelling	Intermediate level of knowledge, redistributes (rather than modifies via an addition such as iron) oceanic properties — heat, dissolved gases, nutrients, requires adding structures to the ocean
Enhancing ocean alkalinity	Direct addition of alkaline material	Intermediate level of knowledge, currently being widely discussed as a promising approach

Category	Approach	Rationale
Increasing ocean albedo	Foam (using organic materials, not particles)	Low level of knowledge, does not capture CO_2 (AM (Albedo Modification) technique)
Increasing ocean albedo	Marine cloud brightening	Intermediate level of knowledge, link between ocean and atmosphere, AM technique

4.8 Distilling the criteria for evaluation

In the initial assessment we employed 17 criteria, and for the purposes of both economy and symmetry it was decided to reduce these to eight for the detailed assessment. It was also desirable to make conspicuous where our contributions to developing criteria build on those of other assessments (National Research Council, 2015a, 2015b; Williamson and Bodle, 2016).

In order to reduce the evaluation criteria, we focussed on what information is available; what is the level of confidence in the information available; to what extent is it really possible to quantify all these criteria to the same extent. Where possible we amalgamated criteria, for example we combined ‘speed to deployment’ with ‘technological readiness’. We also cross-compared our selections with those employed by the CBD (Williamson and Bodle, 2016) in relation to the assessment of Ocean Iron Fertilization. We did not include criteria to address cost or affordability as such information was not available across all the illustrative examples

In summary (and using our wording for the evaluation criteria c.f. the CBD criteria):

1) **Efficacy** – the CBD equivalent is effectiveness;
2) **Technological readiness and knowledge base** - the CBD equivalent is feasibility/readiness;
3) **Negative environmental consequences** (which could also include socio-political risks) – the CBD equivalent is safety/risks;
4) **Environmental co-benefits** - the CBD equivalent is co-benefits; and
5) **Governance challenges** – the CBD equivalent is governance and ethics –

Our additions to the CBD (Williamson and Bodle, 2016) criteria for the WG assessment were:

6) **Knowledge base criterion** (if inadequate for scientific assessment, more research is required);
7) **Detection and attribution criterion**; and
8) **Geographical and temporal scale criterion** (i.e., how long, and over what area, the intended effect will persist).

There was agreement to add a feasibility criterion to replace “Technological readiness”. The WG asserted the need to make sure that in the report we relate our categorization to other existing classifications such as those from the CBD.

4.9 Evaluation of eight illustrative marine geoengineering methods

The evaluation is summarised in Table 4.4 which reveals that the knowledge base for even the best documented approach to date (Ocean Iron Fertilization for Carbon Sequestration, which scored a High) is insufficient to enable a scientific assessment of its regional or global consequences as observations to date are on areas of ocean < 1000 km^2 (Boyd *et al.,* 2007). Hence, in the absence of an adequate knowledge base, less can be said about other criteria in Table 4.4, such as environmental benefits and consequences, and less again about socio-political risks. However, on other criteria, such as scale (geographical and temporal) there is more certainty based on modelling projections that indicate that the Southern Ocean is the only region in which enhanced carbon sequestration might occur (requiring sustained iron fertilization for at least 100 years). Recent modelling initiatives such as CDRMIP have been useful in providing estimates of the potential efficacy of approaches such as ocean iron fertilization, which at most could contribute the removal of 1 Gt C each year (10% of current emissions). However, this upper bound of C removal has to be reconciled with other factors that we know much less about, and hence lack confidence in model parameterizations (e.g. subsurface acidification (Cao and Caldeira, 2010), deoxygenation (Keller *et al.,* 2014), ‘robbing’ nutrients destined for lower latitude waters (Gnanadesikan *et al.,* 2003) to assess the cumulative multi-faceted effects. It also excludes the costs (financial and carbon expended) for the sustained addition (years), monitoring for detection of attribution (years, both of the magnitude of carbon sequestration but also that of any side-effects (beneficial or detrimental). Again, it is not possible to factor any social-political consequences into this multi-faceted cumulative assessment, due to the lack of information on the underpinning fundamental scientific knowledge. Nevertheless, scrutiny of each end-member, in terms of knowledge base, provides invaluable insights into the additional knowledge strands that are required to make a comprehensive assessment, which can be used to guide other approaches in the seven other categories we considered.

Table 4.4 Detailed assessment of representative examples from each geoengineering category, ranging from CDR, AM to hybrid approaches.

Criteria	Ocean Iron Fertilization (OIF)	Enhanced fish stocks	Liquid CO_2 on the seabed	Macroalgae cultivation	Artificial upwelling	Ocean alkalinity as minerals	Reflective Foams	Marine Cloud Brightening (MCB)
Knowledge base	Best studied to date, but knowledge so far is still inadequate to predict global consequences.	Lack of knowledge to date, and hence low confidence. Similar principles to OIF for sequestration, but different timescales that centre on the life cycles of the target fish.	Low knowledge base based on chemistry. Tests were small scale studies on the sea-floor with unanticipated changes in the physical properties of the liquid CO_2.	Medium knowledge. Hybrid approach often linked with IMTA (Integrated Multi-Trophic Aquaculture). Macroalgal carbon for use in biofuels[4] or sequestered into deep ocean[5].	Medium knowledge base. Field test off Hawaii failed after 1 day[1], others based Stommel's perpetual salt fountain[2, 3] presented evidence of enhanced phytoplankton stocks near the pipe outflow[3].	Medium knowledge base - prediction from chemistry models. But lack of knowledge on effects on ecology. Medium confidence.	The basic concept is well understood, uncertainties about how to create a consistent layer. But less information available than on OIF. Low knowledge base.	Medium knowledge. Principles of MCB (using cloud droplets) have been examined. Cloud dynamics less well understood. No field tests so far.
Efficacy	1 pG yr^{-1} removed (maximum potential based on model predictions, and equivalent to ~ 10 % of current emissions.	Unknown. Initial estimates could be inferred from fisheries statistics.	1000 year storage, no geochemical limits.	Initial estimate of sequestration was ~173 Tg C yr^{-1} (range of 61–268 Tg C yr^{-1}) globally[5].	<0.2GtC/ yr projected in maximum deployment scenarios[6], due to upwelling of DIC-rich waters. Main effect is temporary surface cooling, leading to carbon storage in soils (~1 Gt C yr^{-1})[6].	1 pG yr-1 (i.e., 10% of current emissions) if all current global shipping capacity is used.	Very effective at reflecting sunlight (globally > 2 W m^2), but requires continuous application.	Unknown.
Scale (geographic & temporal)	10 % of ocean surface (e.g. Southern Ocean; centennial storage, declines thereafter).	Unknown. Initial estimates could be inferred from fisheries statistics.	Small area of ocean need, very local, < 1% of ocean.	Norway has 90,000 km^2 suitable for seaweed cultivation[4].	To have global impact, tens of Sverdrups would be required, i.e. millons of devices over large areas of the world ocean[6].	Very similar to OIF, ~10% of ocean surface.	Few % of the surface ocean needed for 2 W m^{-2}, based on constant aplication as foams only reflect for a short amount of time.	Similar to foams. Proposed for local applications for protecting reefs.

Criteria	Ocean Iron Fertilization (OIF)	Enhanced fish stocks	Liquid CO_2 on the seabed	Macroalgae cultivation	Artificial upwelling	Ocean alkalinity as minerals	Reflective Foams	Marine Cloud Brightening (MCB)
Feasibility of implementation	Ships of opportunity. A novel delivery mechanism is needed. Technical challenges.	As for OIF, ships of opportunity etc.	High feasibility, but very costly, logistically challenging (building pipelines).	Limited by suitable habitat (depth, nutrients), but floating structures could expand habitat (but issues for nutrient supply offshore).	Millions of deployed ocean pipes and manufacturing and maintenance costs. Quickly reverses once upwelling is stopped, resulting in additional warming relative to 'no deployment' scenario[6]	Logistically challenging at the scale required. ~2 tonnes of mineral per tonne of CO_2 draw-down requires massive mining and transportation efforts. The form of alkalinity/ material used is also an issue.	Large challenge for uniform distribution, and constant application to keep foam in place.	Not operationally tested.
Environmental consequences and co-bene-fits	Potential co-benefits: increased productivity and fisheries, reduced upper ocean acidification. Drawbacks include subsurface ocean acidification, deoxygenation; altered regional meridional nutrient supply, fundamental alternation of foodwebs.	Potnetial drawbacks: Enhanced fisheries will potentially be an additional source of carbon (and eventually CO_2) and may offset carbon sequestration.	Drawbacks: Mortality of seafloor life where ever it is deployed.	Potential benefits: IMTA, i.e., co-culture of species for environmental and economic benefits. Drawbacks: reduced macroalgal diversity; nutrient competition with resident phytoplankton; uncertainties about fate of macroalgal C (exudation, detritus, coverage of seafloor, local anoxia) or extrapolation to offshore waters (no nutrients).	Consequences include redistribution of ocean properties - heat, dissolved gases (in particular oxygen), nutrients. Drawbacks: projections of partial deoxygenation of upper ocean especially in the Pacific[7]; hazards to navigation.	Potential co-benefits: countering ocean acidification and its effects on calcifiers, Trace elements in the minerals will have biological and chemical consequences. Issues related to longevity. Drawbacks, little known about the ecological or environmental effects of adding alkalinity to the ocean.	Potential co-benefits include reduced surface wave height Drawbacks: blocking light from entering the ocean, so significant effects on productivity and chemistry, reduced gas exchange, could alter wind driven ocean currents.	Potential drawbacks: less sunlight reaching upper ocean, altered wind stress with knock-on effects on regional weather patterns (drawback or co-benefit?).

Criteria	Ocean Iron Fertilization (OIF)	Enhanced fish stocks	Liquid CO_2 on the seabed	Macroalgae cultivation	Artificial upwelling	Ocean alkalinity as minerals	Reflective Foams	Marine Cloud Brightening (MCB)
Detection and Attribution (intended and unintended effects)	Detection & Attribution of intended effects (i.e, C sequestration) is less difficult relative to unintended side effect, due to long time scales of deployment, far-field (interbasin) effects.	Use of conventional fishery metrics such as stocks landed. Issues for detection and attribution include relationship between boosting fish stocks, changes to fishing effort, and natural variability in fish stocks.	Not difficult to detect leakage.	Increased biomass is conspicuous but little knowledge around the proposed modes of sequestration is problematic for its attribution. Detection using biomarkers?	Use of multiple ocean tracers - heat, dissolved gases, nutrients to detect and attribute, in conjunction with gauges on each pipe to record pumping rate, along with modelling.	Monitoring ocean chemistry could readily achieved. Attributing negative/ unintended effects impacts could be non-trivial, for example altered food-web interactions.	Attribution of first order effects is not difficult, but second order effects might require modelling. Some changes such as marine light penetration would be more readily detected and attributed.	Difficulties in detection and attribution include: alternation of weather patterns, misattribution of weather extremes. Changing rainfall could effect water and food security.
Socio-political risks (include national security)	Risk of geopolitical conflict, alteration of marine resources, effects on food supply, difficulties of attribution could lead to (mis) attribution of side effects.	More fishery disputes (fast swimming pelagics move out of 'fertilised region' to be caught by others who did not fund the fisheries augmentation. Knock-on effects of ecoogical changes may lead to transboundary effects on fisheries (real or perceived). Difficulties of attribution could lead to (mis) attribution of side effects.	Public perception, fear of leakageof stored carbon (related to public perception), no effects on food security, no direct effects on human populations if C is stored in remote location.	Potential transboundary issues with invasive macroalgae dominating in regions where national coastlines adjoin. Legislation (e.g. Scotland) make it an offence to plant or have a species grow outside its native range. Potential aesthetic effect on tourism, or interference with other marine activities.	Deoxygenation of upper ocean and its effect on regional fisheries. Cooler ocean temperatures may alter weather patterns (rainfall) and affect terrestrial food production. Transboundary effects could lead to geopolitical conflict. Significant intereference with other activities e.g. shipping, fisheries.	Mineral extraction and transport would have socio-political effects. Transboundary issues. Trace elements within the minerals could effect marine resources, food security. Particles could accumulate on coastal areas.	Public perception, tourism, food security issues, aesthetics.	Unknown effects on climate and weather patterns, that would depend upon the scale of deployment (10% of the planet may be a pre-requisite for MCB to have a significant influence on Earth's radiative budget).

Criteria	Ocean Iron Fertilization (OIF)	Enhanced fish stocks	Liquid CO_2 on the seabed	Macroalgae cultivation	Artificial upwelling	Ocean alkalinity as minerals	Reflective Foams	Marine Cloud Brightening (MCB)
Governance challenges for both research and large-scale deployment	Madrid Protocol or equivalent, high seas jurisdiction, transboundary issues. LP amendment are applicable, but are not in force.	Linking fertilisation and the enhancement of stocks is scale-dependent (i.e., inconspicuous at 100's of km^2)[8]. Transboundary issues as with OIF. National biodiversity/ marine protection laws may be relevant (c.f. UN CBD). Likely to fall under LP, as does OIF.	Relatively simple: No transboundary effects, no infringement on national jurisdictions. CO_2 could be defined as an "industrial waste" and thus dumping could be banned under LC, is not be permitted to be dumped under the LP.	Scalable technology amenable to research governance; however issues include containment of trial 'growouts', spread of non-natives; scaling up of C sequestration5. Secondary effects on marine biodiversity may be transboundary (c.f. UN CBD). Offshore nutrient additions could bring this activity under the LC/LP.	Scalable technology should lessen research governance challenge. Amenable to modelling. Potential transboundary effects on fisheries and weather patterns could lead to governance challenges, public backlash. Not adding material to the ocean, so may not fall under the current LC/LP.	Transboundary issues. LP not covered at present, but could be.	High seas jurisdiction, transboundary issues, depending on material used, coastal areas may be effected, likely to fall under LC/LP dumping conventions.	Transboundary changes in precipitation patterns could lead to international legal issues. Potentially could be affected by LP.

4.10 Convergence and divergences between marine geoengineering approaches

Table 4.4 shows a wide range of similarities and departures. The approaches span CDR, albedo modification, and hybrid approaches such as IMTA (Macroalgal culture). This makes it more difficult to compare their efficacy (versus changes in radiative forcing (W m^2)) and uncertainties about how to scale hybrid techniques. The techniques also require different spatial (<1% of the ocean (foams, seabed CO_2; to > 10% of the ocean (OIF, upwelling, alkalization)) and temporal scaling (sustained, centennial for OIF to one large addition (liquid CO_2 on the seabed)) that will have ramifications for detection and attribution (and associated costs), and for transboundary issues and their geopolitical consequences.

As discussed in previously in this report, there are wide variations in the knowledge bases (OIF c.f. fertilization for fish stock enhancement) and hence gaps in the knowledge base required for a scientific assessment. Another important divergence between the approaches is how amenable they are for the application of modelling projections – for example through GEOMIP (the Geoengineering Model Intercomparison Project) or CDRMIP. While GEOMIP had originally been focused on the stratospheric geoengineering techniques, papers have subsequently addressed MCB (e.g. Ahlm *et al.,* 2017; Jones *et al.,* 2009; Rasch *et al.,* 2009; Stjern *et al.,* 2018). CDRMIP has so far looked at OIF, Ocean Alkalization and Artificial Upwelling (Keller *et al.,* 2014 and 2018) and some earlier papers also modelled marine geoengineering techniques (e.g. Oschlies *et al.,* 2010; Gnanadesikan and Marinov, 2008). In the absence of any laboratory or field (constrained, see Figure 4.1) trials and the inhibitions to field (unconstrained, see Figure 4.1) pilot studies such as the CBD decision on geoengineering, the modelling of geoengineering approaches has provided invaluable insights that enable some initial cumulative assessments (i.e., using a range of biogeochemical metrics) of approaches to be made. This approach is likely to be improved further with recent calls for harmonisation, with a plea for other modelling groups to follow the CDRMIP experimental protocol (Keller *et al.,* 2018).

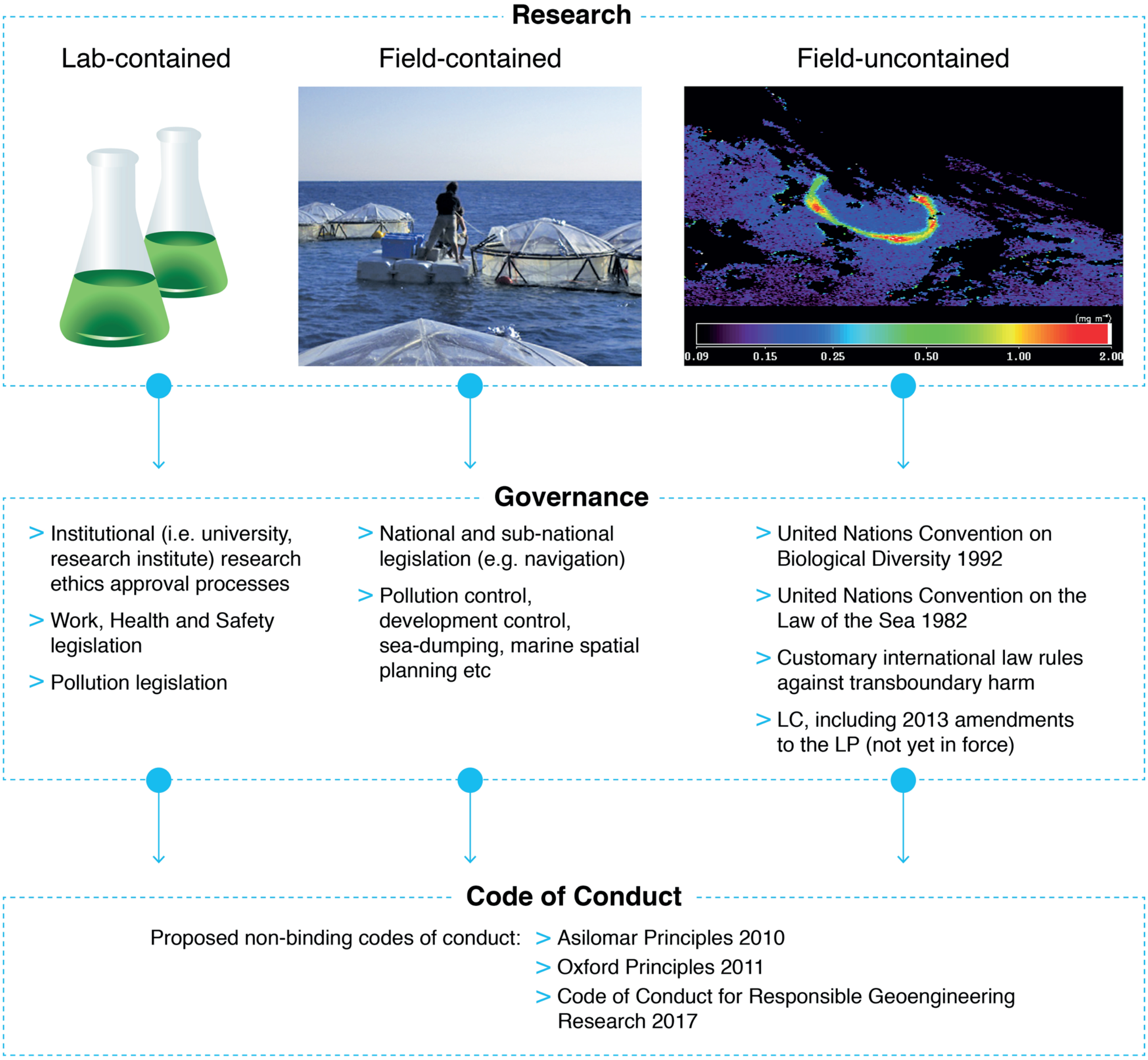
For example, in the case of ocean upwelling, CDRMIP has projected that the cumulative effects are low direct (oceanic) carbon sequestration (< 0.2 Gt C a^{-1}), but high indirect C sequestration on land (1 Gt C a^{-1}) due to the cooling effect of upwelling (Oschlies *et al.,* 2010b), and partial deoxygenation of the upper ocean (including increased volumes of oxygen minimum zones) (Keller *et al.,* 2014). The latter could have detrimental effects on fisheries in the Pacific and hence has the potential for transboundary effects related to altered patterns of food security. Hence, modelling enables progress to be made in comprehensive evaluation of geoengineering approaches, and also illustrates the complex nature of many of these approaches when they are upscaled (in silico) and reveal direct, indirect and unexpected side-effects. However, it must be acknowledged that the many of the processes being modelled (e.g., an ocean mirror of stable foam (Gabriel *et al.,* 2017), olivine particles in surface waters of the global ocean at numerical concentrations similar to the most abundant phytoplankton (Köhler *et al.,* 2013), ocean pumps disrupting the co-evolved vertical structure of some of the largest biomes on Earth (Karl and Church, 2017) have not been tested for feasibility, and importantly, their impacts on the biota have generally been examined only in the context of conventional biogeochemical ocean general circulation models (BOGCMs) that are not designed to account for effects of chemical contamination (e.g., surfactants) or fundamental physical disruptions of marine ecosystem structure (alien inorganic particles, unprecedented vertical mixing).

The last row in Table 4.4 focusses on differences in the regulation of marine geoengineering approaches (OIF c.f. ocean floor CO_2) with respect to both research and implementation and their governance. In many cases the marine geoengineering approaches are scalable technologies which can be developed in a modular manner (see Figure 4.1) which may permit a gradualist approach to research governance or even adaptive governance. In the case of implementation and its regulation, some similarities that are evident between approaches (such as scale for OIF, Ocean Alkalinization and upwelling, each need ~10% of the ocean) may lead to similar issues (such as the likelihood of transboundary effects) that could require a common governance framework. The cumulative effects of these differences and similarities need to be considered with respect to the eventual regulation of each approach vis-à-vis the LP/LC on ocean iron fertilization (an illustrative example of the ocean fertilisation category, see Table 4.4).

4.11 Nature of the knowledge gaps across methods

A wide range of knowledge, that straddles multiple disciplines, is needed to assess each geoengineering approach (Figure 4.2). Moreover, this spectrum of information must commence with fundamental knowledge, i.e., the underlying principles for any marine geoengineering technique, followed by technological knowledge on how to deploy a specific geoengineering approach (for example, the need to add iron to the ocean as a solution at an optimal pH). Subsequent knowledge that is required includes an investigation of potential side-effects, for example the effect of artificial upwelling on inadvertent deoxygenation of surface waters (Keller *et al.,* 2014). Together, these knowledge bases are essential to inform others along this spectrum such as legislation (Figure 4.2).

Ideally, the assessment of individual geoengineering approaches would have sufficient knowledge regarding each of these disciplines, however at present this is seldom the case (Figure 4.2). Indeed, for many geoengineering approaches, for example the deployment of MCB, gaps in technological knowledge preclude any further progress along this spectrum, resulting in a paucity of information on potential side-effects, and hence insufficient knowledge to develop the suitable legislative frameworks. In many cases these knowledge gaps could be filled (at the very least, in part) in using laboratory-based methods (i.e. those covered by conventional research governance within institutions or national codes of conduct, see Figure 4.1). This approach to assessing knowledge bases can be used as a shorthand to compare different approaches across these eight categories (Table 4.2).



- Institutional (i.e. university, research institute) research ethics approval processes
- Work, Health and Safety legislation
- Pollution legislation

- National and sub-national legislation (e.g. navigation)
- Pollution control, development control, sea-dumping, marine spatial planning etc

- United Nations Convention on Biological Diversity 1992
- United Nations Convention on the Law of the Sea 1982
- Customary international law rules against transboundary harm
- LC, including 2013 amendments to the LP (not yet in force)

Proposed non-binding codes of conduct:
- Asilomar Principles 2010
- Oxford Principles 2011
- Code of Conduct for Responsible Geoengineering Research 2017

Figure 4.1 *Links between research approaches used in the development of ocean iron fertilization scientific experiments over two decades and the relevant governance frameworks and code of conduct. This research commenced with lab-contained studies that have conventional governance requirements, and gradually advanced to field research that was enclosed/contained (i.e., large volume (~50 m^3) moored submerged mesocosms are shown) to experiments that were unenclosed and with an areal extent of 1,000 km^2. Each phase required more comprehensive and complex research governance. Could a similar gradualist approach for developing research (and its adaptive governance) be employed across marine geoengineering methods?". Provided by Philip Boyd ©.*

Other aspects of marine geoengineering approaches that can be used to demarcate them include the need to have major infrastructural transformations to upscale some of the marine geoengineering categories. One example is for ocean alkalisation, where model projections show a large C sequestration effect but one that is contingent on using the entire present-day global shipping capability to deliver the alkalising agent. This pointed to the need for cost benefit analysis and for new economic metrics for each marine geoengineering approach (see McCormack *et al.,* 2016).

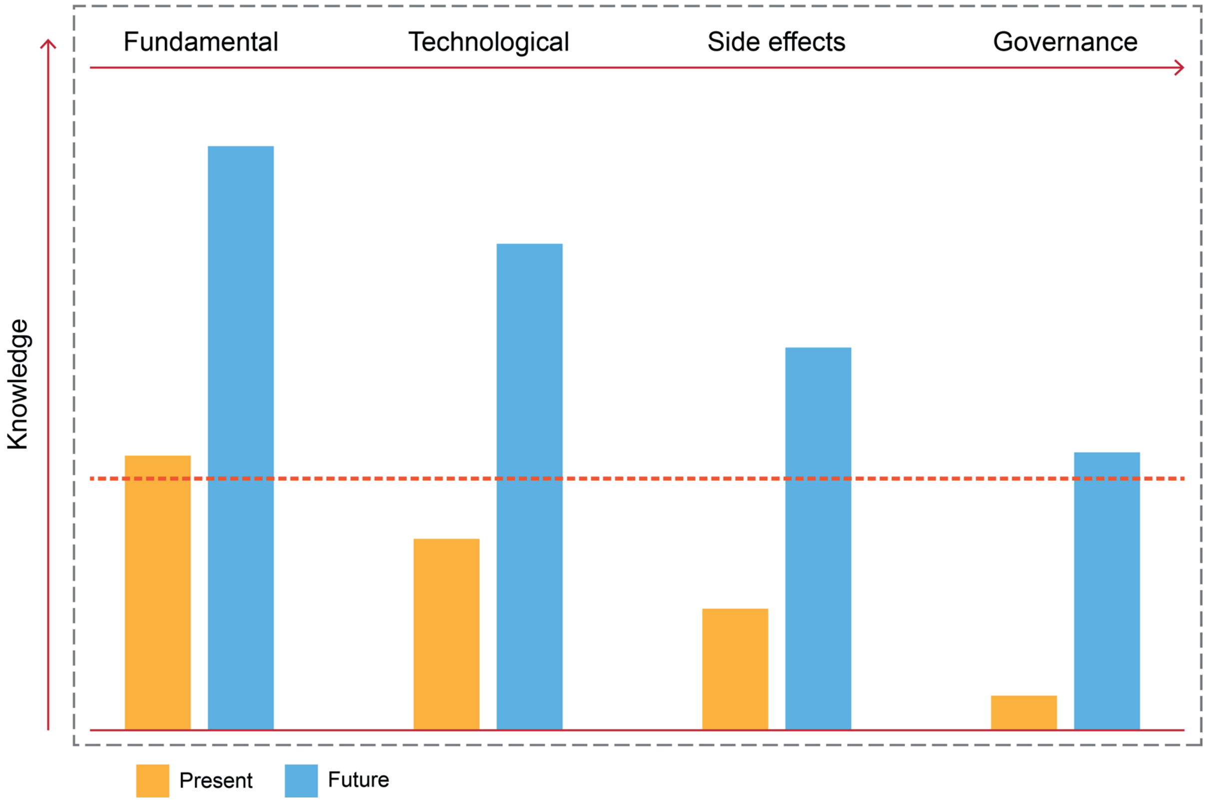


Figure 4.2 *Current knowledge on marine geoengineering approaches from fundamental to legislative. Based on relatively well-characterised techniques such as ocean iron fertilization, most knowledge is required on fundamental scientific issues, since they will inform the subsequent requirements for technology through to those within the broader social-political and legal frameworks. Horizontal dashed line denotes a putative threshold above which decisions can be made with some confidence, based on a wide range of metrics, on the outcomes of a range of approaches. Provided by Philip Boyd ©.*

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

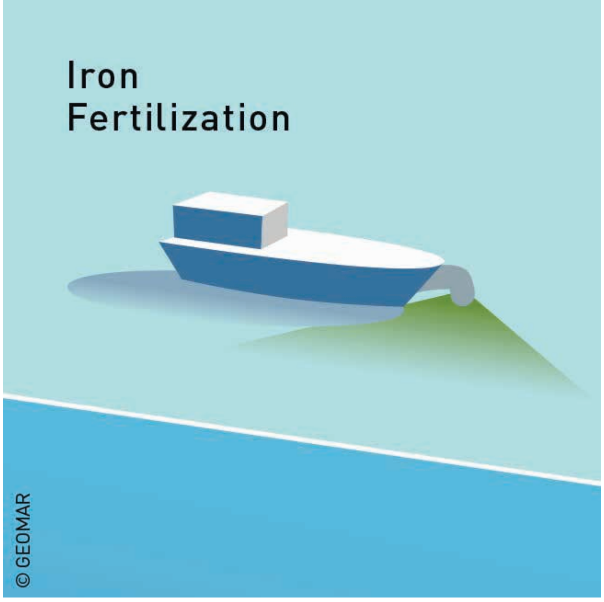


Figure 5.1 *Ocean iron fertilization*

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 is 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).

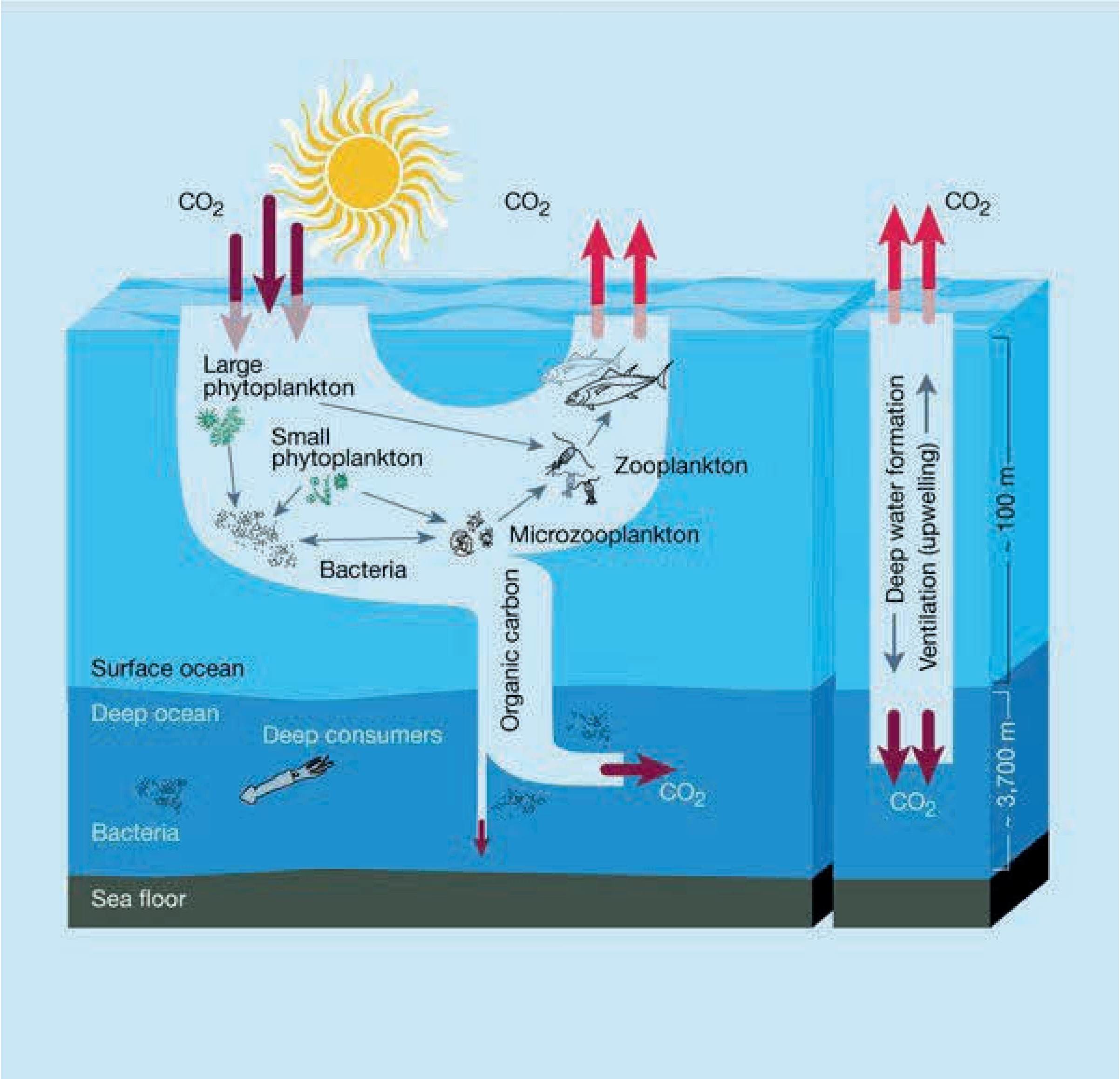


Figure 5.2 *The Biological Pump is a collective property of a complex phytoplankton-based foodweb. Together with the solubility pump (right), which is driven by chemical and physical processes, it maintains a sharp gradient of* CO_2 *between the atmosphere and the deep ocean carbon reservoir (Reprinted 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

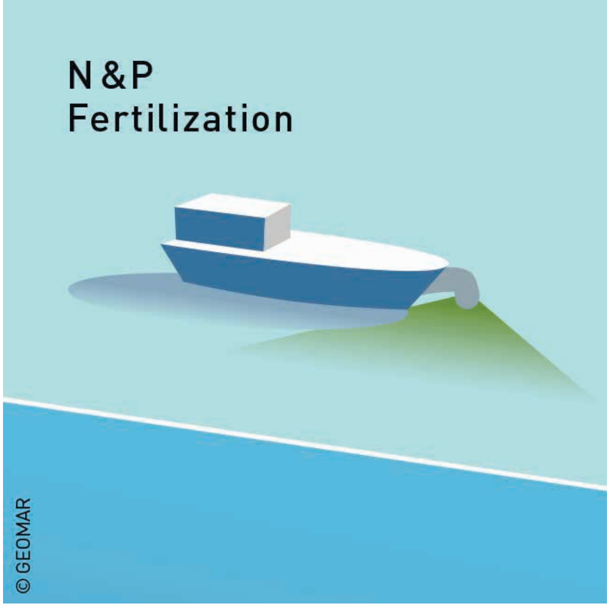


Figure 5.3 *Ocean nitrogen and phosphorus fertilization*

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 (Glibert *et al.,* 2008; Glibert *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.

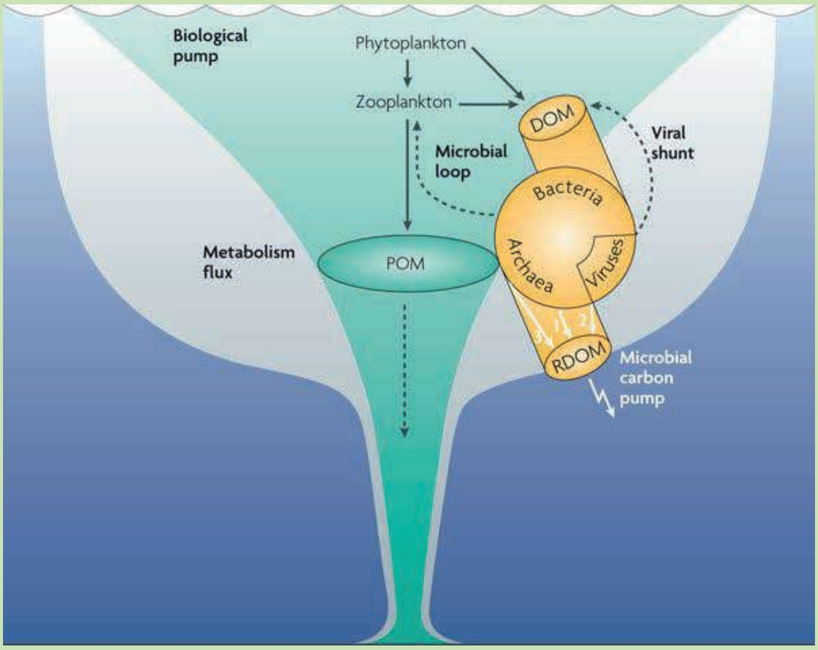
Enhancing Dissolved Refractive Carbon in the Deep Ocean

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

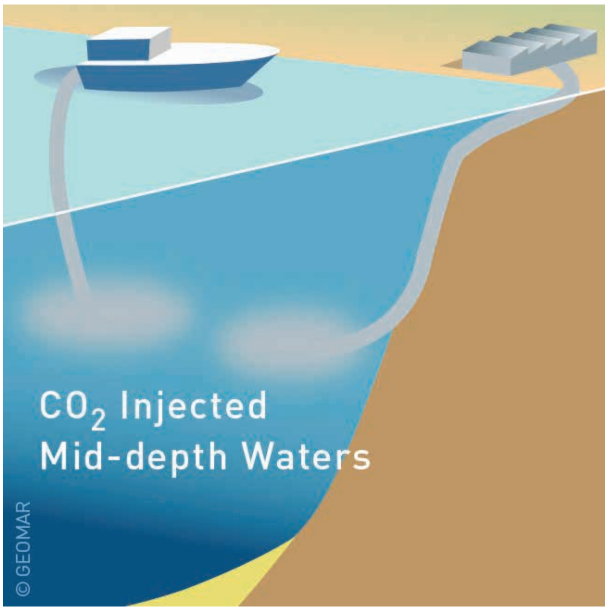

Figure 5.5 *Liquid CO_2 placed in mid/deep ocean depths*

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

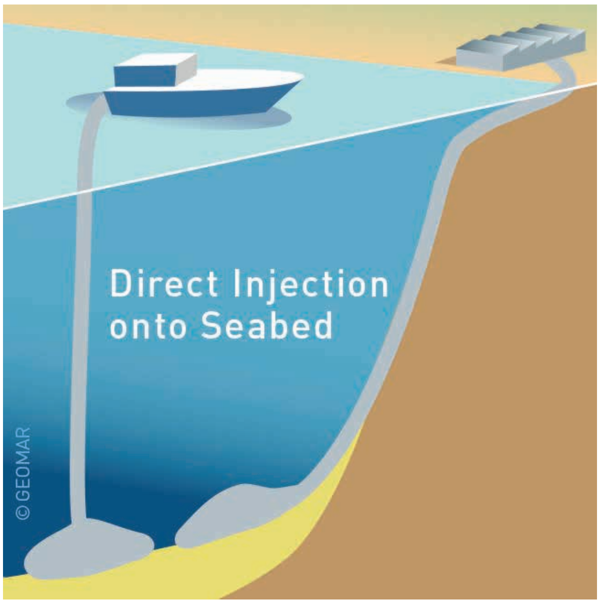

Figure 5.6 *Liquid CO_2 placed on the seabed*

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.

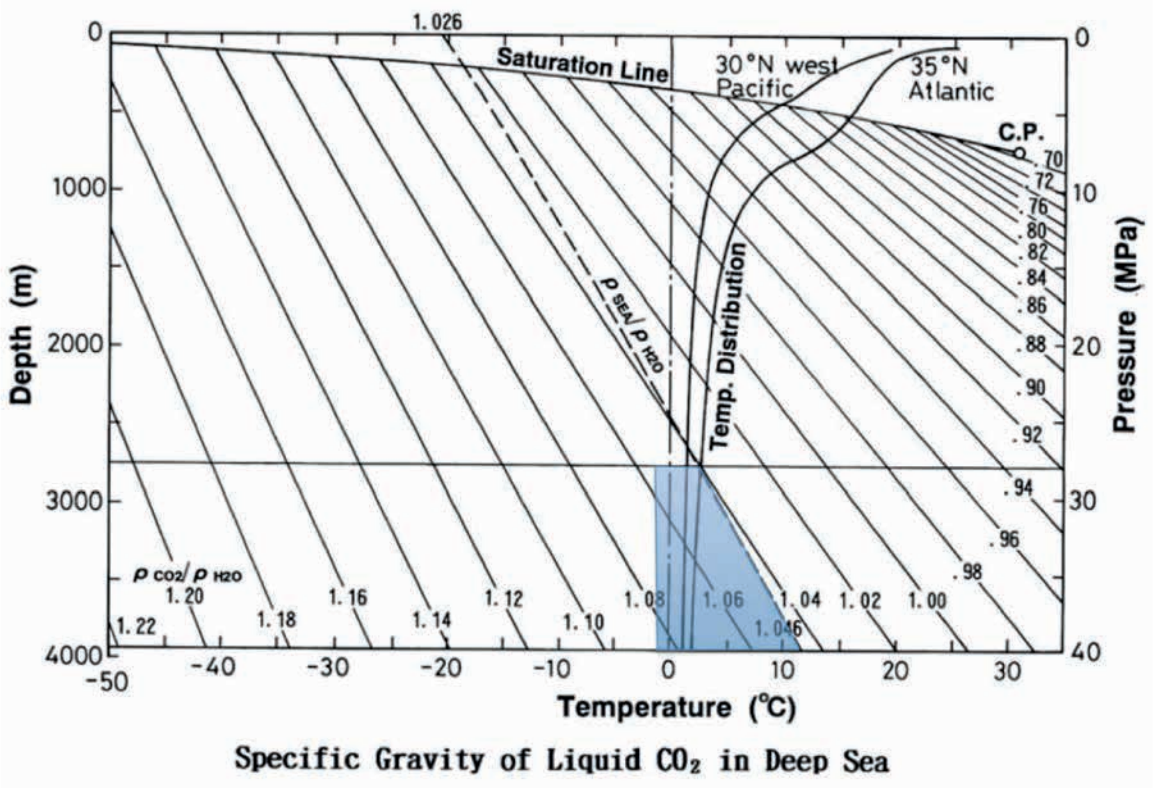

Figure 5.7 *The specific gravity of liquid CO_2 compared to basic ocean water properties (temperature, density, and pressure). The high compressibility of liquid CO_2, and low temperature in the deep-sea, result in gravitational stability of liquid CO_2 at depths ≈>2800 m (blue shaded area). Seawater 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

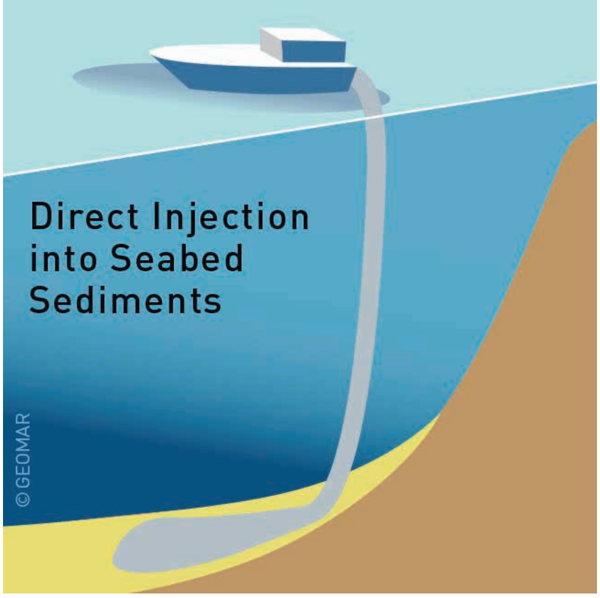

Figure 5.8 *Liquid/Solid CO_2 placed into unconsolidated deep-sea sediments*

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]

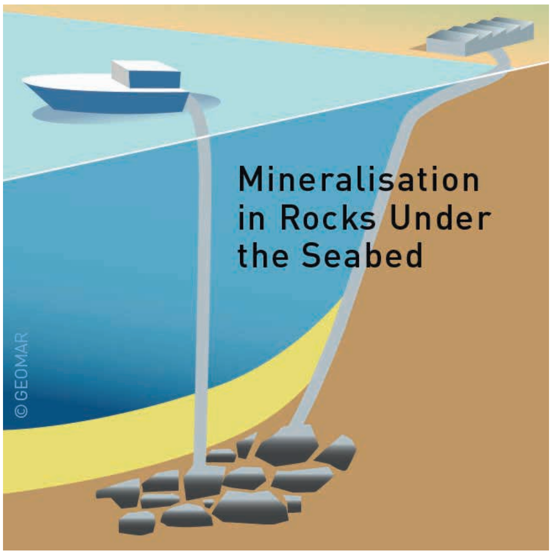

Figure 5.9 *Mineralisation of CO_2 in rocks beneath the seabed*

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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 km^2 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

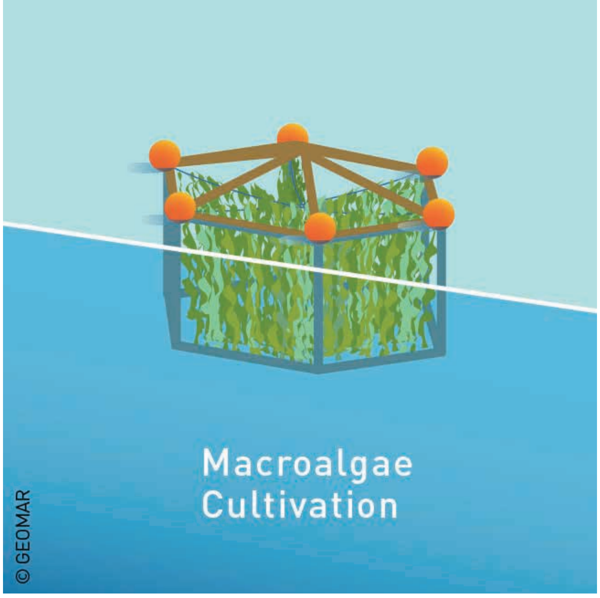

Figure 5.11 *Macroalgal cultivation for sequestration and/or biofuels*

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.

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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

5.10 Ocean pumping – artificial upwelling

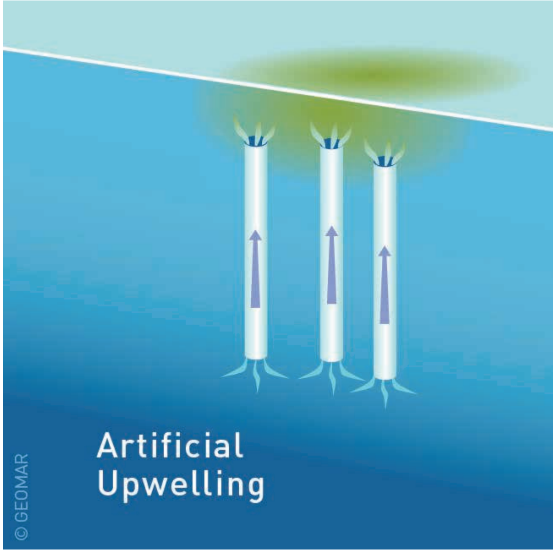

Figure 5.12 *Artificial upwelling*

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

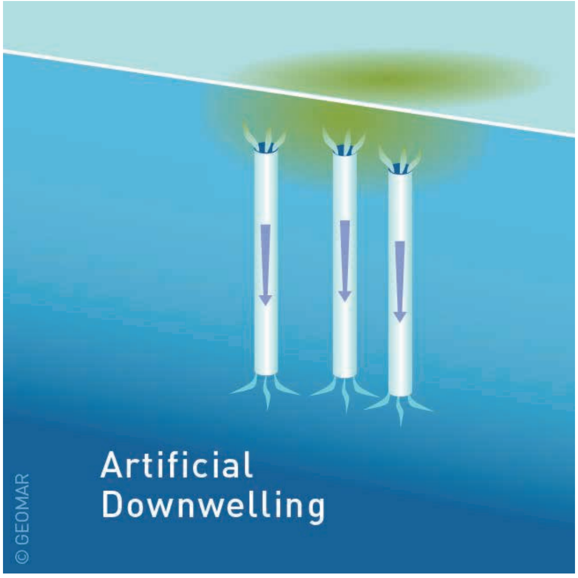

Figure 5.13 *Artificial downwelling*

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

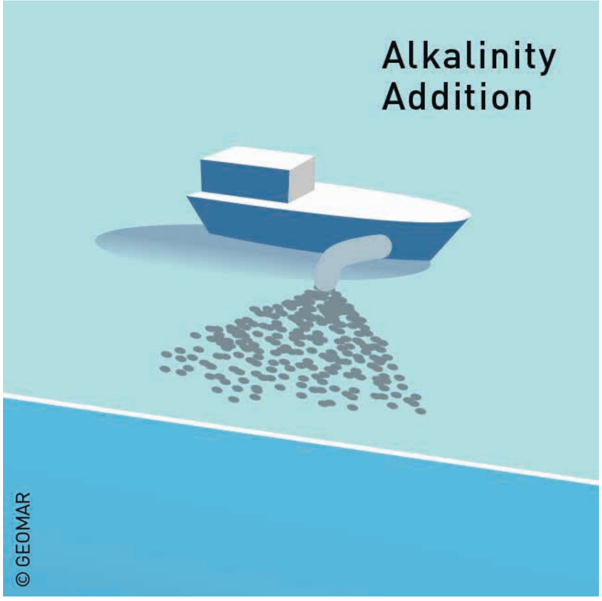

Figure 5.14 *Enhancing Ocean Alkalinity*

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.

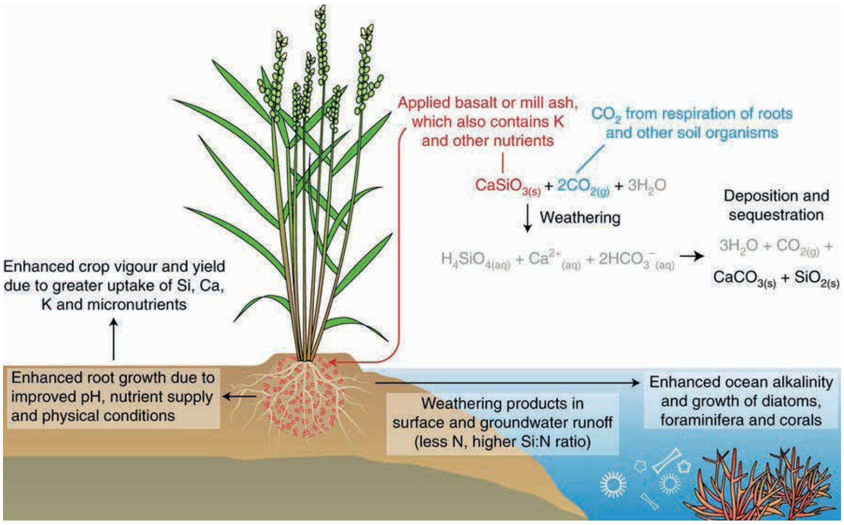

Figure 5.15 *Summary of the potential effects of weathering of crushed basalt or silicate-rich wastes, such as sugarcane mill ash, applied to croplands. As silicate rocks weather, they release nutrients that can improve soil conditions and support crop production, and also generate alkaline leachate, 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

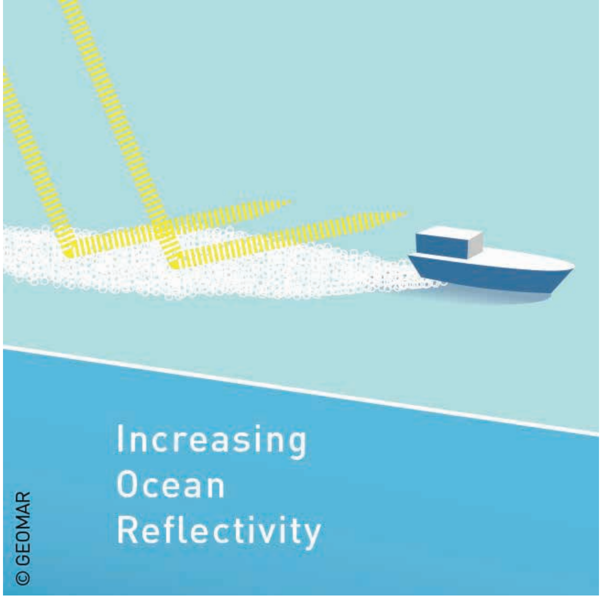

Figure 5.16 *Increasing ocean albedo*

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 sub-polar 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

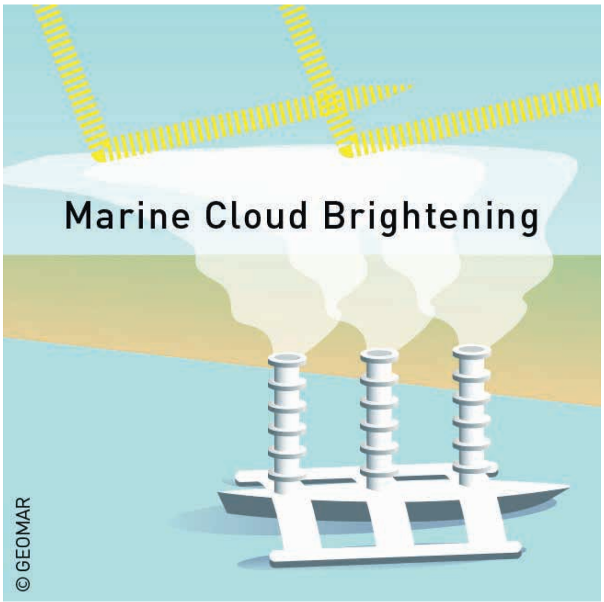

Figure 5.17 *Marine cloud brightening*

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)

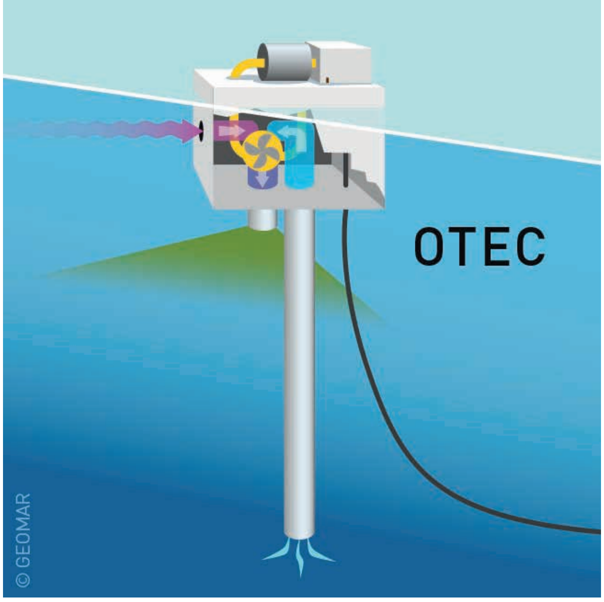

Figure 5.18 *Ocean thermal energy conversion*

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, nearshore 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

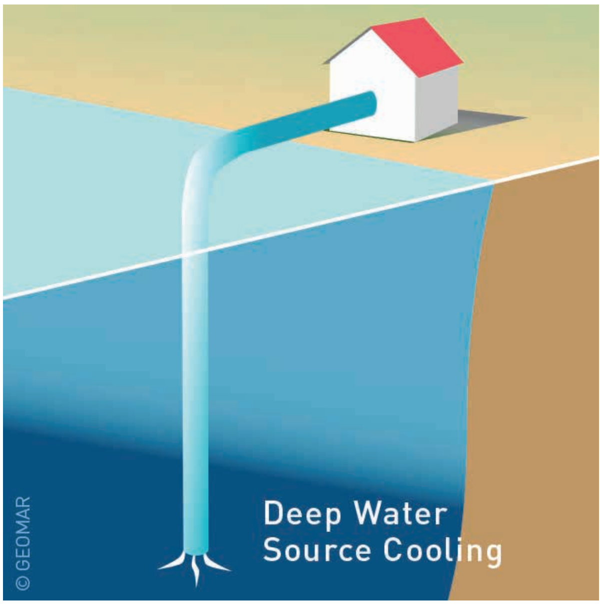

Figure 5.19 *Deep water source cooling / sea water air conditioning*

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://honolulusswac.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

evidence from modelling projections of the detrimental side effect of ocean deoxygenation if this technology was basin-scaled (Keller et al., 2014).

Foams (Aziz et al., 2014), ocean alkalinity (Rau, 2011) and MCB (Latham et al., 2012) have all been subjected to simple lab trials, such as foams produced in the lab and kept stable for weeks in dishes (Aziz et al., 2014) or the production of sub-micron water droplets (using "saltwater" (source and composition undescribed, Cooper et al., 2014); it is evident that these approaches have yet to be demonstrated as effective in the marine environment. IMTA using macroalgae has been subjected to some constrained field trials (Troell et al., 2009) in both Europe and Asia. However, of all of the eight approaches the fertilization for fish stock enhancement looks closest to field deployment based on recent developments in Chile (Jeff Tollefson, 2017) which appear to be inspired by the unauthorized release of iron, to indirectly boost fish stocks, in the North-East Pacific in 2012 (Tollefson, 2012). Interestingly, in the case of iron-mediated fish stock enhancement there has been no attempt to follow the gradualist model from OF scientific research (Figure 4.1) with a gradual evidence-based transition from lab-constrained to field-constrained, before attempting the more ambitious move to field-unconstrained. So, in this latter case, there was no evidence of a triggering transition towards technical readiness that would indicate that an unconstrained pilot study was about to take place, and hence little warning of for the LP/LC to develop legislation (although in this case the proposed entry-point of the technology was within Chilean waters, see section 2.4).

6.2 The existing LC/LP two-step assessment for the Ocean Fertilization Assessment Framework (OFAF)

The existing LC/LP OFAF is available for OF and its research governance. The elements of the OFAF can be summarized as follows:

1 The Initial Assessment determines whether a proposed activity falls within the definition of ocean fertilization and has proper scientific attributes, and thus is eligible to be considered and evaluated in this framework;

2 Environmental Assessment

  .1 The Problem Formulation describes the proposed activity and sets the bounds for the assessment carried out in subsequent steps;

  .2 The Site Selection and Description outlines the criteria used for site selection and data necessary for describing the physical, geological, chemical, and biological conditions at the Proposed Site;

  .3 The Exposure Assessment describes the movement and fate of added/redistributed substances within the marine environment;

  .4 The Effects Assessment assembles the information necessary to describe the response of the marine environment resulting from ocean fertilization activities, specifically by taking into account the short- and long-term effects. This section describes the factors to be considered for the evaluation of the Impact Hypothesis;

  .5 The Risk Characterization integrates the exposure and effects information to provide an estimate of the likelihood for adverse impacts and the magnitude of those impacts. The risk characterization should include a description of the uncertainties associated with its conclusions; and

  .6 The Risk Management is a structured process following risk characterization designed to minimize and manage risk and implement appropriate monitoring and intervention and remediation strategies to manage risks, including mitigation and contingency planning. Risk management procedures, based on a precautionary approach, are necessary to ensure minimization of environmental risks;

3 Decision Making - The determination that a proposed activity is legitimate scientific research, and is not contrary to the aims of the London Convention and Protocol, should only be made upon completion of the entire Framework; and

4 Results of monitoring - The collection and use of information resulting from monitoring informs future decision making and can improve future assessments.

Table 6.1 A cross-comparison of each of the illustrative examples of other geoengineering approaches with that of ocean iron fertilisation to explore what range of regulatory frameworks might be needed in future to accommodate a diverse range of geoengineering approaches. This table is an abbreviated version of Table 4.4.

Criteria	**Role of each criterion when cross-comparing OF with other approaches**[*]	**OF for C sequestration**	**Fish stock enhancement**	**Liquid CO_2 on the seabed**	**Macroalgae**	**Artificial upwelling**	**Ocean alkalinity as minerals**	**Foams**	**MCB using sea water**
Knowledge base	Informs ability to cross compare	High based on proxies	Low, no field studies.	Low with one small field test	Medium, IMTA, some small pilots	Medium, (based on small scale field trials)	Medium, modelling (based mainly on chemistry)	Low, lab experiments	Medium, lab trials with freshwater
Efficacy (per km^2)	Generally, links to scale	med	??	high	??	low	med	high	??
Scale of global ocean required	Important – proxy for transboundary issues	10%	??	<1%	??	>10%	10%	~1%	~1%
Feasibility	Technological – so beyond Research Governance	Largely unknown	Largely unknown	Largely unknown	Largely unknown	Largely unknown	Largely unknown	Largely unknown	Largely unknown
Environmental consequences and co-benefits[†]	Will require research to detail and quantify	Many and large scale (based on proxies)	Many (little information)[‡]	(local scale)	Many (little information)[‡]	Many (from modelling)[‡]	Many (little information on effects)[‡]	Many (no information)[‡]	Many (no information)[‡]
Attribution[†]	Will require research to detail and quantify	Difficult	Difficult (fast swimming long lived fish have been the proposed target)	Easy	Both easy and difficult (1st order effects on biomass accumulation and sequestration, respectively)	medium	Both easy (1st order effects) and difficult (2nd order effects)	Both easy (1st order effects) and difficult (2nd order effects)	Both easy (1st order effects) and difficult (2nd order effects)
Socio-political risks[†]	Will require research to detail and quantify	High	High	High/medium	Medium	High - deoxygenation	High	High	??

Criteria	**Role of each criterion when cross-comparing OF with other approaches**[*]	**OF for C sequestration**	**Fish stock enhancement**	**Liquid CO_2 on the seabed**	**Macroalgae**	**Artificial upwelling**	**Ocean alkalinity as minerals**	**Foams**	**MCB using sea water**
Governance challenges[†]	Will require research to detail and quantify	LC/LP	Covered by the LP definition. There is no onshore/ coastal versus offshore distinction.	LC- Industrial waste	Onshore versus offshore deployment	Covered by the LP definition.	LC/LP compatible?	Fall under dumping conventions	Transboundary

[*] Denotes pertinence of criteria to the ability of approaches to be regulated using a framework comparable to OFAF.

[†] denotes low confidence on the table entries in this row;

[‡] denotes that it is possible to speculate about these from first principles.

An overview of this Framework is given in Figure 6.1.

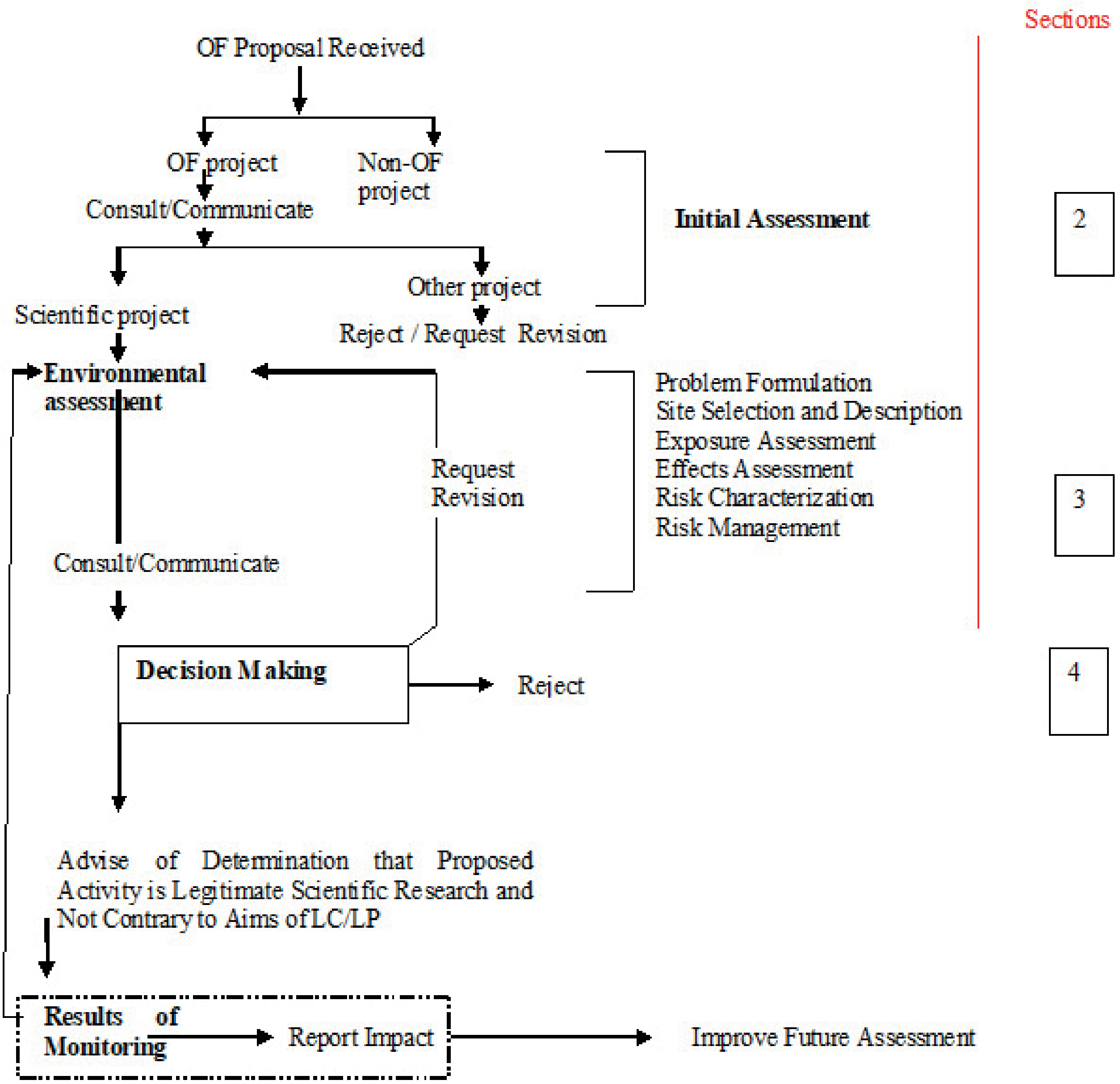

Figure 6.1 *The LC/LP Ocean Fertilization Assessment Framework*[50] *for proposed research. In the LC, there is a two-step process, commencing with an initial assessment, followed by a broader Environmental Impact Assessment (EIA). The Sections referred to in the far right of the figure are the section numbers in the Assessment Framework*

This "Assessment Framework for Scientific Research Involving Ocean Fertilization" (the Framework) is designed for Contracting Parties to evaluate proposed activities that fall within the scope of resolution LC-LP.1(2008). Ocean fertilization is defined as any activity undertaken by humans with the principal intention of stimulating primary productivity in the oceans.

This Framework provides a tool for assessing proposed activities on a case-by-case basis to determine if the proposed activity constitutes legitimate scientific research that is not contrary to the aims of the London Convention or Protocol.

6.3 Utility of developing a pre-assessment framework

To date, there have been no known approaches to have an OF study tested by the OFAF. Why is the OFAF not being used, when clearly there is evidence of proposed unconstrained modification of the ocean, such as a planned iron fertilization of an eddy (~100 km diameter) off Chile for fisheries enhancement (Tollefson, 2017)?

Is the current under-usage of the OFAF due to: the lack of suitable OF proposals? (for example, driven by confusion over the CBD decision on OF, see (Nature Geoscience Editorial, 2009); the use of other entry-points, such as territorial waters, for proposed

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

research (see Tollefson, 2017)[51]; or the need for simpler pre-assessment to encourage participation in this framework and to help define for proposers, and subsequently direct the flow of information towards that needed for a scientific assessment: or simply due to a lack of incentives e.g. funding.

Although the steps in the existing LC/LP OFAF and the annex to the London Protocol 'Guidance for consideration of marine geoengineering activities' (IMO, 2015) fit well with the criteria discussed by the GESAMP WG, it is of value to consider whether they can be supplemented further to initiate and encourage the provision of sufficient information from proposers at an early stage to permit an initial scientific assessment. By setting out in a pre-assessment framework such as a questionnaire, the nature of the information sought to make a scientific assessment, and at what level of detail the information needs to be provided, this could clarify the initiation and development of a dialogue between proposers and scientific assessors. Such a fundamental framework would include a description of concept followed by a justification of approach. The second GESAMP study aim in the ToR requires the identification of approaches that might need to be listed in the LP/LC. But for many approaches there is not enough information available – so we must advocate the provision of the suite of information (i.e., structured guidance as opposed to guidance) that would be needed for a full assessment. In this two-way process, the motivation of proposers to participate must also be considered. Why would it be advantageous to all concerned for proposers to provide information and in having their approaches listed and regulated? There may be reservations about openness and in having their techniques assessed early on. Alternatively, others may be interested in gaining legitimacy for their experiments by having them regulated.

Other motivations for getting proposers involved in assessment could be that they will get state-of-the-art multi-faceted scientific feedback on their proposed approach. Could this be employed as an incentive? Based on limited experience across the WG in their interactions with proposers, the latter often prefer to rely on experts with whom they have made direct arrangements and are not interested in seeking open, outside assessment. Moreover, a consideration is that proposers would be unlikely to want to divulge proprietary information and disinterested in becoming unnecessarily entangled in a governance framework. Hence the questionnaire would need to be carefully designed to obtain sufficient knowledge to make a scientific assessment, but at the same time not requesting a level of information that would encroach on proprietary information. It is possible to develop regulation that does not have to be restrictive (such as codes of conduct or 'soft law'), such that it can also be enabling of research. This may be an incentive for getting proposers involved in the initial assessment processes, providing them with legitimacy and a social/political license to operate. Moreover, by providing scientific advice freely to marine geoengineering proposers and streamlining the process for information-gathering, we could provide incentives to collate and submit information to the LP/LC.

A further incentive to encourage more engagement from proposers of marine geoengineering with governance mechanisms, is for these mechanisms to acknowledge and weigh up the potential climate, environmental, economic and societal benefits of geoengineering. In that way, balanced and fair decision-making would be perceived by the proposers, rather than perceptions of assessments largely based on potential negatives.

6.4 Structured guidance – initial thoughts on development of a questionnaire

We need to consider what we need to know to enable the development of an effective research governance framework. We also need to ascertain whether a range of such frameworks is required to cover the suite of marine geoengineering approaches or whether one generic structure would suffice. Any pre-assessment tool should glean information that relates directly to governance of research, but also must seek fundamental information on the longer-term aspirations of each marine geoengineering approach i.e., its eventual deployment in which the initial scale of a pilot study – for example 10 km length scale for OF (Figure 4.1) – would be upscaled considerably. The development of this pre-assessment tool was beyond the scope of the WG's current Terms of Reference. However, the WG has had preliminary discussions regarding the utility of a questionnaire to provide guidance (see above), from very broad lines of enquiry which become more focussed with each query, for aspiring marine geoengineering proposers to provide information for a pre-assessment.

We suggest that the WG should explore the feasibility of developing a pre-assessment tool, with the intention of soliciting the relevant kernel of information to ensure that any submitted marine geoengineering proposal has sufficient breadth and depth to permit an initial scientific, social and political assessment.

Such a pre-assessment tool must be systematic enough to obtain the relevant information without compromising any proprietary information associated with the planned marine geoengineering techniques. Initial ideas on the type of information and the need for a gradualist approach are outlined below in Box 4.

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[51] Note: Nearshore national waters are covered by the LC (except inside embayments and estuaries i.e. 'Internal Waters' behind the baselines for territorial waters and other limits); the LP requires Contracting Parties to either apply the LP to internal waters or adopt other effective permitting and regulatory measures for internal waters (LP Article 7).

Box 4
Categorization of the marine geoengineering approach (for a proposed activity and/or a generic technique)

Broad-scale approach to marine geoengineering - AM or CDR?

Sub class of approach? – e.g. BECCS within CDR

Environment to be altered? – land /ocean/ atmosphere/ all

Type of perturbation? Physical/chemical/biological/ecological/all

Direct positive and negative effects of perturbation? – e.g. OF CO_2 removal, influence on ocean ecology

Consideration of indirect positive and negative effects of perturbation/ – e.g. ocean pipes – altered ecology, deoxygenation

Discrete /Continuous? D/C?

Stratum to be altered? (surface ocean/deep ocean /all ocean/ stratosphere/ all strata)

Region(s) to be altered in full marine geoengineering deployment? S. Ocean/Pacific/coastal ocean/polar stratosphere/ troposphere/ marine boundary layer/terrestrial biosphere.?

Due Diligence

Consideration of side effects? y/n

Consideration of costs/budget model (for the planned activity) y/n

Pilot study? y/n

Consideration of upscaling? y/n

Modelling simulations (implemented/planned)? y/n

Direct monetary costs (such as implementation of the technology)?

Indirect monetary costs (such as monitoring by the advocate or governance agency)?

Efficiency in units of radiative flux or C removed per $$ outlay?

Anticipated co-benefits? E.g. OIF enhanced fisheries

It is envisioned that additional modules of queries would be required, and that each question would need to be carefully vetted and checked for inherent biases. However, the relative simplicity of the answers – a phrase, or Yes/No might help to stimulate and guide a stepwise collation of the most relevant information.

6.5 Legitimization through holistic participation in governance frameworks

The main incentives for participation in governance may be the opportunity for wide-ranging scientific feedback to improve a proposed technique, and perhaps to a larger extent the legitimization of an approach, for further tests, following approval by an internationally-recognized regulatory body. Such approval should streamline the acceptance of further research into the proposed methodology, which is not the case for other unconstrained approaches that have taken place in the ocean such as the Haida Gwaii iron release in 2012 (Tollefson, 2012).

Another means to enhance the acceptance of an approach through a process such as the OFAF is to bring a portfolio of evidence based on prior experiments of a smaller scale than that of the often-proposed initial unconstrained field trial (see the example from Chile, (Tollefson, 2017)). An example of such a gradualist approach to robustly and sequentially testing technology is presented in Figure 4.1 which illustrates the time-line developed by researchers studying the role of iron supply in the ocean carbon cycle. Such a stepwise construction of a knowledge base could be used to build confidence in an emerging marine geoengineering approach. Much research could already be undertaken under existing legislation (such laboratory safety or biosecurity codes of conduct, see Figure 4.1) and has the potential to advance knowledge in approaches such as marine cloud brightening.

A third way of garnering acceptance of a marine geoengineering approach is to include and weigh up its environmental, economic and societal benefits in the governance evaluation. Note that recital paragraph 21 of the UNFCCC emphasises the need for responses to climate change to be coordinated with social and economic development in an integrated manner with a view to avoiding adverse impacts on such development (see section 8.1.2 below). This indicates the need for the WG to include wider societal issues in any future work.

7 TOWARDS A HOLISTIC APPROACH TO ASSESSING MARINE GEOENGINEERING

Section 3.5 described the need for a holistic assessment to assessing marine geoengineering and this section deals with how we could address a holistic assessment to assessing marine geoengineering.

7.1 Introduction

Assessment and hence governance of geoengineering approaches needs to include many different facets such as natural and social sciences, ethics and geopolitics as well as legal aspects. Initially, the assessment will primarily be driven by available information from science and technology and can be evaluated in the context of fundamental legal, geo-political, economic, and wider societal concerns. More sophisticated, multi-faceted and adaptive assessment and governance requires the development of additional knowledge within each discipline, and thus an evolving governance that is broadly based and informed.

As the body of information on each topic increases – for example for the scientific, or the technological component(s) - then the manner in which an individual topic intersects with other disciplines will change. The dynamic nature of the flow of information, and hence the need for adaptive assessment, is illustrated with the example from the 'ocean pipes' concept put forward by Lovelock and Rapley (2007). They proposed that the nutrient-rich upwelled water from ocean pipes could result in phytoplankton blooms and consequent drawdown of carbon and altered cloud reflectance (from Dimethyl Sulphide).

When first proposed, the underlying science for the ocean pipes concept (Karl and Letelier, 2008; Maruyama et al., 2011 and 2004) appeared not to raise issues that might concern social licence. The subsequent testing of this technology raised issues (catastrophic pump failure in one case - White et al., 2010) as to its feasibility, but again there was no indication of wider societal concerns. The modelling experiment of Keller *et al.* (2014), that embedded many ocean pipes into a global biogeochemical model simulation, revealed an unanticipated side-effect of such a large-scale application of this approach. They reported partial deoxygenation of the upper ocean across much of the Pacific basin, and such an outcome would have knock-on effects for ocean health and marine food security that would raise issues of the social licence of this proposed geoengineering approach.

The WG membership comprises both natural and social scientists, and the former have concluded that there are insufficient details available about even the best resolved marine geoengineering approach to permit a robust scientific assessment. Without this assessment how can a multi-faceted appraisal that includes economics, ethics, (geo)-politics and other societal issues evolve? In this section, the principles underlying, economics, politics and the interface between science and policy are explored, in an initial attempt to consider how such a holistic appraisal can be developed in the second phase of the WG. Clearly, one facet cannot advance without the other if marine geoengineering approaches are to be both grounded on strong underpinning science, and explored, and potentially developed, in a manner that is useful and acceptable to society.

7.2 Summary of prior studies into other aspects of geoengineering

The Royal Society report in 2009 addressed ethics, governance and economics (Royal Society, 2009). However, an extensive literature on ethics and governance has developed since that report was published (Williamson and Bodle, 2016). Likewise, there is an emerging literature in economics that has remained largely conceptual probably due to the uncertainties about most of the geoengineering techniques (Heutel *et al.,* 2016; Klepper and Rickels, 2012). Chapter 6 of the CBD report produced in 2012 (Williamson *e al.,* 2012) covered social, economic, cultural and ethical considerations in relation to biodiversity. The National Academy of Sciences report 'Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration' (National Research Council, 2015a) has a short chapter titled 'Social Context' that covers legal, ethical, political, social and economic issues but does not go into any detail. The EuTRACE report (Schäfer et al., 2015) had a section titled 'Emerging Social Issues' that addressed both perceptions of potential effects of research and deployment and societal issues around potential deployment. The former covered moral hazard, environmental responsibility, public awareness and perception and participation and consultation. The latter covered political dimensions, economic analysis and the distribution of benefits and costs.

The 2016 update on the 2012 CBD report (Williamson and Bodle, 2016) includes a chapter on socioeconomic and cultural considerations relating to climate geoengineering as it affects biodiversity. They stated that despite that apparent wealth of information and analyses, there would seem to be significant gaps in understanding and knowledge:

1 Much of social science research has been directed towards considerations of AM methods in particular, issues associated with stratospheric aerosol injection. The governance of marine cloud brightening (MCB) does not seem to have been explicitly addressed, and when CDR is given attention, it is near-exclusively in terms of ocean fertilization;

2 Nearly all social science publications on climate geoengineering, including analyses of public perceptions and governance, have been authored by researchers in the USA and Europe. As a result, existing information may inadvertently include cultural biases regarding decision-making procedures, management strategies and knowledge;

3 The economic analyses of geoengineering have mostly been relatively simplistic, with main focus on operational costs, rather than environmental or social costs ('external' costs), or price effects. The global distribution of benefits, burdens and risks is not only of

crucial importance for climate change, but how climate change is addressed; and

4 While there is an increasing trend towards multidisciplinary and transdisciplinary programmes on climate geoengineering (that are now beginning to deliver more integrated analyses), there would seem scope for closer connections between social science and natural science studies, with the aim of developing a fully transdisciplinary approach to problem-solving.

Further to the 3rd bullet above, it should be noted that the economic analyses of geoengineering have mostly focused on AM techniques and there are a number of papers considering the externalities (i.e., economic side-effects not fully captured in costings). For example, the paper by Barrett (2008) and the analysis in (Dubner & Levitt (2005) do focus on magnitude of the direct costs, as does the paper with engineering estimates of AM delivery mechanisms by McClellan et al., (2012). Note that Barrett quoted a direct cost of $8 billion per year to offset all greenhouse gas emissions using stratospheric aerosols. Also, the work by Bickel and Agrawal (2013), Emmerling and Tavoni (2013), Goes *et al.* (2011), Moreno-Cruz and Keith (2013) and follow-ups already include explicit consideration of externalities. At the same time, much of the technological specifics of geoengineering interventions are unclear, preventing a meaningful determination of welfare endpoints. More recently, Harding and Moreno-Cruz (2016) documented the evolution of economic thinking around AM techniques and suggested areas for further research.

There is a need to develop each of the strands of research on geoengineering concurrently – research governance/code of conduct; means to collate sufficient info about each technique to provide a scientific assessment; debate about how such an assessment brings in additional metrics from ethics, economics, (geo) politics, the law. The advancement of a comprehensive scientific assessment methodology of geoengineering is an essential parallel development to that of the ongoing evolution of research governance. Together, they can ensure that any future multi-faceted exploration of the merits and challenges of a range of geoengineering approaches is built on a firm foundation.

In the absence of sufficient detail on any marine geoengineering approach to even begin to develop societally-relevant metrics, much can be learnt about how the early scientific rankings across a range of geoengineering approaches were developed (Boyd, 2008b; Royal Society, 2009). In each case the underlying principles of how the Earth System functions were applied to these qualitative or at best semi-quantitative approaches. For example, distinct differences in the residence time of materials in the upper atmosphere (years) versus the ocean (centuries) provided a point of demarcation to reveal differences between potential AM and CDR techniques (Boyd, 2008b; Royal Society, 2009). Can this approach be applied for metrics needed from the social sciences/humanities that are needed for a holistic approach to marine geoengineering? For example, what has been learnt from other large scale (e.g. UV and the ozone hole) and/or new technologies with wider societal implications (GE food; AI; nanotech) Also, the broader outcomes of the Pinatubo eruption can also be placed into a wider societal context, such as the geopolitical implications (Boyd, 2016); this event has been used previously to illustrate the efficacy of a point-source (natural) perturbation on stratospheric cooling of the atmosphere globally (Crutzen, 2006). Oschlies *et al.* (2017) pointed out that there has been little dedicated effort to identifying specific indicators and metrics for assessing climate engineering. They proposed "that such an effort should be facilitated by a more decision-oriented approach and an iterative procedure in close interaction between academia, decision makers, and stakeholders. Specifically, synergies and trade-offs between social objectives reflected by individual indicators, as well as decision-relevant uncertainties should be considered in the development of metrics, so that society can take informed decisions about climate policy measures under the impression of the options available, their likely effects and side effects, and the quality of the underlying knowledge base".

7.3 Geoengineering: geopolitical considerations and belief systems

Given the limited information available on the potential environmental and socio-political implications of marine geoengineering proposals, it is not possible to undertake a holistic appraisal of the potential geopolitical implications of the approaches. Various marine geoengineering approaches will have both positive and negative socio-political effects. Some initial thoughts on which potential (real or perceived) negative socio-economic impacts of marine geoengineering techniques could lead to political risks. include:

1 (Real or perceived) damage to economically and/or culturally significant marine species and environments (i.e. fish stocks, reefs, macroalgal 'reefs'); and

2 (Real or perceived) effects on food security caused by altered biodiversity, altered weather patterns and competition for ocean use.

If these types of negative socio-economic impacts are constrained within national jurisdictions, there would be domestic political risks, including potential public backlash due to real or perceived damage to environment, health, welfare, income, NIMBY (Not In My Back Yard) effects, political division among parties and constituencies in support of the geoengineering testing/deployment versus those opposed to it, protests, etc.

Generating domestic political hypotheses for a given marine geoengineering measure with localized effects would require the application of theories of public perception of risk and domestic political preference formation.

If the negative socio-economic impacts of a given marine geoengineering measure are transboundary, there would be international geopolitical risks, including the potential for mis-attribution of transboundary effects, geopolitical tensions, potential countermeasures, sanctions. However, in all cases, decision-making based on such impacts and responses should also be balanced by consideration of climate, environmental, socio-economic and geopolitical benefits offered by a proposed geoengineering activity.

Understanding what may lead to conflictual or cooperative international geopolitical behaviour in the case of marine geoengineering testing or deployment would require the selection of a set of plausible deploying and non-deploying states and the application of international relations theories to categorize political preferences which could influence these states' geopolitical decision-making behaviour.

To formulate such hypotheses as to what sorts of international geopolitical dynamics may develop as a result of marine geoengineering testing or deployment with (real or perceived) transboundary effects, it would be necessary to know:

1 The type, scale and duration of the transboundary effects (positive and negative) of a given marine geoengineering test or deployment (and to what extent these are detectable/attributable);

2 Which states are testing/deploying a given marine geoengineering technique;

3 Which non-testing/deploying states are likely to be affected by (real or perceived) transboundary effects; and

4 What the political relationship between the deploying and non-deploying states is like (relative power relations, domestic societal preferences, shared norms etc.)

Once there is information about these points, it is possible to formulate such hypotheses as to what sorts of international geopolitical dynamics may develop as a result of specific marine geoengineering testing or deployment approaches. This information also helps us to point out where a more detailed assessment is needed.

7.4 Welfare endpoints and the economics of geoengineering

A holistic approach to geoengineering is needed to address socio-economic, political issues. We considered environmental economics aspects of geoengineering that emphasize the welfare benefits and the welfare costs of a geoengineering measure. It is clear that the criteria that define these welfare impacts have significant bearing on the relative assessment of different interventions and, by implication, on the decision whether or not to deploy a particular geoengineering technique.

A framework for assessing geoengineering technologies needs to include cost benefit analysis in the broadest sense (c.f. (Williamson and Bodle, 2016; Williamson *et al.,* 2012)). Such expanded monetary, environmental and societal economic considerations offer powerful methodologies that are used to structure the process of decision-making about public interventions, to provide conceptual and procedural rigor, and to help rank policy options. Do we want to include economic assessment methods? If so, this could mean employing tools from cost-benefit analysis such as the selection and quantification of welfare endpoints. Welfare endpoints are designated real-world outcomes (such as mortality or labour productivity) whose significance derives from their direct relevance for human wellbeing. Through valuation methods, physical changes in these outcomes are convertible into income-equivalent changes, that is, into a monetary metric. Such an analysis would include a welfare assessment of changes in mortality and morbidity due to a geoengineering intervention and could also include effects on marine commerce and shipping, the fishing industry, marine ecosystem services, tourism, etc. There is a wide range of things that have been assessed previously that could be included in such a welfare endpoint analysis. Thus, the WG could consider which welfare endpoint changes would be potentially large or small, and if net positive or negative. This analysis will need to be technology- and region-specific when assessing economic impacts.

The WG aspires to a holistic approach – including socio-political and regional and intergenerational economic aspects. Therefore, it will seek input from a range of additional social scientists. This strategy will help to frame the work of the WG in a way that is both scientifically and socially relevant.

In order to make progress, we need a parallel effort starting from welfare endpoints that develops an assessment framework of welfare impacts, drivers, and the sensitivity of welfare impacts to changes in those drivers that are influenced by those geoengineering approaches under consideration by the WG. We also need to be very clear on interdisciplinary terminology to avoid miscommunication. These socio-political/economic concepts need to be introduced in this report.

7.5 Navigating the science-policy boundary

There is a growing need for more specialists to sit within the boundary between scientists and policy makers. Although there are policy advisors, such as in the LP process, already effectively operating in this boundary there are not nearly enough for us to improve upon existing networks. A presentation ‘Navigating the science-policy boundary for effective international geoengineering assessment’ given at the second meeting of the WG provided the WG with insights into this topic.

The key points were about the main aim of sustainability science - how is the production of knowledge related to its use by decision-makers? Such an approach focuses on understanding complex, coupled systems involving stakeholders, climate and ecological science and policy structures. In cases were boundary organizations exist, and help to span science-policy boundaries, the production of policy-relevant/useful knowledge is more effective. From these examples, the key attributes of knowledge produced that enable decision makers to use it are:

- *Credibility:* Arguments are trustworthy and expert-based;
- *Salience:* Relevance of scientific knowledge to needs of decision makers; and
- *Legitimacy:* Knowledge is produced in an unbiased way that fairly considers stake holders’ different points of view.

It was considered that the GESAMP WG 41 could be defined as a boundary organization, and that WG 41 outputs should ideally conform to the criteria listed above. The issue of involving proposers of marine geoengineering approaches and other stakeholders was discussed as well as the question of how do we get proposers involved? Do we ‘dangle the carrot’ of legitimization through participation in governance frameworks?

7.6 Inclusion of broader issues within the assessment framework

The inclusion of broader issues, such as environmental economics and geopolitics, would strengthen our ability to provide a framework for a comprehensive assessment (and hence a more holistic appraisal) of all marine geoengineering technologies based on the information available. In the interim, we can do a high-level assessment that highlights where there are knowledge gaps that need to be bridged before a comprehensive assessment can be undertaken. In the subsequent phase of this WG, must seek to develop better ways to obtain the knowledge needed to fill the gaps in the science that have been identified. Additionally, WG 41 must include knowledge on the social components and the identification and demarcation of the topics that require the most pressing attention. This appraisal will permit identification of where in particular more detailed assessments are needed, and if there are any examples from other emerging technologies (nanotechnology, GM foods, Artificial Intelligence, biotechnology) in which progress such as the development of bio-ethics has been made in the broader assessment towards seeking social licence to conduct these novel activities.

8 GOVERNANCE OF MARINE GEOENGINEERING

There has been a voluminous literature published on the governance of geoengineering per se, particularly over the last decade, that is not addressed here. This section briefly discusses the main existing governance provisions for marine geoengineering, in particular on research, that are a subset of the wider geoengineering governance issues, but which have some different specific components. The governance provisions covered here are those of the existing international law, non-binding principles/codes of practice, and governance requirements beyond geoengineering. This section does not cover discussion of concepts for potential models of marine geoengineering governance that could be adopted in future. In addition, the distinctions between geoengineering research and deployment are relevant for governance and are indicative of the need for two modes of governance, one dedicated to research, and another for deployment.

A comprehensive coverage of all international law provisions that might be relevant to marine geoengineering has not been attempted. For example, there is no discussion of the Madrid Protocol to the Antarctic Treaty, the Espoo Convention, the Aarhus Convention or the ENMOD Convention. The purpose of this section is to make readers aware of the most important governance provisions but not to analyse them. Readers are referred to the publications of Reynolds (2018), Scott (2013 and 2015), Redgwell (2011) and Ginsky (2018) for more detailed descriptions of international law related to geoengineering.

Before any implementation of geoengineering can take place, research is required, and a desirable precursor of any field-based research (i.e., at greater scales than can be conducted in laboratories) is a governance framework. There are parallels for such research frameworks such as for weather modification; the techniques are different, but the governance implications can be similar, for example, attribution of cause and effect, and public perception.

8.1 International law

In the context of marine geoengineering the following rules and regimes appear to be the most relevant ones:

Customary international law,

- The UN Framework Convention on Climate Change (UNFCCC)[52],
- The Paris Agreement 2015[53],
- The United Nations Convention on the Law of the Sea (UNCLOS)[54],
- The 1996 London Protocol[55], and
- The Convention on Biodiversity (CBD)[56].

8.1.1 *Customary International Law*

Armeni and Redgwell (2015) reviewed the international legal and regulatory issues of climate geoengineering governance in relation to customary international law and stated:

> “State practice has given rise to a number of customary law principles of general application, the most significant of which is the so-called ‘no harm’ principle. According to this principle, States have a duty to prevent, reduce, and control pollution and significant transboundary environmental harm arising from activities within their territory, jurisdiction or control. This principle has been enunciated in soft law declarations, endorsed inter alia by the General Assembly, the International Law Commission (ILC) and in various multilateral environmental agreements, and in judicial decisions Thus, for example, in the Pulp Mills case, which involved the siting of a pulp mill on a shared watercourse, the River Uruguay,

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[52] https://unfccc.int/

[53] https://unfccc.int/sites/default/files/english_paris_agreement.pdf

[54] http://www.un.org/Depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm

[55] http://www.imo.org/en/OurWork/Environment/LCLP/Documents/PROTOCOLAmended2006.pdf

[56] https://www.cbd.int/

> the ICJ observed that '[a] State is … obliged to use all the means at its disposal in order to avoid activities which take place in its territory, or in any area under its jurisdiction, causing significant damage to the environment of another State'. This obligation not to cause significant harm has achieved widespread recognition, particularly (though not exclusively) in the contexts of shared resources and of hazardous activities. Shared resources are not a settled category; it has already been noted above that the legal status of the atmosphere is unsettled, and that this is only one of the competing concepts which might be applied. Similarly, it is unclear which if any geoengineering activity would constitute a 'hazardous activity' for the purposes of the application of this customary norm; but as noted this is not the sine qua non for the application of the no harm principle, with its emphasis on significant harm.".

and

> "State practice further supports the customary law obligation to consult and to notify of potential transboundary harm, particularly where there are shared resources or hazardous activities being carried out, and the requirement to conduct a prior transboundary environmental impact assessment (EIA). In the Pulp Mills case, the ICJ found the requirement to conduct a transboundary EIA to be a distinct and freestanding obligation in international law where significant transboundary harm is threatened."

A more detailed analysis on the duty to conduct a transboundary EIA can be found in Craik (2015).

Since Armeni and Redgwell wrote this analysis of customary international law in 2015, the ICJ has handed down a new decision on this rule in the "Certain Activities case" between Costa Rica and Nicaragua. This judgement further developed the no-harm rule from the previous decision in the Pulp Mills case, in particular procedural obligations to conduct a transboundary EIA and the duty to notify and consult. The ICJ also recognised a new preliminary obligation to ascertain risk. This comes before the duty to conduct an EIA; for more information see Brent (2017) and Brent *et al.* (2015).

The prevention of transboundary harm under customary international law includes harm to the high seas and other areas beyond national jurisdiction - see Brent *et al.* (2015), ILC (2001)[57], Reichwein *et al.* (2015), Reynolds (2018) and Saxler *et al.* (2015) for further details.

8.1.2 *The United Nations Framework Convention on Climate Change (UNFCCC)*

The UNFCCC was adopted in 1992 and subsequently adopted the Kyoto Protocol in 1997. Since then, the Parties to the UNFCCC adopted the Paris Agreement in 2015 – see below. The UNFCCC sets an overall framework for intergovernmental efforts to tackle the challenge posed by climate change. It recognizes that the climate system is a shared resource whose stability can be affected by emissions of carbon dioxide and other greenhouse gases58. Particular points to note are:

- Recital 1 - "Acknowledging that change in the Earth's climate and its adverse effects are a common concern of humankind";
- Recital 4 "Aware of the role and importance in terrestrial and marine ecosystems of sinks and reservoirs of greenhouse gases";
- Recital 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."; and
- 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".

Without a free-standing convention on governing geoengineering, it seems very likely that the UNFCCC would play a very significant role in the global governance of geoengineering. However, what that role might be, is unclear at this time.

8.1.3 *The Paris Agreement 2015*

The Paris Agreement 2015 was adopted at the December 2015 meeting of the UNFCCC. The agreement's central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change. As indicated in section 1.4, it seems very unlikely that aims of the agreement can be achieved without a significant amount of purposeful/intentional carbon removal. Indeed, the IPCC RCP model simulations that likely played a key role in defining the

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[57] http://legal.un.org/ilc/texts/instruments/english/commentaries/9_7_2001.pdf

[58] https://unfccc.int/fr/node/15897

above temperature targets included carbon removal as represented by Bioenergy with Carbon Capture and Storage (BECCS) (Kato and Yamagata, 2014). See Reynolds (2018) for further discussion of geoengineering and the Paris Agreement.

Prior to the Paris meeting that adopted the 2015 Paris Agreement, nearly all countries submitted ‘intended national determined contributions’ to show their national strategies for addressing climate change. These become ‘National Determined Contributions’ (NDCs) when countries join the Paris Agreement and they have to be revised and updated every five years.

Craik and Burns (2016) analysed the individual provisions of the Paris Agreement to assess which elements of the agreement may influence future debates associated with ‘climate engineering’ options. Their key points of significance were:

- “The potential role of climate engineering under the Paris Agreement arises most directly from the agreement’s objectives themselves, which are likely achievable only with significant recourse to climate engineering. As currently modelled, achieving the 2°C limit is driven by a mixture of emission reductions and removals of CO_2 through CDR technologies;
- CDR technologies fall within the language of article 4, which include CO_2 removals, as part of the mitigation commitments expected from parties through their NDCs;
- Inclusion of CDR technologies by states in their NDCs will raise legal issues respecting technological readiness and equity implications of a balance between emission reductions and removals, which could, in turn, give rise to questions of the supplementarity of CDR approaches;
- The NDCs, which are largely at the discretion of States, provide little purchase for the regulation of CDR technologies. However, the eventual need to use market incentives to realize the development and scaled deployment of CDR technologies will likely require international cooperation to address the inclusion of CDR technologies in market mechanisms. The Paris Agreement institutions and procedural mechanisms, as well as the emphasis on capacity building, transparency and public consultation, provide a basis for future deliberations on the implementation of CDR technologies; and
- It is questionable whether legal regulation of SRM technologies, on the other hand, can be accommodated within the existing Paris framework. Nevertheless, the procedural mechanisms of the Paris Agreement have some potential to satisfy SRM research governance demands for transparency and public deliberation.”

Gallo *et al.* (2017) analysed the ocean-related commitments in 161 NDCs covering 188 nations and found that 70% of them included marine issues. The dominant concerns raised by governments were coastal impacts (95 NDCs), ocean warming impacts (77 NDCs), and fisheries impacts (72 NDCs). Gallo *et al.* (2017) stated “Some NDCs provided specific plans to address these impacts, whereas others include them more generally as adaptation needs. Mangrove conservation, restoration, and management plans are included in 45 NDCs, and are included in both mitigation and adaptation sections. Coral reefs are included in 28 NDCs but are typically included as adaptation components and “Blue carbon mitigation contributions were included in 27 NDCs, encompassing ocean carbon storage and the protection, replantation, or management of mangroves, salt marshes, sea grass beds, or other marine ecosystems”.

8.1.4 *The United Nations Convention on the Law of the Sea (UNCLOS)*

UNCLOS was originally adopted in 1982. Subsequently, an implementation agreement for part XI of UNCLOS dealing with deep-sea mining was adopted in 1994 and an agreement for the implementation of the provisions of UNCLOS relating to the conservation and management of straddling fish stocks and highly migratory fish stocks was adopted in 1995. UNCLOS incorporated much customary international law related to the maritime area at the time it was agreed.

Part XII of UNCLOS ‘Protection and Preservation of the Marine Environment’ covers the relevant environmental protection obligations under the Convention that apply to marine geoengineering activities. Particular points to note are:

- Article 94 Duties of the flag state – States have to exercise their jurisdiction and control over ships flying their flags;
- 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 include pollution from greenhouse gases and marine geoengineering activities;
- Article 195 that prohibits the transfer, directly or indirectly, damage or hazards fron one area to another or transform one type of pollution into another;
- Article 204(2) requires states to monitor the effects of activities which they permit to determine whether they are likely to cause pollution;
- Article 206 requires states to assess potential effects of activities they control if there are reasonable grounds for believing activities may cause pollution/harm; and

- Article 210(6) effectively requires compliance with the London Convention/Protocol with regard to dumping[59].

Part XIII of UNCLOS 'Marine Scientific Research' deals with marine scientific research. Particular points to note:

Article 238 The right to conduct marine scientific research.

- Article 240 General principles for the conduct of marine scientific research - in particular article 240(d) that, in concert with articles 94, 192 and 263, requires States to ensure that marine scientific research, whether conducted in or under their areas of jurisdiction or on the high seas, including by ships under their flag, complies with the marine environmental protection provisions of UNCLOS.
- Article 257 Marine scientific research in the water column beyond the exclusive economic zone – States and competent international organizations have the right to conduct marine scientific research in the water column beyond the limits of the exclusive economic zone.
- Article 263 Responsibility and liability – States and competent international organizations are responsible for ensuring that marine scientific research, whether undertaken by them or on their behalf, is conducted in accordance with the Convention.

The potential importance of UN negotiations for a new international agreement under UNCLOS on the conservation of marine biodiversity in areas beyond national jurisdiction must be recognised. The negotiations for this potential agreement commenced in September 2018 at UN Headquarters in New York[60].

8.1.5 *The London Convention 1972 and the London Protocol 1996*

The 'Convention on the Prevention of Marine Pollution by Dumping of Wastes or Other Matter, 1972 is a freestanding global instrument that was adopted on 29th December 1972 and came into force on 30th August 1975. The London Protocol 1996 was adopted on 7th November 1996 and came into force on 24th March 2006. Note, that it is not a conventional protocol to an international treaty as it will eventually replace the London Convention[61]. Until that time the two instruments operate in parallel, with the Protocol being the operative instrument where a State is party to both instruments – see LP article 23[62]. At the time the London Protocol was adopted, the Parties agreed that no further amendments would be made to the London Convention and that the London Protocol would be the focus of any future amendments.

The London Convention objectives are very similar to those for the London Protocol that are.

- "…the need to protect the marine environment and also to promote the sustainable use and conservation of marine resources" - first recital paragraph
- "Contracting Parties shall individually and collectively protect and preserve the marine environment from all sources of pollution and take effective measures, according to their scientific, technical and economic capabilities, to prevent, reduce and where practicable eliminate pollution caused by dumping or incineration at sea of wastes or other matter. Where appropriate, they shall harmonize their policies in this regard" - Article 2 Objectives.

Article 3.1 of the LP obliges Parties to "…apply a precautionary approach to environmental protection from dumping of wastes or other matter…" and that article will be amended to include "placement of matter for marine geoengineering activities which may be considered for permits according to annex 4" when the marine geoengineering amendments come into force. The precautionary approach does not feature in the London Convention since it was adopted before the emergence of the precautionary principle/approach. However, after the UN Conference on Environment and Development in Rio de Janeiro in 1992, the Convention Parties adopted a resolution in 1993 requiring them "… to be guided by a precautionary approach to environmental protection…" (LDC Resolution LDC.44(14) in document LDC 14/16[63]).

The Parties to the LC and the LP first discussed marine geoengineering issues in June 2007 at the meeting of the Scientific Groups when a proposed ocean fertilization experiment was on the agenda (Brahic, 2007). Subsequently the Contracting Parties to the London Convention and London Protocol (LC/LP) expressed concern about the marine environmental impacts of this proposed activity at their meeting in November 2007.

In 2008, the Parties adopted Resolution LC-LP.1(1) deciding ocean fertilization activities other than legitimate scientific research should be considered as contrary to the aims of both instruments. In 2010, by Resolution LC-LP.2(2) , the Parties adopted an Assessment Framework for Scientific Research Involving Ocean Fertilization (OFAF). However, whilst these Resolutions set out political commitments, neither were legally binding. However, in October 2013 the Parties to the London Protocol adopted amendments to regulate ocean fertilization activities by Resolution LP.4(8) and these amendments also enable

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[59] At their Seventeenth Consultative Meeting, held in 1994, the Contracting Parties expressed their opinion that States Parties to UNCLOS would be legally bound to adopt laws and regulations and take other measures to prevent, reduce and control pollution by dumping. In accordance with article 210(6) of UNCLOS, these laws and regulations must be no less effective than the global rules and standards contained in the London Convention. http://www.imo.org/en/OurWork/Legal/Documents/LEG%20MISC%208.pdf

[60] https://www.un.org/bbnj/

[61] http://www.imo.org/en/OurWork/Environment/LCLP/Documents/22780LDC%20Leaflet%20without%2040%20Anniv%20logo2012Web1.pdf

[62] http://www.imo.org/en/OurWork/Environment/LCLP/Documents/PROTOCOLAmended2006.pdf and http://www.imo.org/en/OurWork/Legal/Documents/LEG%20MISC%208.pdf

[63] http://www.imo.org/en/KnowledgeCentre/ReferencesAndArchives/IMO_Conferences_and_Meetings/London_Convention/LCandLDCReports/Documents/Report%20of%20LC%2016%20November%201993.pdf

the Parties to regulate other marine geoengineering activities within the scope of the Protocol, in future (IMO, 2013). These amendments will enter into for the Contracting Parties that have accepted it on the sixtieth day after two thirds of the Contracting Parties have deposited their instruments of acceptance. Currently, just 3 Parties have accepted the amendments, namely the UK, the Netherlands and Finland.

The 2013 marine geoengineering amendments to the London Protocol have been described in Box 1 in section 2.4 above. New Annex 5 in the amendments, the ‘Assessment Framework for Matter that may be Considered for Placement under Annex 4’ is a generic assessment framework which Parties must use before issuing permits covered by new Annex 4. Section 1.2 of Annex 5 states “The purpose of this Framework is… to be the basis for developing Specific Assessment Frameworks for placement activities listed in annex 4”. Currently, the London Protocol Parties have adopted one specific assessment framework, namely the OFAF. Additional specific assessment frameworks would be developed as required when the London Protocol Parties add additional marine geoengineering activities to new Annex 4 that permit, subject to assessment, that activity to take place in the marine environment.

Some forms of marine geoengineering could potentially be considered to be dumping under the existing LC/LP provisions. For example, the technique ‘Depositing crop wastes in the deep ocean’ (section 5.8 above) would appear to be covered by the existing category of wastes permitted for dumping “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 could be permitted, subject to satisfactory assessments. However, the existing guidance for this category of wastes would need to be reviewed to ensure it was appropriate for such disposals. Also, if an activity were deemed to be a placement activity that was contrary to the aims of the LC (Article III(1)(b)(ii)) or LP (Article 1.4.2.3), then it could be considered to be dumping under the existing LC/LP provisions.

8.1.6 *The Convention on Biodiversity (CBD)*

The CBD[64] was adopted at the UN Conference on Environment and Development in Rio de Janeiro and entered into force on 29 December 1993. It is a multilateral treaty with three main goals: the conservation of biological diversity; the sustainable use of its components; and the fair and equitable sharing of benefits arising from genetic resources.

The CBD’s guiding principle in Article 3 is a statement of states’ sovereign right to exploit their own natural resources and their responsibility to prevent transboundary harm. The CBD notes the precautionary principle/approach in recital 9 but without referring to that term. Among other things, Article 14 says Contracting Parties, as far as possible and as appropriate, are to introduce environmental impact assessment procedures of proposed projects that are likely to have significant adverse effects on biological diversity with a view to avoiding or minimizing such effects and in the case of likely significant transboundary impacts, are to promote notification, exchange of information, and consultation.

The most important CDB decisions related to geoengineering were taken at the 9th and 10th meetings of the Conference of the Parties. The CBD first addressed the subject of geoengineering at the 9th Conference of Parties in 2008 when it adopted decision IX/16 C on ocean fertilisation[65] that stated in paragraph 4:

> “Bearing in mind the ongoing scientific and legal analysis occurring under the auspices of the London Convention (1972) and the 1996 London Protocol, requests Parties and urges other Governments, in accordance with the precautionary approach, 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. Such studies should only be authorized if justified by the need to gather specific scientific data and should also be subject to a thorough prior assessment of the potential impacts of the research studies on the marine environment, and be strictly controlled, and not be used for generating and selling carbon offsets or any other commercial purposes.”

Then at the 10th Conference of Parties in 2010 it adopted decision X/33(8)(w) and (x)[66]:

> “The Conference of the Parties
>
> 8. Invites Parties and other Governments, according to national circumstances and priorities, as well as relevant organizations and processes, to consider the guidance below on ways to conserve, sustainably use and restore biodiversity and ecosystem services while contributing to climate change mitigation and adaptation:
>
> Assessing the impacts of climate change on biodiversity
>
> (w) Ensure, in line and consistent with decision IX/16 C, on ocean fertilization and biodiversity and climate change, in the absence of science based, global, transparent and effective control and regulatory mechanisms for geo-engineering, and in accordance with the precautionary approach and Article 14 of the Convention, 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, with the exception of small scale scientific research studies that would be conducted in a controlled setting in accordance with Article 3 of the Convention, and only if they are justified by the need to gather specific scientific data

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[64] https://www.cbd.int/convention/text/

[65] https://www.cbd.int/decisions/?id=11659

[66] https://www.cbd.int/decisions/?id=12299

and are subject to a thorough prior assessment of the potential impacts on the environment;

> * Footnote reads “Without prejudice to future deliberations on the definition of geo-engineering activities, understanding that any technologies that deliberately reduce solar insolation or increase carbon sequestration from the atmosphere on a large scale that may affect biodiversity (excluding carbon capture and storage from fossil fuels when it captures carbon dioxide before it is released into the atmosphere) should be considered as forms of geo-engineering which are relevant to the Convention on Biological Diversity until a more precise definition can be developed. It is noted that solar insolation is defined as a measure of solar radiation energy received on a given surface area in a given hour and that carbon sequestration is defined as the process of increasing the carbon content of a reservoir/pool other than the atmosphere.

(x) Make sure that ocean fertilization activities are addressed in accordance with decision IX/16 C, acknowledging the work of the London Convention/ London Protocol”

Note that the reference to Article 14 in Decision X/33(8)(w) means that the decision is limited to activities that are likely to have ‘significant adverse effects on biological diversity’.

Subsequently, the COPs XI and XIII reaffirmed the above decisions[67]. COP XIII also noted in Decision XIII/14 paragraph 5 that “…more transdisciplinary research and sharing of knowledge among appropriate institutions is needed in order to better understand the impacts of climate-related geoengineering on biodiversity and ecosystem functions and services, socio-economic, cultural and ethical issues and regulatory options”.

Williamson *et al.* (2012a) refined the definition of geoengineering to “a deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change”. They also provided a summary of selected definitions in Annex I of the report and additional information on options for definitions of climate-related geoengineering in Annex II of the report. Williamson and Bodle (2016) also discussed issues relating to the definition of climate-related geoengineering in Annex I of their report.

Note that the decisions of the CBD are not legally binding as is clear from the language at the beginning of each decisions e.g. “…requests Parties and urges other Governments... “ and “.Invites Parties and other Governments…”. Some such as the ETC Group[68] view the CBD decisions as a de facto moratorium on deployment and on most forms of research into ocean fertilization and other forms of geoengineering, in the absence of science-based, global, transparent and effective control and regulatory mechanisms for geoengineering“. However, others do not view the CBD decisions as a moratorium e.g. Galaz (2011), Horton (2010), Reynolds *et al.* (2016) and Sugiyama and Sugiyama (2010).

8.2 Non-binding principles/codes of conduct

Non-binding principles or codes of conduct can be useful if they are widely adopted by those working in area concerned e.g. the Asilomar guidelines for recombinant DNA[69]. They can be adopted quickly but they have issues of trust, transparency, control and enforcement. Those relevant to geoengineering include the ‘Precautionary Principle/Approach’, ‘Oxford Principles, the ‘Asilomar Guidelines and the Code of Conduct developed by the Geoengineering Research Governance’ (GRGP) project. While the first two cover all geoengineering activities, the latter is aimed specifically at geoengineering research activities.

8.2.1 *The Precautionary Principle/Approach*

The precautionary principle/approach underpins many international agreements (including the LC and the LP – see section 8.1.5 above) and is considered by some international law scholars to be an emerging principle of customary international law. There is a very large literature about the precautionary principle/approach which we do not attempt to address. However, there is a paper by Elliott (2010) specifically about the precautionary principle and geoengineering. He explores the extent to which the precautionary principle can provide guidance for responding to the potential benefits and hazards associated with geoengineering. He argues that it is possible to identify a set of lessons that are common across many different applications of the precautionary principle that can be applied when considering geoengineering proposals.

8.2.2 *The Oxford Principles*

Following publication of the Royal Society report, an ad-hoc group of academics, including two members of the Royal Society Working Group, submitted a list of five high-level principles for governance of research, development, and any eventual deployment of geoengineering technologies to the UK House of Commons Select Committee on Science and Technology in 2009. The Committee had initiated an inquiry into how geoengineering should be governed. They subsequently became known as the ‘Oxford Principles’ and are:

Principle 1: Geoengineering to be regulated as a public good.

Principle 2: Public participation in geoengineering decision-making.

Principle 3: Disclosure of geoengineering research and open publication of results.

Principle 4: Independent assessment of impacts.

Principle 5: Governance before deployment.

See Rayner *et al.* (2013) and Heyward *et al.* (2017) for further details about the Oxford Principles.

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[67] https://www.cbd.int/decisions/?id=13181 and https://www.cbd.int/doc/decisions/cop-13/cop-13-dec-14-en.pdf

[68] http://www.etcgroup.org/content/news-release-geoengineering-moratorium-un-ministerial-japan

[69] https://en.wikipedia.org/wiki/Asilomar_Conference_on_Recombinant_DNA

8.2.3 *The Asilomar Principles*

The Asilomar International Conference on Climate Intervention Technologies was held at the Asilomar Conference Center in California from March 22 to 26, 2010. Among other issues, the conference discussed the Oxford Principles. To promote the responsible conduct of research on climate engineering, recommendations were made to adopt 5 principles[70] that were very similar to the Oxford Principles.

8.2.4 *The code of conduct developed by the Geoengineering Research Governance (GRGP) project*

In January 2016 the 'Geoengineering Research Governance' (GRGP) project was launched by the University of Calgary, the Institute of Advanced Sustainability Studies (IASS), Potsdam and the Institute for Science Innovation and Society (InSIS), Oxford University. This project followed on from the initial development of the Code of Conduct at the IASS (Hubert and Reichwein, 2015).

The Code of Conduct aimed to provide practical guidance on the responsible conduct of geoengineering research. It was designed as a voluntary instrument, though one that was based upon existing legal sources, including general principles, rules of customary international law, treaty-based rules, regulations, international decisions, and policy documents. The guidance in the Code of Conduct was global in scope, and was directed at various State, sub-State and non-State actors involved in the development of regulatory and governance frameworks for geoengineering and their implementation. In particular, GRGP aspired to provide a flexible governance framework. The project commenced at Oxford in February 2016 and continued until December 2017.

The project involved: 1) Interviewing experts to elicit their opinions on the need for and potential effectiveness of such a Code of Conduct; 2) Expert peer review of the Code by legal scholars; 3) An online call for comments on the Code; and 4) A stakeholder workshop to test the application of the Code of Conduct under different scenarios. The workshop was held in June 2017 to clarify and promote a deeper understanding of issues related to the regulation and governance of geoengineering science and innovation through cross-disciplinary exchange. The workshop included 42 experts from around the globe, including academics from different disciplines, international and national policy experts, and members of civil society. Overall, the goal was to evaluate the adequacy of existing regimes and doctrines relevant to geoengineering research and innovation, and to explore options for new regulatory and governance approaches in this space. In October 2017, an updated version of the draft code of conduct which incorporated the insights from these transdisciplinary engagement activities was released[71].

8.2.5 *The Carnegie Climate Geoengineering Governance Initiative (C2G2)*[72]

In early 2017 the Carnegie Climate Geoengineering Governance Initiative (C2G2) was launched[73]. It "… seeks to catalyze the creation of effective governance for climate geoengineering technologies by shifting the conversation from the scientific and research community to the global policy-making arena, and by encouraging a broader, society-wide discussion about the risks, potential benefits, ethical and governance challenges raised by climate geoengineering".

The executive director of the C2G2, Janos Pasztor provided an outline of its guiding principles and future plans at the April 2017 WG meeting. He stated that its principles included a neutral stance on geoengineering (along with the assertion that the main priority should be emissions reduction) and that such impartiality was be needed to fill the large gap in governance that currently exists for both SRM and CDR, both of which C2G2 will focus on. He also stated that with the exceptions of the LC/LP and the UN CBD, there is little discussion on geoengineering taking place related to the policy sphere. He said that the UNFCCC Paris Agreement goals of 2 °C and 1.5 °C means that society cannot responsibly ignore the potential of geoengineering technologies to achieve the 'negative emissions' needed to restrict warming to 2 °C or less. Key goals of C2G2 were stated to include:

1 Foster and enable dialogues in the policy sphere, intergovernmental sphere, among non-state actors, private sector representatives, civil society actors etc;

2 Encourage policy decisions about these issues at the intergovernmental and/or national level through stimulation of dialogue between policymakers regarding decision-making on geoengineering research and development;

3 C2G2 will have a range of outputs: Assessment reports, Codes of Conducts etc.; and

4 Most importantly, C2G2 will develop a network of people in different organizations who are aware of these issues and able to encourage discussion within their organizations, push for policy-relevant decisions.

C2G2 released a summary and full document outlining their updated approach in March 2018[74]. Subsequently, C2G2 released a report 'Carbon Removal and Solar Geoengineering: Potential implications for delivery of the Sustainable Development Goals'[75] in May 2018 and a Technical Briefing Paper on 'Knowledge gaps on climate-related geoengineering in relation to the Convention on Biological Diversity (CBD)'76 in July 2018.

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[70] http://climate.org/archive/resources/climate-archives/conferences/asilomar/report.html

[71] https://ce-conference.org/system/files/documents/revised_code_of_conduct_for_geoengineering_research_2017.pdf

[72] https://www.c2g2.net/

[73] https://www.c2g2.net/

[74] https://www.c2g2.net/wp-content/uploads/C2G2-Our-Approach-Summary.pdf and https://www.c2g2.net/wp-content/uploads/20180323-C2G2-Approach.pdf. – recent c2g2 docs

[75] https://www.c2g2.net/geoeng-sdgs/

[76] https://www.c2g2.net/wp-content/uploads/20180704-C2G2-CBD-ResGaps.pdf

8.3 Governance requirements for marine geoengineering beyond climate mitigation

The LP marine geoengineering amendments described in section 2 above are not limited to activities for climate mitigation, as is clear from the LP definition of marine geoengineering (see Box 1 above). In addition to a diverse range of CDR and SRM techniques (see National Research Council 2015a, 2015b), a number of other approaches are emerging that will also require research governance. Such marine approaches could include ocean fertilisation for fish stock enhancement (Tollefson, 2017), and also the proposed development of so-called hybrid techniques (i.e. combined CDR and SRM, land and ocean, or biotic and abiotic methods or approaches) that combine other benefits in addition to CDR. Examples include ecological approaches –that could potentially combine biofuel production (macroalgae), fish farming, and nutrient removal (macroalgae).

It needs to be clearly understood that marine geoengineering activities beyond climate mitigation, including marine scientific research (Verlaan, 2007), are required to meet all existing customary and treaty obligations related to the protection of the marine environment described above, whether they take place in areas under or beyond national jurisdiction - see section 8.1.4 above.

At present the LP marine geoengineering amendment excludes normal fisheries activities such as aquaculture but large-scale fish stock enhancement (using purposeful nutrient enrichment) may fall under the marine geoengineering amendment, if its effects are likely to be large scale, long-lasting and severe. Hence, it is essential from the start to clarify the purpose of a technique. These other approaches, to enhance marine resources, have the potential to be used to circumvent the LC/LP by interested parties conducting trials of approaches which are akin to marine geoengineering but are not classified as such. In this context it should be recognised that national parties can take more stringent measures within their own jurisdictions than those agreed by the LC/LP; as long as they do not contravene the LC/LP. Under UNCLOS Article 94, States are required to effectively exercise jurisdiction and control over ships flying their flag, even if they are operating outside national waters.

Parties that have ratified/acceded to an international treaty or amendments to one, usually accept that they are bound by its provisions even before it has entered into force. In the case of the LP, this would currently apply to the UK, Netherlands and Finland. While the 2013 LP amendments have yet to enter into force, the Parties to the LC and the LP should still comply with the non-binding decisions regarding ocean fertilization made by the Parties to those agreements – see section 8.1.5 above. Other types of marine geoengineering activities are obviously not affected by those decisions but still could fall within LC or LP controls if they were deemed to be a dumping activity (see 8.1.5 above) or if they were deemed to be a placement activity that was contrary to the aims of the LC (Article III(1)(b)(ii)) or LP (Article 1.4.2.3).

The term ‘entry-point’ refers to the locale at which initial studies or trials are conducted into marine geoengineering and analogous modification of the ocean including fisheries enhancement. There is a danger that the coastal ocean may become viewed as a suitable entry-point since it can potentially be seen to be a way to avoid international legislation such as the LP/LC for activities such as fisheries enhancement (Tollefson, 2017) or pipelines (CO_2 oceanic disposal). This potential trend requires examination of other governance arrangements for the coastal ocean, under national jurisdictions), or UNCLOS. In the case of the LC, ‘internal waters’[77] are not covered by the Convention, but in the case of the LP, states either have to include ‘internal waters’ under the LP or provide equivalent controls. However, UNCLOS has nothing specific on marine geoengineering. This may be an area that governance initiatives such as C2G2 could investigate. There is an urgent need to ensure that such an entry point is made in a public and transparent manner, and to ‘submit to the process of applying for social licence’.

8.4 Distinguishing between research into geoengineering and its deployment

It has been argued that the distinction between geoengineering research and subsequent deployment is artificial with no clear borderline. The paper by Robock et al., 2010) is often quoted in support of this view. However, that paper made it quite clear that it was only considering AM techniques, not geoengineering generally. In the case of most if not all CDR techniques, deployment is very unlikely to be carried out at a global scale like AM; it is much more likely to be the sum of many individual projects at local to regional scales. Note the earlier discussion about scale issues in section 3.2. There are additional distinctions between research and deployment, that are pertinent to the debate on the governance of geoengineering, since:

- Research experiments, particularly for CDR techniques (both marine and terrestrial), will mostly be:
  - at smaller scales;
  - over limited periods of time; and
  - often one-off events.
- In the case of ocean fertilization, the LC/LP Ocean Fertilization Assessment Framework (OFAF) has effectively provided a definition of legitimate scientific research. It states “A decision that a proposed activity is legitimate scientific research and is not contrary to the aims of the London Convention and Protocol should only be made if all earlier steps of the Framework, including the appropriate consultation and communication, have been satisfactorily completed and conditions are in place that ensure that, as far as practicable, environmental disturbance and detriment would be minimized and the scientific benefits maximized”. Any additional activities added to LP Annex 4 in future would seem very likely to include an analogous provision;
- Research would not be performed for any

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[77] Defined as the marine waters on the landward side of the baselines used to measure the width of the territorial sea (12-mile limit) and the Exclusive Economic Zone (200-mile limit).

direct financial or economic benefit from the results of the activity. For example, in section of the OFAF it 2.2.2 states "There should not be any financial and/or economic gain arising directly from the experiment or its outcomes";

- Much, but not all, research may be publicly funded where no direct financial benefit is expected or required; and
- Research experiments would be unlikely to be able to claim financial benefits e.g. carbon credits.

See also Brent *et al.* (2018) discussing rules requiring transparency and disclosure of economic and financial interests. It is important to note that those persons and entities who support research on geoengineering methods are not necessarily advocates of implementation. While the LOHAFEX scientific research project (Thiele et al., 2012) on ocean iron fertilization was conceived as a scientific experiment to study the net transfer of carbon from surface to deep waters, it was „perceived/framed" by some as a geoengineering experiment (Schiermeier, 2009). It also needs to be emphasised that marine research projects often provide key insights into biogeochemical and biological cycles in the ocean, that will improve basic knowledge (and improve prognostic models).

The above distinctions between geoengineering research and deployment are indicative of the need for two modes of governance dedicated to research, and for deployment. Research governance would target the oversight of a spectrum of issues including proof of concept, design of pilot studies, reportage of findings, exploration of upscaling via modelling and field studies. In contrast, governance of deployment might oversee additional issues such as defining environmental baselines, detection and attribution, and monitoring for side-effects. It is likely that both demarcation of these modes of governance, but also some degree of coupling between these modes will be required.

In conclusion, the development of these two distinct modes of governance – for research and deployment – should also consider the need for adaptive governance (Olsson et al., 2006; Banerjee, 2009) and/or anticipatory governance (Foley et al., 2018; Rockström et al., 2009; WEF, 2012) structures. The former may be applied more readily to some geoengineering approaches that to others (Boyd, 2016), whilst the latter has been used for other emerging technologies as a means to provide "a strategic vision due to shortcomings with predictive and precautionary approaches".

9 RECOMMENDATIONS FOR FUTURE WG 41 ACTIVITIES

1 Further work is required to address more completely parts of ToR 2 that the WG was not able to fully address in this report, such as "The potential environmental and social/economic impacts of those marine geoengineering approaches on the marine environment and the atmosphere where appropriate" as well other parts yet to be addressed such as "An outline of the issues that would need to be addressed in an assessment framework for each of those techniques…", .

2 Foster the development of socio-economic, geopolitical and other relevant societal aspects of marine geoengineering assessments, including societally-relevant metrics where possible, to ensure a holistic approach to subsequent assessment process(es) (see National Research Council, 2015a). This multi-faceted approach can apply the lessons learnt from other large-scale environmental issues such as the management of anthropogenically-increased UV that resulted in the 'ozone hole'. This holism will also be informed by the debates around new technologies with wider societal implications (genetically modified food; artificial intelligence; nanotechnology). This activity will require new members to be added to the WG to provide greater expertise on wider societal issues with a view to establishing a knowledge base and a subsequent analysis of the major gaps in socio-economics and geopolitics (see Figure 4.2).

3 Develop a flow chart and questionnaire with associated guidance to elicit information from proposers of geoengineering approaches to enable a preliminary assessment (including constructive feedback) of their technique. The design of this questionnaire will centre on the WG views of what fundamental knowledge is required to provide the scientific foundations needed with which to underpin the parallel development of effective policy to govern these activities. The flow chart and questionnaire with associated guidance would be expressly aimed to facilitate the London Protocol 'Guidance for consideration of marine geoengineering activities' (IMO, 2015). These dual tools, with associated guidance from the WG, could provide a recommended (non-binding) procedure for the consideration of such activities prior to activating the LP guidance referred to above (IMO, 2015). This proactive, consultative approach would also be useful for national authorities and other institutions considering marine geoengineering proposals.

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ANNEX I – MEMBERSHIP OF GESAMP WORKING GROUP WG 41 ON MARINE GEOENGINEERING

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Andreas Oschlies	GEOMAR, Kiel, Germany
Greg Rau	University of California Santa Cruz, USA
Ros Rickaby	University of Oxford, UK
Kate Ricke	Carnegie Institution, Stanford University, USA
Naomi Vaughan	University of East Anglia, UK
Chris Vivian*	Cefas, UK, now retired
Rik Wanninkhof	NOAA, USA

* Co-Chairs

Secretariat, GESAMP Office, IMO:
Edward Kleverlaan - Until July 2017
Fredrik Haag - From July 2017
Chrysanthe Kolia

ANNEX II – WORKING GROUP TERMS OF REFERENCE

The Terms of Reference for this Working Group were agreed at the forty-second session of GESAMP, held in Paris, France, in 2015. The work programme was envisaged to take place over a two to three-year period.

This GESAMP study aim is to:

1 better understand the potential environmental (and social/economic) impacts of different marine geoengineering approaches on the ocean; and

2 provide advice to the London Protocol Parties to assist them in identifying those marine geoengineering techniques that it might be sensible to consider for listing in the new Annex 4 of the Protocol.

The specific Terms of Reference are:

The GESAMP study should provide an overview to GESAMP Agencies and their respective Member States of a wide range proposed marine geoengineering techniques and their potential implications by:

1 providing an initial high-level review of a wide range of proposed marine geoengineering techniques, based on published information, addressing:

  .1 the main rationale, principle and justification of the techniques;
  .2 their potential scientific practicality and efficacy for climate mitigation purposes;
  .3 the potential impacts of different marine geoengineering approaches on the marine environment and the atmosphere where appropriate;
  .4 identifying those techniques:
    i. that appear unlikely to have the potential for climate mitigation purposes, and
    ii. that appear to be likely to have some potential for climate mitigation purposes and that bear further detailed examination;

2 providing a detailed focused review of a limited number of proposed marine geoengineering techniques that are likely to have some potential for climate mitigation purposes addressing:

  .1 The potential environmental and social/economic impacts of those marine geoengineering approaches on the marine environment and the atmosphere where appropriate.
  .2 An outline of the issues that would need to be addressed in an assessment framework for each of those techniques, using the London Protocol Assessment Framework for Scientific Research Involving Ocean Fertilization as a template.
  .3 Their potential scientific practicality and efficacy for climate mitigation purposes.
  .4 An assessment of monitoring and verification issues for each of those marine geoengineering techniques.
  .5 Identification of significant gaps in knowledge and uncertainties that would require to be addressed to fully assess implications of those techniques for the marine environment and the atmosphere where appropriate.

3 produce reports on the above work at appropriate points in the work plan.

The expertise required by the Working Group includes:

1 marine scientists and engineers with expertise in marine ecology (in particular plankton ecology, macroalgae and benthos), fisheries, marine chemistry/geochemistry/biogeochemistry, physical oceanography (including modelling), atmospheric chemistry and climate science;

2 scientists and engineers who have studied marine geoengineering techniques and their potential impacts; and

3 social scientists with expertise including environmental economics.

Provisional work plan

The working methods of the Working Group will be a mix of meetings and intersessional work/correspondence, including video-conferencing/telephone-conferencing where appropriate.

Provisional timeline:

1 Workshop in 1st -2nd quarter 2016 to address point 1 of the Terms of Reference;

2 Deliver a workshop report by end June 2016 addressing point 1 of the Terms of Reference;

3 Deliver draft report addressing point 1 of the Terms of Reference by end October 2016;

4 Workshop in 4th quarter 2016/early 1st quarter 2017 to address point 2 of the Terms of Reference;

5 Deliver a workshop report by end May 2017;

6 Deliver draft final report addressing point 2 of the Terms of Reference by end August 2017;

7 Peer review of the draft report required;

8 Deliver final report by end January 2018; and

9 Provisions for publication, dissemination and outreach (PR).

ANNEX III – BRIEF REVIEWS OF GEOENGINEERING FROM 2009

The Royal Society decided to study the issue of geoengineering in 2008 and it subsequently published the report ‘Geoengineering the climate: Science, governance and uncertainty’ (Royal Society, 2009).

The Royal Society report’s headline messages were:

> *“The safest and most predictable method of moderating climate change is to take early and effective action to reduce emissions of greenhouse gases. No geoengineering method can provide an easy or readily acceptable alternative solution to the problem of climate change.*
>
> *Geoengineering methods could however potentially be useful in future to augment continuing efforts to mitigate climate change by reducing emissions, and so should be subject to more detailed research and analysis.*
>
> *Geoengineering of the Earth’s climate is very likely to be technically possible. However, the technology to do so is barely formed, and there are major uncertainties regarding its effectiveness, costs, and environmental impact.*
>
> *Methods that act rapidly by reflecting sunlight may prove to be ineffective in offsetting changes in rainfall patterns and storms, but current climate models are not sufficiently accurate to provide a reliable assessment of these at the regional level.*
>
> *Methods that act by removing greenhouse gases from the atmosphere involve fewer uncertainties and risks but would have a much slower effect on reducing global temperature. These methods could eventually make an important contribution to mitigating climate change.*
>
> *The acceptability of geoengineering will be determined as much by social, legal and political issues as by scientific and technical factors. There are serious and complex governance issues which need to be resolved if geoengineering is ever to become an acceptable method for moderating climate change.*
>
> *It would be highly undesirable for geoengineering methods which involve activities or effects that extend beyond national boundaries (other than simply the removal of greenhouse gases from the atmosphere), to be deployed before appropriate governance mechanisms are in place.”*

The Royal Society report stated that the governance challenges posed by geoengineering should be explored in more detail by an international body. Also, they advocated that relevant international scientific organisations should coordinate an international programme of research on geoengineering methods with the aim of providing an adequate evidence base with which to assess their technical feasibility and risks and reducing uncertainties within ten years.

One of the report’s key recommendations was:

> *“Further research and development of geoengineering options should be undertaken to investigate whether low risk methods can be made available if it becomes necessary to reduce the rate of warming this century. This should include appropriate observations, the development and use of climate models, and carefully planned and executed experiments.”*

The report provided ratings for effectiveness, affordability, timeliness and safety of 12 geoengineering techniques, only one of which was a marine approach – ocean fertilization. However, in the discussion of ocean ecosystems methods, the report also commented on ocean upwelling/downwelling.

A number of other assessments of geoengineering techniques have been published (Boyd, 2008b; McCormack *et al.,* 2016; McGlashan et al, 2012; McLaren, 2012; National Research Council, 2015a, 2015b; Rickels *et al.,* 2011; Schäfer *et al.,* 2015; US Government Accountability Office, 2011; Vaughan and Lenton, 2011; Williamson *et al.,* 2012a) and those assessments varied in the number of geoengineering techniques assessed from five up to thirty and only a limited subset assessed more than a few marine geoengineering techniques. In addition, (Williamson, 2016) briefly reviewed several CO_2 removal methods.

Boyd (2008b) ranked two AM (1 marine) and three CDR geoengineering techniques (1 marine) against the four criteria of efficacy, affordability, safety and rapidity. He concluded that: *“Geo-engineering proposals for mitigating climate change continue to proliferate without being tested. It is time to select and assess the most promising ideas according to efficacy, cost, all aspects of risk and, importantly, their rate of mitigation.”*

The US Government Accountability Office (2011) assessment was technological and focused primarily on the technical status of climate engineering and the views of a wide range of experts on the future of research. It found that *“climate engineering technologies are not now an option for addressing global climate change, given our assessment of their maturity, potential effectiveness, cost factors, and potential consequences”.* It rated six CDR (2 marine) and four AM techniques against four criteria.

Rickels *et al.* (2011) presented information about five AM (1 marine) and nine CDR techniques (6 marine) with an overview of them against the criteria of:

- leverage effect - where an attempt was made to give a qualitative measurement of the efforts associated with the relevant method versus the results that are achieved (i.e., a high leverage effect means that a little bit of effort gives you a big effect).

- anticipated potential – in Watts/m^2 for AM techniques and Gt CO_2/year for CDR technique. These can be converted using the following factor of 9.6 x 10-4 (W/m^2)/(Gt(CO_2) from Lawrence *et al.* (2018)
- method lifetime - a period of time is specified within which the effect of an AM method wears off after its termination (in terms of a half-life period). For CDR methods, a lifetime is not specified because it is assumed that CO_2 leakages are already taken into account and that CO_2 storage is permanent for the timescales underlying the evaluation.

Rickels *et al.* (2011) also estimated the economic costs of techniques that they had reviewed.

Vaughan and Lenton (2011) assessed nine AM techniques and ten CDR techniques (6 marine) for their effectiveness based on their radiative forcing potential and reviewed potential side-effects. They also estimated the development and deployment timescales, lifetime of effects and controllability of the techniques. In addition, there have been more specific reviews of ocean fertilization techniques (Secretariat of the CBD, 2009; Williamson *et al.* 2012b).

Williamson *et al.* (2012a) assessed four AM techniques (1 marine) and fourteen CDR techniques (5 marine) for their impacts on biodiversity. The report stated:

> *"There is no single geoengineering approach that currently meets all three basic criteria for effectiveness, safety and affordability. Different techniques are at different stages of development, mostly theoretical, and many are of doubtful effectiveness. Few, if any, of the approaches proposed above can be considered well researched; for most, the practicalities of their implementation have yet to be investigated, and mechanisms for their governance are potentially problematic. Early indications are that several of the techniques, both SRM and CDR, are unlikely to be effective at the global scale".*

McGlashan *et al.* (2012) presented a high-level techno-economic assessment of five CDR techniques. The key finding from this study was that *"the degree of scale-up required for negative emissions technologies to have a material impact on atmospheric emissions (i.e. at a ppm level) is probably unrealistic in less than 20 years".*

McLaren (2012) presented a comparative global assessment of around 30 negative emission techniques (i.e. NET's that are equivalent to CDR techniques) with fourteen of them considered in more detail. The paper concludes that:

> *"…this assessment strongly supports the view that NETs cannot be expected to offer an economically viable alternative to mitigation in the coming decades. On the other hand, limited deployment of NETs – in the order of perhaps 10–20 Gt-CO_2 pa (per annum) to complement much accelerated mitigation may become technically and economically plausible by 2030–2050. Significant further technological development and early and appropriate policy intervention would be necessary to release such potential, and the uncertainties involved mean serious moral hazard remains insofar as climate policy decisions rely on the future availability of NETs."*

The Intergovernmental Panel on Climate Change (IPCC), convened an expert workshop on geoengineering in Lima, Peru on 20-22 June 2011 (IPCC, 2012) with the objectives to discuss:

- different geoengineering options, their scientific basis and associated uncertainties;
- associated potential risks and related knowledge gaps;
- effect of impacts and side effects on mitigation cost and the role within the portfolio of mitigation options;
- suitability of existing governance mechanisms for managing geoengineering, including social, legal and political factors;
- key knowledge gaps that could be filled in the shorter and longer terms.

The expert meeting was designed to provide a platform for exchange and discussion among experts from the different disciplines in order to better address the important cross-cutting issue of geoengineering. It was also designed to encourage the consistent treatment of geoengineering options across the IPCC Working Groups' 5th Assessment Reports.

The IPCC in its Fifth Assessment Reports (AR5) addressed geoengineering approaches to a limited extent but it did not formally assess them. The AR5 Working Group I report (IPCC, 2013) addressed the potential effects of CDR and AM methods on the carbon cycle in section 6.5 of the report. The AR5 Working Group II report (IPCC, 2014a) in section 6 on Ocean Systems, discussed geoengineering approaches and their challenges and impacts for the ocean (section 6.4.2.2). The AR5 Working Group III report (IPCC, 2014b) briefly discussed 'geoengineering, ethics and justice' in section 3.3.7 and considered geoengineering approaches including their characteristics and environmental risks in section 6.9. Williamson and Bodle (2016) provided a detailed overview of the coverage of geoengineering in IPCC AR5 (in section 2.2, pp. 30 – 40).

In 2012 the US National Academy of Sciences (NAS) convened a 'Committee on Geoengineering Climate: Technical Evaluation and Discussion of Impacts' that was charged with conducting a technical evaluation of a limited number of "geoengineering" (also known as "climate engineering") techniques that have been proposed so far. The NAS also commented generally on the potential impacts of deploying these technologies, including possible environmental, economic, and national security concerns. The study led to the publication of 2 reports in 2015 titled 'Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration' (National Research Council, 2015a) and 'Climate Intervention: Reflecting Sunlight to Cool Earth' (National Research Council, 2015b) that used different criteria in the two reports to appraise various aspects of the techniques examined. The first of these reports on CDR geoengineering is particularly relevant to the work of the GESAMP Working Group on Marine Geoengineering as most proposed marine geoengineering techniques fall into the CDR category. The NAS report 'Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration' (National Research Council, 2015a) used the following criteria to rank the CDR techniques:

- "Technological readiness, speed to deployment and technical risk
- Time required to scale to maximum deployment with major effort
- Persistence (sequestration lifetime)
- Maximum sequestration amount
- Verifiability: Ability to detect and quantify the rate at which CO_2 was captured and added to the sequestration reservoir
- Verifiability: Ability to detect and quantify the rate at which CO_2 is leaking out of the reservoir
- Verifiability: Ability to quantify increase in carbon stocks of the sequestration reservoir (i.e. verification of change in carbon mass stored)
- Negative environmental consequences
- Socio-political risks (include national security)
- Governance challenges for deployment at scale"

The NAS report 'Climate Intervention: Reflecting Sunlight to Cool Earth' (National Research Council, 2015b) used the following criteria to rank the AM techniques:

- Ability to mask some consequences of greenhouse gas warming, i.e., ability to produce substantial cooling of global mean temperature
- Technological readiness (systems level maturity), technical risk
- Technological readiness (device level maturity), technical risk
- Time required to scale to maximum ("irresponsible/uninformed") deployment with major effort
- If decision made to deploy, time required to develop informed, well-planned, and controlled maximum deployment with major effort
- Time for direct radiative effects to dissipate if albedo modification activity is suddenly stopped
- Relative costs of an albedo modification device (orders of magnitude; when building at scale)
- Relative costs of an albedo modification system (orders of magnitude; when building at scale)
- Ability to detect unsanctioned albedo modification at scale
- Ability to measure the radiative forcing of a large-scale, decade-long albedo modification deployment with sufficient accuracy
- Ability to monitor and attribute the climate response of a large-scale, decade-long albedo modification deployment with sufficient accuracy
- Environmental consequences and risks (geographic extent of impact, adverse consequences, co-benefits)
- Addresses non-warming effects of CO_2 (e.g., ocean acidification, CO_2 fertilization)
- Sociopolitical consequences and risks (include national security)
- Governance challenges for deployment at scale
- How many potential unilateral and uncoordinated actors could have both the technology and resources to deploy at scale

The European Transdisciplinary Assessment of Climate Engineering (EuTRACE) report (Schäfer *et al.,* 2015), provided an overview of a broad range of techniques that have been proposed for climate engineering. To illustrate the range of complex environmental and societal issues that climate engineering raises, the EuTRACE assessment focused on three example techniques: bio-energy with carbon capture and storage (BECCS), ocean iron fertilization (OIF), and stratospheric aerosol injection (SAI). The report assesses the potentials, risks and uncertainties of climate engineering technologies within the broader context of discussions on climate change, mitigation and adaptation. It covers natural science and engineering complexities, emerging societal issues, international regulation and governance, research options, and policy development for climate engineering.

A group of biodiversity and environmental change researchers employed a literature review to identify details of the potential ecological effects of climate engineering techniques (McCormack *et al.,* 2016). They subsequently evaluated this evidence and ranked the effects based on the relative importance of, and scientific understanding about, the consequences of each technique for biodiversity and ecosystems. The study assessed two AM techniques (1 marine) and nine CDR techniques (3 marine). This review highlighted several research priorities, as well as identifying some novel topics for ecological investigation.

UN Convention on Biological Diversity released an update on climate engineering summarised in 26 key messages (Williamson and Bodle, 2016), several of which are relevant to the topic of marine geoengineering considered by the GESAMP WG 41. They include:

> "3. Climate change, including ocean acidification, is already impacting biodiversity and further impacts are inevitable……..Geoengineering techniques, if viable and effective, would be expected to reduce climate change impacts on biodiversity. However, some techniques would lead to biodiversity loss through other drivers….".
>
> "9. The viability of alternative negative emission techniques such as direct air capture (DAC), enhanced weathering and ocean fertilization remains unproven…… The potential contribution of enhanced weathering, on land or in the ocean, to negative emissions is unclear but logistical factors seem likely to limit deployment at large scales. Local marine application might be effective in slowing or reducing ocean acidification, with consequent benefits for marine biodiversity, though there might also be negative effects; e.g. from sedimentation. Enhancing ocean productivity, by stimulating phytoplankton growth in the open ocean and through nutrient addition ("ocean fertilization") or modification of upwelling, is only likely to sequester relatively modest amounts of CO_2, and the environmental risks and uncertainties associated with large-scale deployment remain high."
>
> "10. Carbon dioxide (or other greenhouse gases) captured from the atmosphere must be stored in some form. Options include vegetation, soils, charcoal, or carbon dioxide in geological formations…. Technical considerations relating to safe carbon storage in geological formations, mostly expected to be beneath the seafloor, have recently been reviewed. The main effects of marine leakage would be local ocean acidification with experimental studies indicating that (at least for slow release rates) environmental impacts would be relatively localized. The extensive literature on ocean acidification, including the biodiversity changes observed at natural CO_2 vents, is relevant here. However, relatively few experimental studies on the impacts of high CO_2 on marine organisms cover the full range of values that might occur under leakage conditions. Other forms of storage in the ocean are considered to have unacceptable risks and are not allowed under the London Convention/London Protocol.
>
> "13. SRM may benefit coral reefs by decreasing temperature-induced bleaching, but, under high CO_2 conditions, it may also increase, indirectly, the impacts of ocean acidification. Notwithstanding uncertainties over regional distribution, lowered average global temperatures under SRM would be likely to reduce the future incidence of bleaching of warm-water corals (compared to RCP 4.5, 6.0 or 8.0 conditions). The interactions between ocean acidification, temperature and impacts on corals (and other marine organisms) are complex, and much will depend on the scale of additional measures taken to reduce the increase in atmospheric CO_2. If warming is prevented by SRM, there will be less additional CO_2 emissions from biogeochemical feedbacks; however, relative cooling would reduce carbonate saturation state, that may reduce calcification or even dissolve existing structures (for cold-water corals) if CO_2 emissions are not constrained.
>
> "14. The use of sulphur aerosols for SRM would be associated with a risk of stratospheric ozone loss; there would also be more generic side effects involved in stratospheric aerosol injection (SAI). All SAI techniques would, if effective, change the quality and quantity of light reaching the Earth's surface; the net effects on productivity are expected to be small, but there could be impacts on biodiversity (community structure and composition)."
>
> "15. The climatic effectiveness of marine cloud brightening depends on assumptions made regarding microphysics and cloud behaviour. Many associated issues are still highly uncertain. The potential for regional-scale applications has been identified; their environmental implications, that include salt damage to terrestrial vegetation, have not been investigated in any detail."
>
> "16. Large scale changes in land and ocean surface albedo do not seem to be viable or cost-effective......Changes in ocean albedo (through long lasting
>
> foams) could, in theory, be climatically effective, but would be also accompanied by many biogeochemical and environmental changes, likely to have unacceptably large ecological and socioeconomic impacts."
>
> "Regulatory framework
>
> 20. An amendment to the London Protocol to regulate the placement of matter for ocean fertilization and other marine geoengineering activities has been adopted by the Contracting Parties to the London Protocol. ….The amendment, adopted in 2013, is structured to allow other marine geoengineering activities to be considered and listed in a new annex in the future if they fall within the scope of the Protocol and have the potential to harm the marine environment. The amendment will enter into force following ratification by two thirds of the Contracting Parties to the London Protocol. This amendment, once entered into force, will strengthen the regulatory framework for ocean fertilization and manipulation activities and provide a framework for the further regulation of other marine geoengineering activities….."

Their key message 24 is particularly pertinent to the development of the WG 41 report.

> "24. A recurring question is how research activities (as opposed to potential deployment) should and could be addressed by a regulatory framework. However, once the modelling and laboratory stage has been left behind, the distinction between research and development could become difficult to draw for regulatory purposes. It has been argued that governance can have an enabling function for "safe and useful" research; the London Protocol's concept of "legitimate scientific research" underlying the 2013 amendment can be seen in this context."

The contents of their Table 1.2 are also highly relevant to GESAMP WG 41. That table sets out the main factors and additional issues that might be used to evaluate scientific and societal suitability of climate geoengineering techniques and builds on those developed by prior initiatives including the Royal Society (2009) and Bellamy *et al.* (2012).

A US Gordon Research Conference was held in 2016 dedicated to Solar Radiation Management ('Radiation Management Climate Engineering: Technology, Modelling, Efficacy, and Risks'[78]. Support from a prominent conference series is welcome but is indicative of a potential divergence of debate regarding AM and CDR (Carbon Dioxide Removal) approaches to geoengineering which will require careful consideration. It is clear from the key messages in Williamson and Bodle (2016) that there are inextricable linkages between any modification of the atmosphere and/or the ocean. Hence, we need to ensure that a holistic approach is taken to the study or assessment of any changes (purposeful or inadvertent) to the atmosphere, ocean and marine boundary layer (see Boyd, 2016).

Keller, 2018) briefly reviewed a range of marine geoengineering techniques (2 AM techniques, both marine, and 9 CDR techniques, 6 marine, but not the full range covered in this report. He makes a similar point in the abstract about the knowledge of marine geoengineering techniques to that we have made in this report when he says, "Few methods have been thoroughly evaluated and there are still many unknowns, at both the level of basic understanding and as to whether or not it would even be technologically feasible to implement any of them".

The latest developments in the assessment of geoengineering involve the inclusion of the views of developing nations. Nassiry *et al.* (2017) reviewed the implications of geoengineering for developing countries with a focus on governance and the need to develop a new approach for decision-making about geoengineering. They stated that "So far engagement by developing countries in discussion about geoengineering has been limited. More support is needed to enable developing countries to assess the costs and benefits of geoengineering, including the potential for unintended consequences".

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[78] https://www.grc.org/programs.aspx?id=17348

ANNEX IV – GEOENGINEERING RESEARCH PROGRAMMES

Research into geoengineering, including marine geoengineering, technologies seems likely to accelerate in the next 10 years given the increasing concern about climate change and the likelihood of being able to limit the global mean temperature increase to 2.0 °C or lower. An Editorial (Nature Geoscience Editorial, 2016) referred to proposals for larger scale experiments including one on land-based enhanced weathering in the US due to start in 2017. Minx *et al.* (2017) reported fast-growing research on negative emissions in recent years.

Research on geoengineering takes several forms including:

1 Conference discussions e.g. the Climate Engineering Conference 2017 in Berlin in

2 Programmes of research funded by national science funding bodies e.g. UK Research Councils, the German Research Foundation (DFG) and the Chinese Ministry of Science and Technology

3 Programmes of research funded by private investors or philanthropic foundations e.g. FICER and SCOPEX

4 One-off experiments funded privately and that were not approved by national authorities e.g. Haida Gwaii in 2012

5 Proposals for one-off experiments funded privately e.g. by OCEANOS off Chile in 2017

The 'Fund for Innovative Climate and Energy Research' (FICER)[79] administered by Dr. David Keith of Harvard University and Dr. Ken Caldeira of the Carnegie Institution for Science is relatively well-known and has operated for a number of years.

Publicly-funded geoengineering R&D programmes are starting to be announced or proposed. In January 2017, the US Global Change Research Program (USGCRP) indicated support for further exploration of how geoengineering could be used to tackle global warming in the report 'National Global Change Research Plan 2012–2021: A Triennial Update' (USGCRP, 2017). Subsequently, the US National Academies of Sciences, Engineering and Medicine established a committee for 'Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration' in 2017. Sequestration'. This reported in late 2018 (National Academies of Sciences Engineering and Medicine, 2018) as this report was being finalised.

In April 2017, a group of UK research funding agencies (Natural Environment Research Council; Engineering and Physical Sciences Research Council, Economic and Social Research Council, Department for Business, Energy and Industrial Strategy, Met Office Hadley Centre; Science and Technology Facilities Council) announced dedicated funding of £8 million of a multi-faceted assessment of a range of geoengineering approaches on their scientific and technological merits and also their societal implications[80]. This echoes the recommendations in both 2015 NAS reports on climate intervention. The research will probe the benefits and challenges of a range of approaches to greenhouse gas removal from the atmosphere including accelerated weathering in the ocean. One of the UK projects will assess the practicability of using enhanced weathering of waste materials from mining as a greenhouse gas removal technique. It will investigate the availability of suitable materials, the rates of their breakdown, mechanisms for accelerating carbon dioxide uptake, implications for the ocean, and societal implications.

In addition, a new Centre for Climate Change Mitigation, led by the University of Sheffield, UK has been announced by the Leverhulme Trust which will be funded for up to £10 million over ten years[81]. The Leverhulme Centre's vision is to develop and assess the role of enhanced rock weathering as a means of safely removing large amounts of the greenhouse gas CO_2 from the atmosphere to cool the planet, while also mitigating ocean acidification.

David Keith and colleagues have proposed a Stratospheric Controlled Perturbation Experiment (SCoPEx)[82] to advance understanding of stratospheric aerosols that could be relevant to solar geoengineering. It aims to reduce the uncertainty around specific science questions by making quantitative measurements of some of the aerosol microphysics and atmospheric chemistry required for estimating the risks and benefits of solar geoengineering in large atmospheric models. SCoPEx will address questions about how particles interact with one another, with the background stratospheric air, and with solar and infrared radiation. The first experiment could take place in late 2018 or 2019.

China has also been developing a major geoengineering research programme (Cao *et al.,* 2015). A report in the MIT Technology Review stated "The approximately $3 million program, funded by the Ministry of Science and Technology, incorporates around 15 faculty members and 40 students across three institutions. The researchers are assessing the impact of employing technological means of altering the climate and exploring related policy and governance issues. The effort explicitly does not include technology development, or outdoor experiments..." . (Chen and Xin, 2017) have proposed several policy suggestions for China to strengthen research on and response to geoengineering.

The 2nd Climate Engineering Conference was held in Berlin from 9-12 October 2017 and further information about the conference report is available online.

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[79] https://keith.seas.harvard.edu/FICER
[80] https://nerc.ukri.org/research/funded/programmes/ggr/
[81] http://lc3m.org/about/
[82] https://projects.iq.harvard.edu/keutschgroup/scopex

In November 2017, the US Global Change Research Program published its 4th National Climate Assessment (USGCRP and U.S. Global Change Research Program, 2017) and it considered the potential role of climate intervention in mitigation strategies. The key finding on geoengineering was “Further assessments of the technical feasibilities, costs, risks, co-benefits, and governance challenges of climate intervention or geoengineering strategies, which are as yet unproven at scale, are a necessary step before judgments about the benefits and risks of these approaches can be made with high confidence (High confidence)”.

ANNEX V – INITIAL METHODOLOGY FOR RANKING MARINE GEOENGINEERING TECHNIQUES

It was agreed that the WG would conduct two types of assessment: an initial appraisal of a wide range of techniques many of which have limited information, followed by a detailed assessment, with a focus on proposals that have been through a peer-review process that would enable a more robust appraisal of each technique.

The comparative evaluation of a broad range of marine geoengineering approaches requires scoring or ranking based on evaluation criteria. It was recognized that, besides measures of potential efficacy and environmental risk, policy-focussed evaluation of marine geoengineering approaches would require consideration of factors such as economics (including effects on fishing and tourism) and health (ecosystem and human) effects. As many marine experiments may take place 100's of km offshore in the deep ocean, some experiments may therefore not have direct impacts on coastal societies. Other assessment criteria such as effectiveness could be difficult to score as they depend highly on a wide range of the perspectives. Although it may be possible to get widespread agreement that many techniques are likely to be ineffective, such agreement may not be universal, as some parties may consider them to be effective e.g. as occurs with weather modification activities where the efficacy of methods is disputed (WMO, 2010).

Political and socio-economic evaluation criteria to derive predictions/hypotheses based on accepted principles, probably would not be used in this initial assessment round. Also, ethical considerations would not be addressed in the WG's assessment as this was considered to be beyond the group's remit.

The WG considered who might use the evaluation criteria that might be developed by this WG. Besides proposers of a marine geoengineering technique, the use of criteria is likely to be primarily by those who will be involved in governance – from initial research governance (including field experiments) through to the governance of the deployment of marine geoengineering approaches, and the need for adaptive governance, thereafter - and those who will select topics for research funding. Governance of research would need to take into account that marine geoengineering research could go through several different phases including for example conceptualisation, modelling, small-scale field experiments and larger scale field experiments. Foley *et al.* 2018 have suggested that anticipatory governance should be utilised for geoengineering. They describe it as "a vision for dealing with emerging technologies by building the capacity to manage them while management remains possible". The 2012 Global Risk Report of the World Economic Forum (WEF, 2012) contrasts it with precaution: "More promising is the approach of 'anticipatory governance.' In this model, regulators accept the impossibility of anticipating the potential trajectory of innovations based only on past experience. They embrace the need for dynamic safeguards that can evolve with the system they are safeguarding. Anticipatory governance implies close, real-time monitoring in the direction in which innovations evolve, and involves defining safeguards flexible enough to be continually tightened or adapted in response to emerging risks and opportunities. The model of anticipatory governance is attracting attention in fields ranging from climate change to personalized medicine."

1 – Criteria to be used to assess the proposed techniques

The Terms of Reference (ToR 1.4) requires the identification of those techniques that:

- appear unlikely to have the potential for climate mitigation purposes that will not be examined further, and
- appear to be likely to have some potential for climate mitigation purposes and that bear further detailed examination

The WG considered what criteria should be used to assess the proposed techniques and thus select those that should be considered further under ToR 2. The first phase assessment (i.e. ToR 1) was envisaged to be more about filtering out methods and a qualitative assessment, as there was often little published information about many of the techniques. It was anticipated that the second step (ToR 2) would involve more specific consideration of effects and might involve using modelling methodology etc. to evaluate measures.

The WG agreed to develop a ranking of expert viewpoints of the environmental impacts of marine geoengineering approaches which were to be summarised a spreadsheet format. While the use of aggregating scores (e.g. McCormack *et al.* 2016) is a powerful approach, it is a much more detailed assessment technique than could be used in the first round of assessment. However, such an approach could potentially be employed in the second round. The aggregating score approach involves a large amount of detail but comes up with very robust results if there is: a) adequate information on which to base the assessments, b) sufficient depth and breadth in the panel and c) if the panel can commit the time required to complete the job effectively.

A multi-faceted approach to assessment was considered essential, as was the need to include political and socio-economic assessment criteria, to the extent possible, in a comprehensive analysis, especially given the potential governance/policy relevance of the report. To have a credible assessment of these criteria, we need to involve more social/economic scientists for ToR2. However, it was pointed out that current literature on potential political implications of marine geoengineering is very limited (Boyd, 2016) although there is a chapter 'Social, Economic, Cultural and Ethical Considerations of Climate-Related Geoengineering' in Williamson *et al.* (2012a).

The WG contemplated the possibility of including biodiversity metrics. However, biodiversity is a very broad and nebulous term and thus, it is difficult to apply metrics. Nevertheless, it was agreed that explicit incorporation of ecological integrity into the assessment was highly desirable (Russell *et al.,* 2012) but might not be achievable currently. In ToR 2 it was suggested that we might consider whether we could frame biodiversity in the context of the UN Sustainable Development Goals (SDGs) (e.g. see (Nilsson *et al.,* 2016) i.e. sustainability goals that link into socio-political-economic issues. However, (Cormier and Elliott, 2017) concluded that many of the targets adopted for SDG 14 'Life Below Water' are aspirational rather than fully quantified and are not SMART i.e. Specific, Measurable, Achievable, Realistic and Time Bound. That being the case, it would appear premature to address the SDGs under ToR 2.

The WG considered the possibility of including an economic assessment based on welfare endpoints as these are what human populations value – i.e., how they will be directly affected by biological/chemical changes. There will be an ethical dimension in such an assessment i.e. the relative weight of issues that people consider significant. There are metrics in the literature to help us understand such issues. A major consideration for this WG, was how to bring additional multi-faceted metrics into our assessment - combining economic and political criteria with those for environmental assessment. In ToR 2 the WG thought it may be able to take information about likely welfare endpoints, and how the marine geoengineering methods may affect these endpoints. At present, the economics of marine geoengineering approaches are very underdeveloped so that the extent to which we can draw on existing research is very limited, although we can identify research gaps.

In the fields of economic or political science, there is a very small but emerging literature on the potential socio-political/economic impacts of marine geoengineering approaches. However, as such research has been conducted in other, potentially analogous situations (i.e. the socio-political effects of marine pollution, or changes to the marine environment due to mining activities etc.), they can be drawn upon to hypothesise about the potential socio-economic/political impacts of marine based geoengineering techniques. A link between economic and ecological metrics could be via ecosystem services i.e. how ecological integrity affects human welfare. For example, Magnan *et al.* (2016) outlines some potential effects of marine geoengineering on measures of ecosystem services which could provide insights for evaluation criteria.

The National Academy of Sciences 2015 report on carbon dioxide removal (National Research Council, 2015a) provided a summary overview of the Committee's judgments on 10 aspects of carbon capture and sequestration approaches in Tables 3.3 and 3.4 respectively. These criteria seemed to be the most comprehensive set available in any assessments to date and are shown in Annex V Table 1 below:

Annex V Table 1 – Aspects of carbon capture and sequestration systems used in National Research Council (2015a) to assess CDR techniques.

CO_2 Capture Approaches	**CO_2 Sequestration Approaches**
Technological readiness, speed to deployment and technical risk	Technological readiness, speed to deployment and technical risk
Time required to scale to maximum deployment with major effort, achieving significant capture rate (~1GtCO_2/yr)	Time required to scale to maximum deployment with major effort
Effect per unit cost for pilot scale with currently available technology	Persistence (sequestration lifetime)
Maximum feasible deployment capture rate	Maximum sequestration amount
Verifiability: Ability to confirm that capture has happened and quantify how much CO_2 has been captured	Verifiability: Ability to detect and quantify the rate at which CO_2 was captured and added to the sequestration reservoir
Negative environmental consequences	Verifiability: Ability to detect and quantify the rate at which CO_2 is leaking out of the reservoir
Environmental co-benefits	Verifiability: Ability to quantify increase in carbon stocks of the sequestration reservoir (i.e. verification of change in carbon mass stored)
Socio-political risks (include national security)	Negative environmental consequences
Governance challenges for deployment at scale	Socio-political risks (include national security)
Risk of detrimental deployment from unilateral and uncoordinated actors	Governance challenges for deployment at scale

The criteria each had 3 ranked assessments (e.g., high, medium, low) with which to judge the criteria for each technique, with a level of confidence (high, medium, low) attached to each assessment.

2 – Development of assessment criteria

The WG derived a set of criteria and associated metrics, largely derived from the NAS report shown in Annex V Table 1, that would be used to assess the selected marine geoengineering techniques as set out in Annex V Table 2.

Annex V Table 2 – Criteria and associated metrics to be used for assessing marine geoengineering techniques

Criteria	Rating	Scores
Knowledge base: Level of documented evidence which already exists for the method		
	High	3
	Medium	2
	Low	1
Technological readiness		
	Mature technology exists at scale	3
	Intermediate maturity technology: prototypes exist, not to scale	2
	Emerging technology not ready to deploy: needs prototyping	1
Speed to deployment		
	ready to deploy quickly	3
	Intermediate	2
	Not ready to deploy, needs research	1
Technical risk		
	Low technical risk	3
	Medium technical risk	2
	High technical risk	1
Efficacy at climate mitigation - stabilising GHG equivalents, global temperature and mitigating impacts of climate change e.g. ocean acidification.		
	High	3
	Medium	2
	Low	1
Maximum potential		
	High	3
	Medium	2
	Low	1
Persistence of sequestration - lifetime		
	Millennia	3
	Centuries	2
	Decades	1
Maximum sequestration amount		
	High: >10,000 Gt CO_2	3
	Medium: 1,000<x>10,000 Gt CO_2	2
	Low: order <1,000 Gt CO_2	1
Verifiability - includes:		
• Ability to detect and quantify the rate at which CO_2 was captured and added to the sequestration reservoir		
• Ability to detect and quantify the rate at which CO_2 is leaking out of the reservoir		
• Ability to quantify increase in carbon stocks of the sequestration reservoir (i.e. verification of change in carbon mass stored)		
	Easily	3
	Moderately	2
	Difficult	1

Criteria	Rating	Scores
Predictability - with what confidence can the (intended and unintended) effects be predicted?		
	High	3
	Medium	2
	Low	1
Attribution - with what confidence can the (intended and unintended) effects be (retrospectively) attributed?		
	High	3
	Medium	2
	Low	1
Negative environmental consequences		
	Minor	3
	Medium	2
	Major	1
Environmental co-benefits		
	High	3
	Medium	2
	Low	1
Scale of ocean use for marine geoengineering activities		
	Small	3
	Medium	2
	High	1
Socio-political risks (include national security)		
	Minor	3
	Medium	2
	Major	1
Governance challenges for both research and deployment		
	None	3
	Mainly territorial	2
	Potentially across international borders	1
Potential for interaction/compatibility with other methods and uses of the marine environment		
	Low	3
	Medium	2
	High	1
Knowledge gain from research		
	High	3
	Medium	2
	Low	1

ANNEX VI – GLOSSARY

Abiotic – Not associated with or derived from living organisms.

Afforestation – Establishing forest on land where no forest existed previously.

Albedo – The albedo of a surface is defined as the ratio of irradiance reflected to the irradiance received by a surface. The proportion reflected is not only determined by properties of the surface itself, but also by the spectral and angular distribution of solar radiation reaching the Earth's surface.

Alkalinity – is the capacity of water to resist changes in pH. In seawater it is the difference between the excess concentrations of proton acceptors over proton donors, or the sum of bicarbonate, two times carbonate and borate concentrations in seawater: $HCO_3^- + 2\ CO_3^{2-} + B(OH_4)^-$.

Alkalinization (also alkalization) – The process of becoming or making more alkaline.

Anaerobic – Without oxygen.

Anoxia – Without oxygen.

Anthropogenic – Caused by human activity.

Calcifying – To make or become calcareous by the deposit of calcium salts.

Calcite – A mineral consisting of calcium carbonate.

Coccolithophores – A type of calcifying phytoplankton, typically <10-micron diameter cells, with distinctive plates composed of calcium carbonate known as 'liths'

Convergences – Locations where ocean currents meet, characteristically marked by downwelling of water.

Diatoms – Single-celled planktonic algae which have a cell wall made of silica (silicon oxide).

Dissolution kinetics – Rates of dissolution in chemistry.

Earth System Modelling – Earth system models seek to simulate all relevant aspects of the Earth system. They include physical, chemical and biological processes.

Eddies – Circular currents of water.

Efficacy – The ability to produce a desired or intended result.

Eutrophication – The process by which a body of water becomes enriched in dissolved nutrients (such as nitrates or phosphates) that stimulate the growth of aquatic plant life usually resulting in the depletion of dissolved oxygen.

Flux – The flow of a substance from one location to another.

Fronts – In oceanography, a front is a boundary between two distinct water masses. The water masses are defined by moving in different directions.

Geosynthetic containers – these are containers made from synthetic material used to solve civil engineering problems.

Greenhouse gases – These are the gases which contributes to the greenhouse effect and includes carbon dioxide, methane and nitrous oxide.

Hydrates – A class of compounds containing chemically combined water e.g. CO_2 hydrates and methane hydrates.

Internal Waters – A nation's marine internal waters covers all water and waterways on the landward side of the baseline from which a nation's territorial waters (12-mile limit) is defined. It includes estuaries and the waters within bays less than 24 nautical miles across.

Internal Waves – Gravity waves that oscillate within a fluid medium, rather than on its surface due to different densities of the water masses either side of the interface between them.

Ligno-cellulose – Compounds of lignin and cellulose comprising the essential part of woody cell walls.

Liths – They are the individual plates of calcium carbonate formed by coccolithophores which are arranged around them in a coccosphere.

Marine Boundary Layer – The layer of well-mixed atmosphere over the ocean, often to an elevation of up to 2 km.

Marine Environment – This includes both the ocean and the marine boundary layer.

Mesoscale – Typical horizontal scales of less than 100 km.

Micron – A unit of length equal to one millionth of a metre or one thousandth of a millimetre

Mineral carbonation – Carbon dioxide injected into basalt and peridotite rocks reacts with the calcium and magnesium ions in silicate minerals to form stable carbonate minerals

Nanoplankton – Plankton that range in size from 5 to 60 microns.

Nutraceuticals – A broad umbrella term used to describe any product derived from food sources with extra health benefits in addition to the basic nutritional value found in foods.

Olivine – A silicate mineral containing varying proportions of magnesium, iron, and other elements occurring widely in basalt, peridotite, and other basic igneous rocks.

pH – In chemistry, pH is a logarithmic scale used to specify the acidity or basicity of an aqueous solution. Solutions with a pH less than 7 are acidic and solutions with a pH greater than 7 are basic.

Phytoplankton – Single-celled organisms of that make their own food from sunlight and nutrients in water through photosynthesis.

Pico-cyanobacteria – A type of microorganism less than 2 microns in size that are related to the bacteria but are capable of photosynthesis.

Plankton – The small and microscopic organisms drifting or floating in the sea, a primary food source for many small animals in the sea i.e. the base of the marine food web.

Primary producers – Any green plant or any of various microorganisms that can convert light energy or chemical energy into organic matter.

Prognostic – Of or relating to prediction.

Remineralisation – This is the breakdown or transformation of organic matter (those molecules derived from a biological source) into its simplest inorganic forms.

Sea Surface Microlayer – The sea surface microlayer is the top 1 millimetre of the ocean surface. It is the boundary layer where all exchange occurs between the atmosphere and the ocean. The chemical, physical, and biological properties of the microlayer differ greatly from the sub-surface water just a few centimetres beneath.

Semi-labile – Partially available chemical species.

Sequestration – The secure storage of a substance. In the case of sequestration of CO_2, this is generally taken to mean secure storage for a minimum of 100 years.

Stoichiometric – The quantitative relationship between reactants and products in a chemical reaction.

Stratosphere – The upper part of the atmosphere at a height of between 15 and 50 kilometres

Supersaturated – A solution containing an amount of a substance greater than a saturated solution and therefore not in equilibrium.

Surfactant – A surface active agent. A substance which tends to reduce the surface tension of a liquid in which it is dissolved. Surfactants may act as detergents, wetting agents, emulsifiers, foaming agents, and dispersants.

Thermodynamic – The branch of physical science that deals with the relations between heat and other forms of energy (such as mechanical, electrical, or chemical energy), and, by extension, of the relationships between all forms of energy.

Undersaturated – A solution containing an amount of a substance less than a saturated solution.

Ventilation – The process that transports water and climatically important gases such as carbon dioxide from the ocean interior to the surface where the gases can equilibrate with the atmosphere.

Weathering – The breakdown of rocks on the Earth’s surface by natural chemical and mechanical processes e.g. rain, cold, ice.

Windrows – Streaks of floating material e.g. seaweed, plastic debris etc. on the sea surface. They can be formed by Langmuir circulation (Thorpe, 2004) that consists of a series of shallow, slow, counter-rotating vortices at the ocean’s surface aligned with the wind. These circulations are developed when wind blows steadily over the sea surface.

Zooplankton – plankton consisting of small animals and the immature stages of larger animals.

ANNEX VII – ACRONYMS

AM – Albedo Modification

AR5 – 5th Assessment Report of the IPCC

BECCS – Bio-Energy with Carbon Capture and Storage

C2G2 – The Carnegie Climate Geoengineering Governance Initiative

CBD – Convention on Biodiversity

CCN – Cloud Condensation Nuclei

CCS – Carbon Capture and storage/Sequestration

CDR – Carbon Dioxide Removal

CDRMIP – Carbon Dioxide Removal Model Intercomparison Project

COA – Coastal Ocean Alkalinization

DIC – Dissolved Inorganic Carbon

DOM – Dissolved Organic Matter

ENMOD – The Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques

GEOMIP – Geoengineering Model Intercalibration Project

GESAMP – Joint Group of Experts on Scientific Aspects of Marine Protection (www.gesamp.org)

GRGP – Geoengineering Research Governance Project

GGR – Greenhouse Gas Removal

HNLC – High Nutrient, Low Chlorophyll

IASS – Institute of Advanced Sustainability Studies – Potsdam, Germany

IMO – International Maritime Organization (www.imo.org)

IMTA – Integrated Multi-Trophic Aquaculture

IOC – International Oceanographic Commission (UNESCO) (http://www.unesco.org/new/en/natural-sciences/ioc-oceans/)

IPCC – International Panel on Climate Change

LC – London Convention 1972

LNLC – Low Nitrogen, Low Chlorophyll

LP – London Protocol 1996

MCB – Marine cloud brightening

MCP – Microbial Carbon Pump

MIT – Massachusetts Institute of Technology

NAS – United States National Academy of Science

NETs – Negative Emissions Technologies

OF – Ocean Fertilization

OFAF – Ocean Fertilization Assessment Framework (LC/LP)

OIF – Ocean Iron Fertilization

OTEC – Ocean Thermal Energy Conversion

R&D – Research and Development

RCP – Representative Concentration Pathway (IPCC)

RDOC – Refractory Dissolved Organic Carbon

RDOM – Refractory dissolved organic matter

SAI – Stratospheric Aerosol Injection

SDGs – Sustainable Development Goals (UN)

SRM – Solar Radiation Management

SST – Sea Surface Temperature

UN – United Nations

WCRP – World Climate Research Programme

UNCLOS – The United Nations Convention on the Law of the Sea

UNEP – United Nations Environment Programme (www.unep.org)

UNESCO – United Nations Educational, Scientific and Cultural Organisation

UNFCCC – United Nations Framework Convention on Climate Change

WMO – United Nations World Meteorological Organization (www.wmo.int)

ANNEX VIII – ABBREVIATIONS

Abbreviation	**Meaning**
C	Carbon
CO_2	Carbon Dioxide
^{0}C	Degrees Celsius
E	Exa – prefix meaning 1018
G	Giga – prefix meaning 1,000,000,000 i.e. 10^9
Gt	Gigatonnes i.e. 10^6 tonnes
H	hour
ha	Hectare is a measure of area. 1 hectare is an area equal to a square with 100 metre sides, or 10,000 m^2. There are 100 hectares in 1 km^2.
J/Joule	A unit of energy equal to the energy transferred to an object when a force of 1 newton acts on that object in the direction of its motion through a distance of one metre.
k	Kilo - prefix meaning 1,000 i.e. 10^3
kj/mol	Kilojoules per mol
km	Kilometre
km^2	Square kilometre
M	metres
m^3	Cubic metres
M	Mega - prefix meaning 1 million i.e. 10^6
Mpa	Megapascal i.e. 10^6 Pascals
Mol	The mole is a chemical mass unit in chemistry, defined to be 6.022 x 1023 molecules, atoms, or some other unit.
Molar	Molar concentration is a measure of the concentration of a chemical substance per unit volume of solution.
MW	Megawatts
n	Nano – prefix meaning 10^{-9}
N	Newton – newton is the force needed to accelerate one kilogram of mass at the rate of one metre per second squared in direction of the applied force.
N	Nitrogen
nM	Nanomolar (10^{-9} Moles)
P	Peta – prefix meaning 10^{15}
P	Phosphorus
p	Pico – prefix meaning 10^{-12}
Pa	Pascal – a unit of pressure defined as one newton per square metre.
pCO_2	Partial pressure of carbon dioxide
ppm	Parts per million
Ppmv	Parts per million by volume
P	Peta - prefix meaning 10^{15}
Pmol yr^{-1}	Peta moles per year
Sv	Sverdrup – an oceanographic unit of flow rate. 1 Sv = 1,000,000 m^3 per second
T	Tera – prefix meaning 10^{12}
T	tonnes
µ	Micro – prefix meaning 10^{-6}
µm	Micrometre or micron i.e. 10^{-6} of a metre
WG	Working Group
W/Watts	A unit of power defined as 1 joule per second and is used to quantify the rate of energy transfer.
Watts/m^2	Watts per square metre

ANNEX IX – GESAMP REPORTS AND STUDIES PUBLICATIONS

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