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POLICY BRIDGE

Science, international law, and policy across the air–sea interface

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The objective of this perspective article is to determine the extent to which processes operating across the air–sea interface are considered in international environmental policy. The ocean is usually important but rarely a defining feature in such policies. We will begin with a brief introduction to the existing relevant treaties and policy frameworks. The provisions within these treaties will be analyzed for instances when air–sea interactions are considered and when they are not. We aim to establish that there is a lack of consideration in international regulation of the interaction between the atmosphere and the ocean, something that is not compatible with the environmental reality. Consequently, we point out examples where we think the air–sea interface could have been incorporated in international legislation. The question of why there is a gap between science and policy, regarding air–sea interactions, is posed and our hypotheses for the answers are outlined. The concept of so-called soft law and related instruments, such as the 2015 United Nations Sustainable Development Goals, are discussed. We finalize this review with our recommendations for future policymaking across the air–sea interface.

Keywords: Air–sea interface, Policy, International law, Sustainable Development Goals

Introduction

The Surface Ocean-Lower Atmosphere Study (SOLAS) program, founded in 2004, is an international research effort that pioneers interdisciplinary, cross-boundary research and has participated in related policymaking efforts regarding climate intervention and ocean acidification (Wallace et al., 2010; IGBP et al., 2013). Especially Wallace et al. (2010), a summary for policymakers contracted by the International Maritime Organization (IMO), is a good example where SOLAS scientists were instrumental in the development of policy, in this case the amendments to the London Protocol. Moreover, this engagement emphasizes the importance of science input to the legislative process. Besides significance in the field of climate intervention, policy at the air–sea interface is increasingly important with regard to shipping, pollution, and other means of combating climate change. Consequently, the science guiding and informing this policy at the air–sea interface also gains importance.

In recent years, the SOLAS community has identified the need to include researchers from disciplines outside of the natural sciences, including socioeconomics and law, as well as a diversity of stakeholders. To meet this goal, SOLAS invited 25 social and natural scientists to a workshop in Brussels in October 2016, which was focused on bridging the gap between SOLAS science and societal needs. The group identified SOLAS-related research topics for which several natural and social science disciplines must work together (Marandino et al., 2020). One striking question posed in the Brussels meeting was: Are air–sea interactions adequately accounted for in policy? SOLAS research has shown that the atmosphere and ocean domains are often considered separately but are in fact intimately connected through processes occurring at the air–sea interface. Humans tend to make a clear distinction between the ocean and the air directly above it, with little consideration of the interaction between the ocean and the air, that is, the air–sea interface. The natural coupling in the earth system may not be mirrored in the policies governing these systems since policymaking and the underlying law is traditionally conservative. As such, the domains are separately defined and regulated, which may not be a sufficient and effective strategy. Regulatory frameworks for the governance of the ocean on the one hand and the atmosphere on the other reflect this arbitrary duality (Marandino et al., 2020).

Here, we assess whether regulations consider the biogeochemical interaction between the lower atmosphere and the upper layer of the ocean. First, we chose to focus on international regulations and policy. Regional and national legislation as well as national implementation

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of the treaties and goals that we cover are beyond the scope of this article. One could argue in favour of a comparison of what we discuss here with, for instance, land-atmosphere interaction or the interplay between ocean and land. Yet, the latter two require almost without exception an analysis of national legislation because these interfaces lie very often within national jurisdiction. Even a legal analysis of the influence of offshore windfarms on air–sea interaction would necessarily require reference to national legislation and is not touched upon in this article. Focusing on the interaction between the atmosphere and the ocean fits perfectly within the SOLAS realm. Second, it appears to be a logical step from here to plead for holistic approaches to governance. We thought it therefore indispensable to discuss new ideas for governance that build upon earth system science, multicompartment approaches, and planetary boundaries, such as earth system governance and the Sustainable Development Goals. Yet, we do so through the lens of air–sea interaction.

Policy is compartmentalized

The international regulatory framework for the ocean has as its basis the LOS Convention (Rothwell et al., 2015b; Rothwell and Stephens, 2016). The last president of the conference that negotiated the Convention went as far as stating that the LOS Convention is "a comprehensive constitution for the oceans which will stand the test of time" (Koh, 1982). Other global and regional conventions put flesh to the bones of the LOS Convention, either in a specific field or in a specific region (Rothwell et al., 2015a).

The atmosphere has no such global regulatory framework like the LOS Convention (Murase, 2017; Sands et al., 2018). The international rules for the atmosphere developed much later than the customary international law of the sea and concentrate on the effects of air pollution (Gillespie, 2006; Redgwell, 2018; Sands et al., 2018). Regional efforts on long-range transboundary air pollution, caused by acid rain, led to the 1979 Convention on Long Range Transboundary Air Pollution (LRTAP Convention). Globally, first efforts concentrated on the depletion of the ozone layer through the 1985 Vienna Convention for the Protection of the Ozone Layer and its 1987 Montreal Protocol. The international community addressed climate change for the first time with the 1992 United Nations Framework Convention on Climate Change (FCC Convention; Gillespie, 2006; Sands et al., 2018).

Treaty regimes relevant to air—sea interactions

Table 1 contains all the legal instruments that are dealt with in this article. Whereas it took representatives of more than 150 States almost a decade to negotiate the LOS Convention (Churchill, 2015; Rothwell and Stephens, 2016), many other international conventions have very different histories. To some extent, these different ways of coming into being might explain the differentiated foci of provisions of these regulatory instruments. The LOS Convention is much broader in scope than conventions that deal with a specific form of pollution. Treaties like the International Convention for the Prevention of Pollution from Ships (MARPOL) came into being under the umbrella of the IMO (Rothwell and Stephens, 2016). The Ozone Convention was negotiated within the United Nations Environment Programme (UNEP) over the course of a few years (Yoshida, 2001; Gillespie, 2006). The same is true for the 2013 Minamata Convention on Mercury (Mercury Convention; Redgwell, 2018). The Convention on Biological Diversity was also negotiated under the auspices of the UNEP and opened for signature at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro in June 1992 (Sands et al., 2018). The FCC Convention was also opened for signature at the UNCED.

In addition to UNEP, the prime movers behind the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change that drafted the FCC Convention are the General Assembly of the United Nations and the World Meteorological Organization (Gillespie, 2006; Sands et al., 2018). The efforts to prevent, or at least minimize, transboundary air pollution occurred primarily in Europe and North America. The Stockholm Declaration of 1972 supplied a significant incentive to start negotiations. Subsequent interest in the issue from the G7, the Organisation for European Co-operation and Development, the International Labour Organization and also non-governmental organisations such as the International Union for the Conservation of Nature, finally resulted in the LRTAP Convention (Gillespie, 2006). The 1998 Protocol on Persistent Organic Pollutants to the LRTAP Convention formed a major precedent for the negotiations of the 2001 Stockholm Convention on Persistent Organic Pollutants (POPs Convention), an international treaty that extends its applicability beyond just North America and Europe (Sands et al., 2018).

Examples of when air—sea interaction processes are explicitly considered

The LOS Convention's part on protection and preservation of the marine environment contains 3 provisions that explicitly refer to the interaction between the atmosphere and the ocean:

1) In Art. 194(3)(a) LOS Convention, the drafters list as one measure to minimize the sources of pollution of the marine environment "the release of toxic, harmful or noxious substances, especially those which are persistent [. . .] from or through the atmosphere."
2) This is then further specified in Artt. 212 and 222 LOS Convention, with the latter dealing specifically with enforcement. Wacht (2017) distinguishes here between substances from the atmosphere, such as persistent organic pollutants and greenhouse gases, on the one hand and substances as a source of pollution through the atmosphere, as is the case with acid rain, on the other hand (Wacht, 2017). Yet, this distinction does not appear to be tenable from a scientific viewpoint. Since the provision comprises explicitly both, there is no need for a distinction.

Table 1. Relevant legal instruments (listed chronologically)

Treaty	Year	Abbreviation
London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter	1972	London Convention
International Convention for the Prevention of Pollution by Ships	1973	MARPOL
Protocol Relating to the Convention for the Prevention of Pollution from Ships	1978	MARPOL
Convention on Long-Range Transboundary Air Pollution	1979	LRTAP Convention
United Nations Convention on the Law of the Sea	1982	LOS Convention
Vienna Convention for the Protection of the Ozone Layer	1985	Vienna Convention
Montreal Protocol on Substances That Deplete the Ozone Layer	1987	Montreal Protocol
Protocol Concerning the Control of Emissions of Nitrogen Oxides or Their Transboundary Fluxes	1988	NOx Protocol (to the LRTAP Convention)
Protocol Concerning the Control of Emissions of Volatile Organic Compounds or Their Transboundary Fluxes	1991	VOC Protocol (to the LRTAP Convention)
Convention on Biological Diversity	1992	
United Nations Framework Convention on Climate Change	1992	FCC Convention
Protocol to the 1979 Convention on Long Range Transboundary Air Pollution on Further Reduction of Sulphur Emissions	1994	Protocol on Further Reduction of Sulphur Emissions (to the LRTAP Convention)
Protocol to the London Dumping Convention	1997	London Protocol
UNECE Protocol on Heavy Metals	1998	Protocol on Heavy Metals (to the LRTAP Convention)
UNECE Protocol on Persistent Organic Pollutants	1998	POPs Protocol (to the LRTAP Convention)
Protocol to Abate Acidification, Eutrophication and Ground-level Ozone	1999	Gothenburg Protocol (to the LRTAP Convention)
Stockholm Convention on Persistent Organic Pollutants	2001	POPs Convention
Convention on Biological Diversity, Conference of the Parties, Decision IX/16 Biodiversity and climate change	2008	
United Nations, Report of the Conference of the Parties on its Sixteenth Session, Cancun, 29 November to 10 December 2010 Document FCCC/CP/2010/7/Add.1	2011	
Minamata Convention on Mercury	2013	Mercury Convention
United Nations Framework Convention on Climate Change, Conference of the Parties, Decision 1/CP.21	2015	Paris Agreement

3) Art. 222 LOS Convention concentrates on the enforcement of rules concerning pollution from and through the atmosphere but only in the airspace of a state or on vessels that fly its flag. The enforcement regarding land-based sources that might also go through the atmosphere is subject to another provision—Art. 213 LOS Convention—which does not touch upon the air–sea interface explicitly (Bartenstein, 2017).

Subsequently, other international and regional conventions such as these discussed in this article fill this general framework of rules with more specific content (Bartenstein, 2017). Yet, the Stockholm POPs Convention only explicitly includes air–sea interaction in its preamble, which starts with recognizing “that persistent organic pollutants possess toxic properties, resist degradation, bioaccumulate and are transported, through air, water, and migratory species, across international boundaries and deposited far from their place of release, where they accumulate in terrestrial and aquatic ecosystems.” The preamble of an international treaty, however, does not contain any binding norms.

One of the few instances of where air–sea exchange appears to have been explicitly included in environmental policy is the regulation of ocean iron fertilization. Yet, the overall policy aim of these efforts seems to be the protection of the ocean, not of the atmosphere. International efforts to restrict iron fertilization activities to small-scale scientific research occurred through interpretations of the Convention on Biological Diversity and amendments to the London Convention following concerns raised over the ethical, legal, and scientific merits of this form of climate intervention (Strong et al., 2009). The articles in this special issue on blue carbon and climate intervention cover the governance-related aspects in detail (Johnson et al., n.d.). Here, we focus only on the extent to which the regulation specifically covers air–sea interaction.

The 1972 London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) and its 1996 Protocol do not explicitly address air–sea interactions. Although the general prohibition of incineration at sea of waste is considered under Art. 5 of the Convention, and which where enforced would almost certainly lead to a reduction of atmospheric deposition of contaminants across the air–sea boundary, it is not justified or directed by explicit consideration of air–sea interactions.

As ocean iron fertilization appears to qualify as dumping under the current rules of international law, the State Parties to the London Convention and its London Protocol, containing the regulations on this matter, decided to amend the Protocol at their Consultative Meetings in 2013 to regulate ocean iron fertilization, following a proposal by Australia, Nigeria, and the Republic of Korea (Boschen, 2015). These amendments have yet to enter into force and therefore only allows for small-scale scientific experiments so far (1992 Convention on Biological Diversity, Conference of the Parties Decision IX/16 Biodiversity and climate change). Small-scale research is nonetheless exempted from the proposed rules. It is up to States when to ratify the proposed amendments and this can take considerable amounts of time because the changes do not seem pertinent enough for States to be their priority. That these developments occur so slowly is at odds with the urgency with which humankind must tackle issues concerning climate change. The ocean iron fertilization experiment that was conducted on the high seas off the western Canadian coast in 2012 appears to have used the label of research to operate outside the international rules as explained above (Craik et al., 2013). One can question if this is a desirable outcome of the set-up of the current regulatory framework that is applicable to ocean iron fertilization.

Examples of when air—sea interaction processes are implicitly considered

The International Convention for the Prevention of Pollution from Ships (MARPOL) covers pollution of the marine environment by ships from operational or accidental causes. The article on ship emissions in this special issue deals more specifically with MARPOL (Shi et al., 2023). Here, it is submitted that the air–sea interface is not explicitly considered and, similar to the case of the London Convention discussed below, compliance with MARPOL can be expected to reduce the deposition of contaminants from the atmosphere to the ocean surface (with particular reference to SOx, NOx, and particulate matter). The definition of discharge in its Art. 2(3) includes the emission of harmful substances and, although not made explicit, this can include emissions to the atmosphere.

The LRTAP Convention requires its State parties to initiate and cooperate in research concerning “the effects of sulphur compounds and other major air pollutants on human and the environment, including [. . .] aquatic and other natural ecosystems” (Art. 7). Like in its Art. 9 on monitoring, Art. 6 of its Protocol concerning Emission of Nitrogen Oxides or Their Transboundary Fluxes (NOx Protocol) and the preamble of its Protocol on Further Reductions of Sulphur Emissions, it simply refers to water. Evidently, this does not have to mean the marine environment. Only the preamble of the Convention’s Protocol on Heavy Metals refers to the effects in international waters and the preamble of its Protocol to Abate Acidification, Eutrophication, and Ground-level Ozone mentions the work of the IMO. These 2 cases certainly point to the marine environment and consequently implicitly acknowledge the interaction between the atmosphere and the ocean.

The Convention on Biological Diversity includes in its principle as stated in Art. 3 “the responsibility to ensure that activities with [State parties’] jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.” Indirectly, this responsibility includes any harm to the marine environment that occurs through the atmosphere. These processes should be identified and monitored (Art. 7(c)). Moreover, State parties are urged to introduce procedures for the conduct of environmental impact assessments and notification concerning harm if such instances occur (Art. 14(1)(a) and (d)).

Generally, the law of the sea governing the uptake of greenhouse gases in the ocean focuses on potentially negative effects on the marine environment and its inhabitants but does not consider the potential positive effects for the global climate. No binding norm of the law of the sea currently mentions climate intervention or any form of it explicitly. Röschel and Neumann (2023) provide a review of the framework that governs ocean-based negative emissions technologies. They also use a categorization of international instruments that either directly (explicitly), implicitly, or indirectly govern these instruments. The authors also assess the relevance of governance frameworks for blue carbon. The LOS Convention is essentially permissive regarding climate intervention in the marine environment. States should just consider the rights and duties of other States when conducting activities that amount to climate intervention (Scott, 2015). Whereas certain technologies for climate intervention might amount to pollution, such as ocean iron fertilization, others might not (Scott, 2012; Johansen, 2021).

Despite the fact that the FCC Convention appears to largely ignore the ocean (Freestone, 2018), in its first article, it defines the climate system as “the totality of the atmosphere, hydrosphere, biosphere and geosphere and their interactions.” This also includes air–sea interaction, but the definitions of reservoir, sink, and source in the same article do not touch upon this interaction specifically. The Convention’s principles in Art. 3 also refer to reservoirs, sinks, and sources but again not specifically to the interface between the atmosphere and the ocean. Art 4(1)(d) FCC Convention does oblige parties to the Convention to promote sustainable management as well as the promotion and cooperation "in the conservation and enhancement, as appropriate, of sinks and reservoirs [. . .] including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems." Consequently, the interaction between the atmosphere and the ocean is made here implicitly. The ocean and climate change dialogue that took place at the last couple of Conferences of the Parties to the FCC Convention might concretize this and encourages States to include coastal blue carbon ecosystems in their Nationally Determined Contributions (Röschel and Neumann, 2023).

An example highlighting the importance of air–sea interactions for several societal issues is the accumulation of mercury in the marine food chain. Mercury (Hg) is a ubiquitous pollutant and has been enriched in the biosphere through anthropogenic activities. According to Mason et al. (2012), the main sources of Hg to the biosphere are inputs from atmospheric deposition and rivers, as well as *in situ* production of monomethylmercury (CH_3Hg) and dimethylmercury ($(CH_3)_2Hg$). The consumption of mercury arising from CH_3Hg in fish is the main health risk to people and wildlife (Lambert et al., 2012). Current data suggest that concentrations in the ocean are changing at different rates due to differences in atmospheric sources and that most biological exposure occurs in the surface ocean. Hence, changes in atmospheric mercury inputs achieved by regulatory control strategies should induce food web responses over years to decades, resulting in a decline in human exposure and risk (Mason et al., 2012). Lambert et al. (2012), using U.S. regulatory strategies as an example, states that stronger science and policy integration will benefit mid- and large-scale efforts to minimize exposure to methylmercury. This could be achieved through increased attention to transboundary movement of mercury in air, water, and biota and the coordination of policy efforts across multiple environmental media. However, any such changes could potentially be masked by changes in mercury cycling arising from climate change effects (Dastoor et al., 2022).

Despite the potential importance of these types of processes, when the Mercury Convention in its Art. 9 deals with releases it only explicitly addresses those from land to water and does not touch upon the air–sea interface.

Both technical as well as scientific groups have worked on the evaluation of the effectiveness of the Minamata Convention. They trace anthropogenic and geogenic emissions through the atmosphere and the ocean, which implicitly leads to multi-compartment modeling approaches to quantify those sources as compared to primary anthropogenic emissions. The Task Force on Hemispheric Transport of Air Pollutants (HTAP), organized under the LRTAP Convention, supports this work through the first multicompartment modeling studies including marine biogeochemical models (http://unece.org/hemispheric-transport-air-pollution). Although the LRTAP Convention and the Mercury Convention only consider air–sea interaction implicitly, bodies under the auspices of these international treaties start to consider this interaction increasingly explicit.

Approximately 80% of this mercury is subsequently reemitted to the atmosphere (Driscoll et al., 2013). Although the 2013 Mercury Convention now regulates the use, trade, and disposal of mercury, policy or regulations do not explicitly address processes of air–sea exchange beyond recommendations for improving or expanding research and monitoring. Similarly, air–sea exchange has been a significant process influencing the biogeochemical cycling of POPs, such as polychlorinated biphenyls and organochlorine pesticides (Wöhrnschimmel et al., 2012). In this case, again, regulations or policies that address air–sea exchange are not explicitly addressed in POP management policies (e.g., the 1998 Aarhus POPs Protocol to the LRTAP Convention and the POPs Convention).

Examples of when air—sea interaction processes are not considered/gaps in policies

Notwithstanding the examples above, there are many examples of international legislation where the air–sea interface could play a role but has not found its way into the text of the provisions. The Vienna Convention for the Protection of the Ozone Layer includes provisions for the international sharing of research to promote better scientific understanding of the ozone layer and associated processes. Art. 3 and Annex I (Research and Systematic Observations) of the Convention provide explicit guidance on the scientific research that the parties are expected to undertake and the nature and extent of data to be recorded. However, the focus is primarily on the atmosphere and no specific mention of the ocean is made beyond the expected impact of ozone-induced effects on marine ecosystems (via increased ultraviolet radiation) and on ocean surface temperature (via increasing global temperatures). Similarly, the Montreal Protocol contains explicit direction (Art. 9: Research, development, public awareness and exchange of information) on the research commitments of the parties, but there is no specific inclusion of the air–sea interface. Only recently, it has become clear that emission of nitrous oxide (potentially from the ocean) may be a serious threat to the ozone layer (Bange et al., 2019). Other anthropogenic halocarbons contain also compounds that might be released into the water (via wastewater treatment) and then exchange into the atmosphere (Mehlmann et al., 2020; Grote et al., 2022). The explicit inclusion of the air–sea interface might not have been considered relevant at the time that the Montreal Protocol was negotiated, but now it would make sense to include this explicit mentioning because of these recent scientific findings that ozone-depleting substance could originate from or end up in the ocean.

That Art. 192 LOS Convention only refers to the obligation of States to protect and preserve the marine environment is a logical result of the fact that the scope of the LOS Convention is generally limited to the ocean. Nonetheless, reference to interactions with the atmosphere would reflect a more holistic approach to environmental protection, especially nowadays, 40 years after the conclusion of the LOS Convention. Also Art. 201 LOS Convention, dealing with the scientific criteria for regulation, lacks a connection with atmospheric science. Art. 208 LOS Convention covers pollution that results from the exploitation of resources in coastal States' continental shelves but again does not refer to any effects of this on the atmosphere. Nor does Art. 210 LOS Convention on dumping. Yet, the more specific international convention on dumping, the London Convention and its London Protocol, do address air–sea interaction as discussed above in the case of ocean iron fertilization. The first paragraph of Art. 237 LOS Convention refers to "special conventions and agreements concluded previously which relate to the protection and preservation of the marine environment and to agreements which may be concluded in furtherance of the general principles set forth in this Convention" and the London Convention is considered one of these.

Switching now to the atmospheric side, the NOx Protocol to the LRTAP Convention lists basic obligations for its State Parties in Art. 2. Yet, none of these refers to interaction between the atmosphere and the ocean. This is also true for the basic obligations under its Protocol on Further Reductions of Sulphur Emissions (Art. 2) and under the Protocol concerning the Control of Emissions of Volatile Organic Compounds or Their Transboundary Fluxes (Art. 2) as well as the latter's provisions on further measures, research, and monitoring (Artt. 3 and 5). The provisions on research, development, and monitoring, and even the objective of the Protocol on Heavy Metals to the LRTAP Convention does not include a reference to air–sea interaction (Artt. 6 and 2, respectively) nor do its annexes. The basic obligations (Art. 3) nor annexes of the Protocol on POPs also do contain such a reference. Finally, the latest protocol to the LRTAP Convention, the Gothenburg Protocol, lacks any such reference in the provision concerning its objective, basic obligations, research, development and monitoring (Artt. 2, 3, and 8).

Climate targets, designed to inform policies limiting the impacts of climate change caused by anthropogenic greenhouse gas emissions, have highlighted global temperature increases (United Nations. Report of the Conference of the Parties on its Sixteenth Session, Cancun, 29 November to 10 December 2010 Document FCCC/CP/2010/7/Add.1). Meanwhile, the long-term impacts of increased carbon emissions, such as ocean acidification, have not been targeted in a similar way. Ocean acidification arises from CO_2 uptake by the ocean and is intensified by the anthropogenic increase of atmospheric CO_2 concentration, leading to severe effects on ocean carbon chemistry, and hence on the marine life that rely on, for example, calcium carbonate (Hopkins et al., 2020 and references therein). With this said, Steinacher et al. (2013) show that carbon emissions options are substantially reduced when multiple climate targets—not only CO_2 uptake by the ocean but also reduction of ocean acidification—are considered. Consequently, this emphasizes that temperature targets alone are unable/insufficient to comprehensively act against the risks from anthropogenic emissions.

Development of national legislation concerning ocean acidification has involved scientists and illustrates what can be achieved in a relatively short period of time when there is recognition of an issue. This is very different for international law. That is not to say that the lack of coverage by international law of ocean acidification has gone unnoticed: "there should be further debate on a prudent and cautious pH-threshold being a reasonable normative global goal" (Böhm and Ott, 2019). As noted by Stephens (2015), the FCC Convention does not address ocean acidification. It encourages the use of the ocean as a sink for greenhouse gases, something that might worsen ocean acidification. To a considerable extent, this lack of coverage of ocean acidification in the international regulation of the effects of climate change might be because the issue was not on the agenda during the negotiation of the said Convention (Stephens, 2015).

Interestingly, the objective of the FCC Convention also does not contain mentioning of the interaction between atmosphere and ocean (Art. 2). The provisions on measures to be taken by the State parties to the Stockholm Convention on POPs are also missing the consideration of the air–sea interface (Artt. 3, 5, and 6). The Mercury Convention deals with many aspects of life where humans might get in touch with mercury: its supply, trade, manufacturing, the products that contain it, goldmining, emissions, waste, and contaminated sites (Artt. 3, 5, 4, 7, 8, 11, and 12). Yet again, none of these provisions do refer to the air–sea interface.

Planetary boundaries and Sustainable Development Goals

Beyond legally binding rules, other methods to highlight goals, boundaries, and thresholds have surfaced. One can define these soft legal obligations as "those international obligations that, while not legally binding themselves, are created with the expectation that they will be given some indirect legal effect through related binding obligations under either international or domestic law" (Meyer, 2009). This soft law is not enforceable (D'Amato, 2009). According to Klein, however, this unconventional law-making is important because "it catalyses timely action, or because it 'thickens' a treaty, fills gaps in a legal regime" and so on (Klein, 2022). Yet, much of these soft laws in the environmental sphere have a close connection with the concept of the Anthropocene, the name for the current geological epoch and the first one to show an impact of humankind, making clear the influence that humankind has over geological timescales (Vidas et al., 2015). If humankind manages to stay within the planetary boundaries, this will assure "a safe operating space for humanity" (Rockström et al., 2009) even though the impact of humankind since the Anthropocene will be a lasting one. SOLAS' scientific output feeds in critical information to the quantification of 3 of the 9 planetary boundaries: climate change, biogeochemical flows, and ocean acidification. The concept of planetary boundaries has been picked up in policy debates on an international level (Galaz, 2017). Both the Anthropocene (Vidas et al., 2021) as well as the 9 planetary boundaries appear to have a link to marine governance,

Table 2. SOLAS contributions to SDGs (created by Cliff Law, Minhan Dai and the SOLAS International Project Office)

	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	5 GENDER EQUALITY	7 AFFORDABLE AND CLEAN ENERGY	11 SUSTAINABLE CITIES AND COMMUNITIES	13 CLIMATE ACTION	14 LIFE BELOW WATER	14 LIFE BELOW WATER	14 LIFE BELOW WATER	14 LIFE BELOW WATER	15 LIFE ON LAND	17 PARTNERSHIPS FOR THE GOALS
							14.1 Reduce marine pollution	14.2 Sustainable marine management	14.3 Reduce ocean acidification	14A. Knowledge, capacity & technology transfer		
Greenhouse gases and the oceans	+	++	+	+	+++	+++		++	+++	+++	++	+++
Air–sea interface and fluxes of mass and energy		+	+	+	+	+++		+	++	+++	+++	+++
Atmospheric deposition and ocean biogeochemistry		+	+		+	++	++	++	++	+++		+++
Interconnections between aerosols, clouds, and marine ecosystems	+	+++	+	++	+++	+++	++	+	+	+++	++	+++
Ocean biogeochemical control on atmospheric chemistry.	+	+++	+	+	+	+++				+++	++	+++
Integrated studies: Upwelling, Polar & Indian Ocean		+++	+		+	+++	+	+++	+++	+	++	+++
Climate Intervention		+	+			+++		+++	+++		++	+++
Science & Society		+	+	++	+	+++	+++	+++		+++	+	+++

although some more explicitly than others (Van Doorn, 2022). These boundaries are something more than thresholds (Galaz, 2017). The limit of the global mean temperature change to 2°C, for example, should not be viewed as a planetary boundary but rather as "a compromise between what is deemed possible and desirable" (Knutti et al., 2016). The "sum of the formal and informal rule systems and actor-networks at all levels of human society that are set up to steer societies towards preventing, mitigating and adapting to environmental change and earth system transformation" can be called "earth system governance" with its normative component being sustainable development (Biermann, 2017). This earth system governance is largely built upon the interdependencies and complex interrelationships of the Earth as a system (Biermann, 2017).

These interwoven concepts of Anthropocene, planetary boundaries, earth system governance, and sustainable development—developing both in parallel as well as consecutively—might lead to the expectation that there exists a holistic approach to certain human challenges regarding their environment. This then could possibly overcome the arbitrary division between governance for the atmosphere on the one hand and marine governance on the other. Such progress is far from a new consideration (Allott, 1992). However, the Sustainable Development Goals (SDGs) as they are today do not point to this form of policy holism.

The 2015 SDGs as successors of the Millennium Developments Goals might fit the category of soft law. They are certainly more than just pledges and have evolved into international standards. Both States and private actors have internalized and even "legalized" the SDGs to various extents (Telesetsky, 2022). Although "the SDGs were never conceived of as having any normative intent, they have [. . .] generated a normative effect" (Telesetsky, 2022). It is thus worth having a look to what the SDGs can add to the binding international treaties discussed above addressing the air–sea interface. To a certain extent, most SDGs are tightly interconnected, which fits with the concept of SOLAS science well. SOLAS science does contribute to many of the SDGs; less so to the goals on zero hunger (SDG 2), gender equality (SDG 5), and affordable and clean energy (SDG 6) but very much so to the "biosphere" goals on life on land (SDG 15), life below water (SDG 14), and climate action (SDG 13). For SDGs such as the one on good health and well-being (SDG 3) and sustainable cities and communities (SDG 11), SOLAS core themes dictate how much the SOLAS community can contribute. The articles on the SOLAS themes in this special issue address this more in detail. **Table 2** shows SOLAS' contributions to the SDGs until now. The symbols (+) indicate the relative contribution of each theme to the respective SDG: + low contribution; ++ medium contribution; +++ high contribution. SDG 14 is divided into its targets.

From this table, it appears that not all SOLAS core themes touch upon the target to reduce marine pollution. This might be true when looking at marine pollution through the lens of natural science, although the assessment of mercury above also shows that this element clearly breaches the air–sea interface and amounts certainly to pollution. The same is true for ozone. When in the future, SOLAS scientists look at marine pollution from beyond the natural science and include social science and humanities, the picture might look different. First, SOLAS scientists plan to organize workshops in 2024 to deal with the air–sea interface aspects of marine plastics. These workshops are intended to be interdisciplinary and would address the fluxes as listed in the second row of **Table 2**.

Second, it is arguable that an increased uptake of the ocean of atmospheric carbon dioxide due to anthropogenic emissions amounts to marine pollution (Boyle, 2012; Boyle, 2016). Art. 194(3) of the Law of the Sea Convention that lists, among others, "the release of toxic, harmful or noxious substances, especially those which are persistent, from land-based sources, from or through the atmosphere or by dumping" as a source. The Commission of Small Island States on Climate Change and International Law posed a question to the International Tribunal for the Law of the Sea at the end of 2022 that deals exactly with this topic. The question is what the obligations of States are, under the Law of the Sea Convention, "(a) to prevent, reduce and control pollution of the marine environment in relation to the deleterious effects that result or are likely to result from climate change, including through ocean warming and sea level rise, and ocean acidification, which are caused by anthropogenic greenhouse gas emissions into the atmosphere? (b) to protect and preserve the marine environment in relation to climate change impacts, including ocean warming and sea level rise, and ocean acidification?" (Commission of Small Island States on Climate Change and International Law, 2022). The oral submissions have taken place at the Tribunal in Hamburg in September 2023. The Tribunal is expected to answer the question in 2024. The General Assembly of the United Nations has requested the International Court of Justice in March 2023 to provide an advisory opinion on a similar question but not limited to the law of the sea (United Nations General Assembly, 2023).

All SDGs have targets for which there is one or more indicator to determine if humankind will meet the target by 2030. These targets and indicators of the relevant SDGs for SOLAS science potentially point to the air–sea interface, either implicitly or explicitly. Yet for the SDG on climate action, these targets and their indicators are so broadly formulated (e.g., strengthen resilience to climate-related hazards and integrate measures against climate change into national policies) that they do not point specifically to any physical interaction between the atmosphere and the ocean, although States could of course include this interaction in their implementation of the SDG. The link between the SDG on climate action and other SDGs is very strong: "Tackling SDG 13 is central for sustainable development. Climate change affects our ability to achieve all of the SDGs" (von Schuckmann et al., 2020). Responses to climate change can very well advance other SDGs, such as the one aiming for poverty reduction, for instance (Hallegatte et al., 2016). More specifically, climate intervention in the ocean also necessitates careful consideration of the trade-offs between SDG 13 (on climate action) and other SDGs (in particular SDG 14 on life below water; Singh et al., 2018; Röschel and Neumann, 2023).

As the SDG on climate action points to the strengthening of resilience, so does the SDG on life below water. In its second target, the aim is the avoidance of significant adverse impacts among other things through strengthening resilience. These adverse impacts originate not only on land but also in the atmosphere. An implicit recognition of the air–sea interface is thus present here. However, the most obvious occurrence within the SDGs of addressing this interface is in SDG 14's third target that deals with minimizing the impacts of ocean acidification. While the target does not explicitly list the air–sea interface, it is inherent in the topic of ocean acidification. The link with binding international law is made in another target, aiming at enhancing "the conservation and sustainable use of oceans and their resources by implementing international law as reflected in the" LOS Convention (SDG 14, Target 14.c). The connection between SDG 14 and the other SDGs has been clearly established (von Schuckmann et al., 2020). From a SOLAS perspective, it is worth highlighting the mentioning of harmful algae blooms. Whereas so far, the connection between land and ocean is emphasized in this regard (von Schuckmann et al., 2020), the air–sea interface component of harmful algae blooms connects SDG 14 clearly with the SDG on good health and well-being (SDG 6). Closer cooperation between public health experts and SOLAS scientists presents a great future opportunity for delivering the SDGs.

Recommendations

Overall, direct consideration of ocean-atmosphere exchange appears to be limited in international regulations, both in binding as well as soft law. In the case of international legally binding instruments, only the provision of the LOS Convention dealing with pollution from or through the atmosphere explicitly considers the air–sea interface. Yet, this is in a relatively broad manner, fitting to the LOS Convention's status as "constitution for the ocean." More specifically, the one activity which considers exchange between the atmosphere and the ocean necessarily is ocean iron fertilization. In addition, one of the targets of the SDG on life below water (SDG 14) has as its focus ocean acidification. Although not legally binding, this is another explicit consideration of the air–sea interface. Implicit inclusion of air–sea exchange in regulations occurs concerning ship emissions and mercury.

What we have not considered here is regional and national legislation or the implementation of any of the international agreements and policies. Future research could include this and branch out to comparisons with the land-atmosphere interface and the interaction between ocean and land. Collaboration with other global research projects that cover these interfaces would then be pertinent. This would allow for a more holistic assessment of policies at natural interfaces of the earth system, where multicompartment modeling approaches could assist. A future interdisciplinary focus on marine plastics within SOLAS is currently the most concrete step in this direction.

A key follow-up question on air–sea policy is: "Should this interface be considered in regulations for its process implications?" (Steinacher et al., 2013). If the answer to this second key question is positive, then how do we establish that ocean-atmosphere interaction is important enough for policymakers to consider? Experience within the SOLAS community make it well placed to scrutinize the potential value of such consideration in the future (Marandino et al., 2020). This would not only emphasize the value that SOLAS science has for society, but it will also strengthen its collaborations with social scientists, lawyers and economists, among others. An increasingly significant amount of SOLAS science also has a direct bearing on public health, including but not limited to harmful algal blooms. Closer connections to public health scientists will enrich the value of SOLAS science in the future. The aim to achieve the goals set in international rules and standards are a perfect motivation for interdisciplinary cooperation, for example within the framework of the United Nations Decade of Ocean Science for Sustainable Development. It is quintessential, though, to ask first what policymakers and legislators need from SOLAS scientists. This can range from background information on particular natural processes to active involvement in the development of legislation. Needs might very much differ depending on the topic. Regardless of the level of involvement in these processes, SOLAS scientists should become aware of potential future opportunities where law is developed or created and where they can get involved.

Carbon dioxide emissions and their removal from the atmosphere will be an ongoing topic within SOLAS. The advisory opinions of the International Tribunal for the Law of the Sea and the International Court of Justice are quintessential as authoritative statements on the legal aspects of this. One should consider the consequences for the air–sea interface of future activities such as different technologies to remove carbon dioxide from the atmosphere but also the climate effects of deep-ocean mining. Although much of the SOLAS research has some connection to it, climate change is by no means the exclusive theme of SOLAS. Many other independent atmospheric processes play a role in our earth system. This leads to wonder why the ocean has a separate SDG (SDG 14), but the atmosphere has not (Keywood et al., 2023). Earth system science and its recent spill over into other disciplines, for example law (Kotzé, 2020), only show the importance of future research on the interconnectedness of not only the interaction between the atmosphere and the ocean but also between the natural sciences and other disciplines, both on an individual level as well as on the level of international research projects such as SOLAS.

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There are no competing interests to declare.

Author contributions

Contributed to the conception and design of the article: EvD, CAM, AJP.

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