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From monodisciplinary via multidisciplinary to an interdisciplinary approach investigating air-sea interactions – A SOLAS Initiative

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Abstract

Understanding the physical and biogeochemical interactions and feedbacks between the ocean and atmosphere is a vital component of environmental and Earth system research. The ability to predict and respond to future environmental change relies on a detailed understanding of these processes. The Surface Ocean-Lower Atmosphere Study (SOLAS) is an international research platform that focuses on the study of ocean-atmosphere interactions, for which Future Earth is a sponsor. SOLAS instigated a collaborative initiative process to connect efforts in the natural and social sciences related to these processes, as a contribution to the emerging Future Earth Ocean Knowledge-Action Network (Ocean KAN). This is imperative because many of the recent changes in the Earth system are anthropogenic. An understanding of adaptation and counteracting measures requires an alliance of scientists from both domains to bridge the gap between science and policy. To this end, three SOLAS research areas were targeted for a case study to determine a more effective method of interdisciplinary research: valuing carbon and the ocean's role; air-sea interactions, policy and stewardship; and, air-sea interactions and the shipping industry.

Introduction

The consumption of the ocean's resources affects a growing number of people directly, but only a small percentage of the world's population has a direct experience of the ocean's tangibility (Helmreich 2009), especially regarding the open ocean. It appears logical that the general population must know something about the ocean, its various natural and social interconnections, and its governance, in order to engage in ocean stewardship. This is a challenge in which science has an important mediating role to play. Given the rapid predicted and observable changes in the Earth's climate occurring now and into the future, a more comprehensive approach to scientific research is needed to inform policy decisions and to effectively respond to climate change. This, in part, is what has driven the development of the Future Earth Ocean Knowledge-Action Network. Expertise by both natural and social scientists has long been sought out by policymakers and stakeholders; in the recent past, however, a notable disconnect between the two sets of disciplines remains, often resulting in an imbalanced perspective or incomplete understanding of the issue. As such, many researchers recognize the need for a more holistic approach to climate science. A few review papers have identified the need for greater collaboration and for interdisciplinary higher education, in which knowledge is integrated across disciplines (Brink *et al*., 2020; Fischer *et al*., 2011). However, while attempts have been made to bridge the divide between the natural and social sciences, the approaches have not yielded the fully balanced contribution needed for truly comprehensive understanding. Both Fischer *et al*. (2011) and Brink *et al*. (2020) conducted systematic searches for research papers utilizing interdisciplinary approaches between the natural and social sciences. In the Fischer *et al*. (2011) study, the search provided only 247 articles, and upon inspection of the content, only 81 were found to be relevant. The review study found that there were several obstacles to truly interdisciplinary efforts, including structures created by academic institutions, especially tenure-track criteria, which generally promote disciplinary work. Nearly a decade later, Brink *et al*. (2020) found almost twice as many papers, 467, but still only 77 contained detailed information on interdisciplinary measurements. They concluded that interdisciplinary measurement models of sustainability were "near-unique".

Within the natural sciences, the formation of global working groups (e.g. Scientific Committee on Oceanic Research [SCOR] working groups) has been a useful and efficient way to execute collaborative science and to deal with complex, multidisciplinary issues. However, these types of working groups, in which small diverse committees of experts meet in person to hash out specific issues, have not been common in attempts to bridge the natural and social sciences. Typically, either one token social scientist is entrained by a group of natural scientists, or vice versa. Alternatively, natural scientists commonly complete one part of a project, while social scientists separately complete the other part, their findings are then hastily combined at the end. Additionally, securing joint funding for collaborations from both the natural and social sciences is often difficult. Furthermore, ostensibly joint efforts frequently are carried out separately in practice. This is especially true in climate change research, where atmospheric and ocean sciences data is acquired by natural scientists but analyzed separately in the context of economic and legal issues. There are, however, notable exceptions to this pattern of limited interaction amongst disciplines. Ocean acidification research, an example of best practice, has often been interdisciplinary, leading to important policy decisions by the United Nations, USA, and other nations (Bailey *et al*. 2006).

The value of interdisciplinary, and even transdisciplinary, work on specific marine issues is well recognized; however, its implementation is not straightforward (Glavovic *et al*. 2015). Despite

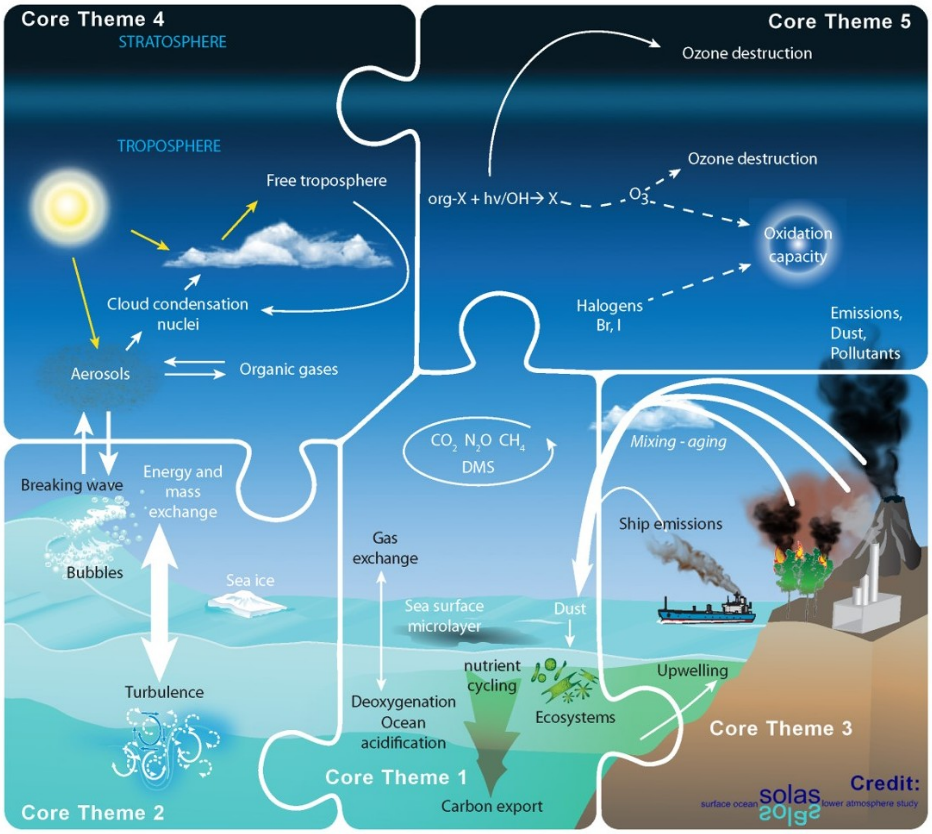

Figure 1. Conceptual diagram of SOLAS scientific foci. For more information about the current SOLAS science plan, please visit https://www.solas-int.org/science.html. Figure from Brévière *et al*. (2016).

this, the crucial need to transcend disciplinary boundaries is seen as a *conditio sine qua non* for future marine research (Markus *et al*. 2017). Challenges arise as marine research has been dominated to date by natural sciences, a realm into which social science has not entered, traditionally (Palsson *et al*. 2013). In fact, the sea is little researched in a sociology context (Cocco 2013), perhaps because humans inhabit the land and social studies have focused on a terrestrially based, state-centered understanding of society (Wimmer and Schiller 2002; Chernilo 2007). Moreover, existing attempts to forge a specialty area around the sociological study of maritime topics remain limited, because most of the theoretical work remains rooted in Central Europe, with little connection to other parts of the world (for instance, Canada and China) where empirical, sociologically-relevant maritime research has a stronger presence (Hannigan 2017). Nevertheless, successful efforts are being made to address this research deficiency within marine science, with evidence that interdisciplinary approaches are beneficial for all researchers involved. For example, Watson *et al*. (2016) brought socio-economists and natural marine scientists together to explore the ecosystem service of waste remediation in the marine environment, resulting in the provision of operational guidance on the long-term sustainable use of this process. Fernandes *et al*. (2017) quantified how the ecological impact of climate change on commercially important marine bivalves could create a cascade of negative economic effects on the fishing industry and its associated revenue and employment.

During the first ten years of the SOLAS, significant gains in knowledge were achieved by scientists in the community and in Earth system science in general (Brévière *et al*. 2015). SOLAS contributes critical scientific information to the quantification of three of the nine planetary boundaries, which have been proposed to define a 'safe operating space for humanity' (Rockström *et al*. 2009; Steffen *et al*. 2015): climate change, biogeochemical flows and ocean acidification. Within these Earth system scale challenges faced by humanity, the programme (Figure 1) is poised to provide a scientific basis for sustainable policy-making. The first SOLAS policy-related interactions dealt with oceanic iron fertilization and ocean acidification. For both topics, SOLAS scientists participated in published summaries for policy makers (Wallace *et al*. 2010; IGBP, IOC, SCOR 2013). These examples highlight that a coordinated research design from the outset is required to achieve an interdisciplinary approach, successfully bridging the gaps between marine scientists, policy makers and practitioners (Weichselgartner and Marandino 2012; Turner *et al*. 2017a). Thus, the goal for future SOLAS research is to develop research questions in order to co-design future projects related to the SOLAS Science and Society

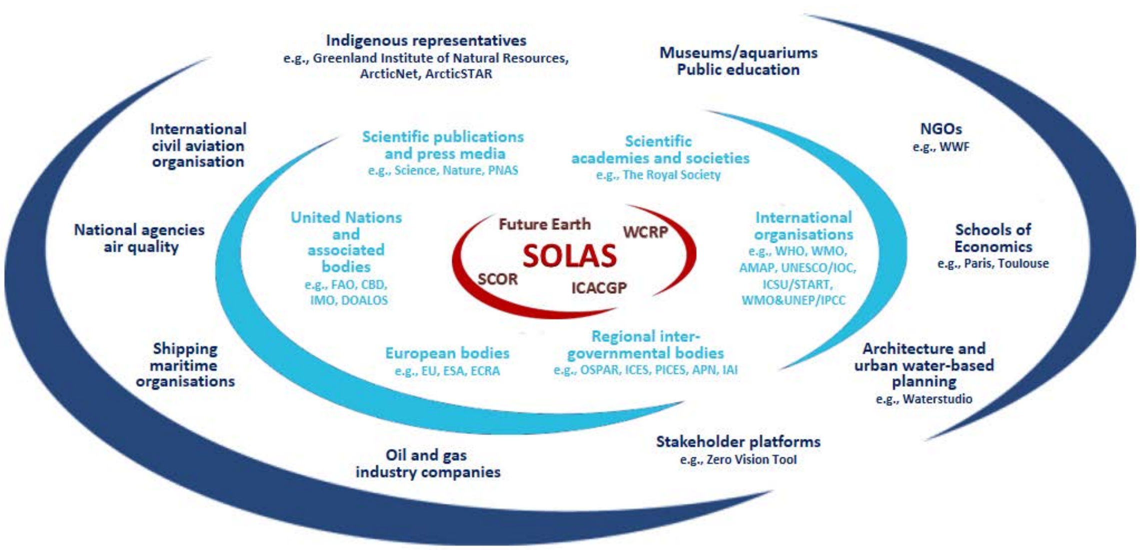

Figure 2. A conceptual diagram with the main stakeholders related to SOLAS science, including examples (Brévière *et al*. 2016).

initiative (Figure 2).

The aim of this paper is to illustrate how the SOLAS community plans to address the need for inter- and transdisciplinary research for the ocean-atmosphere system, which is directly in line with the Ocean KAN that SOLAS "must generate knowledge that decision-makers need to preserve and enhance the health and value of the ocean".

Method

From a broader perspective, there are two possible frameworks for inter- and transdisciplinary SOLAS research: 1) interaction between natural and social science, 2) interaction between science and society. Here the goal was to first focus on the interactions between natural and social science, with the intention to move towards an integration of science and society. Small working groups, comprising experts from different disciplines in both the natural and social sciences, met in person to tackle three predetermined pressing environmental issues (Figure 3). A grassroots effort was made to identify key, as well as developing, links between SOLAS science and the social sciences, and to meet the growing need of bridging the natural and social science gap. The working groups were balanced in terms of both natural and social scientists, each led by one natural and one social scientist. The three issues are: the economics of ocean carbon storage; policy across the air-sea interface and the impact of shipping on air-sea interactions. The structure of the collaborative initiative entailed an initial meeting in October 2016, in which 24 natural and social scientists met in Brussels for a two-day workshop. The first day consisted of presentations on the three topics, then on the second day the breakout groups addressed each of the three topics.

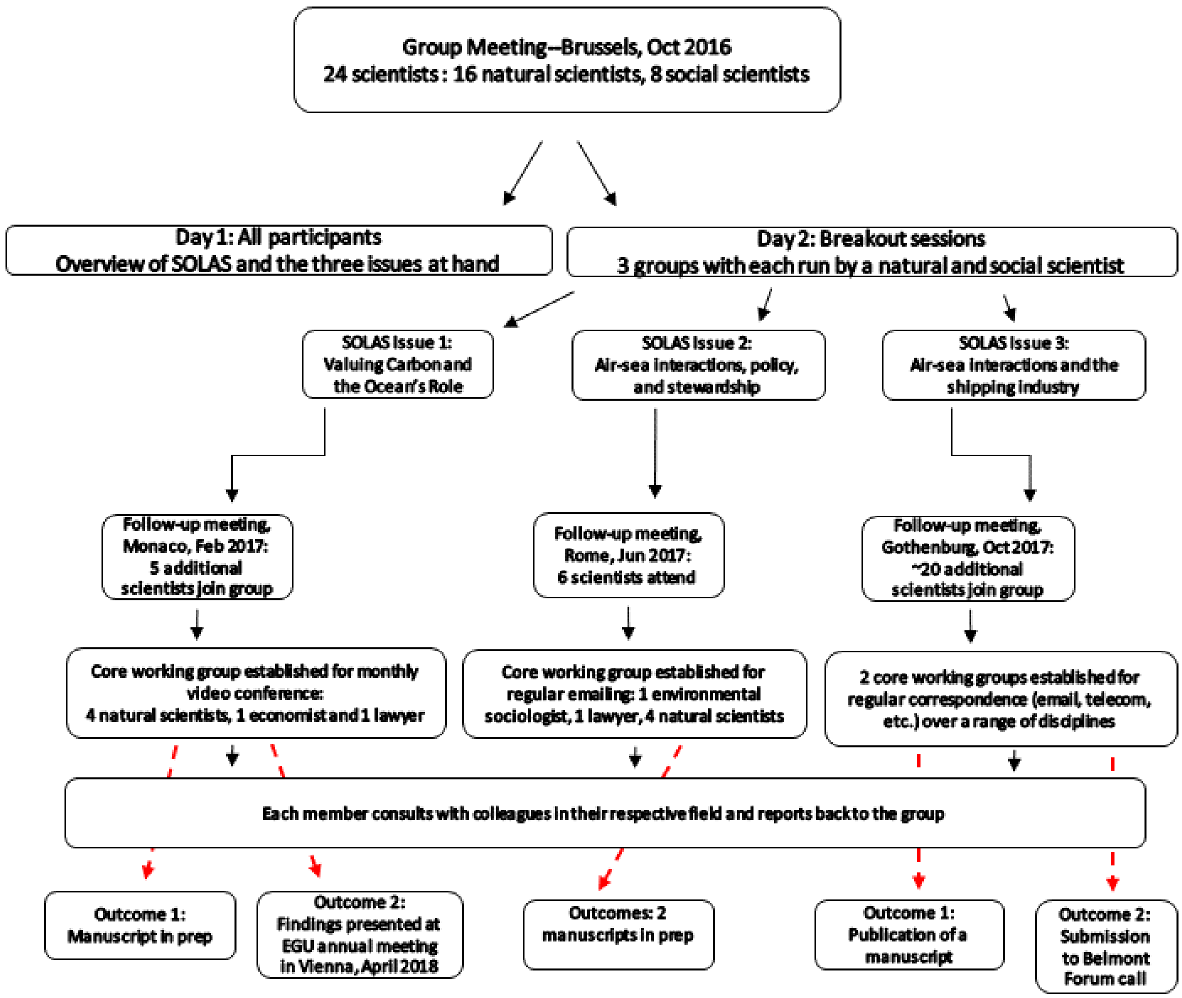

Figure 3. Flowchart illustrating the SOLAS Science and Society initiative process.

From 2017 to the present day, follow-up meetings for each topic are held, and participation has been extended to a wider group who were suggested and selected by members of the initial breakout groups. These meetings mostly consist of regular teleconferences (bi-weekly to monthly, on average), in which tasks were assigned, and collaborative efforts were made towards manuscripts and funding proposals. Additionally, members presented the groups' findings at research conferences. The specific aim was to have at least three concrete outcomes related to these topics in the coming years, such as papers in peer-reviewed journals and research proposals, which are discussed in more detail below.

Targeted research topics

Here the outcomes of the three targeted research topics are summarized, focusing on the interdisciplinary issues identified in the initial workshop. Some of these issues have already been identified and discussed in the literature, while others are novel. All of them present key opportunities for future work to better understand the challenges associated with translating natural science into societal impact (Table 1).

Valuing carbon in the ocean

Background

The ocean system takes up carbon from the atmosphere through both physical and biological mechanisms, currently taking up a similar proportion of anthropogenic CO_2 emissions as the land surface (e.g. Heinze *et al*., 2015). The physical uptake of carbon dioxide (CO_2) by the oceans has increased in response to anthropogenic carbon input to the atmosphere, but this has potentially negative consequences through ocean acidification, which may affect uptake of CO_2 by marine organisms as well as other harmful effects. There have been extensive ongoing discussions in the scientific community about roles and vulnerabilities of the physical, biological and microbial carbon pumps in regulating CO_2 uptake from the atmosphere (Heinze *et al*. 2015), however the ability to manage these processes and their responses to future climate change and rising CO_2 is limited at best. Between these large-scale natural processes and the coastal habitats recognised as valuable Blue Carbon ecosystems lie a broad range of natural processes and potential management options in coastal seas and the open ocean which may offer opportunities to mitigate atmospheric CO_2 (e.g. Gattuso *et al*., 2018).

The term 'Blue Carbon' has typically been used to describe the carbon storage services associated with coastal and intertidal wetlands and sub-tidal near-shore vegetated ecosystems: predominantly salt marsh, mangrove and seagrass (Laffoley and Grimsditch 2009; Pendleton *et al*. 2012). Other systems (e.g. kelp, phytoplankton, water column carbon) have also been considered in some studies (Burrows *et al*. 2014) and discounted as not valuable for management and conservation strategies and, therefore, not thought to be useful carbon stores by others (e.g. Howard *et al*. 2017). The above-mentioned studies, along with numerous others on each side of this debate, discuss the issue of biogeochemical carbon accounting vs. ecological valuation for conservation and, thus, come to different conclusions. To make informed assessments of the potential 'value' of different components of the ocean carbon cycle, the input of experts in ocean biogeochemistry and Earth system science from the domains of SOLAS and related international research programmes (e.g., such as IMBeR, the Integrated Marine Biosphere Research), as well as ecologists and environmental economists, are clearly needed.

Challenges and opportunities

Fundamentally, what should and should not be considered when investigating Blue Carbon depends on the motivation for counting the carbon stored: whether as a conservation mechanism for important and threatened habitats or as an economic mechanism to unlock additional carbon storage potential in marine systems as a means to mitigate atmospheric CO_2 increase (see example in Figure 4). This debate is ongoing in the Blue Carbon community (e.g. Howard *et al*., 2017, Macreadie *et al*., 2019). Here that particular debate was bypassed and a broader 'Marine and Coastal Carbon Sequestration' (MCCS) was defined as any carbon stored in the marine realm by processes whose absence would lead eventually to an equivalent quantity of carbon being released to the atmosphere. All MCCS renders ecosystem services to humanity and it is argued that it is crucial to assess its total economic value, because these calculations allow policy makers to know how important this service is in terms of costs and benefits, whether directly manageable or not. It is also important to account for the balance of the associated uptake or emission of other climate-active gases.

As compared to the terrestrial realm, movement of water throughout the oceans occurs irrespective of geopolitical boundaries (carbon does not stay where it was fixed, unlike, e.g., forest storage where the carbon stays in the trees which fix it for decades or more), thereby presenting unique challenges in attribution and valuation of measures to enhance carbon storage

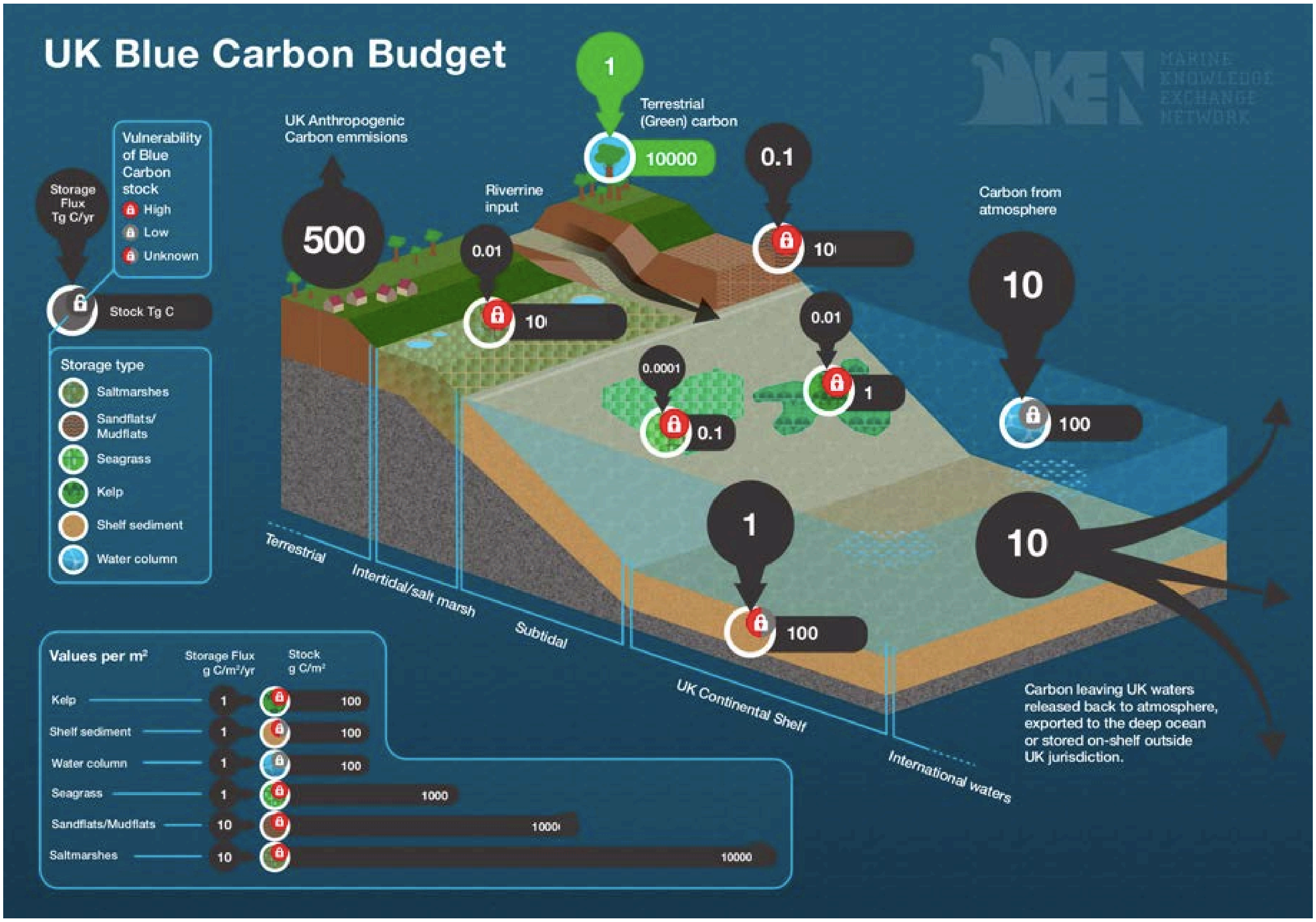

Figure 4. Example assessment of 'Marine and Coastal Carbon Sequestration' (MCCS) from the UK Blue Carbon Project. Standing carbon stocks and fluxes from the coast to the shelf are pictured together with an indication of their vulnerability. Figure from M. Johnson.

in coastal waters. The open ocean is not considered here, as the processes that can be manipulated/controlled are more limited than in coastal areas. Positive or detrimental effects, whether natural or anthropogenic, might originate in territorial waters of any one nation. Depending on the ocean circulation, such effects might materialize in waters of neighbouring states. Furthermore, states bordering upwelling systems, which bring carbon-rich waters from depth, might have large natural effluxes of carbon from their national waters. Such approaches and budgets, as for example pursued by Melaku Canu *et al.* (2015), who account for the total (natural and management-derived) carbon balance of states bordering the Mediterranean Sea, are potentially highly misleading to decision makers; they conflate carbon storage or emissions as a result of management decisions, with unmanageable, natural emissions. These measures largely attribute and value effects of circulation pattern, rather than active measures to enhance carbon storage, or damaging management approaches that lead to the release of carbon. Active measures are crucial for any international agreements or assessments of carbon storage initiatives, while the Melaku Canu *et al*. (2015) approach largely describes natural background conditions, which should not be counted as an asset or mismanagement of individual states. Under no circumstances, for example, would it be sensible or reasonable to attribute a cost to the West African states for the natural carbon emissions from the Mauritanian upwelling where carbon-rich deep ocean waters rise to the surface.

One such active measure is the expansion of macroalgal aquaculture, which has been recognised as having great potential to take up excess atmospheric CO_2 (e.g. Lehahn *et al*., 2016; de Ramon N'Yeurt *et al*. 2012), when it is subsequently sequestered. However the ethical, legal and technological barriers to this measure, the need for environmental protection and scientific oversight and the short timescales over which many orders of magnitude expansion would need to occur present enormous challenges (e.g. Buschmann *et al* 2017; Duarte *et al*., 2017). This highlights the need to rapidly increase research into ocean carbon mitigation solutions considering natural and social aspects simultaneously.

A further point to consider is the time scale of carbon storage. The baseline here is the (former) long-term geological storage of fossil fuels in the Earth system, while at the other end are the short-term annual or multi-annual time scales of economic budgeting and valuation or election frequency. From the Earth system perspective, glacial-interglacial or longer timescales matter to ensure long-term stability of the climate. In terms of uptake of anthropogenic CO_2 and ocean acidification, ocean turnover timescale matters. Carbon credits, as a "cap and trade" instrument, apply at decadal timescales or even shorter, such as election cycles. They can give a monetary value to the cost of polluting the air in order to reduce the pollution. The underlying, yet unanswered, key question is: what carbon storage time scale is applied to or described for MCCS stocks?

Outcome

A series of key questions and knowledge gaps around MCCS were identified (Table 1). These range from the lack of consensus on its definition and purpose to identification of the need to apply Earth-system scale understanding of the ocean carbon cycle if the concept of MCCS is to be used to incentivize positive action, particularly in marine systems beyond those at or very close to the coast. Currently, the group consisting of an economist, a lawyer, three marine carbon specialists, and one air-sea interaction expert is drafting a submission which investigates the opportunities and vulnerabilities of coastal to open ocean carbon storage reservoirs (Figure 3).

<u>Air-sea interaction, policy, and stewardship</u>

Background

A pressing question related to the open ocean is if there are cultural/national differences in how to effectively promote long-lasting stewardship of the high seas. This theme could likely lead to a project studying global attitudes towards the open ocean and the development of methods to promote long-lasting stewardship (including the identification of what methods work and for whom). A sensible start for marine stewardship might be the creation of a stronger awareness among the transnational public, rather than with a set of separate, national policy initiatives. However, because most people do not have direct experience of the high seas, they often rely on representations fraught with sensationalism and ambiguity of an outlaw ocean that is both a source of wealth and danger (Langewiesche 2004). The fact that perspectives on the ocean are subject to change and are often culture-specific complicates this. To communicate effectively and engage the population, crossing national and cultural boundaries must be understood. In other words, the sea must be thought of not only as a medium but also as a social space, which is not merely 'used by society' but rather represents 'a space of society' that is connected and experienced in specific ways by specific people (Lambert *et al*. 2006).

These questions regarding stewardship deal only with the marine environment. Yet the very existence of international projects such as SOLAS shows that, from the perspective of natural sciences, the boundary between the ocean and the atmosphere cannot be clearly drawn. There is much interaction between the surface of the ocean and the lower part of the atmosphere. The policy perspective, however, tends to make a clear distinction between the ocean and the air directly above it, without much consideration of the interaction between them. Regulatory frameworks for the governance of the ocean on the one hand and the atmosphere on the other reflect this compartmentalization. The international regulatory framework for the ocean bases itself mainly on the 1982 United Nations Convention on the Law of the Sea (LOSC; Rothwell and Stephens 2016). The atmosphere lacks a global, all-encompassing regulatory framework like the LOSC (Sands *et al*. 2018) since the international rules for the atmosphere developed later than the customary international law of the sea. Regional efforts on long-range transboundary air pollution, with a focus on acid rain, occurred first in the 1970s with the 1979 Convention on Long Range Transboundary Air Pollution (LRTAP). On a global level, first efforts concentrated on the effects of air pollution, with a focus on the depletion of the ozone layer in the 1980s through the 1985 Vienna Convention for the Protection of the Ozone Layer and its 1987 Montreal Protocol. In the next decade, regulation addressed climate change with the 1992 United Nations Framework Convention on Climate Change as a starting point (Gillespie 2006; Sands *et al*. 2018).

Challenges

This study considers whether the biogeochemical interaction between the lower atmosphere and the upper layer of the ocean is addressed in regulations. Regulations might not target this air-sea interface directly - human-made rules cannot govern natural processes - but they do regulate sources of pollution (e.g., atmospheric emissions at the national and regional level) or designated areas in need of a higher protection (e.g., sulphur control areas [SECAs] for ships). The rationale behind this is that the regulation of activities on land or on ships (i.e. the cause of atmospheric pollution) is mostly a sovereign duty of states - whether land-locked, coastal or flag states - which is exercised in line with their national policies. There is nevertheless a general obligation under the LOSC for states to prevent, reduce and control pollution of the marine environment from or through the atmosphere.

Air-sea exchange is one of the primary processes in the biogeochemical cycling of many chemicals but rarely is it the defining feature that requires regulation. The role of the atmosphere-ocean interface in the cycling of mercury, a highly toxic substance, serves as an example. The dominant source of mercury to the ocean is atmospheric deposition and approximately 80% of this is subsequently re-emitted to the atmosphere (Driscoll *et al*. 2013).

The use, trade and disposal of mercury is now highly regulated, including via the 2013 United Nations Minamata Convention, but processes of air-sea exchange are not explicitly addressed in policy or regulations, beyond recommendations for improving or expanding research and monitoring (UNEP 2013). Similarly, air-sea exchange has been a significant process influencing the biogeochemical cycling of persistent organic pollutants (POPs), such as polychlorinated biphenyls and organochlorine pesticides (Wöhrnschimmel *et al*. 2012). In this case, again, regulations or policy addressing air-sea exchange are not explicitly addressed in POP management policies (e.g. the 1998 Aarhus POPs Protocol to the LRTAP Convention).

One instance of where air-sea exchange can be considered to have been explicitly included in environmental policy is the regulation of ocean iron fertilization. This process has been promoted as a carbon mitigation scheme whereby iron is added to ocean surface waters to promote phytoplankton production and subsequent draw down of CO_2 from the atmosphere. Thus, carbon is sequestered by incorporation in plankton and the ensuing removal via sedimentation and long-term storage in ocean sediments (Wallace *et al*. 2010). However, international efforts have been made to restrict iron fertilization activities to small-scale scientific research through interpretations of the Convention on Biological Diversity and amendments to the London (Dumping) Convention following concerns raised over the ethical, legal and scientific merits of this form of climate intervention (Strong *et al*. 2009). However, the overall policy aim is to protect the ocean, not the atmosphere.

All in all, direct consideration of ocean-atmosphere exchange appears to be limited in current international regulations. Thus, a key follow-up question on air-sea policy is: should the air-sea interface be considered in regulations for the implications of the physical and biogeochemical processes in which it is involved (Steinacher *et al*. 2013)? If the answer to this second key question is positive, how do ocean-atmosphere interactions become established as a topic that policy-makers are able to address in regulations? Experience within the SOLAS community in advising policy makers, for example in the field of climate mitigation, make it well-placed to scrutinise the potential value of such consideration in the future.

Outcome

A multidisciplinary group is now working on the identified key questions in promoting lasting open ocean stewardship and on policy across the ocean-atmosphere interface (Table 1, Figure 3). This activity seeks to highlight the main gaps in understanding to support future research proposals. The work on policy across the ocean-atmosphere interface aims at highlighting the potential need for an explicit integration of this interface in policy-making through an analysis of relevant international legislation, where this would improve the policies' effectiveness through a more holistic approach. So far, it appears that policy-makers hardly explicitly consider this interface. A session to be included in the Sustainability Research + Innovation Congress 2020 in Brisbane, Australia proposes to explore these gaps in relation to policy across the air-sea interface and addresses discrepancies between ocean-atmosphere science and policy. The session deals with the influence of the atmosphere on the ocean and/or feedbacks from ocean to atmosphere that could or should have a direct or indirect impact on marine policy, any social science perspectives that relate to the air-sea interface, and topics that address the integration of ocean and atmosphere regulatory frameworks and governance.

Table 1. Topics and outcomes from the SOLAS Science and Society approach to interdisciplinary research.

Topic	Disciplines involved	Key interdisciplinary research questions arising	Anticipated future outcomes of better interdisciplinary working
Valuing carbon and the ocean's role	Environmental economics, ocean carbon and nutrient biogeochemistry, air-sea gas exchange, marine ecosystem services, marine biogeochemistry	*What carbon is 'valuable'?*	A marine and coastal carbon valuation system grounded in biogeochemistry
		How to attribute marine carbon storage to nation states for carbon credits?	A legal framework with natural science underpinning to support nation states in positive action to protect or enhance marine carbon stocks
		How to account for timescales of carbon storage?	New economic approaches to marine and coastal carbon sequestration valuation based on biogeochemical knowledge
Air-sea interaction, policy and stewardship	Biogeochemical oceanography, atmospheric chemistry, environmental sociology, ocean surface physics, international law of the sea, ocean-atmosphere interactions	*Is the interaction between the lower atmosphere and the upper layer of the ocean sufficiently addressed in governance?*	More comprehensive governance that encompasses all impacts to coupled air-sea system
		How are air-sea interactions established as important without overstating the effect?	Interdisciplinary assessment of the significance of air-sea interaction in regulation, either implicitly or explicitly
		Are there cultural/national differences in how to effectively promote long-lasting stewardship of the	Culturally specific public awareness campaigns about the open ocean grounded in

		open ocean?	interdisciplinary science
Air-sea interactions and the shipping industry	Ecological economics, microbial and marine trace gas biogeochemistry, international law of the sea and the environment, boundary layer meteorology, atmospheric chemistry and physics, innovative shipping, fluid dynamics	*What is the value of clean air and water, especially in coastal and pristine environments?* *Is this applicable as sustainability and circular economy for marine ecosystem services?* *How can future shipping be sustainable?*	Interdisciplinary evaluation of the effects and risks of shipping emissions to the atmosphere and the ocean Actions to support the move to a more circular economy can motivate the shipping industry to develop sustainable/clean technologies International policy dialogues for global emission control, improved standards, technologies and monitoring guidelines for application of exhaust gas cleaning systems.

Air-sea interactions and the shipping industry

Background

During the last decades, shipping traffic has grown faster than the world economy (UNCTAD 2017) and this trend is expected to continue in the future. There is growing concern about the marine environmental impacts of shipping traffic, from both operational and accidental discharges of pollutants (oil residues, bilges, garbage, ballast water, air pollutants), which may negatively affect the marine environment at scales from species-level to broader effects on ecosystem services. To combat anthropogenic climate change, strict emission controls of greenhouse gases and pollutants in maritime transport are needed and (will be) implemented in a stepwise manner by flag states and port states (see next paragraph for details). Within international law, the ability of coastal states to impose and enforce their own environmental and navigation regulations on foreign ships is limited. Instead, states use international conventions established through the International Maritime Organization (IMO) in which flag states have a dominant position. Increased interaction between natural scientists and social scientists might lead to progress in developing new international conventions concerned with green shipping, clean scrapping of ships and improved port management.

Approximately 80% of fuel used by the global shipping fleet in 2010 was low-cost, heavy fuel oil (HFO) (Smith *et al*. 2015). Today, commercial shipping still mainly uses HFO outside specially designated emission control areas (such as SECAs and in port areas), emitting significant amounts of sulphur, nitrogen, metals, hydrocarbons, organic compounds and aerosols to the atmosphere during combustion (Eyring *et al*. 2005; Turner *et al*. 2017b). As some of these compounds have a limited residence time in the atmosphere, they are deposited relatively close to the source and dissolve or suspend in the surface ocean. In 2015, the IMO adopted a reduction in the maximum ship sulphur emission (from 1% to 0.1% of fuel mass) in the SECAs of North Europe and North America (included in the International Convention for the Prevention of Pollution from Ships-MARPOL-Annex VI) while the EU Sulphur Directive EU 2016/802 applies the same objective in the ports of EU-member states outside SECAs. From January 2020, the IMO requires all shipping in international waters to reduce sulphur emissions from 3.5% to 0.5% of fuel mass. Some states, such as China, require an S-content of 0.5 % instead of 3.5% for ships in their main ports and coastal waters, for example in Shenzhen Port Area, Hong Kong harbour, ports in the Yangtze River Delta, the Pearl River Delta and the Bohai Sea. Several sulphur emission reduction technologies exist for achieving the international emission limits. Open-loop (and to some extent closed-loop) exhaust gas cleaning systems ('scrubbers') are increasingly used to comply with stricter fuel emission regulations, especially since the new regulations started in 2020. The increased costs associated with high-quality, low-sulphur content fuel oil have shaped scrubber technology to be an attractive and viable alternative especially for larger vessels that still use HFO (Lindstad *et al*. 2017). However, little is known about the chemical composition of the scrubber effluent and its ecological consequences for marine life and biogeochemical processes (Endres *et al*. 2018). Ecotoxicological studies on marine pollutants (e.g. metals and polycyclic aromatic hydrocarbons) imply that scrubber wash water could have a harmful effect on marine organisms and marine ecosystems (Ivanina and Sokolova 2015). Scrubber technology focuses mainly on the removal of sulphur from the exhaust. Other pollutants, such as fine particulate matter, heavy metals and organic compounds are not reduced to the same extent.

Challenge

Although the use of new technologies, such as scrubbers, benefits the environment by significantly reducing ship emissions to the atmosphere, their use may lead to other, as yet unascertained and unquantified, negative impacts on the marine environment (Endres *et al*. 2018). In the long term perspective, it is likely that long-distance shipping will replace fuel oil by cleaner alternatives, such as liquefied natural gas (LNG) or methanol in order to comply with the IMO strategy on reduction of greenhouse gas emissions by 70% by 2050 compared to 2008. The consequences of increasing LNG or methanol use needs to be investigated, especially as both are known to leak methane to the atmosphere, which is a stronger greenhouse gas than carbon dioxide. For these topics, it is important to collaborate with industrial partners in order to find economically viable solutions that do not create additional environmental hazards.

Ship emission models such as STEAM3 (Jalkanen *et al*. 2009; Jalkanen *et al*. 2012; Johannson *et al*. 2017), combining ship traffic data from Automatic Identification System with a technical database consisting of ship emission factors and other characteristics, allow modelling of global ship emissions. The ability to more accurately forecast the release of greenhouse gases and pollutants using such models is a potentially powerful tool for ensuring compliance with legislation and regulations and to assess the future environmental impact of maritime transport. However, due to its complex nature, this requires further modelling efforts, validation by in-situ measurements of emissions on-board and in the surface ocean, and the integration of future socio-economic developments, such as future regulations on fuel types and ship emissions.

Outcome

Several interdisciplinary research priorities have been identified within this initiative, which will help develop an environmentally sustainable shipping industry, and avoid the transformation of one type of pollution into another (Endres *et al*. 2018 - a direct result of the SOLAS process, Table 1, Figure 3). Among these, more attention should be paid to improve implementation, compliance, and enforcement of adequate environmental standards by flag states (the jurisdiction under which a vessel falls) and port state control. In addition, experimental studies are crucial to increase understanding of the ecological and biogeochemical effects of ship-sourced pollution (e.g., scrubber wash water discharges). To better forecast the effects of ship emissions and future projections of scrubber technology usage, atmospheric and ocean model studies need to be improved with high resolution monitoring data of ship traffic and pollutants in water and air, coupled with socio-economic models. To this end, a Collaborative Research Action on Transdisciplinary Research for Ocean Sustainability proposal (ShipTRASE, call initiated by the Belmont Forum and JPI Oceans) has been granted to an international consortium of natural scientists, engineers, lawyers, and economists to investigate short-term (with scrubber technology) and long-term (LNG) ship emissions on air-sea interactions and subsequent feedbacks with policy and the economy. This proposal is direct outcome of the SOLAS initiative described here.

Outlook/Suggestions for future implementation

Since the launch of Future Earth at the Planet Under Pressure meeting in London, 2012, the need for increased integration of the natural and social sciences has risen to even more prominence. Future Earth developed the Ocean KAN to support this integration, which underscores the call for solution-oriented research. This paper provides a look at how the SOLAS community would like to address this research need and outlines the initial steps that must be taken. This publication is intended to act as a foundation that enables the air-sea interaction community to confront relevant issues at the natural and social science interface. Through this process we have determined that our overarching goal is to galvanize the participation of non-natural scientists over a range of disciplines, from economy to law to sociology and environmental psychology, within the SOLAS network We have identified the following challenges: 1) achieving effective communication, which we can tackle by changing the lack of a common language between the disciplines and the frequent use of jargon; 2) the use of different methodologies, which can be mitigated by forging close relationships across disciplines in order to obtain insight into the various research styles; 3) obtaining the appropriate balance between curiosity-driven fundamental research and the perceived need to co-design science jointly as a product of scientists and stakeholders. This last concern is often expressed by scientists stating that a co-design approach might be considered too ‘top-down’ and that the added scientific value may not always be evident. In addition, it might be difficult to convince some traditional fundamental research funding agencies to allow for appropriate financial schemes and time frames to accommodate co-designed research, and the complementing co-produced outcomes, to serve both science and stakeholders.

The wider implementation of the collaborative structure discussed above is proposed. Topics that can be considered include harmful algal blooms and macroalgae farming. The outcome of these efforts was a more holistic and comprehensive approach to pressing and globally relevant issues that is often achieved with more traditional cursory collaborations between the natural and social sciences. The success of this collaborative model for the three working groups suggests that this approach should be more frequently adopted in interdisciplinary research between natural and social scientists, especially in addressing SOLAS issues. Future endeavors could entail the expansion of existing working groups such as those of the SCOR to include social scientists, economists and lawyers. It could also mean collaborative sessions at major annual research conferences that include members of both the natural and social science communities. Furthermore, researchers should lobby their academic department to partner with other departments at their institution. Examples of such collaborations include the Martin School and Environmental Change Institute at the University of Oxford, the Global Systems Institute at Exeter University, and the Grantham Institute at Imperial College, which encourage interdisciplinary research. Additionally, the Canadian ocean acidification research program (COARP) was jointly led by natural scientists and economists from Dalhousie University. Finally, existing programs should strive to achieve better inclusivity and appropriate participation amongst disciplines. For instance, the International Panel for Climate Change (IPCC) assessment report (IPCC, 2014) was comprised of multiple working groups, but none of them had significant representation from the social sciences. Even Working Group II on Impacts, Adaptation and Vulnerability, which aimed to 'assess the vulnerability of socioeconomic systems to climate change', did not have economists serving as co- or vice chairs. Considering this, it is recommended that enhanced efforts are made to ensure that existing organizational structures become more equitable in terms of representation from the natural and social sciences.

In the transition to interfacing directly with society, we see that certain changes to our method could be beneficial. For example, a better definition of the issues and key messages could be a helpful starting point for framing research ideas. Tools such as the Responsible Research and Innovation website (www.rri-tools.eu) can be an effective starting point for future discussions related to SOLAS science and society. There is a clear need to find compromises to overcome perceived differences in the goals, timelines and resource needs between the social and natural science communities, and stakeholders. Different perspectives must be identified and collated in order to respond to challenges within the marine system, yet the purpose of the integration for different collaborative projects may not always be the same (Frodeman *et al*. 2012). Furthermore, starting from a natural science perspective may not be the most effective way to identify overlaps between social and natural science disciplines. A better starting point might be scientific topics that are more immediately connected to public rights and responsibilities. These may then lead into SOLAS research specialities. Because targets and goals can differ between scientific communities and the wider population, a systematic understanding of those different perspectives will help to bridge that gap. The inclusion of other disciplines would allow us to consider the objectives and the moral dilemmas from the perspective of different actors, determine the arguments for and against different solutions, and pinpoint how to find the best outcomes, including those for the oceans. The work presented here can lead the way to future co-designed research on additional topics fitting to the SOLAS mission and to its sponsors, such as Future Earth, in general.

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