UK-NORWAY
BILATERAL WORKSHOP ON SCIENCE AND THE LAW OF THE ENVIRONMENT

Held on 9 – 10 March 2023

Meeting report

THE ROYAL SOCIETY

Det Norske Videnskaps-Akademi
The Norwegian Academy of Science and Letters

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Cover image
Marine zoological study showing a side view of the male Cuckoo wrasse (*Labrus mixtus*). Plate 12 from the book, *Icones rerum naturalium, ou figures enlumlinees d'histoire naturelle du Nord*, by Peter Ascanius, published in 1772. Peter Ascanius was elected a Fellow of the Royal Society in 1755..

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Introduction

There are many environmental issues where relevant scientific knowledge and applicable international law are both incomplete, and/or do not interact adequately. In order to explore ways in which this situation could be improved, the Royal Society and the Norwegian Academy of Science and Letters (DNVA) convened a bilateral workshop meeting in Oslo, 9 – 10 March 2023. Two contrasting and controversial topics were selected for discussion, one in the atmosphere and one in the ocean, and one where international law is already developed and one where it is lacking. These topics were the Deep Sea Mining of minerals (DSM), and Solar Radiation Management or solar geoengineering (SRM), in particular the Stratospheric Aerosol Injection (SAI) method. The purpose was (a) to improve mutual understanding of the capabilities, limitations and interactions of science and the law relating to these topics, and (b) to produce briefing documents on them, to inform senior policy makers in the UK and Norway (and elsewhere) about the state of knowledge on the technical feasibility and environmental impacts of these two topics, and the implications for the application and development of international law. The participants (listed in Annex 1) comprised scientists and lawyers with expertise in each of the topics, together with additional experts invited to facilitate the process.

Disclaimer

This report is a record of these discussions, and is not a formal statement of the policies of the Society or DNVA. It is based upon two scoping papers that had been prepared beforehand as a basis for the discussions, revised as necessary, together with a summary of the conclusions reached, as agreed by the participants during and after the meeting.

The summary and briefing note is available at **royalsociety.org/uk-norway-bilateral-workshop-science-law-environment**

Mining of deep sea minerals (DSM): environmental and legal implications. Do we need to strengthen the UN Law of the Sea?

1 Introduction

Elements like nickel, cobalt, copper, and manganese are required for the clean energy transition. These elements are abundant on the deep-sea floor in nodules eg in the Pacific, whilst metals such as zinc, lead, gold and silver are found as sulphide deposits in active parts of the mid ocean ridges. Critical raw minerals of importance for industry and subject to high supply-risk include various minerals available from the deep seabed, such as cobalt, platinum, rare earth elements (REEs) and titanium (identified as critical minerals by both EU and US) and manganese, nickel tellurium and zinc (included on the 2022 US list of critical minerals). Which of these elements are most likely to drive deep-sea mining depends on their price and the concentration in deep-sea environments, compared to those of alternative sources, and at present may be Co and Ni. Whether deep sea sources of these prove to be economically favoured depends on the alternative sources and the environmental consequences of their extraction. It is possible that other developments that are considered desirable on environmental grounds (eg greater use of electric vehicles) may be limited, or require a choice between extensive mining on land or deep-sea mining.

There are at present considerable gaps in our basic knowledge of the biodiversity and ecosystem function of the deep ocean, as well as in our knowledge of ocean complexity and how this relates to earth-system processes. Given this high level of uncertainty, it is difficult to judge the appropriate balance between the risks and benefits of deep sea mining, and it would be appropriate to consider how the precautionary principle should be applied. In addition there is considerable interest in moving towards a circular economy, with much greater emphasis on re-use and recycling of scarce resources, including minerals, rather than continuing to exploit new resources. These are fundamentally ethical considerations that are arguably not adequately represented in the UN Law of the Sea and its implications for deep sea mining. This reflects the widespread need to improve the process of rational (evidence-based) policy formation in a context that incorporates both economic and political considerations.

2 Environmental aspects

a) There are various classifications of the types of marine environment from which metals might be extracted (typically into three). It is important to consider these because:

   i. Some types have geographically unique ecosystems and mining would wipe out species, while others environments are widespread so that mining of a portion of the environment would have local impact but less extinction impact.

   ii. Some types are in national waters, while others are not, so the international agreements required will differ.

   iii. There are different types of metal ores (and associated mining challenges)

b) There are many likely environmental impacts of deep-sea mining. For nodule and crust mining the major impact will be habitat loss in the extremely large areas to be mined, combined with adverse effects over a wider area impacted by sediment plumes. These impacts will be exacerbated by the very slow recovery of these ecosystems, some of which will not recover at all eg, the fauna living on and in manganese nodules. For sulphide mining there could be impacts on globally unique hydrothermal vent fauna if proper regulation is not applied. For all mining types, release of returned water into the water column following dewatering of ores on the support vessel could have serious impacts on midwater organisms. Loss of ecosystem function and biodiversity are therefore serious threats related to deep-sea mining[1]. Many other potential impacts have been described such as habitat fragmentation, noise and light pollution and impacts on global geochemical cycles[2, 4].

c) Combined with the considerable gaps in basic knowledge of the biodiversity and ecosystem function of the deep ocean and gaps in our knowledge of ocean complexity and how this relates to earth-system processes, plus clear indications within the existing science base that impacts are likely to be considerable, it can be argued that there is at present an inadequate basis on which to grant mining exploitation contracts[3, 4]. Contractors are currently encouraged to develop an environmental baseline in the exploration phase. This baseline includes a range of critical parameters, under loose headings of oceanography, geology, ocean chemistry and biology. The aim of the environmental baseline is to support the environmental impact assessment and resulting Environmental Impact Statement. It is scrutiny of the EIA and the baseline which will determine whether there are sufficient data and information to understand the impact. Contractors are likely to be the only groups which regularly undertake the necessary sampling of the deep ocean, and the crucial question is whether the data so gathered are sufficient?

d) The centrality of minerals and metals to the future diffusion of low-carbon technologies, implies that materials security and the future potential impacts of proposed deep-seabed mining need to be actively incorporated into formal climate planning. Exploitation technologies and operational practices also need to be able to demonstrate minimal harm to the environment and no net loss of biodiversity. Several assessments (eg one by Fauna & Flora International) suggest that the impacts of deep seabed mining cannot be effectively mitigated or managed, and recommend a moratorium on deep seabed mining at least until a number of specific items have been further investigated and fulfilled[5].

e) The process for establishing such a moratorium, if it were considered necessary, is however not clear. The General Assembly of the UN might be considered an appropriate body to do this. However, the International Seabed Authority (ISA, see section 3) is not an organ of the UN and so it is not clear how it would be implemented. Similarly, if the assembly of the ISA were to agree to a moratorium, there are several issues that would need to be resolved, for example those arising from the two year rule which Nauru has triggered (see section 3(d)). Unless there are appropriate regulations in place, it would be difficult for the ISA to undertake the actions required to establish a moratorium.

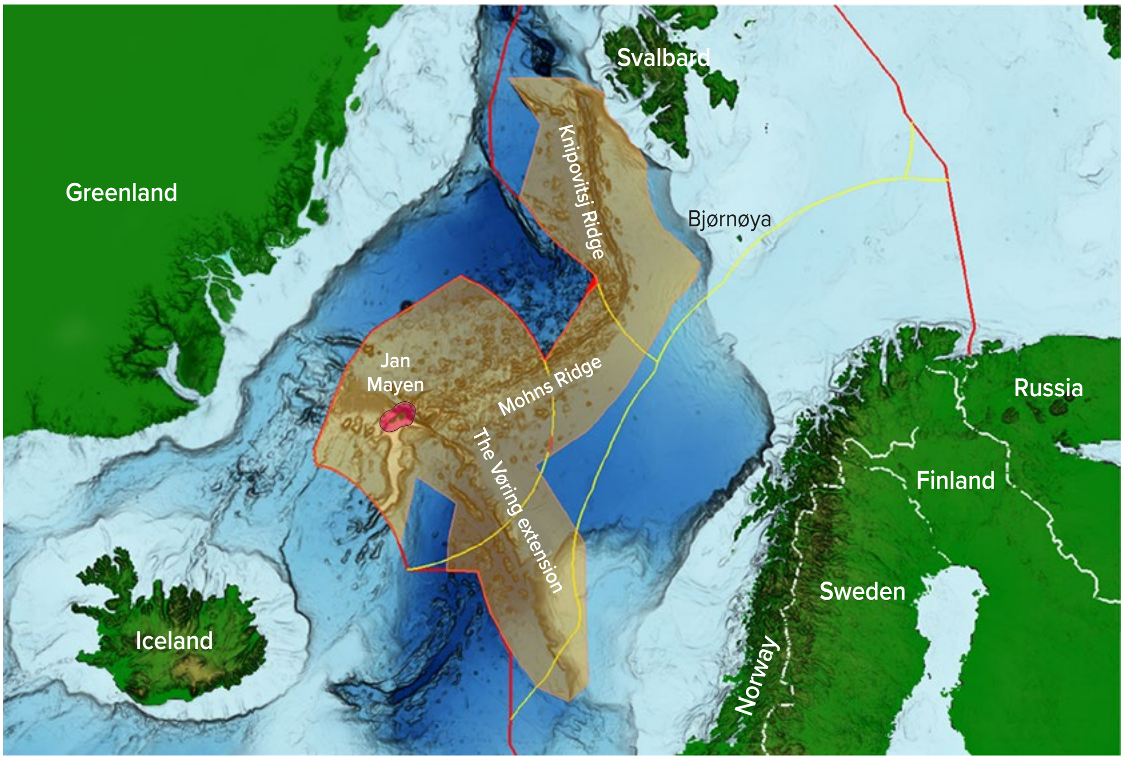
f) Proponents of deep sea mining argue that it may offer a means of securing a dependable supply chain of critical metals, possibly including rare earth elements (REEs) for the energy transition, protected from possible geopolitical ruptures (eg, a Chinese monopoly of REE supplies). Some maintain that it could be preferable from an environmental perspective in comparison to equivalent processes for terrestrial mining (in terms of being less intrusive than comparable land-based mining, potentially directly impacting a smaller area and achieved without the toxic waste products generated by land-based mining)[6]. Critics say this is greenwashing and call for alternatives to DSM to be more fully explored – including recycling of existing materials, reduction of demand and improvement of terrestrial mining methods, in pursuit of a more sustainable, circular economy[3, 6].

3 Legal and ethical aspects

a) Contracts[7] to explore and exploit these resources within 'the Area' (UNCLOS/ISA terminology for areas beyond national jurisdiction) fall under the jurisdiction of the International Seabed Authority (ISA) which is an autonomous international organization established under the 1982 United Nations Convention on the Law of the Sea (UNCLOS)[8] and the 1994 Agreement[9] relating to the Implementation of Part XI of the Convention. The ISA is the organization through which states which are parties to UNCLOS organize and control all mineral-resources-related activities in the Area as the common heritage of mankind. In so doing, the ISA has the mandate to ensure the effective protection of the marine environment from harmful effects that may arise from deep-seabed related activities. It has its headquarters in Kingston, Jamaica and came into existence on 16 November 1994 upon the entry into force of UNCLOS. Whilst the ISA has a mandate, this is not exclusive, as States also have obligations (under Article 209) to protect the marine environment of the Area from activities under their jurisdiction or control. There is however still scope to explore and explain what this mandate means, and how competing values are to be mediated. Within coastal States' EEZs, national regimes apply (subject to the principles of international law regarding marine environmental protection, Environmental Impact Assessment, the precautionary principle, etc.). At present, the ISA is working to develop a comprehensive Mining Code, intended to enhance the regime and govern the entire life cycle of deep seabed mining operations, including the forthcoming exploitation phase.

FIGURE 1

Map showing the area that the Norwegian government has proposed to open for environmental impact assessment (EIA) of ocean sea floor mineral exploration and exploitation. The area covers 592,500 km^2.



Source: Sokkeldirektoratet / The Norwegian Offshore Directorate[10].

b) Norway and the UK together with a few other European countries have parts of the mid ocean ridges positioned within the outer boundary of their continental shelf, see Figure 1. Some of these countries have submitted claims for the exclusive rights to these areas. In relation to deep seabed mining activities within national jurisdiction, various activities have occurred throughout Europe. For example, Nautilus's Solwara 1 project in Papua New Guinea to mine for sulphides at depths of 1,600 metres would have been the first project of its kind, but was halted after Nautilus's financial collapse. In 2017, Japan became first State to successfully trial large-scale deep water mining activities at a depth of 1,600 metres within its EEZ, off the coast of Okinawa. Saudi Arabia and Sudan have revived a project within their national waters, to retrieve sulphides from deep sea mud on ocean floor of Red Sea (Atlantic II Deep project). In Norway, the UK and elsewhere there is significant interest in starting the prospecting and exploitation of mineral resources within the boundaries of the sea floor claimed nationally.

The Norwegian Government on 20 June 2023 submitted a White Paper (No. 25, 2022 – 2023) to the Norwegian national assembly proposing to open up for mineral exploration and eventual exploitation on the Norwegian continental shelf provided the seabed mineral resources can be managed within sound and sustainable frameworks based on the precautionary principle and an ecosystem-based approach[11]. The UK and other countries also have specific interests in the Pacific in the Clarion Clipperton Zone.

c) Internationally there is also widespread interest in exploiting deep sea minerals and elements within the Area for economic gain. The ISA has signed 31 contracts for exploration of the sea floor in regions in the western Pacific, along the mid-Atlantic ridge and in the Indian Ocean. The expectation is that each of these will lead to an exploitation contract[12] and, in anticipation, the technology is being developed by numerous organisations, but no applications for exploitation contracts have been made as yet.

d) Nauru has requested that the rules for approving such contracts be finalised by 2023. The time limit for exploitation was initiated by Nauru under paragraph 15 of section 1 of the Annex to the Agreement relating to the implementation of Part XI. This provides the context for the urgent need to respond to the pressure to stop or control mining.

e) Nevertheless, the consequences of deep ocean floor industrial activity are still not well understood, while European countries and industry obviously have an interest in taking a lead.

f) Some guidance on the requirements for EIAs (including those in areas within national jurisdiction) has been provided by the existing Exploration Regulations, but the examples provided have been criticised[4, 13], and the requirements under the Exploitation Regulations may be different.

g) There are ethical issues beyond harm to the environment that are relevant, for example trade-off of different harms, and benefits from potentially competing needs such as green technology versus ecosystem functions. Categorisation and quantification of such issues (eg economic value, inherent values, who decides or should speak for non-commercial interests, (some may consider that states and the ISA are complicit in the exploitation aspects of the regime, so that states may not be able to speak objectively about competing environmental concerns).

h) Other legal/ethical considerations to take into account include:
   i. Concerns re the potential negative impact of DSM on the economies of developing States that are land-based mineral producers;
   ii. The need to take into account impacts on the natural capital of the seabed (including ecosystem services) when gauging economic costs and benefits of DSM;
   iii. The extent to which the developing DSM regime can continue to evolve and adapt to address emerging challenges as more becomes known re impacts of DSM activities;
   iv. the nature of the Area as a global commons;
   v. the Biodiversity Beyond National Jurisdiction (BBNJ) negotiations which will in part fill a gap, when they have entered into force.

4 Why should the Royal Society and The Norwegian Academy of Science and Letters engage in the matter?

a) There is a growing concern nationally and internationally about the potential consequences of ocean floor mining, not least because the deep ocean floor is still largely unexplored, but has complex and biologically diverse ecosystems. Life in the deep ocean also supports important long term carbon sequestration processes and hence influences the regulation of the climate system. Significant ocean impacts, such as loss of biodiversity, from sea floor activities and mining can be of global consequence. The environmental concerns have since 2011 led to a call for a moratorium of deep-sea mining and exploitation. Several countries and multinational companies like Google, BMW, Volvo and Samsung SD have now signed a call from World Wildlife Foundation (WWF) to this effect.

b) If mining has to take place, it is important to find the mining method with the least environmental impact. The choice at the moment is between land mining and deep sea mining (or a combination of these). It is therefore important to compare the different advantages and disadvantages of land mining and deep sea mining to be able to find the best solution.

c) However, the carbon storage potential of deep-sea sediments is often overstated. Most metal-rich environments have very low (or zero) sedimentation rates, and hence effectively zero carbon uptake. The biodiversity impacts are likely to be the important ones. An important component of this is the genetic diversity of the environment, which is a resource that we have barely started to understand or exploit. It is often characterised by Digital Sequence Information (DSI), which is already a contentious topic in various UN legal discussions of the environment and its resources (including in Convention on Biological Diversity).

d) Norway and the UK together with a few other European countries have parts of the mid ocean ridges positioned within the outer boundary of their continental shelf, see Figure 1, and section 3(b) above. It is therefore a timely topic for a joint workshop between the Royal Society and The Norwegian Academy of Science and Letters in order to:
   i. lay out the scientific status of knowledge of the deep ocean floor minerals and elements, the technology available and required for their mapping and exploitation, and the environmental consequences thereof; and
   ii. examine the adequacy of the international legal framework for effective protection and safeguarding of this part of the global commons.

5 Potential problems: what might go wrong?

a) For nodule and crust mining the problem is the scale of the mining operations that will destroy vast areas of the surface of the seabed year after year. For nodules about 90 km^2 will be destroyed per million tons of mined ore, and each contractor will mine between 2 and 12 Mt per year and there are currently 19 contracts for exploration[1, 4]. This could mean destruction of 3,400 to 20,500 km^2 of seabed per year. For crusts the destruction rate will be around 25 km^2 per year per million tons of mined ore, with a minimum of 2 Mt to be mined per contractor per year and currently 5 exploration contracts. This equates to destruction of at least 250 km^2 of guyot and seamount tops per year. Plume generation will be particularly bad in nodule areas due to the fine-grained mud and could potentially double the area impacted. The mining will take place in areas where the ecosystems are poorly understood but probably include many long-lived animals that reproduce very slowly. Each sample collected in nodule areas in the central Pacific still has more new species than known ones. Experiments show extremely slow recovery rates in nodule areas and the inability of many animals to return, because their substrate (the nodules) has been permanently removed or altered[4, 14].

b) Polymetallic sulphides are formed at hydrothermal vents and exploration is concentrated around active hydrothermal vents which are relatively easy to locate. Active vents have unique ecosystems and species that are very rare. Mining, however, is not likely on hot vents and is more likely to occur on inactive and extinct vents within 10 – 20 km of the ocean ridge axis. Since these ore bodies could be quite large and are three-dimensional, mining could be located on a small site for many years. Regulations could be devised to prevent impacts from extraction and plumes on active vents and any other vulnerable ecosystems such as coral gardens, but have not yet been established.

c) De-watering of all ores on the support vessel will require the dumping of the produced water which will be contaminated with particles and potentially toxic materials in large amounts over long periods of time. This could have major impacts in mid-water organisms, eg filter feeding animals. Regulations could require this water to be dumped near the seabed where it will mix with the benthic sediment plume generated by the mining process.

d) In all cases so far the exploration contracts appear to give rights to the contractor with the expectation that they can apply to mine anywhere in their exploration area. For example, there are no conservation measures in the 1.25 million km^2 of contract blocks in the Clarion Clipperton Zone – all conservation areas had to be defined outside of the area of contract blocks. Many active hydrothermal vent sites lie within exploration blocks along the mid-Atlantic ridge, and it has been suggested[13] that these and any new ones found should be protected, but it is not clear whether contractors may have prior rights to mine them.

6 Options for action with their advantages and disadvantages

a) Actions could include trying to persuade the ISA to develop more specific regulations, eg regulations could be considered to limit the amount of mining in any contract block or larger area, though this might be difficult unless the ISA has a mandate to set such limits. Regulations could also be established to control plume generation and spread, and require the returned water plume to be discharged near the seabed.

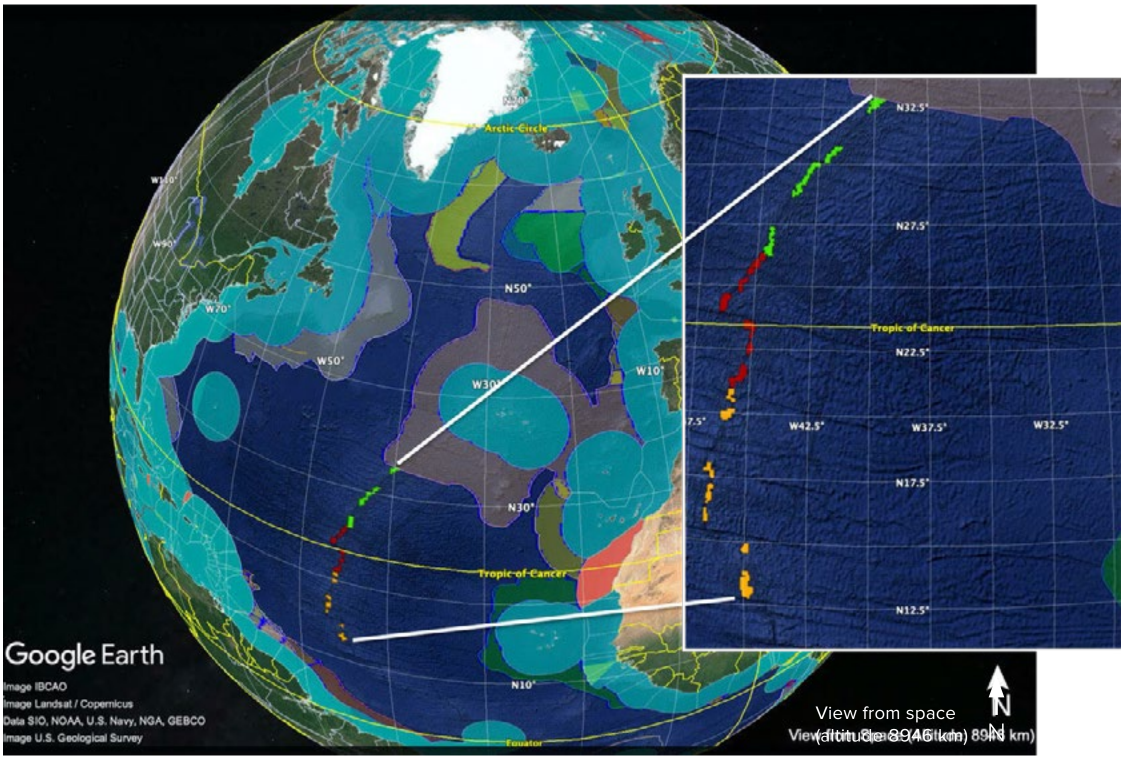
b) In addition, actions could be aimed at improving the governance structure within the ISA. There have been calls for the Legal and Technical Commission (LTC) to have a standing committee on science, so that it would have better access to relevant information, especially on environmental aspects where at present it has limited expertise. This has so far been resisted by the LTC and ISA secretariat, but it would have substantial long-term benefits.

c) The ISA could also be encouraged to create a regulatory body to oversee the activities of the contractors and to further develop the mining code including its requirements for environmental protection. This body could be separated from the current secretariat which has the dual remit of promoting mining and protecting the environment. Such a body is envisaged under UNCLOS but its establishment is being delayed until mining begins, which will be too late. Input to the mining code from people with a marine regulatory background would also be beneficial.

d) The ISA is currently drawing up its mining code to regulate deep sea mining with a large amount of text already produced for the main code and for standards and guidelines to accompany the code. The drafting is being carried out by the ISA's Legal and Technical Commission (LTC) on behalf of the ISA's Council with work being done behind closed doors. Input to the process can be through the Council – the UK and Norway share an alternating seat on the Council, with the UK being active in 2022 and Norway in 2023. The Foreign Office take the lead for the UK. Input could also be made through the Assembly (167 states plus the EU). Contractors and observers also attend and make comments at Assembly meetings. The biggest impacts are made when member states combine to write a common submission especially if the states are distributed around the World. States that sit on Council may therefore have the biggest impact[15].

FIGURE 2

Map of the North Atlantic showing 200 mile limits and extended continental shelf claims. Three exploration claim areas are shown south of the Azores along the mid-Atlantic Ridge.



KEY

- Poland
- France
- Russian Federation

Source: The Atlantic Regional Environmental Management Plan (REMP) Project[16].

Workshop conclusions and recommendations for deep sea mining of minerals (DSM)

In relation to deep sea mining of minerals (DSM), the participants noted that:

1. There have been substantial developments in international law* since the adoption of UNCLOS in 1982 and the 1994 Agreement on the implementation of Part XI, that will significantly affect the procedures of the International Seabed Authority (ISA) for managing exploration and exploitation of deep sea minerals, especially in relation to protection of the marine environment and its biodiversity.
2. Some substantive consequences of these developments (for example requirements relating to Environmental Impact Assessments and Management Plans) may conflict with some operational targets such as the two-year rule, and may eventually have to take precedence over them.
3. There is nevertheless at present considerable urgency to define the environmental thresholds for action required for implementation of the ISA exploitation regulations under current schedules.
4. The size of long-term future markets for minerals that are at present in short supply (notably nickel and cobalt) are uncertain, especially because rapid development of alternative battery technologies may lead to reductions of demand, reducing the economic incentives to undertake deep sea mining.
5. There are major uncertainties (knowledge gaps) in our understanding of the structure and function of deep-sea ecosystems, that limit our ability to ensure that the marine environment and biodiversity are adequately protected.
6. The ISA is responsible both for regulating exploration and exploitation activities in the deep seabed, consistent with the common heritage of mankind principle, while ensuring that mining activities are undertaken in a manner that ensures effective protection of the marine environment, and there are tensions imposed by the need to reconcile these objectives.
7. Some states have called for a moratorium on exploitation, but the legal basis for this, the level of support for it, and practical aspects of its application all remain uncertain, given the near universal international acceptance of the UNCLOS regime for DSM, and the difficulties likely to be encountered in seeking to amend or otherwise suspend the regime.
8. The Legal and Technical Commission (LTC) of the ISA has limited capacity for the evaluation of environmental issues, and would benefit from further development of partnerships that facilitate greater access to relevant external expertise.
9. The ISA Strategic Plan for Marine Science (ISBA/25/A/15) includes Strategic Direction 4: to provide and encourage marine scientific research in the Area by forming a strategic alliance to assist in the promotion of marine scientific research directed towards providing the scientific knowledge necessary to ensure effective protection of the marine environment.

They concluded that it would be highly desirable

10. To continue to establish new strategic partnerships to facilitate access by the ISA and LTC to appropriate independent expertise on marine environmental science, in accordance with Strategic Direction 4, as is being planned for the establishment of the thresholds for action required for the finalisation of the ISA exploitation regulations.
11. For the ISA to establish the Inspectorate envisaged under the exploitation regulations, in good time to minimise any conflict of interest and to ensure that sufficient pre-exploitation monitoring is undertaken to establish environmental baseline conditions with adequate precision.
12. For Environmental Impact Assessments, and scientific investigations such as monitoring that are conducted by contractors and consultants, to be peer-reviewed by appropriate groups of independent experts, as part of the public consultations required by the draft regulations for exploitation.

* These include; The Convention on Biological Diversity (CBD, 1992) and associated Protocols; The Protocol to the London Convention (LCP, 1996);The Johannesburg Declaration on Sustainable Development (2002) and the adoption of the Sustainable Development Goals (2015); and most recently the Agreement on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ) in 2023.

13. For the large-scale development of exploitation to be delayed until scientific understanding of the deep sea environment and its ecosystems is sufficient for the impacts of deep sea mining to be adequately assessed, and for a mechanism to fund the necessary research to have been established.

14. To ensure transparency by facilitating public access to reports of the results of scientific investigations and of the proceedings of relevant expert groups, for example by ensuring that environmental data produced by contractors are made available in a timely way through the ISA DeepData portal, and that EIAs are made available for peer review by the Council before decisions are made as to the issuing of contracts for exploitation.

15. To promote capacity-building for scientific investigations to address the high uncertainties especially in relation to the structure and function of deep-sea ecosystems.

16. To ensure adequate attention to ethical aspects of exploitation of resources, especially in relation to issues of informed public consent, and inter-generational equity.

The participants therefore suggest that

17. The Royal Society and DNVA could assist the ISA:
    a) to set up strategic partnerships, ideally with participation of appropriate international organisations such as the Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP);
    b) to convene expert scientific and technical working groups to provide urgent advice that may be required to enable finalisation of the exploitation regulations.

18. The Royal Society and DNVA could organise expert workshops and facilitate links to expertise, to assist the ISA in their development of the exploitation and exploration regulations, standards and guidelines, and advise on:
    a) the evaluation of scientific knowledge gaps, and the research necessary to close such gaps;
    b) expanding the potential for industrial co-funding of relevant research;
    c) the scope, scale and quality standards for monitoring, including independent monitoring needed to verify that undertaken by contractors, and to extend this beyond exploited areas to determine any far-field effects;
    d) the appropriate application of the precautionary approach, for example by limiting the rate of expansion of exploitation activity (a possible subject of a workshop with the ISA and contractors).

19. Advice on the composition and effective operation of scientific advisory groups could be based on that available from the OECD and others.

20. Monitoring outside the exploited areas could well be coordinated and financed by a consortium of contractors, using the Joint Industry Programme model used by the oil and gas industry.

21. The ISA could consider setting in advance a progressive upper limit on the total area where exploitation is permitted (or the quantity of minerals that can be harvested), in a way that does not benefit one contractor over another, and so enable the results of research and monitoring to be used to guide the gradual development of both exploitation activity and measures to ensure its satisfactory regulation.

Does international law need to evolve to prevent unilateral implementation of solar radiation management (SRM)? If so, how?

1 Introduction: Why solar radiation management may be needed

It is widely recognised that an adequate response to the global climate crisis requires massive reductions of greenhouse gas emissions. Current plans for the necessary transformation of the global energy system are however also recognized to be inadequate to meet the goals of the Paris Agreement (see eg the UNEP Emissions gap report 2022[17]). Other possible so-called climate intervention responses include development of methods to remove greenhouse gases (especially carbon dioxide) from the atmosphere (CDR), and solar geoengineering technologies. Such technologies have been reviewed *inter alia* by the UK Royal Society (2009)[18] and the US National Academy of Science (2015)[19]. They are as yet not fully developed and remain the subject of ongoing research[20].

2 Solar geoengineering or solar radiation modification, science perspectives

2.1 In solar geoengineering, or solar radiation modification (SRM), engineering techniques are applied to slightly increase the proportion of incoming solar radiation that is reflected back to outer space. It is not a substitute for reducing greenhouse gas emissions, but applied on the right scale it is hypothesized that it could act as a temporary measure to limit warming while the mitigation of greenhouse gas emissions is enforced.

For this meeting the focus was on solar radiation modification by stratospheric aerosol injection (SAI). Solar geoengineering sometimes also includes marine cloud brightening (MCB) which increases scattering of solar radiation, and/or cirrus cloud thinning (CCT) which allows more heat to escape to space. SAI takes place in the stratosphere where particles that are deposited there typically will reside there for 1 – 2 years and therefore SAI has a global impact, while MCB and CCT involve emitting particulate matter in the troposphere where it typically will reside for (much) less than a month and have a primarily regional impact.

2.2 In IPCC Assessment Report 6 from WGIII[21] a thorough assessment is provided on the state of the science of solar radiation management. A cross-working group summary assesses Solar Radiation Modification (SRM) proposals, not only stratospheric aerosol injection (SAI), but also Marine Cloud Brightening (MCB), Cirrus Cloud Thinning (CCT) etc, their potential contribution to reducing or increasing climate risk, as well as other risks they may pose (categorised as risks from responses to climate change), and related perception, ethics and governance questions. Material for reflection and possible recommendations for future research and governance can be found there[22].

2.3 As solar geoengineering has the potential to reduce the rate of warming or maintain global mean surface temperatures by increasing planetary albedo, many aspects of climate change could conceivably be offset. It could indeed over-compensate for the projected increase in global-mean precipitation, producing a net reduction in global mean precipitation. There are therefore concerns that solar geoengineering could produce regional shifts in hydrological conditions that would be greater or more harmful than those expected under climate change.

Irvine *et al*[23], analysed the fraction of locations that see the magnitude of local climate change increased (exacerbated) or decreased (moderated) by solar geoengineering deployed to halve future warming. Halving the warming it turned out that the net reduction in global-mean precipitation seen in scenarios that offset all warming, was avoided. In their idealized simulations, they found that temperature and extreme temperature was reduced in all locations and most regions saw reduced changes in water availability and extreme precipitation, with only a small minority (less than 0.4 %) of the ice-free land area saw greater change in these hydrological variables. They also found that the CO_2-induced increase in simulated tropical cyclone intensity was largely offset despite the fact that the warming was only halved.

In a follow-on paper in 2020 Irvine and Keith confirmed that similar results held for a realistic simulation of stratospheric aerosol geoengineering[24]. In their prior work it was found that halving warming with an idealized solar constant reduction would substantially reduce climate change overall, exacerbating change in a small fraction of places. With a more realistic representation of stratospheric aerosol geoengineering using the data from the geoengineering large ensemble (GLENS) and using a linearized scaling of it, they found that halving warming with stratospheric aerosols moderates important climate hazards in almost all regions. The dampening effect of such a 'half-solar geoengineering' measure seems to be quite evenly spread and also extend to quantities such as 5-day extreme precipitation and moisture availability (precipitation minus evaporation). Thus, while concerns about the spatial inequality of solar geoengineering impacts are appropriate, the GeoMIP[25] results[26] indicate that the quantitative extent of inequality may be overstated.

2.4 There are, however, reasons to caution against relying too heavily on these kinds of model conclusions when building a case for or against solar aerosols injection (SAI), for two main reasons:

i. Limitations in modelling. Current models, even if they show overall agreement in their SAI response as documented by Irvine *et al*, have a range of known issues. Firstly, aerosol processes – notably aerosol-cloud interactions, but also cloud responses to top-of-atmosphere cooling in general – are poorly represented and/or not well validated. One indicator of this is the role cloud representation seems to play in the wide spread of climate sensitivities in CMIP6 models. For SAI, this means that there is a lack of both process understanding and observational validation that may affect the global and regional responses of many models in similar ways (since they build on the same limited knowledge). More importantly, though, many models have significant, well known biases in their climatologies in many highly populated areas, including Africa and South and East Asia, which means that even if the overall SAI response was correct, regional responses (in precipitation, winds, seasonality, ...) will not be. We have a wide range of literature now that documents very strong climate effects from regional aerosol changes, but also very low model agreement, due to heterogeneity in process representation, climatologies and dynamical interactions with modes of variability. Even if the SAI forcing is at top-of-atmosphere, some of the same issues in regional responses will be relevant.

ii. Limitations in the questions that have been posed. There are more recent concerns that may perhaps be less recognized. For example there is increasing recognition that the physical hazards the modelling community is quantifying, such as extreme precipitation indicators or precipitation minus evaporation, are not necessarily the quantities that cause actual impacts on society or nature. A simple example is that once one looks at the effects of SAI on global monsoon precipitation, rather than regional mean or extreme precipitation, the conclusions seem to be that SAI has an outsized effect relative to global warming.

2.5 Sun *et al*[27], found that for the same amount of stratospheric aerosol injection, a larger reduction in global temperature occurs under tropical SAI compared with Arctic SAI. The simulated result in the last 40 years shows that, for a 10 Tg/yr injection, global monsoon precipitation decreases by 1.1 % (relative to the 1 % annual increase in CO_2 experiment) under Arctic SAI, which is weaker than under tropical SAI (1.9 %). Further, tropical SAI suppresses precipitation globally, but Arctic SAI reduces the Northern Hemisphere monsoon (NHM) precipitation by 2.3 % and increases the Southern Hemisphere monsoon (SHM) precipitation by 0.7 %. These results do not seem consistent with the results reported above by Irvine *et al*. The effects of both a weakened and a strengthened monsoon are dramatic, evidence of which may be a part of the global monsoon variability seen in recent years. Hence, we first need to use (or even develop) hazard indicators (and metrics) that are more representative of actual impacts, and then quantify them in an SAI context (keeping in mind the challenges mentioned in point (i) above. Next, there is a need to connect to the communities that assess the full extent of climate risk, i.e. including vulnerabilities and exposure to these expanded hazards. All this is doable, and speaks to an increased effort in SAI research, but as of yet there is only little available knowledge beyond the 'standard' hazard indicators, or in terms of full blown climate risk assessments.

2.6 We lack robust knowledge on the efficacy and consequences of solar radiation management (SRM) on a wide range of scales, and developing this knowledge would likely require large and interdisciplinary research programs that apply a wide range of tools in order to understand processes ranging from the aerosol microphysics in an injected aerosol plume to the response of the large-scale atmospheric dynamics and associated precipitation changes.

3 To what extent is solar radiation management technically and economically feasible?

3.1 In a review of possible very high-altitude platforms for stratospheric aerosol injection, Smith *et al* (2022)[28] state that there is increasing confidence that SAI deployment would be both aeronautically feasible and extraordinarily cheap relative to other prospective measures by which to combat climate change or its impacts. They further summarize the literature on SAI deployment by saying that in order to achieve an atmospheric endurance on the order of 12 – 18 months rather than mere days or weeks, aerosols intended to cool the planet would need to be deployed above the vertically turbulent troposphere and in the relatively quiescent stratosphere.

If deployments occurred in the tropics and subtropics, this implies deployment altitudes above 16 km. To avoid having material immediately re-enter the troposphere as well as to allow for atmospheric and seasonal variation, a deployment altitude of 20 km is commonly assumed. Studies of alternative lofting concepts such as balloons, rockets, guns, or tethered hoses conclude that at 20 km, the most efficient and reliable lofting technology would be fixed wing, self-propelled, air-breathing jets. Few jets can achieve such an altitude and those that do carry comparably tiny payloads. However, conceptual design studies show that a fleet of jets appropriate to the deployment mission could be reliably created using existing engines, wing planforms, and sub-systems for a developmental budget of a few billion dollars[29]. This would be a novel assemblage of well-established technologies.

However, modelling studies have suggested that higher deployment altitudes are positively correlated with atmospheric endurance, yielding a greater stratospheric aerosol mass and therefore radiative forcing efficacy per unit of aerosol deployed. Moreover, compared to injections at lower altitude, injecting sulfur at higher altitude results in less heating of the tropopause which, in turn, reduces the amount of water vapor that is lofted into the stratosphere. Water vapor enhances the longwave radiative forcing in the stratosphere and reduces the thickness of the total column ozone. At latitudes in the tropics and subtropics considered viable for deployment, achieving a targeted level of cooling would require roughly 80% more material were it deployed at or near the tropopause relative to a deployment 5 km above the tropopause.

3.2 High-altitude injection at 25 km would substantially enhance the forcing efficacy of the aerosols compared to injections at 20 km. Studies assessing the feasibility of deployment platforms at an altitude of 25 km seem to be lacking. No existing aircraft is suitable for this purpose. In their paper Smith *et al*, 2022 review five possible concepts[30] for deployment at 25 km and conclude that all of them would multiply costs, complexity, and operational risk substantially relative to deployment at 20 km.

3.3 Recently Gao *et al*[31], published a geoengineering procedure that builds on existing technology and with some observational backing for it. They reported observations of pyrocumulonimbus clouds being formed above forest fires in Oregon, United States during the summer of 2017. These clouds are thunderstorms bringing fire and smoke to the top of the troposphere (12 – 14 km) where the temperature stratification suppresses further vertical transport into the stratosphere. In the Oregon fires it was seen that its content of soot (black carbon) which absorbs solar radiation efficiently gave rise to enhanced buoyancy which brought particulate material to 20 km height where its residence time is long (a year or more). Gao *et al* (2021) made model calculations of what it would take of man-made soot and particles in the upper troposphere to obtain a particle layer in the stratosphere which would enhance the global albedo sufficiently to slow down climate change. Loads of particles mixed with soot can be transported to 12 – 14 km altitude in the upper troposphere with existing aircraft. This is not possible with existing technology to stratospheric levels of 18 – 20 km.

3.4 In a review paper published in 2018 of stratospheric aerosol injection tactics and costs in the first 15 years of deployment, Smith and Wagner[32] summarized the findings: In a future solar geoengineering deployment scenario, the increase in anthropogenic radiative forcing beginning 15 years hence is halved by deploying material to altitudes as high as ~ 20 km. After surveying an exhaustive list of potential deployment techniques, they settled upon an aircraft-based delivery system, and concluded that no existing aircraft design—even with extensive modifications—can reasonably fulfill this mission. However, they also concluded that developing a new, purpose-built high-altitude tanker with substantial payload capabilities would neither be technologically difficult nor prohibitively expensive. They calculated early-year costs of ~ $1,500 per ton of material deployed, resulting in average costs of ~ $2.25 billion/yr over the first 15 years of deployment. They further calculated the number of flights at ~ 4,000 in year one, linearly increasing by ~ 4,000/yr. They argued that, while cheap, such an aircraft-based program would unlikely be a secret, given the need for thousands of flights annually by airliner-sized aircraft operating from an international array of bases.

4 Open science issues around solar radiation management

There are at least two major scientific uncertainties in addition to those concerning the likely beneficial impacts of SRM, and those concerning its technical feasibility. First of all there are uncertainties in assessing the adverse effects from solar radiation management that need significant global attention. Second, it is possible that solar radiation management may exacerbate other related environmental issues.

4.1 Uncertainties in assessing the adverse effects from solar radi ation management

It is not clear whether the potential adverse effects from solar geoengineering are capable of being represented adequately in current generation models, given the known shortcomings of these models. In a Perspective paper in PNAS[33] Tim Palmer and Bjorn Stevens note that "Even after being tuned to match observed irradiance at the top of the atmosphere, models differ among themselves in their estimates of surface temperature by an amount that is 2 to 3 times as large as the observed warming and larger yet than the estimated 0.5 °C uncertainty in the observations. The de-emphasis of this type of information, while helpful for focusing the reader on the settled science, contributes to the impression that, while climate models can never be perfect, they are largely fit for purpose. However, for many key applications that require regional climate model output or for assessing large-scale changes from small-scale processes, we believe that the current generation of models is not fit for purpose."

Similarly, in a *Comment in Nature Climate Change*[34] Julia Slingo *et al*, argue that "ambitious partnership (is) needed for reliable climate prediction. Current global climate models struggle to represent precipitation and related extreme events, with serious implications for the physical evidence base to support climate actions. A leap to kilometre-scale models could overcome this shortcoming but requires collaboration on an unprecedented scale."

It is moreover not clear what criteria should be used to judge whether a climate model is good enough to be used to assess the potential for significant favourable or adverse effects compared to the climate change effects they are trying to offset. Indeed, if there is to be (say) a UN body of scientists to inform world leaders on the impacts of solar geoengineering, does this body have the tools to make informed recommendations? If not, what is needed? It has been suggested (Tim Palmer, pers comm) that this may include "one or more federated 'CERN for Climate Change' institutes that would accelerate the development of km-scale global climate models, to be run on dedicated exascale computers. Such models, in my view, are a sine qua non for taking solar geoengineering seriously."

4.2 Solar radiation management could exacerbate related environmental issues

Solar radiation management may exacerbate related environmental issues, such as depletion of stratospheric ozone. In the 2022 Quadrennial stratospheric ozone assessment there is a chapter in "Stratospheric aerosol injection and potential impacts on ozone"[35]. In the executive summary it says that:

"Stratospheric Aerosol Injection (SAI) has the potential to reduce global mean temperatures. However, SAI cannot fully offset the widespread effects of global warming and produces unintended consequences, including effects on ozone. Details of these effects depend on the specifics of the SAI scenario and SAI injection strategy. Model simulations of SAI reveal large differences in surface cooling per unit sulfur injected, which are attributed to differences in representing key processes. The net effects of large-scale SAI on stratospheric ozone are mainly driven by i) increases in aerosol surface area, ii) stratospheric halogen and nitrogen concentrations, and iii) aerosol-induced heating of the stratosphere, which change both stratospheric ozone chemistry and stratospheric dynamics. These simulated changes are strongly model-dependent.

Additional ozone depletion due to SAI is simulated in spring over Antarctica, with magnitudes dependent on the injection rate and timing. Simulations of strong SAI show an increase in total column ozone (TCO) in mid-latitudes (40 – 60 °N) in the winter Northern Hemisphere.

The injection of aerosols other than sulfate is expected to change the effects on ozone via associated changes in heterogeneous chemistry, dynamics and transport. Aerosol types that are more chemically inert and absorb less solar radiation may reduce chemical and dynamical impacts on stratospheric ozone respectively. However, the laboratory studies and climate model simulations sufficient to quantify these effects have yet to be performed."

4.3 **Ocean acidification, acid rain, black carbon deposition**
The rate of ocean acidification would not directly be influenced by solar radiation management, so mitigation of CO_2 emissions would still need to continue and be intensified. The injection of sulphate aerosol particles in solar radiation management would contribute to acid rain, although the quantities required would not be large in comparison with other anthropogenic sources. If black carbon particles were used instead, their deposition on light surfaces like sea ice or glaciers could cause a decrease in global albedo causing more radiative heat to be trapped in the earth-atmosphere system. Such unintended consequences could have significant transboundary impacts and create additional environmental problems and geopolitical tensions.

The deposition of particulate matter in the stratosphere would need to be repeated every one or two years, depending on the estimated residence times of the particulate matter. The permanent character required in solar radiation management needs to be properly assessed. If the consequences of geoengineering prove not to be as expected, and the intervention needs to be discontinued, then the global atmospheric temperature could increase sharply in a so-called 'termination shock'.

5 Current state of research on solar radiation management, and ethical implications

5.1 In the summer of 2022 there was a Gordon Research Conference on Climate Engineering[36]. One reflection after the conference is that there is actually now a very large body of research being carried out in the US on solar radiation management, and particularly marine cloud brightening (MCB) and stratospheric aerosol injection (SAI). Some of the most respected US atmospheric science departments (eg University of Washington and Harvard University) have large research groups working on this topic, and likewise NOAA, DoE and NASA labs are deeply engaged in this research.

5.2 Nevertheless, there are also researchers who are strongly opposed to even doing research on this topic, whether it is in the form of numerical model simulations or small-scale field experiments (for the purpose of process understanding rather than climate intervention). A common argument is that the research will itself increase the likelihood of implementation, but in fact research will often rather reveal new undesirable side effects associated with implementation of solar radiation management, and could thus equally well provide discouragement for it.

5.3 Others will simply argue that there are more important and urgent problems for climate researchers to address than solar radiation management. In Europe, the impression is that this view is even more widespread, and the lack of ongoing European research projects on solar radiation management (both on the national and EU level) is a testament to that.

5.4 Meanwhile, developing countries, many of which are carrying the brunt of the consequences of unmitigated global warming, are turning their attention to evaluating the balance of risks and possible benefits of such technology[37]. The likelihood of implementation increases with every year of mitigation inaction that goes by, and the technology necessary for implementation is currently being developed. For example, a recent paper which received considerable media attention presents a delivery method for aerosols into the Arctic stratosphere, but alarmingly there has hardly been any research on how the climate system would actually respond to such an implementation[38].

5.5 Robust knowledge on the efficacy and consequences of SRM on a wide range of scales is lacking, and developing this knowledge would likely require large and interdisciplinary research programmes that apply a wide range of tools in order to understand processes ranging from the aerosol microphysics in an injected aerosol plume to the response of the large-scale atmospheric dynamics and associated precipitation changes. Research may well uncover evidence to motivate abandoning the technology rather than developing it. Premature implementation with our current (poor) state of knowledge would be extremely risky, and it would be naive for researchers to ignore the problem and hope that it will go away.

6 Ethical aspects of geoengineering research: the Oxford Principles

The Oxford Principles of geoengineering research[39] were submitted to UK House of Commons Science and Technology Select Committee in December 2009. The Committee endorsed the principles and recommended that they be developed further. In its official response, the UK government likewise endorsed the principles. This endorsement is the first (and only?) official national-level policy statement on geoengineering in the world to date and represents an important step forward in ensuring that research into geoengineering is carried out in a responsible manner.

The Oxford Principles are as follows:

i. Geoengineering to be regulated as a public good.

ii. Public participation in geoengineering decision-making

iii. Disclosure of geoengineering research and open publication of results

iv. Independent assessment of impacts

v. Governance before deployment

7 International law on solar radiation management

7.1 Geoengineering which may involve deliberately changing the global albedo by releasing substances into the atmosphere with large and unforeseen consequences, is to some extent covered by applying general rules, eg. customary international legal rules on transboundary harm and environmental impact assessment (EIA) or general treaty rules relating to biodiversity (CBD) or on the protection of the oceans (UNCLOS). However, none of these were framed with geoengineering in mind, and their adequacy is doubtful, so further developments may be necessary. Some possibilities are as follows:

7.2 **The UN International Law Commission and Protection of the Atmosphere**

The UN International Law Commission has completed its work on 'Protection of the Atmosphere'. The Special Rapporteur of the UN International Law Commission on Protection of the Atmosphere and International Law was professor Shinya Murase[40]. The International Law Commission (ILC) is composed of 34 international lawyers working in their individual capacity, and is one of the major lawmaking organs of the United Nations. Edvard Hambro and Jens Evensen, two leading Norwegian international law experts, made great contributions as its members from Norway in the 1970s and 1980s. The ILC commenced its work on the 'Protection of the Atmosphere' in 2014. ILC has considered the topic with the reports by the Special Rapporteur as input[41]. The ILC concluded its work on the topic in July 2021, with the adoption of the draft guidelines and the commentaries thereto[42]. With the conclusion of that work, Professor Murase is no longer Special Rapporteur. The UN General Assembly Sixth (Legal) Committee discussed the draft guidelines at the October – November 2021 session and resolution 76/112 was adopted[43]. Professor Murase does not think there will be any further development for making the draft guidelines into a binding convention, and that it is unlikely that the law of the atmosphere will become an autonomous branch of international law (like the law of the sea, law of outer space, etc.) in the foreseeable future[44].

In its reports the ILC says that the atmosphere, being a dynamic and fluctuating substance, needs to be treated as 'One Atmosphere,' while the existing treaties are fragmented, leaving significant gaps in terms of geographic coverage, regulated activities, controlled substances and applicable legal rules. In The Special Rapporteur's Fourth Report in 2017 is discussed the question of 'interrelationship' with other fields of international law, most notably, the law of the sea. There are intrinsic links between the atmosphere and the oceans. Maritime environment is gravely affected by pollution from or through the atmosphere, while the changes in the conditions of the sea have been considered as causing extreme weather and natural disasters on land. Sea level rise and its effects (eg forced migration from low-lying or small island countries) are the questions that need to be tackled by international law. Collaboration with atmospheric scientists has proven to be indispensable in the ILC's exercise of progressive development of international law on the topic[45].

The ILC's set of guidelines on the Protection of the Atmosphere would provide a basis for elaborating a framework convention, dealing with the questions of both transboundary air pollution and climate change in a comprehensive manner, that could be modeled after Part XII (on the maritime environment) of the 1982 UN Convention on the Law of the Sea.

7.3 The Committee on the Peaceful Uses of Outer Space (COPUOS)[46] was set up by the UN General Assembly in 1959 to govern the exploration and use of space for the benefit of all humanity: for peace, security and development. The Committee was tasked with reviewing international cooperation in peaceful uses of outer space, studying space-related activities that could be undertaken by the United Nations, encouraging space research programmes, and studying legal problems arising from the exploration of outer space. The Committee was instrumental in the creation of the five treaties and five principles of outer space. International cooperation in space exploration and the use of space technology applications to meet global development goals are discussed in the Committee every year. Owing to rapid advances in space technology, the space agenda is constantly evolving. The Committee therefore provides a unique platform at the global level to monitor and discuss these developments, but it is not clear whether COPUOS would regard the stratosphere as falling within its remit.

7.4 The Convention on Biological Diversity (CBD). Solar radiation management is not subject currently to a moratorium, but its usage may be regarded as being restricted by certain international instruments, such as the Convention on Biological Diversity (CBD)[47]. For example, CBD decision X/33 para 8(w) states ' … no climate-related geoengineering 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' (see Lockley (2016))[48].

7.5 Existing international law on atmospheric pollution, examples. Other atmospheric pollution issues are regulated through several international conventions, either global ones such as the Montreal protocol for the protection of the ozone layer (under the Vienna Convention), or regional conventions like the Convention on Long Range Transport of Air Pollutants in Europe under UNECE which successfully has contributed to strong reductions in emissions of sulphur dioxide, nitrogen oxides and volatile organic compounds over Europe, and EU directives to improve air quality or reduce national emissions.

Small-scale field experiments with negligible transboundary impacts may arguably be sufficiently covered by 'normal' environmental regulations. The 'moral hazard' risk (or other socio-political risks) might justify blocking such research, but this would conflict with the customary rights for free scientific exploration. There are however a number of cases where international law would currently be inadequate to control certain aspects of solar geoengineering:

- The latent or actualized weather modification potential of larger scale marine cloud brightening (MCB) and/or cirrus cloud thinning (CCT) tests (at scales ~ 100 x 100 km^2) or deployment thereof.
- Large-scale tests of solar geoengineering with non-negligible transboundary impacts. There are at present no known research proposals for such tests, though a nation planning to deploy would be likely to undertake sub-scale testing.
- Unilateral or 'unauthorized' deployment of solar geoengineering. This might be global or regional MCB, CCT, or stratospheric aerosol geoengineering deployment, that primarily affects a region (eg, the Arctic) with limited more remote climate effects that are difficult to determine.
- National deployments occurring wholly in a nation's territory whose effects largely, but not exclusively, occur within its territory.
- Multi-lateral but not universal deployments.
- UN-based deployment.

Unlike Stratospheric aerosol geoengineering (SAG), Marine cloud brightening (MCB) and Cirrus cloud thinning (CCT), both offer the potential for weather modification. The particles that would be released to modify cloud properties in MCB or CCT geoengineering would only persist for a few days and so could reach (and cease) their full effect in days, whereas for SAG the particles have a lifetime of a year or two. The fact that deployments of MCB or CCT could be modulated within the timescale of reliable weather forecasts means that deployers would have the choice of choosing between forecasts with and without the deployment.

The ENMOD treaty[49] blocks the use of environmental modification for hostile purposes (in response to the US efforts to use cloud seeding to flood enemy supply lines in the Vietnam War) but does not apply to non-hostile uses of such technologies. In a note entitled *Geoengineering: Reining in the weather warriors* on their web site[50], the Chatham House (an independent policy institute in the UK) says that "countries are increasingly using technology to change conditions in the atmosphere, oceans and ice to improve weather to their advantage or lessen global warming. However, the results of these interventions can cross borders and what may be good for one country may not be good for its neighbors. This is not a hypothetical problem. Iran has already accused Israel of stealing its water by using cloud-seeding that reduces rainfall over its territory. China, which already artificially alters its weather over major cities, plans to be able to modify weather over half its territory by 2025, to the alarm of neighbors including India. And two Middle East rivals – the United Arab Emirates and Saudi Arabia – are scaling up rain-making operations. The best mechanism for policing such interventions can be found in the ENMOD UN convention. The Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques, known as the ENMOD Convention, came into force in 1978 and has been ratified by 78 countries, including Russia, the United States, Britain, China and Germany." It is however not clear whether the Convention would be able or willing to extend its remit to cover non-hostile interventions.

Some field experiments have already occurred or are planned, including:

- E-Peace[51] – the first marine cloud brightening field experiment, planned as a perturbative experiment to understand cloud properties.
- The Australian Barrier Reef MCB test, conducted and funded as part of a broader Australian project to develop environmental modification options to maintain the great barrier reef.
- SCOPEX – planned, though currently stalled, a Harvard University stratospheric balloon experiment for stratospheric aerosol geoengineering (with 1 kg of aerosols to be released).

8 Why should Royal Society and The Norwegian Academy of Science and Letters engage in the matter?

8.1 The United Kingdom and Norway are countries with advanced atmospheric science traditions with research groups that actively participate as experts both in IPCC, the Biodiversity Convention (BDC), in the Montreal Protocol monitoring and follow up through the regular assessments published by WMO and UNEP in collaboration with ISC and others, in CLRTAP – The Convention on Long Range Transport of Pollutants[52], and in the International Nitrogen Initiative (INI) which is a part of the Future Earth programme.

8.2 UK and Norway also have a history of international engagement in the legal aspects of environmental issues extending far beyond their national boundaries. Furthermore, there is an urgent need for leadership in pursuing an international legal framework like the law of the atmosphere seen in the light of the significant environmental and political pressures on this part of the earth system. The Royal Society and The Norwegian Academy of Science and Letters aim through this workshop to offer scientific support and academic leadership in this field.

9 Potential problems: What might go wrong?

9.1 A barrier to future development of an international legal framework on protection of atmosphere is differences between the views of various States and the international community concerning the issues outlined in this paper. This is not unique for the theme raised in the paper, of course, but we need to be aware of factors such as general skepticism in the international political community to treaties. There is moreover no 'competent international organization' (like IMO for shipping) or a UN Committee (like COPUOS for outer space) to develop standards for the protection of the atmosphere.

9.2 The crisis of international cooperation caused by the war in Ukraine has resulted in political confrontations and a very limited cooperation between large States in several international fora which are indispensable for developing international solutions on environmental issues, such as international legal work on the protection of the atmosphere as well as work on the combatting of global warming.

9.3 Solutions of the energy crisis in the long run need to be sought in renewable energy sources (wind and solar farms, nuclear energy) but due to these recent events (illustrating for example how gas pipelines are vulnerable to sabotage) in the short term it is likely that continuing use of coal will maintain or increase greenhouse gas emissions. This may mean that geoengineering as a tool to reduce global warming will receive more attention in spite of uncertainties as to its effectiveness and feasibility.

9.4 At a national level, a barrier could be the different levels of interest in geoengineering, and differences as to how far States have come in developing national policies. For instance, UK has already endorsed a set of principles mentioned earlier in this paper, while in Norway geoengineering was described in the 2009 Government White Paper on *Global environmental challenges*[53] more as a measure of last resort, as it prefers using other means to address climate change. In the White Paper it was argued that there is a need for an international framework to regulate geoengineering without going into any broader discussion as to the desirability of such an approach. The absence of a clearly defined policy might nevertheless not hinder States from unilateral decisions on geoengineering.

10 Options for action, with their advantages and disadvantages

Four possible options for international action were discussed:

a) Do nothing (no action). Advantages: Easy and cheap. The primary disadvantage is obviously that the inadequate status quo of the international law development relevant to solar geoengineering is preserved, while some States may choose to go ahead with such measures unilaterally.

b) Develop a treaty such as a binding multilateral instrument on the atmospheric protection addressing solar geoengineering. Advantages: results in a normative framework for States to be implemented at the national level, and could establish possible monitoring mechanisms etc. Disadvantages: like all treaties, may take long time to develop. Also it is unlikely there is sufficient political will for it in the international community.

c) Develop soft law instruments addressing various aspects/standards or calling for a moratorium or banning solar geoengineering due to its little understood consequences. Advantages are more flexibility and perhaps a shorter time perspective. This could build on recommendations developed by expert groups and scientific communities. Disadvantages are the non-binding character, so that it would be ineffective against 'unauthorized' use, and difficulty in monitoring whether States are meeting their obligations?

d) Continue academic scientific research and exchange and dissemination of ideas, seeking to illuminate the issues described in this position paper and suggesting pathways forward. Engage in a dialogue with national authorities and international fora, including non-governmental organizations. Create a timeline for developing an agenda and draft positions, and set targets for action further.

11 Outstanding questions

If geoengineering were ever to be pursued, some difficult questions would need to be addressed. These include:

- Who would decide on the right amount of geoengineering?
- What is the 'right' average global temperature to aim for?

Any system of governance would need to provide for these issues to be resolved.

Workshop conclusions and recommendations for solar radiation management (SRM)

In relation to solar radiation management, the participants noted that:

1. SRM is a high-risk response to climate change which could potentially be deployed to achieve a temporary reduction in atmospheric temperatures to protect national, commercial or indeed global interests if temperature continues to increase, overshooting the goals of the Paris Agreement. However, SRM is likely to cause a range of foreseen and unforeseen side-effects, requiring trade-offs since these may include damages as well as benefits to both people and the environment.
2. Regionally and globally we are already encountering an increasing number of extreme weather situations with significant potential for societal damage and instability. The pressure for SRM to be deployed is likely to grow, but we are as yet not prepared as a global community if a stakeholder with the political and/or financial resources were to unilaterally go ahead and do a full-scale experiment with or deployment of SRM (eg stratospheric aerosol injection).
3. We therefore urgently need to advance the state of knowledge related to all aspects of SRM, and thereby enable society to be prepared for a situation in which pressure for SRM deployment increases. This could conceivably happen abruptly and rapidly, for instance in response to extreme events exacerbated by global warming.
4. SRM may distract the attention from climate mitigation. The international governance structure for SRM is immature. Unilateral SRM has the potential to create international conflict. The chances for unilateral SRM action grow as the gap widens between societal impacts and risks associated with climate change, and the success of mitigation measures. Research and field experiments may receive funding and be carried out in organisational structures that are not transparent or open for independent critical review and discussion.
5. Stratospheric aerosol injection (SAI, mimicking stratospheric volcanic injection), and marine cloud brightening (MCB, mimicking ship emissions) are examples of solar radiation management[54]. Of these there is greater confidence that SAI could produce a cooling effect that would measurably counteract global warming, and that could be realised in technical and cost terms.
6. There is a GeoMIP programme that is part of CMIP (the Climate Model Intercomparison Project, a part of World Climate Research Programme WCRP co-sponsored by WMO, IOC and ISC) which organises SRM-related model experiments and keeps track of the publications arising thereof.
7. In climate model calculations SAI causes reduced global and regional temperatures that are broadly similar to the results of model experiments where CO_2 emissions are reduced, although regionally the induced temperature changes can be significantly different. The calculated changes in precipitation are however much more variable and more uncertain than the temperature response, and even the sign of the regional changes often does not agree among models. Thus SRM offsets climate change only imperfectly, it only masks the warming, and the prediction of its effects is uncertain.
8. With SRM deployed to mask the effects of carbon emissions, ocean acidification would continue.
9. The lifetime of stratospheric aerosols is typically around two years, and SRM is therefore a measure that would have global impacts. For SRM to have a long-term (decadal or longer) effect, a similar long-term commitment to maintaining the stratospheric aerosol level would be required. Aerosols in the troposphere that would cause marine cloud brightening would be removed in a matter of weeks. MCB is therefore a regional measure that would have to be maintained on a continual basis.
10. SRM research to understand the consequences of SRM includes earth system modelling, field experiments and process studies (eg. of aerosol-cloud interactions and their changes as the stratosphere is loaded with aerosols). Earth system modelling is relatively advanced, but still leaves very large uncertainties to be addressed. It would be highly controversial to move out of the laboratory to do large-scale experiments. Governance, liability and compensation mechanisms have not been adequately addressed. SRM would be likely to make the sky slightly hazier, add slightly to acid rain and delay the ozone layer recovery by several decades.

11. It is not inconceivable that stratospheric aerosol injection could actually enhance regional (and even global) heating. For instance, if it turns out that SAI causes rainfall patterns to change so as to dry out rain forests, this would be likely to trigger enhanced CO2 emissions from soils causing a further warming of the climate.

12. There has as yet been only a little open and transparent international research on SRM, and no field experiments of importance. There are no international mechanisms for research funding or for assessing environmental impacts, no framework for international policy making, and no regulations framed specifically with SRM in mind. There is a significant risk that SRM could be used selfishly by the powerful, and it is conceivable that scientists may have to make definite statements about the effects of SRM before they have adequate confidence in them. In such circumstances, only an international advisory body would have adequate credibility, and it would be desirable for an international body (such as the WMO), but politically not straight forward, to assemble relevant evidence and develop authoritative consensus statements.

13. International law of the atmosphere constitutes a ‘classic regime complex’ covering both regional and global issues. There are at least ten relevant international treaties, but none of these instruments govern SRM comprehensively.

14. In addition to treaty instruments, there are customary law rules and principles which may apply, but these are general in their application and lack the specificity of detailed regulatory measures, or dedicated oversight and compliance mechanisms. Relevant principles are also found in key documents such as the 1992 Rio Declaration Principles on Environment and Development[55].

15. The UN International Law Commission’s (ILC) work on Protection of the Atmosphere 2013 – 2021, resulting in draft guidelines on the protection of the atmosphere[56] is highly relevant, and failure to develop these into legislation may be seen as a major missed opportunity.

16. Scientific knowledge and uncertainty urgently need to be addressed, especially through a commitment to collect (and share) more data. An equivalent example in treaty form is article 7 of the BBNJ treaty[57] which requires for its implementation the “use of the best available science and scientific information” and establishes a dedicated Scientific and Technical Body to promote this.

17. Although SRM activities are not specifically covered by international law, they would not take place within a legal vacuum. If there are risks of significant transboundary harm, the general rules of international law require: cooperation; prior notification and consultation; environmental impact assessment (EIA) including screening; and due diligence measures to prevent significant harm, including for activities carried out by private actors. Failure to comply with these rules could lead to international responsibility and liability, and potentially affected States may also be able to take anticipatory action.

18. Potential adverse impacts of SRM activities on vulnerable populations and ecosystems will also bring into play global and regional treaty regimes that address human rights obligations (eg the right to food) and environmental obligations such as the conservation of biological diversity under the Convention on Biological Diversity.

They concluded that it would be highly desirable:

19. To apply some form of the precautionary principle/approach and prioritise long-term over short-term goals.

20. To improve understanding of the crucial issue of how SRM (SAI) would be likely to impact on regional and global weather patterns, by making appropriate investments in earth system modelling and supporting observations (c.f. the Destination Earth Digital Twin concept under development in Europe) including government support for the creation of a small international network of high-resolution climate prediction centres, each with dedicated exa-scale computing capability, to develop and run small multi-model ensembles of the kilometre grid-scale models needed to do so.

21. To refrain from implementation of SRM before accepted governance structures are established. These should include sharing of data, economic benefits and procedures, since these are principal concepts in international law (solidarity; transparency; equity) and apply to all involved (nations and international organisations) and to the different aspects (science, national strategic security interests, commercial interests, governance interests).

22. To follow the Oxford Principles, as appropriate general principles of conduct for research, including their preamble[58].

23. To develop relevant international law, building upon the work done by the International Law Commission on the Protection of the Atmosphere, as soon as possible in order to ensure that a regime is in place before SAI becomes an operational reality. However, since formal agreement and adoption of a new (or modified) international treaty is not likely in the near future, states should meanwhile comply with existing general applicable rules and voluntarily apply the non-binding ILC Guidelines. Through practice consistent with the Guidelines, such application could influence the emergence of customary international law.

24. To create an international and interdisciplinary task force of scientists and political and commercial stakeholders, in order to build SRM knowledge and risk assessments, monitor any plans for implementation, technological and commercial solutions and distribute the information in a transparent manner. Such a voluntary but international coalition-like body could:
    a) Adopt principles for scientific advice for policy making[59] allowing for the involvement of independent science experts;
    b) Motivate and contribute to an IPCC Special Report on SRM;
    c) Consider the conclusions and where appropriate pursue the recommendations of the Climate Overshoot Commission[60];
    d) Work in collaboration with established and successful global organisations, like the WMO or UNEP, and UK, Norwegian and other national scientific academies eg to establish scenarios and storylines, and use these as a basis for evaluating options;
    e) Provide information relevant to possible Resolutions by the IUCN** or other international bodies;
    f) Consider whether there is a need for an international entity for the brokering of 'cooling credits' in the future.

25. For the Royal Society and DNVA, in concert with other Academies (including those in developing countries) to set up a task force to inform their national governments about the precarious state of knowledge, transparency and the possible risks and benefits related to SRM, in order to stimulate a diplomatic effort to reduce these deficiencies and to voluntarily establish responsible rules, regulations and other governance.

The participants therefore suggest that:

26. SRM research should take full advantage of the extensive gathering of climate variables through the operational practices of weather prediction, climate adaptation and climate mitigation (emissions) where WMO is the global organising entity. [Note: weather and climate data are a public good].

27. A clearing house for information on proposals for SRM experiments would be beneficial and could be established voluntarily.

28. Additional public (and transparent) funding for all aspects of SRM research and knowledge enhancement is urgently needed, to complement the philanthropic funding that dominates at present. Such funding would likely have most impact if invested in relatively large coordinated and interdisciplinary projects, in which the problem is addressed holistically, as opposed to disciplinary 'silos' in which only certain aspects of SRM are studied in isolation.

29. Diplomatic efforts to promote global agreements of the kind required for responsible handling of SRM need to be stepped up by nations that are particularly concerned, since the current geopolitical situation is demanding and not conducive for this.

** The International Union for Conservation of Nature (IUCN) is a membership organisation uniquely composed of both government and civil society organisations.

Workshop general observations

I. Of the 12 worst natural disasters globally in 2021, 11 were related to climate and climate change.

II. There is a serious risk that progress in reducing greenhouse gas emissions will be inadequate to avoid breaching climate thresholds such as the 1.5 °C warming of the Paris Agreement, and lead to pressure to deploy geoengineering methods such as SRM.

III. There is moreover a risk of unilateral SRM deployment by an individual State or a non-State actor (eg a corporation), and there are currently no specific rules of international law on SRM to prevent or regulate such action.

IV. There is therefore need for international governance of some sort bringing together political and commercial parties (as well as relevant research on both the technical feasibility and environmental impacts of SRM).

V. Widespread and rapid adoption of electric alternatives to fossil fuels (especially for transport) requires greatly increased use of battery technology. Supplies of some minerals currently needed for this are expected to become inadequate, and Deep Sea Mining (DSM) of such minerals is being actively pursued.

VI. DSM is regulated by the International Seabed Authority (ISA) established under the UN Law of the Sea (UNCLOS). However the environmental impacts of DSM are uncertain, and need to be determined, as they could lead to loss of biodiversity and serious harm to the environment, which may limit the scope for its deployment and development unless adequately mitigated.

VII. It is thus possible that foregoing DSM on account of its environmental impacts could impede the transition to low-carbon technologies that is needed to reduce the impacts of climate change.

VIII. There is therefore a potential link between the two topics, since if DSM were to be abandoned, that might delay the transition away from fossil fuels, and increase the likelihood that SRM may be implemented.

IX. In both these areas, the requirement is therefore to balance the likely risks (and benefits) of doing something, against the risks (and benefits) of doing nothing. In such situations the Precautionary Principle/Approach is a helpful (and widely accepted) prerequisite guiding principle, but it does not by itself provide answers to specific questions of what measures need to be taken, and by whom.

X. The Precautionary Principle therefore needs to be operationalised to determine what actions are necessary to ensure that irreversible risks can be avoided, and that risks of adverse impacts, especially those on the most vulnerable people and/or ecosystems, can be kept sufficiently small, both now and in the future. One way to achieve this may be to require that a pessimistic estimate of the likely benefits must outweigh a comparably pessimistic estimate of the likely risks.

XI. The discussion of SRM was focused on the SAI technique, and that of DSM on exploitation in areas beyond national jurisdiction. However many of the conclusions on SRM would also apply to other techniques such as marine cloud brightening (MCB), and many of those on DSM would also be relevant in areas within national jurisdictions.

APPENDIX 1

List of participants

Meeting co-chairs
Professor Catherine Banet, Scandinavian Institute of Maritime Law, Faculty of Law, University of Oslo, Norway
Professor Øystein Hov, The Norwegian Meteorological Institute, Norway
Professor Catherine Redgwell, University of Oxford, UK
Professor John Shepherd, University of Southampton, UK.
Law experts
Professor Richard Barnes, University of Lincoln/University of Tromsø, UK
Dr Joanna Dingwall, University of Glasgow, UK
Professor David Freestone, George Washington University Law School, USA
Professor James Harrison, Edinburgh Law School, UK
Dr Maria Madalena das Neves, Norwegian Centre for the Law of the Sea, UiT The Arctic University of Norway, Norway
Professor Ernst Nordtveit, University of Bergen, Norway
Professor Alla Pozdnakova, Scandinavian Institute of Maritime Law, University of Oslo, Norway
Professor Christina Voigt, Faculty of Law, University of Oslo, Norway
Science experts
Professor Rolf Birger Pedersen, University of Bergen, Norway
Professor Sir Ian Boyd, University of St Andrews, UK
Professor Lene Buhl-Mortensen, Institute of Marine Research, Norway
Professor Gideon Henderson, Department for Environment, Food & Rural Affairs, UK
Dr Pete Irvine, University College London, UK
Dr Jens Laugesen, DNV, Norway
Professor Tim Palmer, University of Oxford, UK
Dr Gordon Paterson, Natural History Museum, London, UK
Professor John A Pyle, University of Cambridge, UK
Dr Bjørn H. Samset, CICERO/NMBU, Norway
Professor Michael Schulz, Norwegian Meteorological Institute, Norway
Professor Trude Storelvmo, University of Oslo, Norway
Professor Philip Weaver, UK

Expert advisors
Dr Harald Brekke, Norwegian Petroleum Directorate, Norway
Professor Hans Petter Graver, DNVA, Norway
Professor Anders Elverhøi, University of Oslo, Norway
Dr Jan S. Fuglestvedt, CICERO, Norway
Evening speaker
Professor Jan-Olav Henriksen, MF Norwegian School of Theology, Religion and Society, Norway

Image: Workshop attendees, (standing, left to right) Jan S Fuglestvedt, Ian Boyd, Gideon Henderson, Tim Palmer, David Freestone, Harald Brekke, Anders Elverhøi, Lene Buhl Mortensen, Michael Schulz, Alla Pozdnakova, Ernst Nordtveit, Gordon Paterson, John Pyle, Maria Madalena das Neves, Jens Laugensen, Joanna Dingwell, Bjørn Samset, James Harrison; and (seated, left to right) Richard Barnes, Phil Weaver, Trude Storelvmo, Catherine Redgwell, John Shepherd, Catherine Banet, Øystein Hov, Hans Petter Graver, Christina Voigt, Peter Irvine. © Thomas B Eckhoff, The Norwegian Academy of Science and Letters.

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For further information
The Royal Society
6 – 9 Carlton House Terrace
London SW1Y 5AG

T +44 20 7451 2500
W royalsociety.org

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