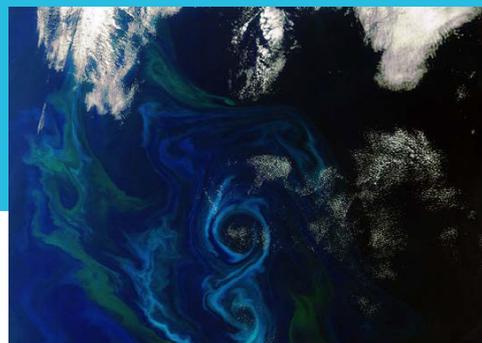




# SOLAS 2015-2025

## Science Plan and Organisation

Linking Ocean-Atmosphere Interactions with Climate and People



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## Front Cover Images

Left: View of the air-sea interface seen from 1m below under very calm conditions. Small-scale capillary waves are visible in the brightest part of the image. Photo: Brian Ward, taken during the STRASSE/SPURS campaign in the sub-tropical North Atlantic in September 2012.

Right: In this Envisat image, a phytoplankton bloom swirls a figure-of-eight in the South Atlantic Ocean about 600 km east of the Falkland Islands. Photo: ESA

## Back Cover Images

Left: Envisat captures dust and sand from the Algerian Sahara Desert, located in northern Africa, blowing west across the Atlantic Ocean. Photo credit: ESA

Right: Each year, the Arctic Ocean experiences the formation and then melting of vast amounts of ice that floats on the sea surface. Photo credit: USGS/ESA

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Juergen Weichselgartner

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SOLAS International Project Office  
GEOMAR Helmholtz Centre for Ocean Research Kiel  
Duesternbrooker Weg 20  
24105 Kiel, Germany  
URL: <http://www.solas-int.org>

# SOLAS 2015-2025

## Science Plan and Organisation

Prepared by past and present members of the SOLAS Scientific Steering Committee:

Emmanuel Boss, USA  
Phillip Boyd, Australia  
Minhan Dai, China  
Anja Engel, Germany  
Cristina Facchini, Italy  
Andrew Jessup, USA  
Diego Gaiero, Argentina  
Huiwang Gao, China  
Christoph Garbe, Germany  
Véronique Garçon, France  
Roland von Glasow, UK  
Michelle Graco, Peru  
Cécile Guieu, France  
Christoph Heinze, Norway  
Ilan Koren, Israel  
Cliff Law, New Zealand  
Maurice Levasseur, Canada  
Lisa Miller, Canada  
Yukihiro Nojiri, Japan  
Patricia Quinn, USA  
Alfonso Saiz-Lopez, Spain  
Eric Saltzman, USA  
V.V.S.S. Sarma, India  
Rafel Simo, Spain  
Jacqueline Stefels, Netherlands  
Parvatha Suntharalingam, UK  
Doug Wallace, Canada  
Brian Ward, Ireland

and science officers of the SOLAS International Project Office:

Emilie Brévière  
Stefan Konradowitz

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# Table of Contents

	<b>Executive Summary .....</b>	<b>5</b>
<b>1</b>	<b>Introduction .....</b>	<b>7</b>
<b>2</b>	<b>Science Plan .....</b>	<b>12</b>
2.1	SOLAS Core Themes .....	12
2.1.1	<i>Greenhouse gases and the oceans .....</i>	12
2.1.2	<i>Air-sea interface and fluxes of mass and energy .....</i>	17
2.1.3	<i>Atmospheric deposition and ocean biogeochemistry .....</i>	21
2.1.4	<i>Interconnections between aerosols, clouds, and marine ecosystems .....</i>	27
2.1.5	<i>Ocean biogeochemical control on atmospheric chemistry .....</i>	33
2.2	SOLAS Cross-Cutting Themes .....	39
2.2.1	<i>Integrated topics .....</i>	39
2.2.2	<i>Research on environmental impacts of geoengineering .....</i>	42
2.2.3	<i>Science and society .....</i>	45
<b>3</b>	<b>Organisation and Management .....</b>	<b>47</b>
3.1	Organisation .....	47
3.2	Communication, Capacity Building, and Global Networking .....	48
3.3	Data Management .....	50
3.4	Linkages to other Projects and Activities .....	51
3.5	Outlook .....	54
<b>4</b>	<b>Acronyms .....</b>	<b>55</b>
<b>5</b>	<b>Appendices .....</b>	<b>58</b>
5.1	Outcome of selected Scientific Synthesis Activities .....	58
5.2	'Added value' of SOLAS .....	61
<b>6</b>	<b>References .....</b>	<b>65</b>



# Executive Summary

In 2004, the Surface Ocean-Lower Atmosphere Study (SOLAS) was established to provide international science coordination and capacity building whose objective was:

*To achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and the atmosphere, and of how this coupled system affects and is affected by climate and environmental change.*

The SOLAS project is unique in connecting the biogeochemical-physical oceanic and atmospheric scientific communities. Thanks to this innovative collaboration over the past decade, the SOLAS community has made important scientific discoveries, while also coming to understand the critical role of SOLAS science in many aspects of the human realm. Now, the need for continued coordination remains compelling, both to address new problems and to develop new approaches to persistent questions.

Progress in SOLAS science is needed to assess the impact of anthropogenic emissions on future climate and ecosystem services, as well as the environmental consequences of policy options. These include various geoengineering strategies that propose manipulation of the surface ocean-lower atmosphere environment to mitigate future climate change. SOLAS is the only organisation in place to facilitate integrated ocean-atmosphere research, across disciplinary and national boundaries. Important services provided by SOLAS to the research community include coordination of international field programmes; exchange of data, analytical techniques, and ideas; optimal utilisation of research platforms; and the development of the next generation of SOLAS researchers.

The new SOLAS science plan forms a solid basis to continue the operation of International SOLAS for the period 2015-2025, under the sponsorship of the Scientific Committee on Oceanic Research (SCOR), Future Earth, the World Climate Research Programme (WCRP), and the International Commission on Atmospheric Chemistry and Global Pollution (iCACGP). The human biogeochemical footprint on the planet is now so large that future quality and sustainability of environmental resources will be determined by societal choices as well as natural variability. There is an enormous benefit to society in understanding the environmental consequences of societal trends and policies. For the SOLAS realm, providing the critical knowledge for competent decision-making will require improved process-level understanding of biogeochemistry, and an enhanced observational capacity, particularly for remote regions of the atmosphere and oceans. Significant investment will be required to maintain existing observing systems, develop and deploy new sensors for in situ and remote observations, and improve infrastructure for the archiving and distribution of 'big data' for both research and operational products.

The SOLAS science mission will be organised around five core themes:

Core Theme 1: Greenhouse gases and the oceans

Core Theme 2: Air-sea interface and fluxes of mass and energy

Core Theme 3: Atmospheric deposition and ocean biogeochemistry

Core Theme 4: Interconnections between aerosols, clouds, and marine ecosystems

Core Theme 5: Ocean biogeochemical control on atmospheric chemistry.

In addition, the study of these themes will be integrated in efforts to understand key environments, such as upwelling systems, the polar oceans, and coastal waters, as well as to evaluate the environmental efficacy and impacts of geoengineering proposals, policy decisions, and societal developments. Innovative structures will be developed to pursue additional SOLAS priorities in capacity building and inter-organisational cooperation in more efficient ways. The SOLAS community is committed to finding new ways to further contribute toward constructive solutions of

societal concerns. SOLAS will work with other Future Earth projects to co-design interdisciplinary projects related to science policy and sustainability. Current SOLAS structures that have worked successfully will be maintained. The organisation of SOLAS will continue with an International Project Office, remaining at GEOMAR in Kiel until 2020, and a guiding Scientific Steering Committee representing the diversity of the SOLAS community.

# 1 Introduction

The coupled domain of the surface ocean and lower atmosphere is a complex, highly dynamic component of the Earth system. Air-sea fluxes of biogeochemically active materials and energy exert a major impact on global biogeochemistry and climate. Some of the largest uncertainties in projecting future global environmental trends are attributable to an insufficient understanding of the physical and biogeochemical interactions and feedbacks between the ocean and atmosphere (IPCC 2013).

The scientific questions driving SOLAS research are highly challenging, inherently multi-disciplinary in nature, and broad in scope. They include the following:

- What controls the ocean-atmosphere exchange of greenhouse gases?
- How does atmospheric deposition of materials impact ocean biological systems?
- How do oceanic emissions of highly reactive gases impact atmospheric chemistry?
- What are important feedback loops between the oceanic and atmospheric systems?

Underlying all of these issues is the need to better understand the physics and biogeochemistry of the air-sea interface and the processes that control the exchange of mass and energy across that boundary.

Since 2004, SOLAS has facilitated scientific synthesis activities (see 5.1), as well as international coordination and capacity building for scientists engaged in research in the SOLAS domain (see 5.2). SOLAS links scientists in seventy countries and has national representatives in thirty countries. This large community has asserted the need for continued coordination in order to facilitate the international exchange of data, analytical techniques, and ideas; to optimise the utilisation of research platforms; and to develop the next generation of SOLAS researchers.

This Science Plan and Organisation (SPO) of SOLAS outlines efforts, activities, and structure for the period of 2015-2025, under the sponsorship of the Scientific Committee on Oceanic Research (SCOR), Future Earth, the World Climate Research Programme (WCRP), and the International Commission on Atmospheric Chemistry and Global Pollution (iCACGP). It starts with a brief description of the goals and accomplishments of the first phase of SOLAS (2004-2014), and the structure and scientific scope of the next phase. Additional information about SOLAS can be found on the project's website at [www.solas-int.org](http://www.solas-int.org).

## SOLAS Goals and Accomplishments 2004-2014

In its first phase, the principal goals of SOLAS were 1) to develop international connections and collaborations between researchers across the globe; 2) to promote the recruitment and development of young SOLAS researchers; and 3) to promote communication of SOLAS science with the broader community. The original SOLAS Science Plan and Implementation Strategy was organised around three focal themes (SOLAS 2004):

- Focus 1: Biogeochemical interactions and feedbacks between ocean and atmosphere
- Focus 2: Exchange processes at the air-sea interface and the role of transport and transformation in the atmospheric and oceanic boundary layers
- Focus 3: Air-sea flux of CO<sub>2</sub> and other long-lived radiatively active gases.

Three Carbon groups were established between SOLAS and the Integrated Marine Biosphere Research project (IMBeR), in collaboration with the International Ocean Carbon Coordination

Project (IOCCP, in collaboration with the Global Carbon Project) to coordinate carbon cycle research on 1) surface ocean systems, 2) interior ocean, and 3) ocean acidification. In 2009, as part of a mid-term strategy planning process, SOLAS identified several specific research themes: 1) sea-ice biogeochemistry and interactions with the atmosphere; 2) ocean-derived aerosols: production, evolution and impacts; 3) atmospheric control of nutrient cycling and production in the surface ocean; and 4) air-sea gas fluxes at eastern boundary upwelling and oxygen minimum zone (OMZ) systems (Law et al. 2013).

Summaries of the scientific discoveries and accomplishments of the past 10 years of the SOLAS project have recently been published (Liss & Johnson 2014, Brévière et al. 2015). Some of the important scientific discoveries include, among others:

- Synthesis of global ocean carbon datasets and improved estimates of global air-sea CO<sub>2</sub> exchange (Box 1)
- The first direct air-sea gas flux measurements over the ocean and advances in gas-transfer modelling (Box 2)
- New insights into nutrient cycling in the ocean and revision of global biogeochemical budgets (Box 3)
- A growing recognition of the contribution of marine gels to primary marine aerosols (Box 4)
- Insights about iodine chemistry in the marine boundary layer (Box 5)
- Understanding of regional high-sensitivity and high-priority systems for integrated studies (Box 6)
- Iron fertilization experiments in several oceanic environments and an understanding of the limitations of ocean fertilization as a climate-change mitigation tool (see 2.2.2).

Along the way, the SOLAS International Project Office (IPO) has helped establish national networks in 30 countries, with the newest networks developed in Sweden and Israel. SOLAS organised a series of highly successful Open Science Conferences (OSCs) (Damp, Germany; Halifax, Canada; Xiamen, China; Barcelona, Spain; Cle Elum, USA; Kiel, Germany). In addition, SOLAS organised six international summer schools (Corsica, France, and Xiamen, China) involving more than 400 international students and producing a textbook (Le Quéré & Saltzman 2009). The SOLAS IPO also coordinated numerous scientific workshops and facilitated the development of various SCOR working group proposals and IGBP Fast Track Initiatives, maintained community communication via newsletters and e-bulletins, and helped coordinate a range of scientific synthesis activities (see 5.1 and 5.2).

## **SOLAS Rationale and Scientific Scope 2015-2025**

By its fundamental nature, SOLAS science deals with interactions that occur across a broad spectrum of time and space scales, and which involve the exchange of gases, particles, water, and energy between the ocean and the atmosphere. Processes occurring at the atmosphere-ocean interface are critical to the Earth's climate and ecosystem services. SOLAS spans many scientific domains, including chemistry, biology, optics, physics, mathematics, computing, socio-economics, and consequently interactions between natural and social scientists and a diversity of stakeholders. Despite the accomplishments of SOLAS over the last decade, international coordination is still needed to foster this interdisciplinary research.

SOLAS science continues to be an area of high uncertainty in understanding the Earth system. Rapid changes in ocean-atmosphere interactions are underway, and we urgently need to observe and understand these changes. International coordination is critical for progress in this field for scientific, logistical, societal, and educational reasons. In executing that coordination, SOLAS will contribute to several of the seventeen Sustainable Development Goals (SDGs)

adopted by the 194 countries of the United Nation (UN) General Assembly during a historic UN summit in September 2015. SOLAS science is relevant to the following SDGs: 1. No Poverty; 2. Zero Hunger; 3. Good Health and Well-being; 7. Affordable and Clean Energy; 11. Sustainable Cities and Communities; 13. Climate Action; 14. Life below Water; and 15. Life on Land. In addition, SOLAS is important to the more universal goals, such as: 4. Quality Education; 5. Gender Equality; 8. Decent Work and Economic Growth; 9. Industry, Innovation and Infrastructure; 10. Reduced Inequalities; and 17. Partnerships for the Goals.

The SDGs place greater demands on the scientific community than did the Millennium Development Goals (MDGs), which they replace. Addressing climate change, renewable energy, food, health, and water provision requires coordinated global monitoring and modelling of many factors: social, economic, and environmental. Moreover, metrics need to be developed to measure progress towards the targets on local, national, regional and global levels and across sectors. Monitoring and evaluation procedures and standards need to be set up (see Lu et al. 2015). SOLAS is a bottom-up organisation, whose scientific priorities evolve in response to such scientific developments and community needs. This is reflected in the original science plan in 2002, the mid-term strategy initiatives in 2009 (Law et al. 2013), and now in this new Science Plan and Organisation (SPO). Discoveries in the SOLAS realm over the last decade have substantially changed our views of how the Earth system works and have revealed gaps in our understanding, some of which had not even been conceived when the first SOLAS science plan was written.

#### Current knowledge gaps:

1. Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) are the most significant long-lived greenhouse gases (GHGs) after water vapour. Physical and biogeochemical processes in the surface ocean play an important role in controlling the fluxes of these gases between the ocean and atmosphere. What are the sensitivities of these processes to climate and environmental change?
2. What processes influence turbulence at the surface ocean boundary layer and fluxes of gas, mass, and energy across the air-sea interface?
3. How do marine biogeochemical and ecological processes interact in response to natural and anthropogenic material input from the atmosphere? How do global warming and other anthropogenic stressors alter the uptake of atmospheric nutrients and metals by marine biota in different oceanic regions?
4. The interconnections between aerosols, clouds, and marine ecosystems are among the largest sources of uncertainty in future climate projections. What are those interconnections, and how are they sensitive to climate change?
5. What are the marine biogeochemical controls on the release of reactive gases into the atmosphere and how will future changes in oceanic biogeochemistry and anthropogenic emissions interact to influence atmospheric chemistry?

The SOLAS 2015-2025 SPO will approach the overarching goal of understanding air-sea interactions on two fronts:

1. to identify and understand the interactions through which the surface ocean and lower atmosphere are inherently connected, and
2. to develop the tools for integrating SOLAS scientific knowledge into societal decision-making to safeguard the future trajectory of Earth's climate and habitability.

Going forward, it is clear that SOLAS still has an important role to play in these efforts, because

1. SOLAS fulfils a unique role as the only non-governmental, science-based organisation focused on ocean-atmosphere biogeochemical-physical interactions.

2. Although SOLAS has made significant strides in bridging the gap between the disparate communities, there still remain discernible barriers between the oceanographic and atmospheric sciences. SOLAS plays a critical role in overcoming these barriers and providing a framework for ocean-atmospheric scientists to work together on complex problems.
3. Interest in SOLAS research continues to grow, as evidenced by the ongoing activity of existing national committees and the continued entry of new members.
4. The SOLAS science community is uniquely equipped to evaluate the efficacy of ocean-based climate change mitigation and adaptation strategies.

Objectives:

Instead of the three focal themes of the first SOLAS science plan, the SOLAS SPO 2015-2025 focuses on five core themes that have been developed by the SOLAS scientific community as a series of white papers (see 2.1):

Core Theme 1: Greenhouse gases and the oceans

Core Theme 2: Air-sea interface and fluxes of mass and energy

Core Theme 3: Atmospheric deposition and ocean biogeochemistry

Core Theme 4: Interconnections between aerosols, clouds, and marine ecosystems

Core Theme 5: Ocean biogeochemical control of atmospheric chemistry.

These five core themes will be investigated in integrated, system-based projects across the globe (Fig. 1), as well as in focused laboratory and numerical modelling studies. The design process for the new science plan has involved community input through the 2012 SOLAS OSC (Cle Elum, USA), a SOLAS early career scientist workshop (Plymouth, UK, 2013), a focused writing workshop (Galway, Ireland, 2014), and two rounds of open community review, as well as several Scientific Steering Committee (SSC) meetings. Discussion sessions at the 2015 SOLAS OSC (Kiel, Germany) served as an ideal platform to develop the implementation plan for the next decade of SOLAS.

SOLAS 2015-2025 will develop a leadership structure based on the five core themes, with the formation of a group responsible for each core theme, for developing research goals, workshops, and synthesis activities. In parallel, SOLAS will develop new approaches to facilitate capacity building (see chapter 3), interactions with partner organisations, and co-design of targeted projects to meet societal needs with regard to geoengineering, air quality, marine resources, among other issues. The structure of SOLAS 2015-2025 will continue to be based on a SSC that provides oversight for the IPO. The SSC membership will reflect the broad diversity of the SOLAS community in terms of scientific expertise, geography, and gender, as well as change in support of developing scientific challenges. In recognition of the scope of Future Earth, the SSC will include either an ad hoc or standing committee member with expertise in the societal aspects of surface ocean-lower atmosphere interactions. This member will come from a related scientific field, such as marine pollution, or from a policy or resource economics background.

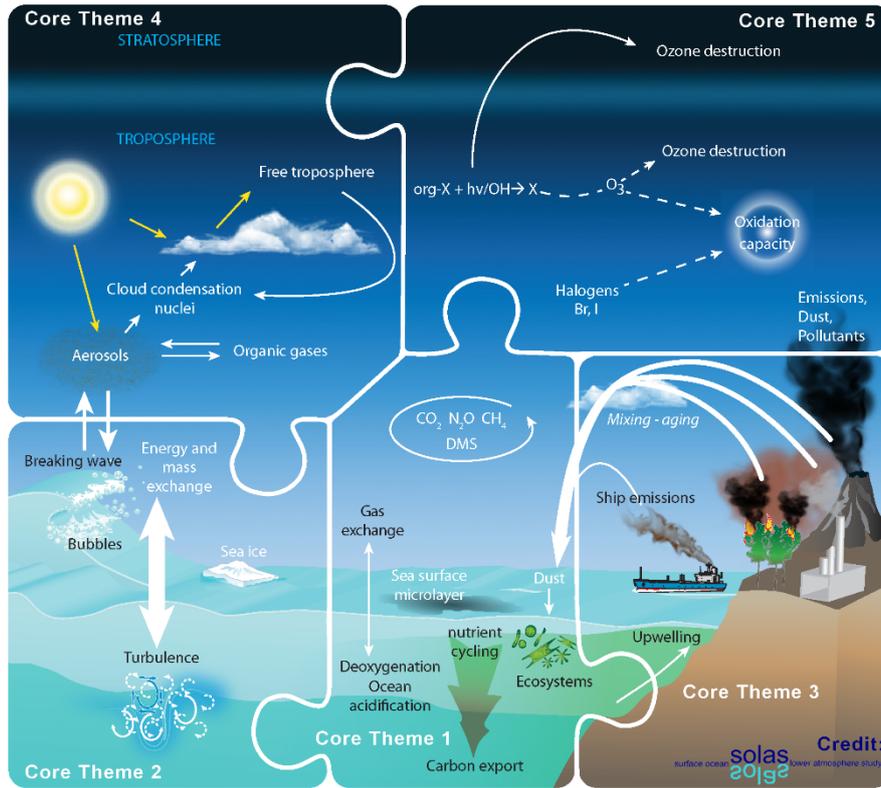


Fig. 1: Interactions among the five SOLAS Core Themes

## 2 Science Plan

### 2.1 SOLAS Core Themes

#### 2.1.1 Greenhouse gases and the oceans

Carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are the most significant long-lived greenhouse gases (GHGs) after water vapour. Physical and biogeochemical processes in the surface ocean play an important role in controlling GHG fluxes between the ocean and the atmosphere. Understanding sensitivities of these processes to climate and environmental change is of direct importance for the mitigation of climate change.

- Which surface ocean processes are controlling GHG cycling at regional to global scales?
- What are the feedback mechanisms between climate change and oceanic GHG emissions?
- How can we assess future oceanic fluxes of GHGs in a changing ocean and atmosphere?

#### Introduction

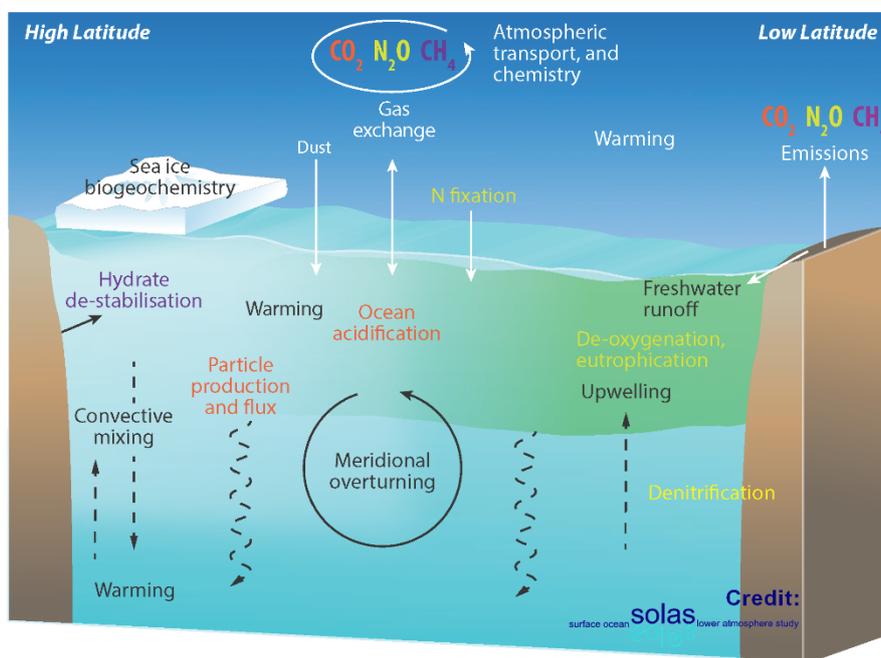
The major driving forces for current climatic change are additions of greenhouse gases (GHGs) to the atmosphere, arising either directly or indirectly from human activities. In addition, changing aerosol sources influence the radiative budget of the Earth system (see 2.2.1). The natural cycles of GHGs in the ocean and troposphere interact with these anthropogenic inputs and lead to climatic feedbacks, as well as to environmental impacts, which need to be identified, quantified, and predicted on local to global spatial scales, and on a variety of different time scales.

#### Scientific and Societal Rationale

There exists no paleo-analogue for the current increase in GHGs. Oceanic and atmospheric measurements capturing changes in GHGs are still scarce in specific key regions, for example, the Southern Ocean, upwelling systems, and coastal waters (see 2.2.1). The modulation of GHGs through biologically induced changes, for example, in response to ocean acidification and warming, is poorly understood. Nitrous oxide and methane cycles are even less understood than the carbon cycle, especially in view of changing physical and biological processes.

A firm understanding and quantification of GHG sources and sinks is key to adequately predicting future climatic and environmental changes during the ongoing Anthropocene (Crutzen 2002). Therefore, it is necessary to provide the best possible description of the present state of GHG budgets and related Earth system variables as a reference point for comparison once climate change has progressed more significantly. We also need to determine the relevant processes in GHG cycling and evaluate the postulated and emergent feedbacks, and impacts, as well as vulnerabilities due to multiple drivers including warming and perturbations of the carbon and associated nutrient cycles (N, P, Si, Fe) (see Fig. 2). Since the oceanic GHG budgets probably can be quantified more accurately than terrestrial budgets (e.g., Keeling et al. 1996; Canadell et al. 2007; Watson et al. 2009; Le Quéré et al. 2015), ocean GHG research can contribute to constrain the range of estimated terrestrial emission/uptake rates. Integrated predictive capabilities of the distribution of key GHGs in the ocean-atmosphere system, includ-

ing ecosystem impacts, biogeochemical feedbacks, and vulnerabilities, will support a better design of mitigation and adaptation measures for management of the carbon and nutrient cycles worldwide.



**Fig. 2:** Processes and impacts/stressors associated with long-lived greenhouse gases

## State of Present Understanding

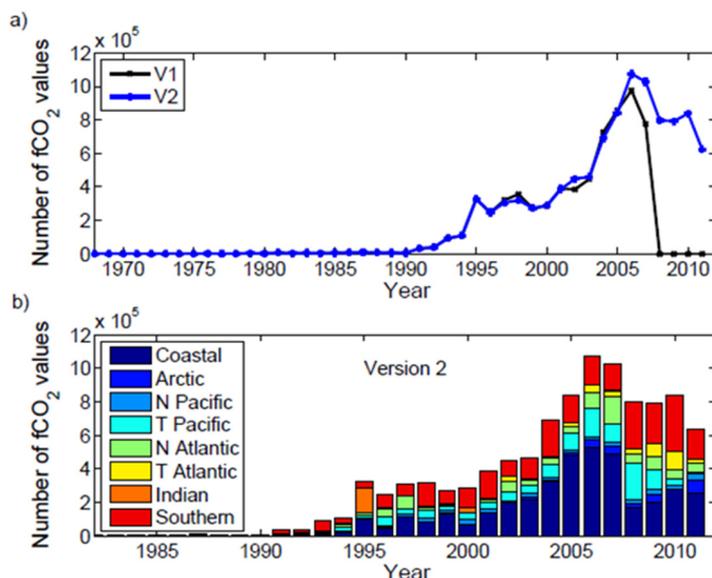
CO<sub>2</sub> is the major anthropogenic GHG directly emitted into the atmosphere, partially taken up by ocean and land. For the decade 2005-2014, the average emissions were  $9.0 \pm 0.5 \text{ GtC yr}^{-1}$ , with average uptake rates by the ocean of  $2.6 \pm 0.5 \text{ GtC yr}^{-1}$  and by land of  $3.0 \pm 0.8 \text{ GtC yr}^{-1}$  (Le Quéré et al. 2015). Uptake of anthropogenic CO<sub>2</sub> by the ocean is dominated by inorganic chemical buffering of carbonic acid and is coupled to large-scale mixing and ocean circulation that maintain transport of saturated waters into the ocean interior and their replacement by water masses with depleted CO<sub>2</sub>. In the recent past, decreases in CO<sub>2</sub> sinks have occurred in regions that have been identified as critical for anthropogenic carbon storage, for example, northern North Atlantic and Southern Ocean (Le Quéré et al. 2007; Watson et al. 2009). The Southern Ocean is projected to become one of the strongest sink regions for anthropogenic carbon by the end of this century.

Recent research has also focused on other important GHGs influenced by human behaviour and climate/environmental changes, such as CH<sub>4</sub> and N<sub>2</sub>O. In the ocean, GHG cycles are inter-linked with biological processes. For instance, CH<sub>4</sub> and CO<sub>2</sub> are produced and consumed during methanogenesis and methane oxidation; N<sub>2</sub>O production is highest via nitrification and denitrification during organic carbon remineralisation at suboxic conditions and may be modified through ocean acidification. Carbon dioxide is taken up during primary production, but calcification can increase CO<sub>2</sub> levels in seawater. Biological processes are expected to change in response to ocean warming, acidification, eutrophication, and deoxygenation.

### Box 1: Selected Achievement of SOLAS 2004-2014

#### Global ocean carbon datasets and estimates of global air-sea CO<sub>2</sub> exchange

SOLAS contributed to and enabled a suite of high-quality ocean greenhouse gas data syntheses as a result of an international community effort. One key dataset is the surface ocean  $f\text{CO}_2$  data synthesis, SOCAT. This dataset is the most complete, consistent observational record of sea surface CO<sub>2</sub> partial pressure ever. Next to water vapour, CO<sub>2</sub> is the most important greenhouse gas in the Earth system. CO<sub>2</sub> from human activities is the most important driving agent for the ongoing climate change and progressing ocean acidification. The Surface Ocean CO<sub>2</sub> Atlas (SOCAT) dataset is continually updated to include the most recent datasets and to make them publicly available for the scientific community and public stakeholders worldwide. The SOCAT version 2 includes 10.1 million  $f\text{CO}_2$  values originating from seagoing fieldwork by scientists in 18 countries (Fig. 3). The data were collected on 110 ships, 13 moorings, and 3 drifters. Quality control was carried out by 37 scientists from 12 countries. The dataset is available for individual in situ data as well as in gridded form. The SOCAT dataset is one of the most widely used global Earth system data syntheses ever and is employed in many different applications. The dataset is used for performance assessments of Earth system models, greenhouse gas budget calculations, determination of anthropogenic carbon loads in the ocean, trends of ocean acidification in various parts of the ocean, and atmospheric inverse approaches in order to determine air-sea CO<sub>2</sub> flux and its variations. Finally, SOCAT observations are systematically combined with ocean models through a series of data assimilation methods. SOCAT data from the present and the recent past provide a vital legacy dataset for future generations of climate scientists. This dataset will serve as a benchmark for the changing state of the Earth system, especially in the coming decades when climate change and ocean acidification will have progressed with massive impacts.



**Fig. 3:** Number of  $f\text{CO}_2$  observations included in SOCAT V2 (Bakker et al. 2014)

Biological processes may modulate anthropogenic CO<sub>2</sub> uptake rates. For instance, a change in particle size spectra under warming leading to increased stratification and less CaCO<sub>3</sub> ballasting could reduce the carbon remineralisation depth and increase CO<sub>2</sub> outgassing (Laws et al. 2000; Klaas & Archer 2002). In addition, ocean acidification may increase bacterial remineralisation of CO<sub>2</sub> and decrease the net oceanic carbon uptake (Piontek et al. 2010; Segschneider & Bendtsen 2013).

Moreover, enhanced biological carbon consumption in response to elevated CO<sub>2</sub> levels may be a potential negative feedback (Riebesell et al. 2007). Deoxygenation in conjunction with eutrophication and decreased overturning, especially close to continents, may impact N<sub>2</sub>O and CH<sub>4</sub> cycling (Naqvi et al. 2010). In this respect, Arctic Ocean shallow shelves (sub-sea permafrost areas) and continental margin areas may be susceptible (Blastoch et al. 2011; Shakhova et al. 2013), although these issues still require clarification (see e.g., Berndt et al. 2014). Thus, future oceanic GHG cycling is expected to undergo critical changes, but our current knowledge is insufficient for reliable predictions.

## Future Approaches

The multiple drivers for modifications of GHG fluxes – such as changes in ice cover, reactive nitrogen input into the ocean, ocean warming, acidification, deoxygenation, and increasing stratification – need to be linked dynamically to impacts and feedbacks at the ecosystem level, and from regional to global scales. This can be achieved by perturbation studies, like laboratory, mesocosm, or in situ experiments, and by Eulerian time-series observations. In addition, a biogeographical approach is needed; case studies in selected regions of high sensitivity for driving factors and respective strong response signals should be carried out along physical and biogeochemical gradients in order to groundtruth experimental findings.

To better quantify and predict oceanic GHG budgets and related air-sea fluxes the highly heterogeneous continental margins have to be included in global and national budgets. For an adequate representation of continental margins and shallow seas, higher resolution coupled ocean-atmosphere models (including biogeochemical cycles) need to be developed. This is of particular importance for upwelling systems and areas of large N<sub>2</sub>O production. In order to assess variations in GHG fluxes within the ocean and across the air-sea interface, a far denser observing system is needed. Automated systems need to be installed not only on ships, but also on autonomous platforms (e.g., Argo floats, gliders) and moorings. High-accuracy sensors should be used to monitor, for instance, changes in seawater carbonate chemistry and impacts of ocean acidification. At present, some profiling floats are equipped with bio-optical and biogeochemical sensors (e.g., irradiance, backscattering, nutrients, O<sub>2</sub>, CDOM, Chl *a*) together with temperature and salinity sensors. These biogeochemical and bio-optical quantities serve, for example, to compare and validate remotely sensed oceanographic data from satellites. The network of these Bio-Argo floats should be considerably expanded in the future. Underwater vehicles (autonomous and remotely operated underwater vehicles) are needed for related process studies, especially for sediment-water interaction studies. Satellite observations of oceanic and atmospheric processes (e.g., Henson et al. 2012; Land et al. 2013) need to be linked to oceanic measurements in a more systematic way. Remote sensing is the only tool that provides consistent global coverage. Development of new tools and application of existing ones by a growing community is an utmost necessity. Cloud and aerosols parameters, as well as upper ocean ecosystem parameters, are regularly obtained with remote-sensing tools. Following the satellites SCIAMACHY and GOSAT, a constellation of satellites such as CarbonSat will advance our knowledge on the natural and human sources and sinks of the greenhouse gases carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>). As of now, a suite of recent data syntheses and collections on marine carbon and nitrogen cycles has emerged (GLODAP, CARINA, PACIFICA, SOCAT, MEMENTO, SeaWiFS, MODIS, GOSAT, among others). However, there still remain several oceanic areas that are highly under-sampled in space and time.

For climate projections on time scales of several centuries, coupled Earth system models (ESMs) have been developed that include the most up-to-date knowledge on chemical and biogeochemical processes. Output datasets are available through large international model intercomparison projects (MIPs) such as CMIP5 and CMIP6. Assimilation of data into biogeochemical ocean models is still in its infancy, but progress has been made in implementing

sequential methods for optimisation of these models. The emergent constraint approach (Cox et al. 2013) can provide a shortcut for identifying the potentially most reliable models for future projections. The combination of observations and models through systematic performance assessment and data assimilation will improve the models through optimisation of free parameters in process descriptions and also elucidate the reason for regional variations in marine GHG sources and sinks.

### Community Readiness

Worldwide projects such as SOLAS, IMBeR, IOCCP, and GCP have largely contributed to recent achievements in quantifying marine GHG fluxes. Also, complementary research foci can be combined effectively. For example, the more biogeochemical approach of SOLAS and the more ecosystem-related approach of IMBeR can be seamlessly bridged so that both project communities benefit from each other. The recently established international ocean acidification coordination centre (OA-ICC) is underpinning this collaboration. Continent- and basin-wide projects – such as the Ocean Carbon and Biogeochemistry Program USA (OCB), the EU 6<sup>th</sup> and 7<sup>th</sup> Framework Programme with CARBOOCEAN, CARBOCHANGE, EPOCA, and the North Pacific Marine Science Organization (PICES), among others – have provided resources to carry out research work. Linking the South American and, in particular, African communities still requires much improvement (e.g., cooperation with CSIR South Africa and Morocco). Ocean carbon cycle research is also supported through CLIVAR. The community is linked to the Group on Earth Observations/Global Earth Observation System of Systems (GEO/GEOSS) and the Global Ocean Observing System/Framework for Ocean Observing (GOOS/FOO) through several projects and satellite Earth observations are being exploited through the ESA OceanFlux initiative. A research initiative that would integrate knowledge produced by the recent CLIVAR Ocean Heat Content research focus, Stratospheric Processes and their Role in Climate (SPARC), and SOLAS on air-sea exchanges would be an exciting avenue to ensure synergy between physical and biogeochemical fluxes. The international SCOR WG #143 will harmonise oceanic N<sub>2</sub>O and CH<sub>4</sub> measurements by providing a reference measurement protocol and, moreover, will provide a concept for the establishment of a global network of ocean time-series measurements of N<sub>2</sub>O and CH<sub>4</sub>.

### Impacts of SOLAS Science on Sustainability

Optimal information and knowledge concerning GHG fluxes are the foundation for informed policy decisions on measures for climate mitigation and adaptation. Integration of ocean-atmosphere GHG cycling is therefore a sine qua non for any development towards sustainability. Because emissions and levels of GHGs in the atmosphere and ocean are tightly coupled to energy production, food supply, land use (including fertiliser applications), traffic, and health, this research theme links strongly to the Future Earth programme. It is also relevant to the following UN SDGs: 2. Zero Hunger; 3. Good Health and Well-being; 7. Affordable and Clean Energy; 11. Sustainable Cities and Communities; 13. Climate Action; 14. Life below Water; and 15. Life on Land. Past and future SOLAS efforts to understand the marine GHG cycles should also be more directly linked with the work of the parallel Future Earth project on Analysis, Integration and Modelling of the Earth System (AIMES).

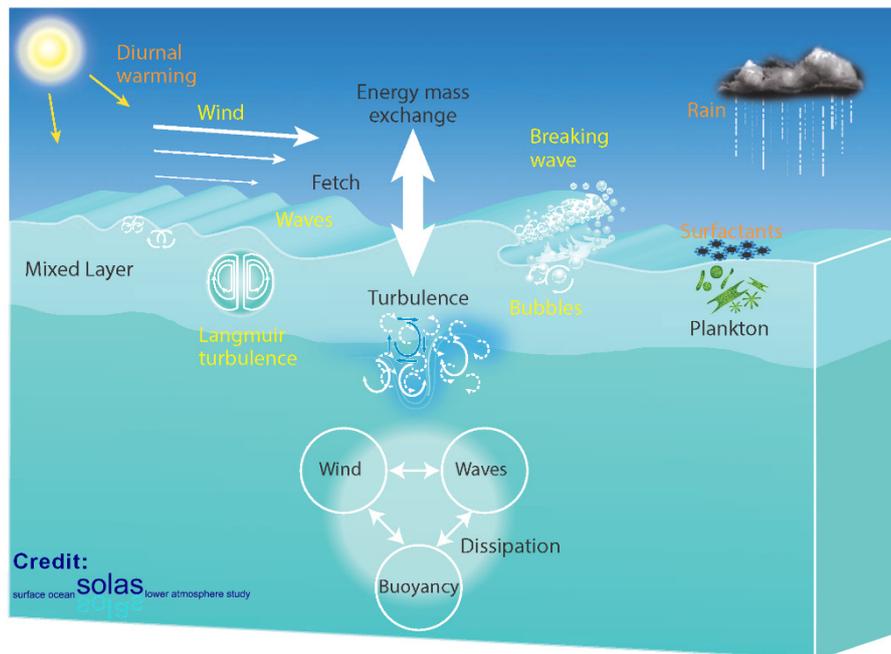
## 2.1.2 Air-sea interface and fluxes of mass and energy

Ocean-atmosphere fluxes play a critical role in the regulation of climate. We therefore need to come to a mechanistic understanding of physical, chemical, and biological processes affecting exchange of gas, mass, and energy across the air-sea interface from nano to global scales.

- What are the biogeochemical mechanisms that influence fluxes of gas, mass, and energy at the surface ocean boundary layer?
- How can the turbulence-controlling processes be incorporated into parameterisation schemes describing the air-sea fluxes of mass and energy?
- What are the feedbacks between processes governing air-sea fluxes and climate?

### Introduction

Until 2014, SOLAS included three over-arching foci, of which Focus 2 was concerned with processes responsible for air-sea exchange of mass, momentum, and energy. Although SOLAS made substantial scientific progress on this topic, considerable research is still needed. Core Theme 2 of SOLAS 2015-2025 is concerned with the oceanic and atmospheric processes that act upon the air-sea interface and serve to regulate the fluxes of mass and energy between the ocean and atmosphere, a coupled system. Thus, the new Core Theme 2 is a logical follow-up of the previous SOLAS Focus 2. Figure 4 shows the critical processes controlling air-sea fluxes and operating at the air-sea interface.



**Fig. 4:** Dominant processes controlling air-sea fluxes of mass and energy in the open ocean. Turbulence-generation (yellow) and -suppression (orange) processes in the surface ocean boundary layer are likely to be the key to better describing fluxes in models.

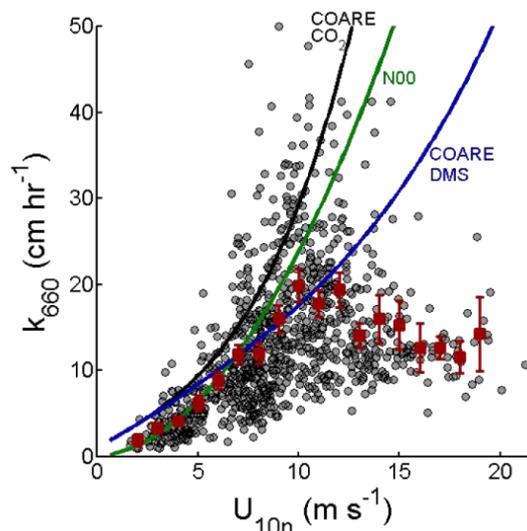
## Scientific and Societal Rationale

All exchange between the ocean and atmosphere must cross the air-sea interface. It is through the fluxes of momentum, heat, freshwater, gases, and aerosols that the ocean and atmosphere communicate. Uncertainties in air-sea exchanges constrain our ability to understand and model our changing climate (Fairall et al. 2010). Without more accurate knowledge of air-sea fluxes, we cannot properly evaluate ocean-atmosphere coupled models to enable accurate predictions from weather to climate time scales.

### Box 2: Selected Achievement of SOLAS 2004-2014

#### Eddy covariance estimates of air-sea exchange

There has been significant improvement in our understanding of air-sea fluxes derived from the initial ten years of SOLAS. Although micrometeorological direct estimates of the air-sea fluxes of heat and momentum have reached a level of maturity, eddy covariance measurements of CO<sub>2</sub> were successfully carried out for the first time during the GasEx98 experiment in the North Atlantic (Wanninkhof & McGillis 1999; McGillis et al. 2001). Since then methods for quantifying gas exchange using the direct covariance method have improved. For example, Miller et al. (2010) described a technique to remove the water vapour fluctuations with the gas stream, leading to reduction in the scatter of the gas transfer velocity. More recently, Landwehr et al. (2015) described a new method for flow distortion and motion correction that significantly improved the agreement of direct flux measurements made from a ship underway. The inclusion of processes other than wind speed has also improved direct flux estimates, and it has been widely recognised that ocean surface waves play a large role of air-sea fluxes. Bell et al. (2013) showed that air-sea DMS fluxes were diminished at higher wind speeds (Fig. 5), attributed to the idea that swell waves inhibit surface turbulence leading to reduced air-sea gas transfer.



**Fig. 5:** DMS gas transfer coefficients vs. horizontal wind speed (grey circles) and 10 min average DMS gas transfer coefficients vs. mean horizontal wind speed (red squares) during the Knorr\_11 cruise in the North Atlantic, expressed as  $k_{660}$  and  $U_{10n}$ . For reference NOAA COARE model output using the turbulent/molecular coefficient are plotted (Bell et al. 2013).

## State of Present Understanding

Ultimately, the exchange of mass and energy between the atmosphere and ocean is limited by transfer across a thin diffusive layer at the sea surface. This interfacial boundary, also referred to as sea surface microlayer (SML), is central to a range of physical, biogeochemical, and

climate-related processes (Cunliffe et al. 2013). Organic surface films, including surface-active (surfactant) material, accumulate in the SML and modify gas exchange rates by changing sea surface hydrodynamic boundary conditions, in turn altering turbulence, and by forming a direct resistance barrier for volatile gases with high solubility (McKenna & McGillis 2004). A better understanding of the impacts of surfactants on air-sea fluxes as well as of processes determining SML thickness and composition may help to improve gas transfer parameterisations, which have primarily been based on measurements of flux versus wind speed in the past.

Air-sea fluxes can be measured directly using the eddy covariance method. However, such measurements require sophisticated instrumentation and, therefore, fluxes are usually characterised by parameterisations, which relate the fluxes to more readily accessible measurements. Wind speed is the most widely used parameter, but others include air temperature, sea surface temperature (preferably the ocean skin temperature), specific humidity, and atmospheric and surface ocean partial pressure of CO<sub>2</sub>. The advantage to using wind-speed parameterisations is that they can be readily derived from satellite data or numerical models, but models using simple wind-speed parameterisations failed to match observed gas-exchange rates. A better parameterisation for quantifying air-sea fluxes should address physical and biogeochemical processes at the surface boundary in order to accurately represent interfacial turbulence (Kitaigorodskii & Donelan 1984; Asher 1997) and gas diffusion constants. A quantitative understanding of the turbulent processes at the air-sea interface is likely to be the key to understanding air-sea exchange, and the dissipation rate of turbulent kinetic energy ( $\epsilon$ ) is the most appropriate parameter with which to parameterise air-sea fluxes. The challenge in SOLAS 2015-2025 will be to provide an accurate description of the surface boundary, its structure, biogeochemical composition, and spatial heterogeneity together with measurements of dissipation and to develop a robust method for scaling the turbulence at the air-sea interface.

## Future Approaches

Wind generates surface ocean boundary layer turbulence via stress on the surface, wave breaking, and the interaction between current and Stokes (wave-induced) shear. Enhanced dissipation levels will be observed at the surface from breaking waves (Agrawal et al. 1992; Terray et al. 1996), but this source of turbulence is expected to decay rapidly with depth. The interaction between the Stokes and current shear leads to Langmuir circulations (Langmuir 1938) that produce Langmuir turbulence, but observational difficulties have limited studies to large eddy simulation (LES) modelling.

Recently, technology has progressed to the point where measurements of the sea surface microlayer have become practical (Schnieders et al. 2013). Measurements to investigate the sea surface microlayer have made tremendous progress through experimental studies such as in wind tunnels, where physics and biogeochemistry of the air-sea interface are studied simultaneously (Krall 2013). The air-sea fluxes of gases (e.g., carbon dioxide) can be described with measurements of the air-sea partial pressure difference of CO<sub>2</sub> and determination of the transfer coefficient,  $k$ , which can itself be described in terms of the Schmidt number  $Sc = \nu/D$  and a function based on a velocity  $Q$  (m s<sup>-1</sup>) and length  $L$  (m) (Lamont & Scott 1970; Jähne et al. 1987; Soloviev & Schlüssel 1994; Fairall et al. 2000). Lamont & Scott (1970) derived a relationship which described  $f(Q, L)$  in terms of  $\epsilon$ , and there have been very few results to verify a  $k$ - $\epsilon$  relationship. Recent efforts by Belcher et al. (2012) derived an expression for  $\epsilon$  in terms of velocity and length scales, with the assumption that  $\epsilon$  is a linear combination of wind, wave and buoyancy forcing within the mixed layer. Although Belcher et al. (2012) proposed a series of scaling factors for  $\epsilon$ , more work is needed to provide universal scaling parameters. Therefore, these LES and atmospheric boundary layer modelling efforts will allow the determination of dissipation in the absence of direct measurements.

The depth of the surface ocean boundary layer is a critical length scale for parameterising turbulence, and it is generally assumed that the mixed layer depth (MLD) is equal to the mixing layer depth (XLD) (Sutherland, Reverdin et al. 2014). Some of the differences are inherent in their respective definitions (see Stevens et al. 2011), but physical processes, such as entrainment across the thermocline at the base of the mixed layer, or sudden changes in surface forcing, can result in significant differences between these length scales (Brainerd & Gregg 1995; Cisewski et al. 2008). It is important to distinguish between MLD and XLD length scales for parameterising air-sea interfacial  $\epsilon$  (Sutherland, Christensen, et al. 2014).

Experiments under different open ocean conditions need to provide direct estimates of the fluxes (not only heat and momentum, but also gas and aerosols) as a basis for all process studies, and direct covariance measurement instruments should be added to buoys on a more routine basis. Dissipation estimates must be provided so that there is a complete dataset of the fundamental process that drives the fluxes (Fairall et al. 2010). Other parameters need to be provided, including high-quality meteorological measurements, 2-D wave spectra, whitecapping, surfactants, rainfall, and temperature profiles. In addition, comprehensive background information characterising the scales of variability and heterogeneity in surface concentrations and forcing at a study site is necessary prior to initiating flux studies, and remote sensing is particularly useful in this regard.

Recently, instrumentation has been improved to make ocean-going measurements of fluxes of oxygenated volatile organic compounds feasible (Marandino et al. 2005; Yang et al. 2014). Particularly, the exchange of these volatile gases, as well as gases of a greatly varying Schmidt number, will help to identify and quantify transfer processes on different scales. Together with recent advances in techniques for research in small-scale interactions (Garbe et al. 2014), this will undoubtedly lead to significant progress in our knowledge in this inherently interdisciplinary area of research in the next phase of SOLAS. In collaboration with other communities, SOLAS will provide synergy between the understanding of physical and biological air-sea fluxes.

### Community Readiness

The problem of adequately describing air-sea fluxes of mass and energy is complex, and simplistic parameterisations are not sufficient to represent the fluxes in models. Although parameterising air-sea transfer with dissipation is appealing, it is challenging to measure (Garbe et al. 2014).

SOLAS 2015-2025 needs to bring together different communities to study air-sea fluxes and processes influencing them: oceanographers and atmospheric scientists, but also LES modelers, wave modellers, biologists, and technologists for developing new observational techniques. The problem of adequately describing air-sea fluxes is a fundamental part of SOLAS but is also relevant to a broader community; for example, modellers require an accurate description of surface fluxes for model forcing and initialisation.

### Impacts of SOLAS Science on Sustainability

Interactions between the ocean and atmosphere are predominantly controlled by the air-water interface, which is the boundary between compartments. Oceanic ecosystems and their components, such as phytoplankton, are strongly dependent on the air-sea interface and fluxes of mass. This can be through vertical transport of nutrients, but also of gases such as CO<sub>2</sub>, O<sub>2</sub>, and CH<sub>4</sub>. Marine phytoplankton produces half of the world's atmospheric oxygen, the oxygen upon which terrestrial animals, including humans, depend. Conversely, from a human health perspective, phytoplankton organisms can be harmful through the production of potent biotoxins

or through the production of massive blooms, which result in oxygen depletion leading to mass mortality of ocean life. Aerosols released from the air-sea interface, including marine toxins, as well as salts and non-toxic organic matter, directly impact the air quality in coastal communities, with implications for human health. Understanding factors influencing mechanisms of air-sea exchange is essential for making predictions of these effects in a changing climate and consequently enhancements or reductions of the fluxes in the future. This research theme strongly links to the following five UN SDGs: 2. Zero Hunger; 3. Good Health and Well-being; 11. Sustainable Cities and Communities; 13. Climate Action; and 14. Life below Water. The insights from SOLAS projects on the mechanics and chemistry of air-sea exchange are valuable contributions toward the partner Future Earth project, Monsoon Asia Integrated Regional Study (MAIRS).

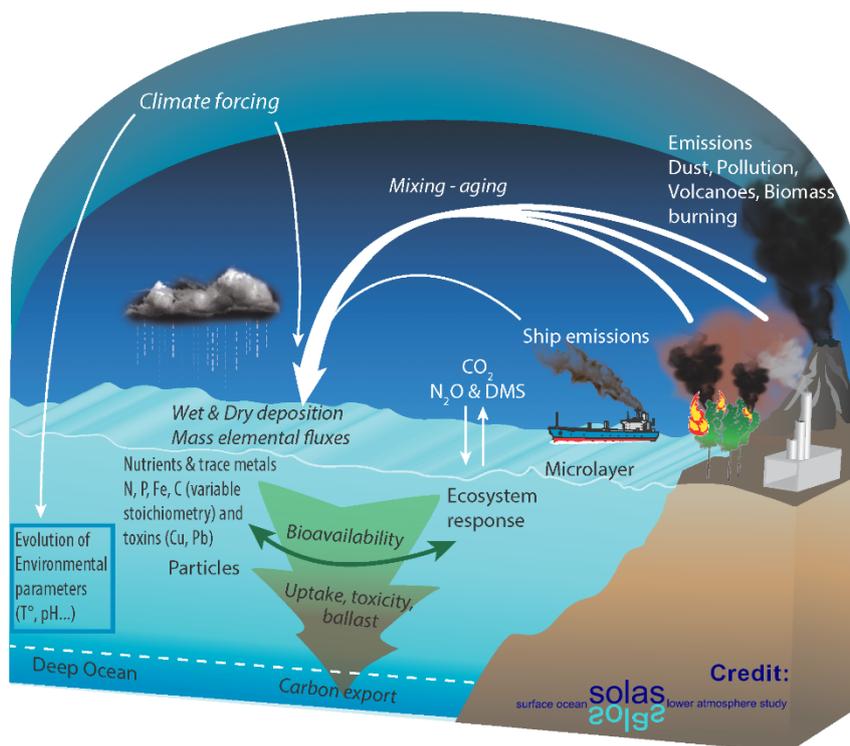
### 2.1.3 Atmospheric deposition and ocean biogeochemistry

Atmospheric depositions play a fundamental role in marine ecosystems with consequences on local, regional and global biogeochemical cycles, as well as on the climate system.

- How do biogeochemical and ecological processes interact in response to natural and anthropogenic material input from the atmosphere across different regions?
- How do global warming and other anthropogenic stressors synergistically alter the uptake of atmospheric nutrients and metals by marine biota in different oceanic regions?
- What are the large-scale impacts of atmospheric deposition to the ocean on global elemental cycles (e.g., C and N) and climate change feedbacks in major marine biomes?

#### Introduction

The ocean receives from the atmosphere a broad range of particles of continental origin, macro- and micronutrients, and toxic elements that affect vast regions, including sensitive zones far from land. These materials are delivered in chemical forms and concentrations that are different from the upward supply of internally recycled nutrients from within the ocean. This atmospheric deposition is a result of both natural processes (e.g., dust emission/deposition, volcanic eruptions) and human activities (such as fossil fuel combustion, biomass burning, and agriculture) that deliver to the surface ocean nitrogen, sulphur, organic/black carbon, trace metals, and toxic elements (Fig. 6). Human activity is also altering dust emissions via land-use changes, with hitherto unresolved feedbacks on climate and ocean biogeochemistry. Despite a significant number of laboratory, field, and modelling studies over the past decade, the links between atmospheric deposition, nutrient availability, ocean biogeochemistry, ocean productivity (up to high trophic levels), carbon cycling, and feedback to climate are still poorly understood and barely quantified.



**Fig. 6:** Main issues, processes, and species relating to Core Theme 3 (processes are indicated in italics)

### Scientific and Societal Rationale

This theme focuses on the relationships between natural and anthropogenic atmospheric inputs, the marine carbon cycle and feedbacks to climate. Interest on the impacts of atmospheric input on the biogeochemistry of the ocean is quite recent (only few decades), but many (if not all) current Earth system models assessed in the 5<sup>th</sup> Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5) use simplistic parameterisations (e.g., the use of a global constant for aerosol solubility) to simulate the bioavailable products of atmospheric nutrient deposition (e.g., iron from dust). However, the fundamental processes driving atmospheric inputs (aerosols emission, transport and aging, processes within the water column) to the oceans are still poorly understood, hampering numerical projection of the impacts on marine biogeochemical cycles in the context of climate change. Ongoing and future anthropogenic and global changes, both increasing emissions (global pollution, changes in land-use practises, coastal and shelf eutrophication, etc.) and changing surface ocean conditions (e.g., stratification, acidification) may change atmospheric deposition fluxes, turnover times in the surface mixed layer, the stoichiometry of the ‘new nutrients’ coming from the atmosphere, and their bioavailability. In turn, these changes may affect both biodiversity and microorganism adaptive strategies for nutrient competition. Fundamental differences in how microbial community structures respond to changing atmospheric inputs (i.e., impacting the balance between carbon fixation and respiration) may result in opposite effects on the carbon budget (sink or source), with direct implications for the way we think about productivity in the ocean, climate change and, therefore, atmospheric CO<sub>2</sub> uptake and fisheries.

## State of Present Understanding

The impact of atmospheric deposition on biota has been documented in several oceanic settings (Guieu et al. 2014). In both field and laboratory experiments, aerosol additions have changed biomass standing stocks, primary and bacterial production, and N<sub>2</sub> fixation (Paytan et al. 2009; Giovagnetti et al. 2013; Liu et al. 2013). The magnitude and direction (sink or source of carbon) of the responses appear to be largely dependent on the trophic state of the surface waters (Marañón et al. 2010). In recent years, volcanic ash deposition has received particular attention as a major player in controlling ecosystem productivity in both high- and low-nutrient, low-chlorophyll areas (Hamme et al. 2010; Achterberg et al. 2013; Langmann 2013; Lindenthal et al. 2013; Olgun, Duggen, Andronico et al. 2013; Olgun, Duggen, Langmann et al. 2013). However, our ability to predict the impacts of atmospheric deposition to marine ecosystems is still hampered by limited knowledge of the specific sources and transport pathways of the atmospheric material delivered in various oceanic regions.

Material transported in the atmosphere originates from a variety of natural and anthropogenic sources (GESAMP 1989; Duce et al. 1991) and contains both macro- and micronutrients (N, P, C, Si, S, and trace metals, including iron; see Jickells et al. 2005; Mahowald et al. 2005; Duce et al. 2008; Mahowald et al. 2008) and potentially toxic elements and components (for example, copper, lead, mercury, PAHs, and pesticides; see Jurado et al. 2005; Paytan et al. 2009). The important anthropogenic sources include combustion of fossil fuels (including ship-based emissions), biomass burning and production, and use of fertilisers (Duce et al. 2008; Luo et al. 2008; Hunter et al. 2011; Hassellöv et al. 2013; Ito 2013). The main natural source of land-derived particles to the open ocean is wind-blown dust from arid soils (Jickells et al. 2005; Mahowald et al. 2008), followed by an episodically important contribution from volcanoes. The proportion of the organic fraction of atmospheric nutrients has been recently documented (Kanakidou et al. 2012), highlighting the role of organic matter in transporting nitrogen and phosphorus to the ocean.

Atmospheric processing during transport influences both the supply and impact of atmospheric material delivered to the surface ocean (Baker & Jickells 2006; Krishnamurthy et al. 2009; Trapp et al. 2010). For example, the extent to which dust interacts with anthropogenic acids (H<sub>2</sub>SO<sub>4</sub>, HNO<sub>3</sub>, and organic acids) and photochemical processes (Chen et al. 2011) during transport increases the solubility of some elements, including N and Fe (Desboeufs et al. 2001; Geng et al. 2009; Paris & Desboeufs 2013), enhancing their potentially bioavailable supply to the surface ocean (Johnson & Meskhidze 2013). Future changes in atmospheric chemistry (Lamarque et al. 2011) will likely impact the acidity of cloud droplets and, thus, the bioavailability of atmospheric chemical elements. Despite these few studies, our understanding of these reactions, the conditions under which they are important, and how they may be changing, is still insufficient to effectively incorporate them into predictive regional or Earth system models.

Bioavailability is also linked to post-depositional processes in the ocean. Since the inception of SOLAS, we have learned that chemical interactions between mineral dust-derived nanoparticles and marine organic matter, including biogenic polymeric gels, could be important for nutrient transfer, release, and scavenging (Wagener et al. 2010; Wuttig et al. 2012; Bressac & Guieu 2013; Kadar et al. 2014). Lithogenic (dust) ballasted POC could be an important contribution to carbon export (Ternon et al. 2010; Bressac & Guieu 2013). The oceanic biological pump is a key factor that regulates the ocean's sequestration of persistent organic pollutants that can be bioaccumulated (Galbán-Malagón et al. 2012). Bioavailability of atmospheric nutrients to the marine biota depends both on the origin of the aerosols, atmospheric processing and subsequently on the spatio-temporally varying environmental conditions in surface waters (e.g., temperature, light, oxygen, pH, salinity, dissolved organic matter concentration). More detailed formulations of the reactions controlling bioavailability of atmospherically derived nutrients are still needed in Earth system models to improve our future projections of the biological carbon pump (Tagliabue & Voelker 2011).

### Box 3: Selected Achievement of SOLAS 2004-2014

#### Nutrient cycling in the ocean and global biogeochemical budgets

Quantifying the supply of new nutrients to the ocean from external sources such as atmospheric deposition has been an important focus for much SOLAS research over the past decade. Nitrogen is an essential nutrient, and reactive nitrogen (Nr) deposition, mainly derived from anthropogenic combustion and agricultural sources from densely populated regions throughout the world, was shown to have changed significantly in its spatial and temporal distribution over the past 150 years (Duce et al. 2008). In 1860, Nr deposition to most of the ocean was  $<50 \text{ mg N m}^{-2} \text{ yr}^{-1}$ , with only a few areas  $>200 \text{ mg N m}^{-2} \text{ yr}^{-1}$ . By 2000, deposition over large ocean areas was  $>200 \text{ mg N m}^{-2} \text{ yr}^{-1}$ , reaching  $>700 \text{ mg N m}^{-2} \text{ yr}^{-1}$  in several areas, with strong plumes of deposition extending far downwind of major urban areas in Asia, North and South America, Europe, and West Africa. The ratio of 2030-to-2000 deposition rates (Fig. 7) indicates up to a factor of 2 increase in Southeast Asia, the Bay of Bengal, and the Arabian Sea; up to a 50% increase off western Africa; and up to 30% across essentially all the mid-latitude North Atlantic and North Pacific. In 2030, atmospheric Nr contributions to marine primary production could approach current estimates of global marine biological  $\text{N}_2$  fixation, another source of Nr to the ocean. Based upon the comparison of atmospheric deposition with vertical supply from sub-surface waters, atmospheric deposition was shown to supply most of the new N to the mixed layer in some low-nutrient, low-chlorophyll (LNLC) regions (Guieu et al. 2014). On a global scale, the few modelling studies that have investigated the role of atmospheric nitrogen showed that atmospheric deposition had a very modest effect on marine productivity, export production, or carbon uptake, but identified significant effects regionally, potentially supporting  $>25\%$  of the export production (Krishnamurthy et al. 2009, 2010). These effects may have been underestimated, in particular in LNLC ocean areas, as the episodic nature of atmospheric deposition was usually not considered in models (Guieu et al. 2014).

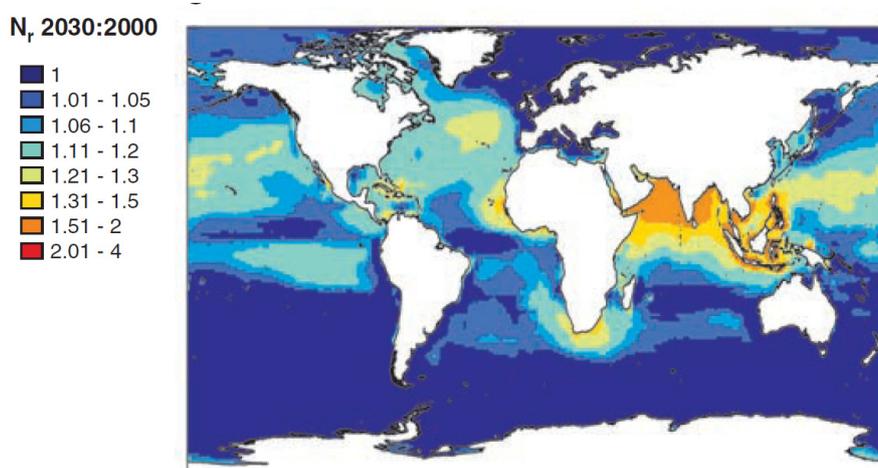


Fig. 7: Ratio of the projected flux of Nr to the ocean in 2030 to that in 2000 (Duce et al. 2008).

Substantial geographical gaps still exist in our knowledge of how atmospheric deposition impacts ocean biogeochemistry. Although the supply of new nutrients to the ocean from the atmosphere has been extensively addressed in iron-limited regions (Boyd et al. 2007), much less attention has been paid to the importance of atmospheric deposition in other low-nutrient, oligotrophic regions, where it likely represents an important source of new macronutrients to the surface mixed layer (De Leeuw et al. 2013; Guieu et al. 2014). In these regions atmospheric

nitrate deposition may also affect long-term ocean nutrient ratios (Zamora et al. 2010; Singh et al. 2013) and, thus, impact estimates of marine N<sub>2</sub> fixation. Therefore, atmospheric impacts in low-productivity regions of the ocean have been underestimated by models, as they typically overlook large synoptic variations in atmospheric deposition and the associated nutrient and particle inputs (Guieu et al. 2014). Atmospheric deposition also can be important for coastal and marginal seas as shown recently downwind of Asian dust and megacities in the northwestern Pacific Ocean (Kim et al. 2011; Shi et al. 2012). The processes involved may potentially affect carbon sequestration globally, considering the importance of those areas in the global ocean carbon cycle (Laruelle et al. 2014).

## Future Approaches

New or improved tools (such as methods for very low-level nutrient analyses; new experimental 'clean' enclosures for artificial seeding experiments, simultaneous remote sensing of atmosphere and ocean, among others) are rapidly expanding our capacity to effectively study the impacts of atmospheric deposition on ocean biogeochemistry. However, we still require more systematic measurements of atmospheric deposition and nutrients in the surface mixed layer in regions where atmospheric (natural and/or anthropogenic) supply plays an important role, particularly nitrate- and iron-limited regions. Although reliable measurements of dry deposition remain technically difficult, it will be beneficial to deploy more wet and dry deposition and particle characterisation measurements on repeat sampling lines across regional deposition and surface water biogeochemical gradients, using both research vessels and voluntary observing ships. Particularly on research vessels, these transects should ideally accommodate rate measurements and nutrient manipulation experiments to gain insight into the proximal controls of plankton composition and process rates. New remote sensing tools such as lidar, polarimeters, and hyper-spectral imagers should complement those approaches.

A network of coupled atmosphere-marine time-series sampling sites in both hemispheres, building on existing time-series stations that monitor both atmosphere and ocean properties (e.g., BATS, CVOO DYFAMED, HOT, and SEATS) is also needed (Schulz et al. 2012). This network should utilise not only ships, but also buoys and island sites, and the temporal resolution of sampling at each site needs to be sufficient to resolve variability in both atmospheric deposition and ecosystem responses. Existing numerical models can help predict the relevant time scales, and remote sensing approaches can contribute to get more synoptic pictures. International coordination will be critical in establishing and maintaining this network to ensure data quality, intercomparability, and availability. These time series sites should also become focal points for more detailed experiments and process studies. In addition, the impacts of ship plumes should be considered explicitly by evaluating how shipping traffic patterns are co-located with ocean-atmosphere observing sites.

Modelling particularly needs to address the variable stoichiometry of atmospheric nutrients and surface ocean biota, with better representations of competitive interactions between plankton groups, aerosols, and organic matter aggregation and export processes. Regional coupled modelling between the atmosphere and the ocean with chemistry modules in both the atmosphere and ocean should also be strongly encouraged. With these combined international comparative studies and time-series data, the SOLAS community should be able, within ten years, to provide the mechanistic information necessary to develop realistic descriptions of atmospheric deposition impacts on marine ecosystems within regional and Earth system models.

## Community Readiness

The international research community is already actively studying the coupling between atmospheric deposition and marine ecosystems, but there is need for improved coordination, because of the multidisciplinary nature of the research. In general, during the first phase of SOLAS, each group targeted an atmospheric/oceanic region with particular characteristics that match their research interests. There is a growing interest by researchers to synthesise the common knowledge (Guieu et al. 2014) in order to allow efficient integration of future regional research programmes. A 'Marine Atmospheric network' for long-term observation of the link between atmospheric material transport and marine biogeochemistry (Schulz et al. 2012) would facilitate both communication between groups working in different areas and development of universal parameterisations for implementation in numerical models. In addition, SOLAS 2015-2025 will support the implementation of the required transdisciplinary process studies in broad oceanic and atmospheric settings essential to tackle the questions discussed above. Finally, research at the ocean-atmosphere interface is evolving with time (e.g., the literature on the potential impacts from ship-based emissions and volcanic ash has ballooned since the inception of SOLAS) and multidisciplinary meetings, such as SOLAS workshops and Open Science Conferences, are still invaluable venues for people with different expertise (e.g., dust, volcanoes inputs, air pollutants, and marine biogeochemistry) to gather and develop approaches to studying new problems. SOLAS intends to play a key role in the establishment of an educational framework to promote such integrated research and tools.

## Impacts of SOLAS Science on Sustainability

The linkages between atmospheric deposition and ocean biogeochemistry concerns global and regional pollution issues, health of the ocean, fisheries, ocean fertilization, and CO<sub>2</sub> sequestration. In tackling fundamental scientific questions on the impact of atmospheric deposition on ocean biogeochemistry and marine ecosystems, we will provide critical information on how ongoing anthropogenic and natural changes in atmospheric composition will impact both ocean productivity and carbon storage. Global transport of pollutants and in particular the impact of ship plumes on the ocean, is particularly relevant as traffic volumes are projected to increase, but the resulting impact on the ocean is largely unknown. This question is acutely urgent in the Arctic Ocean, which is already disproportionately affected by climate change and where major shipping routes are likely to be established in the coming decades as ice coverage decreases. This research theme strongly links to the following six UN SDGs: 2. Zero Hunger; 3. Good Health and Well-being; 7. Affordable and Clean Energy; 11. Sustainable Cities and Communities; 13. Climate Action; and 14. Life below Water.

## 2.1.4 Interconnections between aerosols, clouds, and marine ecosystems

Interconnections between aerosols, clouds, and marine ecosystems are one of the largest sources of uncertainty in future climate projections.

- How are aerosol load and properties linked to the marine ecosystem?
- How do aerosols affect marine clouds?
- What are the feedbacks between clouds and the marine ecosystem?

### Introduction

At any given moment, clouds cover more than half of the sky and are responsible for more than half of the Earth's albedo. Clouds are also a key component of the water cycle. Any change in cloud properties can affect the Earth's energy budgets, as well as amounts of fresh water over the continents. Cloud droplets form around aerosols. Without aerosols, the high humidity levels required for homogenous nucleation would imply no or very little cloud formation. Cloud lifetime and optical properties, as well as rain extent, depend heavily on aerosol size, concentration, and chemical properties.

Aerosols can be classified by their origin (land or ocean), their size, or whether they are natural (such as desert dust and seaspray) or anthropogenic (such as pollution or man-made forest fires). Aerosols are emitted directly from the surface, such as through the wind-driven production of desert dust and seaspray. In addition, aerosols are created in the atmosphere through nucleation.

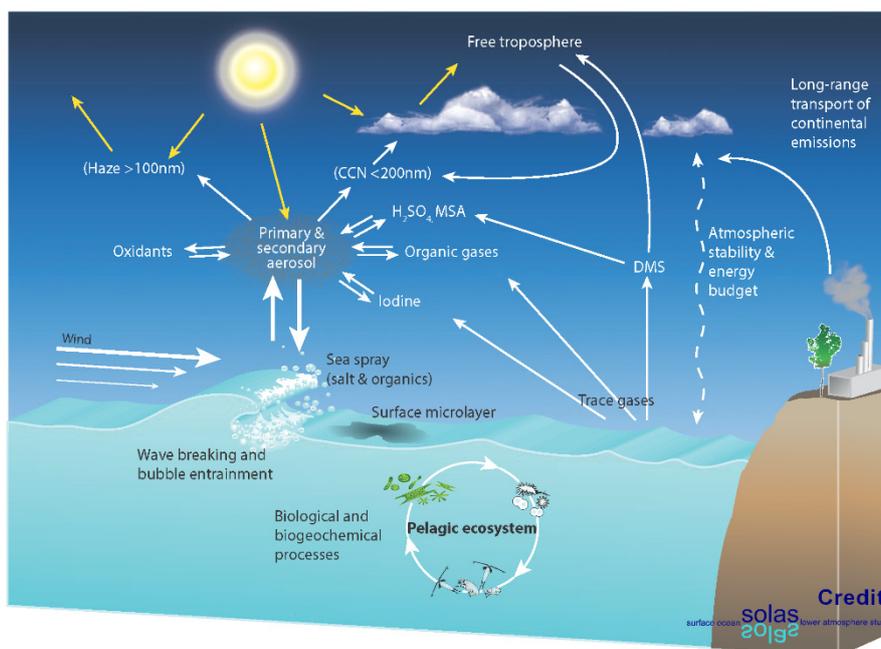
Due to the inherent complexity, interconnections between aerosols, clouds, and marine ecosystems are not well understood. Assessing the system as a whole is required for an accurate understanding of how a change in one component is manifested in another. In addition, more accurate projections of the evolution of climate and the ocean biosphere can only be achieved through a better understanding and quantification of these potential interactions and any associated feedbacks. The intent of this theme is to assess interactions between key components of aerosols, clouds, and marine ecosystems and associated feedbacks.

### Scientific and Societal Rationale

Although clouds play a major role in climate and account for more than half of Earth's albedo, they are the least understood component of the climate system and carry the largest uncertainty in global warming projections (Sherwood et al. 2014). Interactions between aerosol and clouds and impacts of the biosphere on both aerosols and clouds strongly contribute to this uncertainty. Links between oceanic ecosystems and clouds may act as either amplifiers or buffers of climate variability.

Changes in cloud properties may impact ecosystems, including plankton physiology and dynamics, by altering incident radiation, precipitation, surface winds, the ocean mixed layer energy budget, and sea surface temperature. At the same time, aerosols alter the microphysical (e.g., cloud droplet number concentration and size distribution) and macrophysical (e.g., extent and lifetime) properties of clouds by acting as cloud condensation nuclei (CCN) and ice nuclei (IN). Therefore, changes in the aerosol loading and properties result in changes in the cloud optical properties, extent in the atmosphere, and lifetime (Tao et al. 2012; Rosenfeld et al. 2013; Altaratz et al. 2014).

We distinguish between two types of aerosol sources, marine and continental, impacting the atmosphere overlying coastal and open ocean regions (Fig. 8). Transported terrestrial aerosol can be generated from natural sources such as desert dust and biogenic emissions (either as primary or secondary aerosol) or from human sources like urban and industrial pollution. A large fraction of the emission and production of marine, or ocean-derived, CCN occurs in remote regions where concentrations of continentally derived CCN are low. In these regions, clouds are particularly susceptible to small changes in aerosol concentration and properties (Carslaw et al. 2013; Koren et al. 2014).



**Fig. 8:** Ocean sources of atmospheric primary and secondary aerosol and subsequent atmospheric processing. Also shown are aerosol direct and indirect radiative impacts

Due to the scarcity of measurements and limited modelling capabilities, the emission, formation, transformation, and climate effects of aerosols are poorly understood. Hence, this theme will focus on first-order problems, including the biological, physical, and chemical processes that determine emission, production, and composition of ocean-derived aerosols; their interaction with long-range transport of continental aerosols; and how both aerosol types affect atmospheric conditions and clouds.

A first step is to obtain data, from in situ measurements as well as through remote sensing, necessary to estimate local aerosol production, determine the mass and number concentration of long-range transported aerosol, and characterise local cloud properties, all in the context of properties of the underlying surface seawater carbon pool and ecological state (e.g., bloom dynamics). These data will be used to develop much-needed, empirically constrained parameterisations of the local emission flux and production rates of ocean-derived sea spray aerosol (SSA) and gaseous precursors of secondary aerosol (SA), as well as the entrainment flux of long-range transported aerosol and impacts on cloud properties. Improved empirical parameterisations will require the development of new methodologies for better resolving the size distribution, chemical and optical properties of MBL aerosols (marine and long range transport). Such

information will provide the much needed initial conditions of CCN and radiative properties for cloud-resolving models (CRMs), chemical transport models (CTMs), and global climate models (GCMs) to better estimate the impacts of ocean-derived and long-range transported aerosols on clouds and radiation budgets, and to understand feedbacks of aerosols on marine ecosystems.

A concerted effort involving shipboard measurements, remote sensing, and modelling studies is required to achieve these goals. The research will be interdisciplinary in nature, involving both oceanographers and atmospheric scientists. Current limitations in funding and ship time require that resources be pooled and that the effort be internationally coordinated.

## State of Present Understanding

Primary ocean-derived SSA is produced from the entrainment of air bubbles as waves break on the ocean surface. When injected to the atmosphere, the bubbles burst and yield SSA composed of both inorganic sea salt and organic matter (OM). SSA is highly enriched in OM relative to seawater, especially for particles less than 500 nm in diameter (O'Dowd et al. 2004; Keene et al. 2007; Facchini et al. 2008; Bates et al. 2012). The composition of the organic fraction is not fully known, but has been reported to be composed of viruses, bacteria, microalgal debris, and biogenic polymeric and gel-forming organic material (Facchini et al. 2008; Hawkins & Russell 2010; Orellana et al. 2011). The processes controlling the source of the organics are not well understood and the impact of organics on the ability of SSA to act as CCN or IN and nucleate cloud droplets is very uncertain (Modini et al. 2010; Fuentes et al. 2011; Ovadnevaite et al. 2011; Prather et al. 2013). Current model estimates of the flux and climate impact of SSA either do not take into account the organic component or parameterise the organic component based on surface seawater chlorophyll concentrations derived from large-scale satellite retrievals (Rinaldi et al. 2013; Partanen et al. 2014). In a recent paper, Burrows et al. (2014) observed that this is no reasonable to ignore the organic component for ocean regions characterised by intense seasonal algal blooming where a large-scale correlation between organic enrichment in SSA and biological activity has been reported. Differences in oligotrophic, low-chlorophyll ocean regions submicron SSA, enriched by 10-15% in OM, indicates a source of organic matter from the background oceanic DOM reservoir (Quinn et al. 2014). To date, globally valid proxies have yet to be developed for flux parameterisations of the organic fraction of SSA (Quinn et al. 2014). However, the North Atlantic Aerosols and Marine Ecosystems Study (NAAMES) mission is investigating the key processes controlling ocean system function, their influences on atmospheric aerosols and clouds and their implications for climate. Observations obtained during four targeted ship and aircraft measurement campaigns, combined with the continuous satellite and in situ ocean sensor records, will enable improved predictive capabilities of Earth system processes.

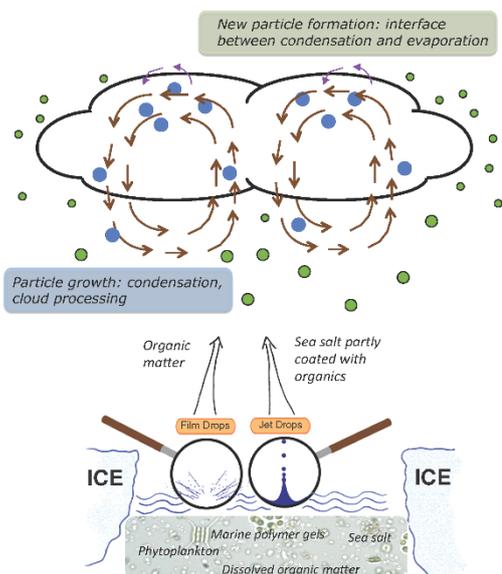
Secondary aerosols (SA) form by nucleation of low volatility, oxidised products of trace gases and subsequent growth by condensation of semi-volatile species on the seed particles. SA also form through aqueous phase processing in clouds (Ervens et al. 2011). The most studied SA production process in the marine atmosphere is the oxidation of biogenic dimethyl sulfide (DMS) into sulfuric and sulfonic acids. Aerosol produced by nucleation of DMS oxidation products in the MBL is the basis for the CLAW hypothesis that describes a negative feedback loop between a surface ocean ecosystem and clouds (Charlson et al. 1987). It suggests that an increase in the flux of DMS from the ocean to the atmosphere will result in an increase in CCN concentration and cloud albedo. The resulting brighter clouds will lead to a decrease in incident solar radiation, which will, in turn, reduce the production of a DMS precursor by phytoplankton. The lack of observations of MBL nucleation over the open ocean, along with evidence for primary (wind-driven) and free tropospheric sources of MBL CCN (including DMS), has led to the realisation that sources of CCN to the MBL are much more complex than originally thought (Carslaw et al. 2010; Quinn & Bates 2011; Clarke et al. 2013).

### Box 4: Selected Achievement of SOLAS 2004-2014

#### Contribution of marine gels to primary marine aerosols

Over 20 years ago, as part of the GAIA theory, biological regulation of climate was proposed whereby emissions of dimethyl sulfide (DMS) from oceanic phytoplankton resulted in the formation of sulfate aerosol particles that acted as cloud condensation nuclei (CCN) in the marine boundary layer (MBL). The increase in CCN was hypothesised to lead to an increase in cloud albedo, resulting in a decrease in the amount of solar radiation reaching the surface ocean. These changes in incident radiation and surface temperature would then initiate a climate feedback, reducing DMS emissions from phytoplankton. In the last decade, several SOLAS-related observational studies questioned the key role attributed to DMS in the CLAW hypothesis.

Several new findings related to ocean surface biological production pathways and cycling were found in the last two decades, suggesting alternative pathways. For example, a unique discussion on “Marine gels and their impact on atmospheric aerosol and clouds” was carried out in a SOLAS/IGAC Workshop held in Kiel in December 2012. Scientists from the marine and atmospheric communities have joined forces, each with unique perspectives, tools, and data to bring to bear on the role of polysaccharide gels in marine organic matter cycling, primary organic aerosol formation, and cloud condensation nuclei activity. This meeting revealed that by combining the collective expertise of these communities the field could be advanced rapidly. The number of airborne marine polymer colloidal gels or marine gels will primarily influence the number of CCN and the resulting optical properties of the cloud droplets (Fig. 9). There is thus growing evidence that marine gels may contribute significantly to the primary marine aerosol and cloud condensation nuclei over remote areas of the ocean. The SOLAS workshop was a step toward developing a common vocabulary and research agenda for understanding the environmental behaviour and impact of these fascinating biomaterials.



**Fig. 9:** Ocean-leaving organic gels as sources of CCN in the remote MBL. Sea salt and organics are emitted as a result of wind-driven bubble bursting (credit: Caroline Leck)

Nucleation events have been observed at coastal sites (Modini et al. 2009; O’Dowd et al. 2010; Chang et al. 2011) and sulfuric and sulfonic acids have been shown to nucleate new particles in the presence of organic condensable species in smog chamber studies (Metzger et al. 2010;

Dawson et al. 2012). In particular, these studies show that organic compounds are likely to initiate the nucleation process. How these results apply to open ocean conditions is yet to be determined. Recent improvements in observational tools (Kulmala et al. 2013) should reveal the actual contribution of boundary layer nucleation to the total CCN number concentration.

The growth of primary organic SSA by condensation of surface active and hygroscopic compounds is also suggested as a CCN source (Andreae & Rosenfeld 2008; Clarke et al. 2013). Recent work suggests that bursts of nanoparticles can occur by in-cloud downsizing of primary organic aerosols (Karl et al. 2013). All in all, the contribution of primary and secondary sources to CCN number concentration is yet to be fully assessed. The task stands as a formidable challenge due to the reaction of freshly emitted SSA with existing atmospheric gases and particles soon after emission, resulting in a blurring of the distinction between SSA and SA.

Aerosols can reside in the atmosphere for days to weeks (Williams et al. 2002; Jaenicke 2008) and, therefore, can be transported 1000s of kilometres from their source. As a result, local aerosol concentrations in coastal and open ocean regions can be dominated by aerosol that has been transported from continental regions within the boundary layer or through the free troposphere with subsequent entrainment to the boundary layer (e.g., Clarke et al. 2013). Continental and marine aerosols can interact, resulting in complex internal and external particle mixtures (Andreae & Rosenfeld 2008) whose properties must be considered when assessing impacts on surface seawater biota and any associated feedbacks.

Attempts to evaluate the impact of ocean conditions on cloud formation and properties, and the radiative budget on a global scale, require the ability to distinguish between ocean and continental sources of aerosols that exist in the marine atmosphere. The effects of marine ecosystem changes associated with global change (such as water warming and stratification, regional oligotrophication or eutrophication, and ocean acidification) on the formation and properties of ocean-derived aerosols and clouds remain uncertain. Equally uncertain are the feedbacks of naturally driven or global change-associated changes in clouds and aerosols on marine ecosystems.

## Future Approaches

As stated above, assessing interconnections between aerosols, clouds, and marine ecosystems will require observations that allow for the estimation of fluxes of local aerosol production and determination of the optical properties, and composition, mass, and number concentration as a function of particle size. These determinations are required for both long-range transported and locally produced aerosols, as is the characterisation of local cloud properties, over a range of surface seawater conditions. Observational requirements for making progress on this broad goal are listed below:

- New approaches for determining the emission flux of SSA and SA precursors, especially at high wind speeds, to reduce associated uncertainties;
- Development of techniques for the identification of the most important players among marine SA precursors (beyond DMS, isoprene and iodine) and to determine their sources, volatility, and aerosol yields; amines and semi-volatile hydrocarbons are suggested as target candidates;
- New techniques that allow for counting and characterising nascent ultra-small aerosols to better assess the frequency and mechanisms of particle nucleation in the marine boundary layer;
- Model ocean (Prather et al. 2013) and in situ measurements able to elucidate processes that modify aerosol in the MBL, including growth, aging, photochemistry and internal mixing; and implementation of these processes in models;

- Simultaneous studies of surface ocean plankton taxonomy/ecophysiology/bloom dynamics, surface concentrations of aerosol precursors and aerosol characteristics to constrain and model the biological and environmental drivers of biogenic aerosol emission; time-series studies (both short-term through bloom phases and long-term through seasons and years) and across-provinces studies will be fundamental tools. This is precisely what NAAMES is attempting to do: combining ships, aircrafts, satellites, autonomous sensors, and modelling data to address knowledge gaps on ocean plankton and their biogenic aerosol emissions;
- Development of methods to discriminate between ocean- and continentally derived aerosols found in the marine atmosphere to allow for assessment of the impact of the marine biosphere on tropospheric aerosols and clouds;
- High-quality and high-resolution measurements of the physical properties of the surface ocean mixed layer and the atmospheric MBL to decouple ocean-derived aerosol effects on marine clouds from physical effects;
- In situ and high-resolution satellite observations of aerosols, winds and cloud properties to improve process understanding and develop parameterisations of marine-cloud interactions; participation by the marine aerosol community in the development of new remote sensing platforms/drones and sensors, ensuring their relevance to ocean-aerosol-clouds feedbacks and informing the overall community of the remote sensing potentials; and
- Development of high-resolution numerical models to integrate cloud microphysics into small-scale process dynamics.

## Community Readiness

There is a growing effort among the oceanographic and atmospheric science communities to address this issue, largely triggered by SOLAS during the last decade. Yet field studies with balanced contributions from both sides of the ocean-atmosphere interface are rare and should be emphasised in the future. Development of a common language (both concepts and terminology) to be shared by the two communities is in its infant stages, but is needed for progress in addressing interconnections between aerosols, clouds, and marine ecosystems. Direct cooperation between the ocean and atmospheric sciences is required in the building of truly coupled ocean-atmosphere modules in Earth system models. Hence, there is a clear need to build frameworks that will bring the two disciplines together to facilitate the exchange of ideas and enhance the results of future experiments.

## Impacts of SOLAS Science on Sustainability

This theme is relevant to a sustainable future for several reasons: the production of climate-active aerosols and clouds by the oceans must be considered when accounting for ecosystem services. The pelagic ocean provides aerosols that scatter sunlight, as well as water vapour and seeds for cloud condensation, in addition to food provision, CO<sub>2</sub> sequestration, CO<sub>2</sub> production, waste dumping and recycling, transportation and recreation, and cultural reference. Aerosols stand as one of the largest paradoxes in global change mitigation efforts. Since the Industrial Revolution, global dimming by anthropogenic aerosols has acted as the most powerful counterforce to greenhouse gas-derived warming (IPCC 2007). Some studies have proposed that the dimming is in fact local, concentrated over places affected by heavy pollution. Detailed aerosol measurements are now being part of some campaigns (e.g., TARA expeditions, NAAMES) in which scientists will measure and specify aerosols in pristine environments. Such measurements will help us estimate local natural aerosol loading in marine pristine environments and long-range transport. Energy flux measurements in such areas will help to better understand trends in the dimming and whether the effect is restricted to places controlled by heavy anthro-

pogenic contribution.

Since the decade of the 1980s when the harmful effects that aerosols have on health, visibility, and cultural heritage were fully recognised, the development of cleaner and more efficient combustion technologies has led to reductions in anthropogenic aerosol emissions, at least in the most industrialised countries. The benefits of this reduction have (and will) come along with an acceleration of warming by reduction of atmospheric dimming. An accurate assessment of the effects of aerosol emission policies on climate requires a solid knowledge of the current and projected roles of natural (including marine) aerosols on the energy balance at the regional and global scales. This research theme is relevant to the following UN SDGs: 2. Zero Hunger; 3. Good Health and Well-being; 7. Affordable and Clean Energy; 11. Sustainable Cities and Communities; 13. Climate Action; 14. Life below Water; and 15. Life on Land. The continuing efforts on the part of SOLAS to understand the links between aerosols, clouds, and marine ecosystems would likely benefit from stronger links to partner Future Earth project ecoSERVICES.

## 2.1.5 Ocean biogeochemical control on atmospheric chemistry

Ocean emissions of reactive gases and aerosols influence atmospheric photochemistry, air quality, and stratospheric ozone.

- What are the marine biogeochemical controls on the release of photochemically reactive gases into the atmosphere?
- How will future changes in ocean biogeochemistry and anthropogenic emissions ( $\text{NO}_x$ , VOCs) interact to influence tropospheric photochemistry and stratospheric ozone?

### Introduction

The atmosphere's photochemical system is influenced by a wide range of natural ocean emissions of reactive gases and aerosols. These emissions can influence the ability of the atmosphere to process and remove anthropogenic pollutants and maintain the levels of stratospheric ozone. Oceanic emissions also interact with pollutants in coastal regions, altering chemical reactions and influencing air quality. It is increasingly clear that biogeochemical cycles in the ocean are also affected by anthropogenic emissions and the deposition of nutrients and pollutants to surface waters (see 2.1.1 and 2.1.3). Despite the significant progress made in recent decades, the biogeochemical controls on ocean-atmosphere exchange of reactive gases and aerosols are still poorly understood. The goal of this theme is to assess how air-sea interactions impact atmospheric chemistry and how future changes in oceanic ecosystems will influence the oxidation capacity of the troposphere and future trends in stratospheric ozone.

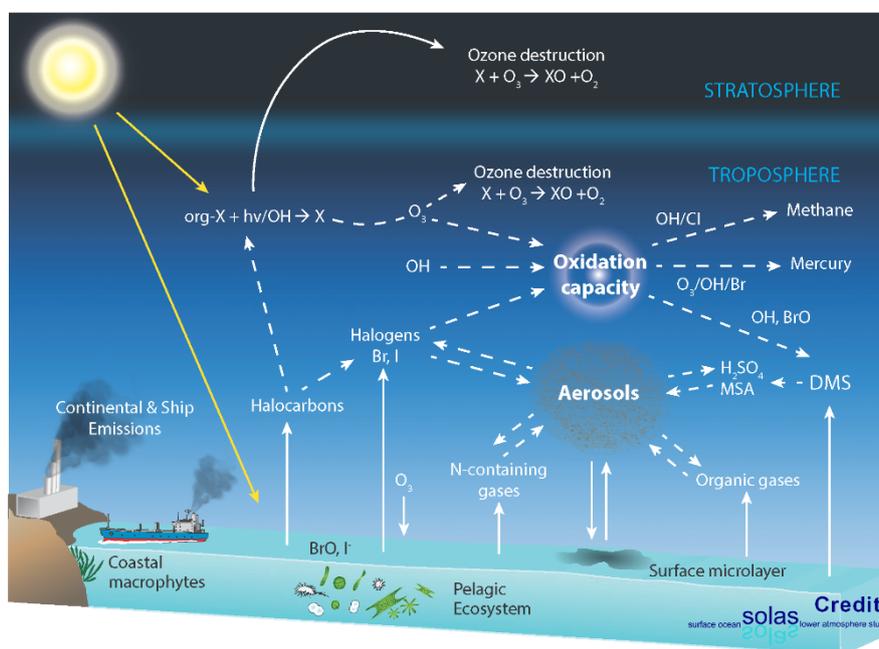
### Scientific and Societal Rationale

The impact of human activities on air quality and stratospheric ozone are among the most significant global environmental issues. Large uncertainties remain in our understanding of the ocean's role in atmospheric chemistry, and how it will evolve with future changes in anthropogenic emissions and climate. Ocean emissions have the potential to alter the abundance of key reactive chemicals that affect the levels and lifetimes of tropospheric ozone and the greenhouse gas methane. The ocean also has the potential to influence stratospheric chemistry through the

emissions of very short-lived ozone-depleting substances, affecting the protective shield against harmful ultraviolet solar radiation and the Earth's energy budget. Although stratospheric ozone depletion was caused by anthropogenic emissions of long-lived halocarbons, which have been addressed under the Montreal Protocol, the future recovery of stratospheric ozone may be influenced by interactions between atmospheric chemistry and ocean biogeochemistry. Ocean-atmosphere interactions influencing air quality and photochemistry can occur both on local and regional scales in the coastal urban environment, and on global scales involving remote regions of the ocean. The challenge of understanding these interactions requires a coordinated, multi-disciplinary international effort.

## State of Present Understanding

Oceanic emissions can have a significant impact on atmospheric chemistry. Several classes of chemicals emitted from the ocean have the potential to impact global atmospheric chemistry. These include a wide range of organic and oxygenated organic compounds, and sulphur-, nitrogen-, and halogen-containing compounds that significantly impact the global budgets of these elements. The chemical interactions between ocean and atmosphere are bidirectional, that is, the ocean is both an important source of reactive gases and a major depositional sink for the oxidation products of atmospheric photochemistry (Fig. 10). The linkages and feedbacks between atmospheric deposition and emissions are poorly understood, and are a major area of current research. Ocean emissions influence both the gas phase chemistry and aerosol chemistry of the overlying atmosphere. Here, we focus primarily on photochemical processes. Those aspects of the problem tied directly to aerosols, clouds, and marine ecosystems are discussed in 2.1.4.



**Fig. 10:** Simplified schematic depiction of the most important couplings between ocean biogeochemical cycles and atmospheric chemistry

Recent evidence shows that marine emissions of bromine and iodine can exert a significant effect on tropospheric photochemistry. There is a limited but growing database of direct observations of reactive halogen compounds over the ocean. Gas phase bromine and iodine compounds released from the sea surface and from marine aerosols undergo a series of gas phase and aerosol-mediated reactions that can catalytically destroy tropospheric ozone. New data suggests that photochemical cycling of reactive bromine and iodine cycling can account for about one-third of photochemical ozone destruction in the North Atlantic (Read et al. 2008). Global model studies based on such data suggest that ocean-derived bromine and iodine significantly impact the ozone budget in both the marine boundary layer and the free troposphere (Saiz-Lopez & von Glasow 2012). It has long been suspected that the release of iodine from the sea surface is tied to the deposition of tropospheric ozone (Ganzeveld et al. 2009), and laboratory experiments suggest that this interaction may occur via the formation and release of HOI, and to a lesser extent I<sub>2</sub>, at the sea surface (Carpenter et al. 2013). This raises the possibility of a feedback loop between ozone levels and biogeochemical iodine cycling. Such a feedback would represent a new link between anthropogenic emissions and ocean biogeochemistry (Prados-Roman et al. 2015).

Reactive chlorine has been observed in marine air at levels that may influence the atmospheric life-time of methane. In coastal, highly polluted air, interactions between sea-salt aerosols and pollutants lead to the formation of ClNO<sub>2</sub>, which results in rapid Cl-based photochemistry (Osthoff et al. 2008). There is evidence that marine aerosol acidification and aerosol-pollutant interactions can influence photochemistry even after several days of transport over the ocean. Recent studies have shown the presence of Cl<sub>2</sub> and HOCl in European outflow air over the tropical Atlantic Ocean. The consequent generation of Cl atoms has the potential to affect the lifetime of many organic compounds in marine air, including the greenhouse gas methane. Globally, most of the photochemical loss of methane occurs in the marine troposphere by reaction with OH radicals. The new observations suggest that increasing pollutant levels may increase the role of Cl as an additional sink for methane (Lawler et al. 2011). Such processes are not accounted for in the current generation of air quality and chemistry/climate models.

The factors controlling emissions of short-lived, ozone-depleting halocarbons are not well understood. It is well established that halogen atoms (Cl, Br) released from halocarbons lead to the catalytic destruction of stratospheric ozone. The majority of the chlorine and bromine in the stratosphere is derived from anthropogenic emissions of long-lived compounds that are controlled under the Montreal Protocol. However, a portion of stratospheric ozone depletion can be attributed to the emissions and transport of so-called “very short-lived substances” or VSLs (Salawitch 2006; Sinnhuber & Folkins 2006; Hossaini et al. 2012). These are defined as trace gases of natural or anthropogenic origin whose chemical lifetimes are comparable to transport times in the troposphere (<0.5 years). Hence, they are non-uniformly distributed in the lower atmosphere and their effects on the upper atmosphere are highly sensitive to their chemistry and transport, and to the location of their emissions. It has been shown that the tropical oceans play an important role in the delivery of VSLs to the stratosphere (Quack & Wallace 2003).

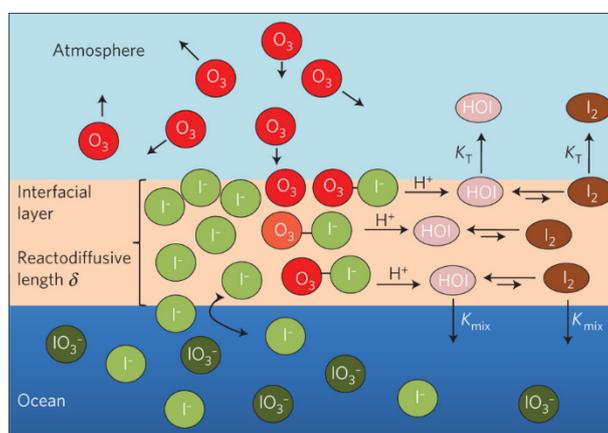
A wide range of volatile halogenated and sulphur-containing compounds are produced biologically and photochemically in seawater and are released to the marine atmosphere. These compounds can be generated in biologically productive waters in tropical regions where strong vertical uplifts in the atmosphere efficiently entrain near-surface air into the lower stratosphere. We have a limited understanding of the chemical composition and air-sea fluxes of photochemically reactive compounds, and of the biogeochemical processes that control emissions. There is a very limited database available for developing climatologies for oceanic emissions of reactive substances and an even greater lack of data regarding the ecological and biogeochemical processes controlling emissions. The most extensively researched oceanic emission is dimethyl sulfide, because of its role as an aerosol precursor (Lana et al. 2011; see 2.1.4). For most of the reactive gases, including halogens and organics, there is little basis for assessing emissions on

a regional and seasonal basis, or for determining interannual variability. There is also a need for process studies to understand the biogeochemistry controlling variability in surface ocean emissions and to assess how those emissions may change with the many stressors on oceanic biological systems such as changes in oceanic nutrient deposition, stratification, deoxygenation, and acidification.

### Box 5: Selected Achievement of SOLAS 2004-2014

#### Atmospheric iodine levels influenced by sea surface emissions of inorganic iodine

The self-cleansing capability of the atmosphere is influenced by natural ocean emissions of reactive gases and aerosols, including sulphur-containing compounds, organic and inorganic halogens, organic gases, and halide-, nitrogen- and organic-containing aerosols. Furthermore, natural biogeochemical cycles in the ocean are affected by anthropogenic emissions with implications in atmospheric chemistry and the deposition of pollutants to the surface ocean. In recent decades, major progress has been achieved in understanding the importance of natural emissions from the ocean on the composition and reactivity of the troposphere. The quantification of the bidirectional fluxes is, however, still very uncertain and recent discoveries of new interactions show that our knowledge about ocean-atmosphere interactions is still limited. Very recent laboratory experiments have shown that inorganic iodine (HOI mainly, and to a lesser extent  $I_2$ ) can be directly released from the ocean surface following ozone deposition and subsequent oxidation of iodide at the air-sea interface (Carpenter et al. 2013) (Fig. 11). This emission mechanism is controlled by surface ozone concentrations, wind speed, and the concentration of aqueous iodide. The coupling between tropospheric ozone and ocean iodine highlights the importance of a better understanding of how background natural oceanic biogeochemical cycles are, and will continue to be, affected by anthropogenic emissions.



**Fig. 11:** Schematic of the production of HOI and  $I_2$  following the reaction of ozone with iodide at the sea surface (Carpenter et al. 2013).

In many cases, there are no observations of important chemicals or contradictory observations that require further research. A notable example is glyoxal, an oxygenated volatile organic compound that participates in aerosol formation and tropospheric photochemistry. Satellite and in situ sensors report significant levels of glyoxal over the ocean, which are inconsistent with currently known marine sources (Sinreich et al. 2010; Mahajan et al. 2014). Recent direct flux

measurements show bidirectional fluxes, implicating a role for organic photochemical reactions in the marine microlayer as a source. The marine microlayer is a complex and poorly characterised membrane between ocean and atmosphere. The role of the microlayer in oceanic emissions is not well understood and fundamental advances in understanding its properties are needed.

### Future Approaches

Progress in this area requires field studies combining atmospheric and oceanic measurements to characterise 1) the chemical composition and spatial/temporal variability of sea surface emissions of organohalogen compounds, volatile organic carbon and volatile oxygenated organic carbon compounds; 2) the generation of reactive volatile species at the sea surface; and 3) the biogeochemistry of oceanic emissions. Progress on these topics will require survey-type missions, process-oriented intensive campaigns to study surface ocean cycling, air-sea exchange rates, and atmospheric photochemistry. Atmospheric field experiments and associated modelling studies are needed in order to understand the rates and pathways of atmospheric cycling of reactive emissions and how they interact with both the natural marine atmosphere and with anthropogenic pollutants in continental outflow regions. Instrument development and laboratory investigations of reaction mechanisms and kinetics are also needed. Marine biogeochemical studies are needed to assess the relationship between emissions and the biological factors controlling them, such as seasonality, bloom dynamics, microbial ecology, and trophic state. Such studies should include both field measurements and quasi-controlled environmental studies in the laboratory and in mesocosms.

Such studies will have various regional foci, depending on the process under study. For example, studies of tropospheric chlorine cycling should focus on regions of continental outflow, such as the western Pacific or eastern Atlantic. For VLS, studies should focus on the Indonesian “maritime continent” and tropical western Pacific, where a region of strong atmospheric uplift overlies biologically productive waters. These campaigns should be supported by model studies to improve process understanding. Modelling studies are also needed to upscale from the regional scale to the global scale and to assess climate and biogeochemical impacts.

Many fundamental questions regarding reaction pathways, especially related to multiphase reactions, remain to be answered. Hence, laboratory studies that address these issues are essential. Particularly needed are laboratory, mesocosm, and field studies of the mechanisms of production of atmospherically relevant gases and the processes that control their emissions from the sea surface, and investigation of how future changes in ocean nutrients, pH, among others, will impact these processes at the organism or ecosystem levels.

### Community Readiness

SOLAS has made a major contribution to the establishment of an international community and the training of the next generation of scientists through its open science meetings, focused workshops, and summer schools. Individual countries have their own SOLAS programmes (e.g., the SOPRAN project in Germany), which have built a community and contributed greatly to achieve the scientific goals of SOLAS. This is a great achievement, but an ongoing effort is required to maintain the links in this “new” community.

Research on ocean biogeochemical control on atmospheric chemistry requires collaborative interaction among scientists trained on different topics, which in some cases are trained in different institutions, attend different scientific conferences, and publish in different journals, utilising very different vocabularies. These scientists include microbiologists, biomolecular

chemists, chemical oceanographers, tropospheric/stratospheric chemists and dynamists, and climate scientists. Progress in this area will require scientists who share a common understanding of the complex interconnections between the ocean, atmosphere, and climate. The issues related to atmospheric composition have a strong connection with the International Global Atmospheric Chemistry (IGAC) project, as well as the international Commission on Air Chemistry and Global Pollution (iCACGP).

The atmospheric chemistry and dynamics communities are fairly well linked via joint consortia (e.g., the recent EU-funded SHIVA consortium) and assessments, most prominently the WMO Scientific Assessment of Ozone Depletion. New efforts are needed to extend these linkages to the other communities listed above. Important partnerships include the IGAC/SPARC Chemistry-Climate Model Initiative (CCMI), the SPARC Stratospheric Sulfur and its Role in Climate (SSiRC) activity. Coordination of these collaborations is essential to enable progress in this important field.

### Impacts of SOLAS Science on Sustainability

The ocean provides a vast amount of ecosystem services to humanity. Pollution of the troposphere diminishes these services. Furthermore, it is likely that the processes listed above are affected by global change, but given the link with greenhouse gases, global change is also affected by oxidative processes of marine gases and particles in the troposphere.

Maintaining a healthy stratosphere is one of the most fundamental requirements to sustain life on Earth. The costs of stratospheric ozone degradation include human health risks, damage to oceanic ecosystems and food webs, potential changes in genetic mutation rates, and damage to agricultural crops and livestock. In addition, there are many interactions between stratospheric ozone and other elements of the climate system, such as the climate forcing by changes in the stratospheric composition and dynamics. There is a direct societal interest in understanding the risks associated with various forms of human activity. The Montreal Protocol was an outstanding example of how dramatic environmental change (e.g., the Antarctic ozone hole) galvanised nations and society to successfully cope with an urgent global environmental issue. The longer-term climate/ozone/ocean-emission interactions discussed here have the potential to change the “baseline” of ozone-depleting gases, which the Montreal Protocol seeks to regulate. Finally, some proposed geo-engineering schemes involve changing surface oceanic biogeochemistry. It is important to have a multidisciplinary community capable of assessing such schemes for the full range of possible environmental consequences. This research theme is relevant to the following UN SDGs: 2. Zero Hunger; 3. Good Health and Well-being; 7. Affordable and Clean Energy; 11. Sustainable Cities and Communities; 13. Climate Action; 14. Life below Water; and 15. Life on Land. Going forward, SOLAS will be even better able to contribute directly to global sustainability efforts through our association with Future Earth, particularly through the Oceans and Natural Assets Knowledge-Action Networks.

## 2.2 SOLAS Cross-Cutting Themes

### 2.2.1 Integrated topics

In the complex, non-linear system of the surface ocean and lower atmosphere, the five SOLAS core themes interact and influence each other. Understanding the processes involved and making predictions will not be possible by studying these themes independently. We have identified several example oceanic systems where integrated studies are particularly urgent, needing to be either initiated or expanded. These are broad topics that overlap, which is intentional, and this list is not exclusive; quite to the contrary, we expect that SOLAS scientists will continue to identify additional regional, high-sensitivity, and high-priority systems for integrated studies. Other integrated topics that have been proposed or are in development include the Indian Ocean, coral reefs, pollutant transport, oligotrophic gyres, and impacts of catastrophic and extreme events, as well as many others.

#### Box 6: Selected Achievement of SOLAS 2004-2014

- Strong national communities have developed to study regional air-sea exchange processes in East Asia, South America, and Turkey.
- Climate-induced strengthening of the southwest monsoon is increasing biological productivity in the Arabian Sea and increasing the spread of hypoxic waters (Gomes et al. 2014).
- The eastern tropical Pacific (ETP) is one of the largest marine sources of the greenhouse gas nitrous oxide (N<sub>2</sub>O). However, in the future the expansion of oxygen minimum zones could cause average N<sub>2</sub>O concentrations in the Pacific to decrease (Bange et al. 2009; Zamora et al. 2012).
- Stratification from sea-ice melt and river run-off in the Arctic Ocean can severely limit gas exchange and primary production, largely negating anticipated increases in CO<sub>2</sub> draw-down by an ice-free Arctic (Cai et al. 2010; Else et al. 2013).
- Sea ice is a major, dynamic reservoir of climatically active gases and actively exchanges material with both the atmosphere and the underlying water (Loose et al. 2011; Vancoppenolle et al. 2013).
- Ocean dynamics dominate over biogeochemical processes in controlling oxygen fluxes in the Peru upwelling zone (Montes et al. 2014).
- Similar to heat, CO<sub>2</sub> fluxes in partially ice-covered waters, such as leads and polynyas, are as much as an order of magnitude higher than predicted from open-water parameterisations (Loose et al. 2009; Else et al. 2011).

### Upwelling Systems

Upwelling systems, both coastal and equatorial, are natural laboratories for studying the impacts of multiple stressors on air-sea exchange processes and marine ecosystems and services. The coastal upwelling areas, such as those of the Humboldt, Benguela, and Somali Currents, are among the most productive systems in the world ocean and support important fisheries. This high productivity is intimately linked with shallow Oxygen Minimum Zones (OMZs), where low oxygen, high CO<sub>2</sub> concentrations, low pH values, and shallow aragonite saturation horizons co-occur. The OMZs are also characterised by intense nitrogen and sulphur cycling, which impacts the structure and function of the ecosystem (Naqvi et al. 2000; Lam & Kuypers 2011; Ulloa et al. 2012; Schunck et al. 2013). The dominant processes producing and fixing N<sub>2</sub> and the mechanisms that determine the balance between organic matter recycling and production are

still largely unknown in these environments. When OMZ waters upwell and impinge on the euphotic zone, they release significant quantities of greenhouse gases, including CO<sub>2</sub>, N<sub>2</sub>O, and CH<sub>4</sub>, to the atmosphere (Farías et al. 2007; Friederich et al. 2008; Paulmier et al. 2008; Paulmier & Ruiz-Pino 2009; Naqvi et al. 2010; Capone & Hutchins 2013). In addition, photochemical processes may also consume O<sub>2</sub> and produce CO, CO<sub>2</sub>, and ammonia in upwelled waters (Kitidis et al. 2011; Kitidis et al. 2014). The coupling between upwelling, productivity, and oxygen depletion feeds back onto the biological productivity of these systems and their role as sinks or sources of climate-active gases (Law et al. 2013).

Due to the complex interactions between physical and biogeochemical processes in upwelling systems, we need to adopt an integrative approach to study these regions: ocean, atmosphere, land, and in coastal areas impacted by human activities, socio-economic dimensions. This work is intimately involved with the SOLAS themes on greenhouse gases (see 2.1.1) and oceanic impacts on atmospheric chemistry (see 2.1.5) through the linkages between upwelling and air-sea exchanges of biogenic gases, ecosystem structure, acidification, and deoxygenation. We also do not yet understand the impacts of both submeso- and meso-scale variability in ocean circulation (eddies, fronts, filaments) and winds (direction, intensity) on oxygen minimum zone dynamics and air-sea exchange (see 2.1.2), which is also likely impacted by as yet unidentified variations in sea-surface surfactant activity in response to ecosystem and climatological variations. An additional gap we need to address is how aerosols link ocean temperature and stratocumulus clouds (impacting regional radiative budgets) in upwelling zones (see 2.1.4). Finally, at low latitudes, upwelling systems are often bounded by desert landscapes, and the balance between (micro)nutrient inputs from above versus below is still uncertain, particularly on various time scales (see 2.1.3).

Economies of the countries neighbouring upwelling zones, which are largely supported by marine resources, urgently need improved capacity to predict variations in ecosystem structures and coastal water quality relating deoxygenation and acidification. Waters with low oxygen levels and pH values are increasingly encroaching on productive coastal waters in upwelling zones, with impacts on ecosystem productivity, biodiversity, and the quality of life in coastal communities. The air quality in mega-cities adjacent to upwelling zones, such as Lima, Dakar, and Mogadishu, are particularly susceptible to as yet poorly understood interactions between anthropogenic contaminants, marine aerosols, and greenhouse gases. The relationships between upwelling dynamics, the marine ecosystem, and atmospheric chemistry that are the focus of SOLAS science not only help these societies manage fisheries and aquaculture, but also have implications for all coastal marine ecosystem services, including air cleansing, and cultural and recreational activities.

## Polar Oceans and Sea Ice

Changing sea ice coverage in the polar oceans is impacting air-sea exchanges of both energy and climatically active substances. The dynamics and consequences of changes in sea-ice characteristics and distribution in the polar oceans are critical to understanding and modelling feedback effects and future scenarios of climate change. Sea ice was long assumed to inhibit air-sea gas and material exchange, but thanks to extensive research over the last ten years, much of which was conducted by SOLAS scientists, we now understand that sea ice is a very rich and complex system that actively exchanges with both the atmosphere and the underlying water. Within the ice, biotic and abiotic processes interact in changing ways throughout the freeze-melt cycle (Thomas & Dieckmann 2010), and thus, sea ice is an active participant in the biogeochemical cycles of many elements, producing climatically active atmospheric aerosols (Leck & Bigg 2010), modulating the surface ocean ecosystem (Arrigo et al. 2010), contributing to substantial seasonal gas fluxes, and possibly facilitating long-term export and CO<sub>2</sub> sequestration in deep waters (Loose et al. 2011). In addition, air-sea gas exchange rates in partially ice-

covered waters appear to be at least an order of magnitude larger than what would be expected from observations in ice-free waters (Loose et al. 2009; Else et al. 2011), while stratification and the geochemistry of both ice melt and river runoff can substantially limit air-sea CO<sub>2</sub> exchange in summer Arctic waters (Cai et al. 2010; Else et al. 2013). Therefore, because of the annual sea-ice formation and melt cycle, coupled with increasing areas of open water in summer and first-year sea ice in winter, the polar oceans are year-round hot spots for air-sea interactions.

As a complex medium located at the air-sea interface, sea ice directly and substantially impacts, in ways that are often counter-intuitive, the exchange of gases and aerosols (Vancoppenolle et al. 2013), as well as heat and momentum, between the ocean and the atmosphere (see 2.1.2). To develop the new parameterisations required to represent air-sea fluxes in the presence of sea ice, we must understand not only sea-ice biogeochemistry, but also how fluxes are enhanced in partially ice-covered seas and how sea-ice melt and stratification impact fluxes during the open-water season. In addition to controlling air-sea CO<sub>2</sub> exchanges in polar waters, sea-ice dynamics impact CH<sub>4</sub> emissions (Zhou et al. 2014) and acidification processes (AMAP 2013) in as yet unpredictable ways. Because sea-ice formation regions supply the deep waters of the global ocean, the impacts of air-sea exchange processes in polar waters propagate throughout the global ocean, eventually influencing deoxygenation and acidification states at lower latitudes (see 2.1.1). Halogenated aerosols released during sea-ice formation and growth appear to play a vital role in controlling ozone dynamics (Simpson et al. 2007), and releases of sulphur and organic gel aerosols also likely impact other aspects of polar atmospheric chemistry (see 2.1.5), but the feedbacks into the marine ecosystem are still almost completely unknown (see 2.1.4). Finally, because the sea-ice cover accumulates and stores atmospheric fallout of both nutrients (Lannuzel et al. 2008; Nomura et al. 2011) and contaminants (Macdonald et al. 2000), releasing them to the water column in concentrated pulses, sea ice exerts a fundamental control over the impact of atmospheric deposition on the marine ecosystem (see 2.1.3).

The controls exerted by sea ice on air-sea exchange processes are intimately connected to the life-styles and livelihoods of people living in the Arctic. In particular, transport of contaminants (including mercury and persistent organic pollutants), air quality, and ecosystem structure and development have immediate impacts on the quality of life in this extreme environment. In addition, as the Arctic Ocean becomes more accessible, with the loss of thick, multi-year ice, increases in shipping and fossil fuel development will contribute more contaminating materials into the air-sea dynamics of the area. Beyond direct impacts on local Arctic communities, sea ice in both the Arctic and Southern oceans plays a critical role in the global carbon cycle, controlling the air-sea balance of greenhouse gases and the composition of the ocean's deep waters in complex ways and with as yet unpredictable feedbacks.

## Coastal Waters

In intensively utilised coastal seas, anthropogenic impacts combine with natural variability in physical forcing and biogeochemical processes to increase system vulnerability. The coastal regions cover only 7% of the global ocean surface, but they support a disproportionate fraction of oceanic primary production and calcification, fisheries, and other marine ecosystem services, and most human interaction with the ocean occurs in these areas. Hence, the response of coastal biogeochemical cycles to stress (climate warming, ocean acidification, ocean circulation changes, among others) and the associated feedbacks and interactions between stressors (e.g., eutrophication plus acidification; Cai et al. 2011) will be disproportionately important in coastal waters, in comparison to the rest of the ocean. These coastal waters are important components of nearly all ocean biogeochemical cycles and play an important role in climate regulation, acting as hot spots for CH<sub>4</sub>, N<sub>2</sub>O, and DMS emissions, as well as for strong air-sea CO<sub>2</sub> fluxes in both directions (Naqvi et al. 2000; Chen & Borges 2009; Naqvi et al. 2010). These areas also suffer eutrophication due to riverine nutrient inputs and are directly impacted by

atmospheric deposition of terrestrial materials, both nutrients and contaminants.

Developing a process-based understanding of air-sea exchange is particularly challenging in coastal waters, because of the complex interactions between waves and bubble injection, variable winds, marine and terrestrial surfactants, and the impacts of river waters and stratification (see 2.1.2). In addition to serving as strong regional source and sink areas for both greenhouse (see 2.1.1) and other climatically active gases (see 2.1.5), coastal waters serve as a vital link between the marine system and cloud formation, through the aerosols released by both natural (wave action and algal blooms) and anthropogenic (e.g., high ship traffic) processes, with as yet unpredictable ecosystem feedbacks (see 2.1.4). Of course, the impacts of atmospheric deposition on marine ecosystems and biogeochemistry are particularly acute in coastal waters, with large supplies of terrestrial nutrients, dust, and contaminants (see 2.1.3).

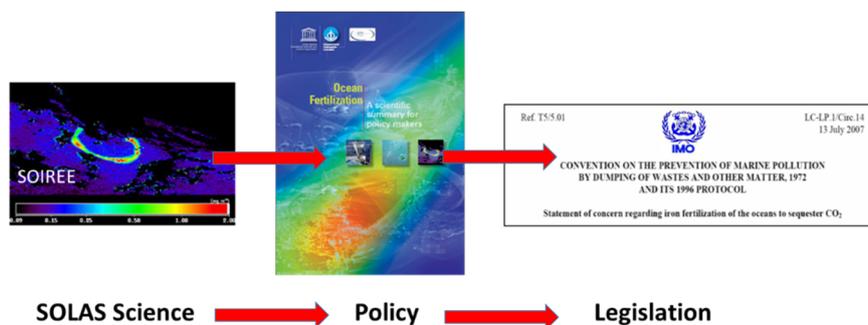
Coastal waters are where the interactions between the marine system and human society are strongest and most obvious. Issues of fisheries and aquaculture management, air quality, water quality (e.g., eutrophication, deoxygenation, acidification, harmful algal blooms), and recreation all come into play to at least some extent along the entire human-inhabited global coastline, but become critical in highly populated areas, such as around mega-cities. Terrestrial atmospheric inputs to the coastal ocean, gases and aerosols released from the coastal ocean, and the processes that control those transports across the air-sea interface (i.e., SOLAS science) are critical to human quality of life, particularly within the context of global change.

## **2.2.2 Research on environmental impacts of geoengineering**

A dominant thread running through the above themes is the focus on feedbacks and interactions with climate. Understanding and quantifying ocean-atmosphere interaction is an essential requirement for developing the predictive capability required to inform decisions on adaptation to, and mitigation of climate change. Potential future mitigation options include geoengineering, the deliberate manipulation of the environment to counteract greenhouse gas-induced climate change. As some geoengineering approaches involve the deliberate enhancement of natural processes associated with the ocean-atmosphere interface, SOLAS research into the marine carbon cycle and air-sea exchange of gases and particles can make an important contribution by assessing their impact. As geoengineering will likely alter ecosystems and their functions, both observational evidence and model predictions are required to characterise potential ecosystem responses (Russell et al. 2012). By addressing the complexity of ocean-atmosphere interactions SOLAS science will be highly relevant to establishing the beneficial and detrimental effects of both Carbon Dioxide Removal (CDR) and Solar Radiation Management (SRM) techniques, and provide robust evaluations for policy-makers and society on the risks and uncertainties associated with climate engineering (Royal Society 2009).

One example of SOLAS activities relevant to geoengineering is the mesoscale iron addition experiments (Boyd et al. 2007), which examined the role of iron availability in controlling oceanic primary production. Overall, these experiments have shown that although large additions of iron sulphate to surface waters increased primary production in some oceanic regions, a corresponding increase in carbon export to deep waters was not apparent (Boyd et al. 2007). These experiments also provided a wealth of information on the influence of nutrient fertilization on ocean-atmosphere exchange and impacts on ecosystem structure and function (Law 2008; Boyd et al. 2012; Williamson et al. 2012), including potentially deleterious effects (Trick et al. 2010). Synthesis of the mesoscale iron addition experiments by SOLAS resulted in a Summary for Policymakers on Ocean Fertilization (Wallace et al. 2010; Williamson et al. 2012), and contributed towards international governance including development of an assessment frame-

work for future ocean fertilization experiments (IMO 2007) (Fig. 12). From a logistical perspective, these experiments demonstrated the critical requirement for effective monitoring, using an extensive trans-disciplinary observational framework, including multi-ship operations, aircraft support and remote sensing, to track response over large spatial and temporal scales. Any future iron addition experiments will need to cover greater spatial scales (i.e.,  $10^4 - 10^5$  km<sup>2</sup>) and longer periods (i.e., months-years) than previous experiments, in order to minimise mixing and dilution artefacts and improve quantification of carbon sequestration (Watson et al. 2008). A deliberate iron addition off the Canadian west coast has been controversial (Tollefson 2012) and highlights the need for international regulation and oversight to ensure independent pre-assessment, monitoring, and verification. Ultimately, if large-scale fertilization (or any other geo-engineering technique) were to be implemented, an effective observational framework would be essential for establishing the initial baseline state and natural variability against which subsequent change would be assessed, and for verifying the effectiveness and permanence of carbon sequestration (Herzog et al. 2003) and associated ecosystem impacts.



**Fig. 12:** Conceptual diagram of the pathway of SOLAS research to policy and international regulation. The figures (from left) show a satellite ocean image of showing elevated chlorophyll *a* resulting from the mesoscale iron addition experiment SOIREE in the Southern Ocean (Abraham et al. 2000), the cover of the SOLAS-IOC report "Ocean Fertilization: A Summary for Policy Makers" (Wallace et al. 2010), and the heading of a statement of concern regarding iron fertilization (IMO 2007) that led to inclusion of an amendment on ocean fertilization in the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (known as the London Protocol).

An alternative approach to deliberate fertilization experiments is to study natural analogues, such as the addition of micronutrients to the surface ocean associated with volcanic emissions (Hamme et al. 2010), dust plumes (Jickells et al. 2005) (see 2.1.3), and island wake effects (Blain et al. 2007). One benefit of these 'natural perturbation' approaches is that ecosystem and biogeochemical responses, such as changes in cycling and air-sea flux of climate-reactive substances and carbon sequestration (see 2.1.1), can be examined over greater temporal and spatial scales (Achterberg et al. 2013) than in the deliberate fertilization experiments. Other related CDR techniques of relevance to SOLAS science include macronutrient fertilization, as with nitrogen addition to oligotrophic waters, and artificial upwelling (Karl & Letelier 2008; Oschlies et al. 2010). Carbon Capture and Storage (CCS) techniques, though primarily considered for the mid-water and deep ocean, require a thorough understanding of the ocean carbon cycle, and also an effective monitoring framework to determine both immediate impacts at injection sites and the long-term fate of sequestered carbon. The transfer of CO<sub>2</sub> from the atmosphere and surface ocean by CDR techniques such as CCS may increase ocean acidifica-

tion (see 2.1.1) at mid-water depths (Cao & Caldeira 2010) and also, in the case of ocean fertilization, increase mid-water oxygen utilisation. Consequently, these approaches require a detailed understanding of the underlying physical and biogeochemical processes, and also how they may be altered by future climate change. Accelerating natural geological processes by 'enhanced weathering' to raise ocean alkalinity has been considered for its potential to lower atmospheric CO<sub>2</sub> and arrest ocean acidification (Köhler et al. 2010; Williamson & Turley 2012). SOLAS research into the carbonate system and other biogeochemical cycles in the coastal zone, as detailed in section 2.2.1, would inform evaluation of these techniques and their ecosystem impacts.

SRM is a geoengineering approach aimed at stabilising global temperature by reducing incident sunlight and enhancing surface cooling, using techniques such as the injection of sulphate particles into the stratosphere and salt particles into the lower troposphere. These techniques may potentially influence atmospheric chemistry and surface ocean dynamics on a variety of scales, with associated impacts on biogeochemistry and ocean-atmosphere exchange (see 2.1.2 and 2.1.4).

For example, implementation of stratospheric SRM approaches requires understanding and modelling of the sensitivity of the surface ocean to the potential changes in precipitation, salinity, and light, including increases in UV radiation that may arise from the resulting reduction in stratospheric ozone (Russell et al. 2012). The existing low cloud condensation nuclei (CCN) concentration over the remote open ocean offers potential for geoengineering by increasing the albedo of marine stratocumulus clouds; consequently, SOLAS research into the influence of surface ocean biogeochemistry and physics on CCN production and marine cloud properties is highly relevant (see 2.1.4 and 2.1.5).

Indeed, the study of aerosol-cloud interaction has been a primary aim of several SOLAS-related field studies (Wood et al. 2011), with emissions from ships and other sources investigated to determine the cause-and-effect of particles on clouds (Russell et al. 2013). Such research provides insight into the potential effectiveness of these SRM techniques, as observations show that the indirect effects of aerosols on clouds may sometimes result in warming rather than cooling (Leaitch et al. 2010; Chen et al. 2012). Though likely premature at this stage, any consideration of altering marine cloud properties would entail longer-term ecosystem interaction studies, which would require an artificially sustained source and, importantly, careful consideration of unexpected consequences. On smaller scales, process studies of aerosol-cloud interactions in the marine boundary layer are important for improving understanding of indirect effects and representation of these effects in global climate models.

SOLAS observational, experimental, and modelling studies will continue to inform scientists, policy-makers, and the public on the environmental impacts of potential geoengineering via studies of the natural biogeochemical cycles of nutrients and carbon (see 2.1.1 and 2.1.3), and the processes and species that determine aerosol production and composition and cloud properties (see 2.1.3, 2.1.4, and 2.1.5). Information collected from these and other SOLAS studies will contribute to the development and improvement of ocean biogeochemistry and Earth system models, which can then be applied to the evaluations of geoengineering techniques (Keller et al. 2014). Thus, SOLAS science has very important contributions to make toward Future Earth activities, such as Earth System Governance (ESG) and Integrated Risk Governance (IRG) projects, as well as toward the Natural Assets Knowledge-Action Network.

## 2.2.3 Science and society

### Motivation

The surface ocean and lower atmosphere are intrinsically coupled, and their interaction is critical for controlling the functioning of the Earth system. The exchange of energy, momentum, and mass (including heat, moisture, pollutants, trace gases, and particles) plays a vital role in the climate system. Human activity has modified this coupled system by altering the composition of the atmosphere and the health of the ocean. SOLAS research aims to provide key understanding, predictive capabilities, threshold identification, informed assessments, and sustainable solutions to the challenges posed by current and future changes in the ocean-atmosphere system.

### Science for Society

Knowledge and research infrastructure created under the leadership of SOLAS contribute to long-term observing and prediction capabilities of the coupled ocean-atmosphere system. Subjects addressed by SOLAS include climate regulation, evaluation of extreme weather events, cloud-aerosol interactions, carbon dioxide sequestration, air quality assessments, waste sinks and bioremediation, expansion of oceanic oxygen minimum zones, transport and accumulation of pollutants, and the fate of oil spills at the air-sea interface. Aerosols released from the air-sea interface, including marine toxins, as well as salts and organic matter, directly impact air quality in coastal areas, with implications for human health. SOLAS assesses the scope and structure of marine ecosystem services and contributes to the best possible use of nature-based solutions for sustainable development. SOLAS science thus contributes to optimising the welfare of populations inhabiting regions susceptible to hazards driven by the ocean-atmosphere coupled system. In doing so, SOLAS themes fall within six of the eight key global challenges of Future Earth: nexus (water, energy, food for all), decarbonisation (decarbonise socio-economic systems), natural capital (safeguard natural assets), cities (help reduce the footprint of cities towards healthy, resilient and productive cities), health (improve human health), and governance (social resilience). Links with the Oceans and Natural Assets KANs will be the primary mechanism through which SOLAS will contribute to these Future Earth efforts. Figure 13 illustrates the three levels of interactions envisioned with Future Earth: via the Core Themes, via targeted policy-relevant themes, and via proactive liaisons with Future Earth initiatives.

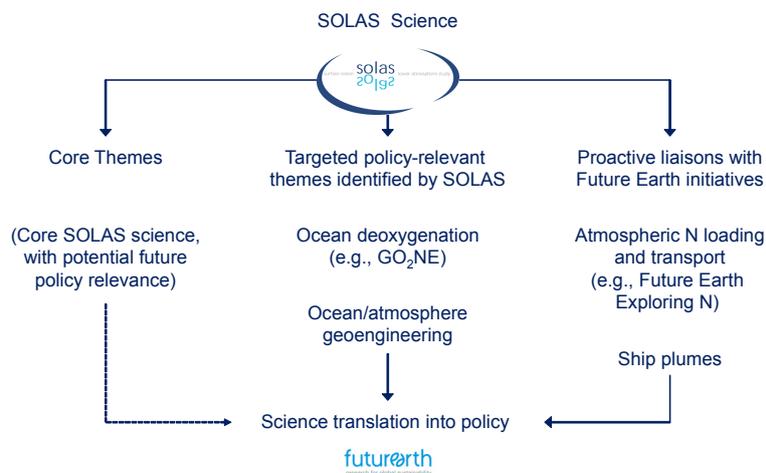
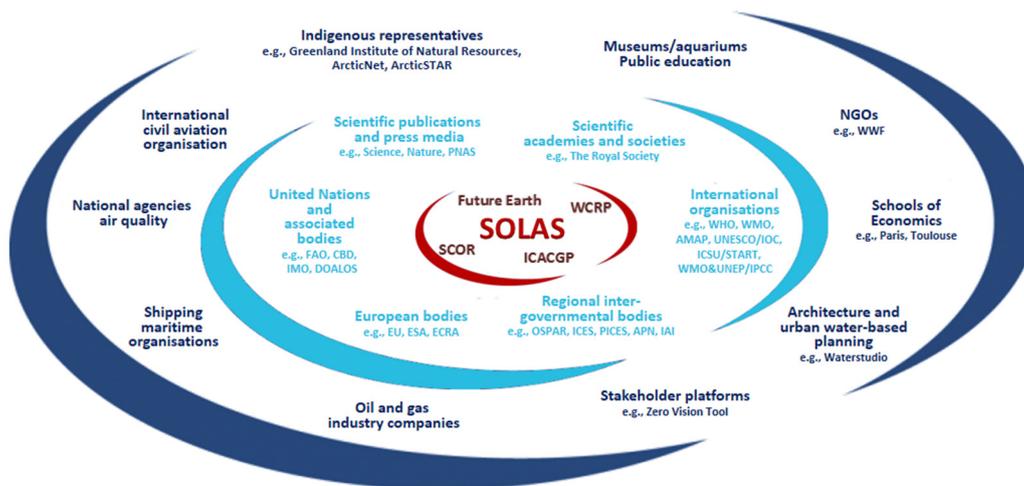


Fig. 13: SOLAS science and Future Earth linkages

Deep insight into the dynamics of ocean-atmosphere exchange and capabilities to quantify exchanges is critical to create feasible pathways towards sustainability. Climate mitigation policies based on greenhouse gas budgets must take into account the role of ocean-atmosphere fluxes for future projections. Several of the geoengineering schemes currently debated for climate mitigation are directly linked to the ocean-atmosphere system, including ocean iron fertilization, sea spray generators, ocean foams, and modification of ocean upwelling. The study of geoengineering issues in direct link with society and policy makers has been made a SOLAS priority, with specific representation on the SSC. In addition, social scientists working on risks, economy, Law of the Sea, or sustainable development will be invited to all future SSC meetings, and we hope to eventually increase our engagement with social scientists with at least one position on the SSC.

Informed assessment of the feasibility, efficacy and potentially unintended effects of geoengineering will be derived, to a significant extent, from SOLAS science. SOLAS will also be instrumental in examining the effectiveness of policies for sustainability by providing quantitative assessments on regional to global scales. A focus will be on framing these public issues to bridge the divide between expert and public understandings. SOLAS has identified a number of stakeholders with whom to engage: governmental bodies, non-governmental agencies/groups, international organisations, private sector, e.g., insurance companies, urban water-based planning, and general public, among others (Fig. 14).



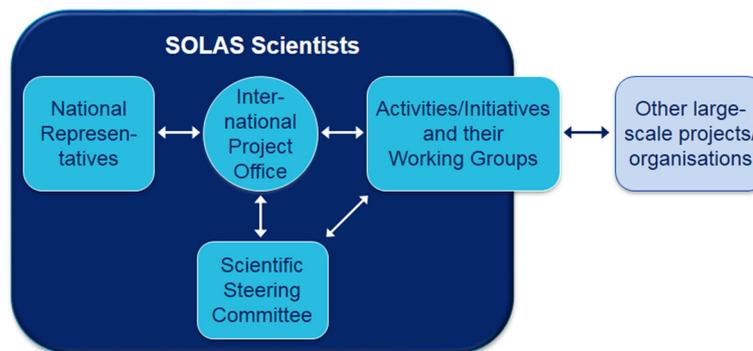
**Fig. 14:** SOLAS stakeholders

Finally, SOLAS has long and sound experience in capacity building, having already fostered a new generation of environmental scientists educated with a holistic perspective, through the SOLAS Summer Schools, as well as other activities. SOLAS serves as a crucible for young scientists who are designing innovative approaches to their research, including facilitating the global societal transition towards sustainable development goals. Capacity building, particularly in developing countries, is a long-lasting tool towards equity in governance.

## 3 Organisation and Management

### 3.1 Organisation

SOLAS is, in essence, a global community of ocean and atmosphere scientists with an International Project Office (IPO) as a central hub. Overall scientific direction for the project is the responsibility of the Scientific Steering Committee (SSC). Membership in SOLAS is open to all and does not require an affiliation to a theme. Figure 15 illustrates the organisational structure of the SOLAS community, which currently numbers about 2,200 individuals.



**Fig. 15:** Organisational structure of SOLAS

The SOLAS SSC represents a broad spectrum of disciplines and nationalities, and includes both mid-career and senior scientists. The continuing success of SOLAS relies on the input of engaged SSC members. SSC members are responsible for providing scientific guidance to and overseeing the development, planning, and implementation of SOLAS science. The SSC is tasked with communicating ongoing SOLAS activities and encouraging publication and dissemination of SOLAS science results. Members of the SSC are also expected to interact with the SOLAS IPO regularly on various issues. Furthermore, the SOLAS SSC encourages national governments, and regional and international funding agencies to support the implementation of core research and the achievement of SOLAS goals. In addition to an annual 3-day meeting, SSC members communicate regularly through e-mails and webinars to maintain momentum on important topics. The SOLAS sponsors appoint the SSC members for a term of three years, renewable once. The SSC chair is appointed by the sponsor programmes, and is assisted by a vice-chair and two to three additional SSC members, forming an Executive Committee. The Executive Committee is regularly consulted by the IPO, particularly for significant matters.

The SOLAS IPO, based at GEOMAR Helmholtz Centre for Ocean Research Kiel, in Germany, carries out the day-to-day operation of the SOLAS project, as a whole, and serves as the primary communication and information hub for the various project elements, including interactions with other global change organisations. Activities include maintaining the SOLAS website and databases, organising meetings and workshops, and writing and editing SOLAS publications. Office staff are also engaged in the development and execution of SOLAS science plans. As SOLAS enters its second decade, the IPO will remain in Kiel, funded by GEOMAR until 2020, staffed with at least one person. Additional funds to support IPO operations are raised through ongoing efforts.

Currently, thirty countries have a SOLAS national representative. These are scientists who have taken the initiative to form a national SOLAS network. They are approved by the IPO and serve as coordinators of the scientific and communication activities within their countries, as well as acting as the interface between the SOLAS SSC and the scientists and funders in individual nations. The national representatives report annually to the IPO and SSC.

Over the coming decade, part of the research described in this SPO will be executed by Activities and Initiatives. Activities are defined as on-going efforts to implement specific aspects of the science plan, and initiatives are focussed on novel, emerging issues. Both structures may be joint efforts with other large-scale projects or organisations, when necessary (see 3.4). Particular Activities and Initiatives will be established on topics for which international coordination is needed, as was done for the SOLAS Mid-term Strategies in 2008. Initiatives are intended to be short-term entities with the potential to transition into activities, which may be renewed, with regular reporting to the IPO and assessment by the SSC. We expect our Activities and Initiatives to form Working Groups (WGs) focused on specific tasks and composed of scientists from around the world who agree on terms of reference, to be reviewed by the SOLAS SSC.

In addition to supporting bottom-up Initiatives, SOLAS plans to issue competitive yearly calls for new Initiatives and Activities dedicated to specific themes, depending on project finances. In doing so, SOLAS hopes to stimulate ideas, address emerging needs, and benefit from the willingness of the international community to advance SOLAS science. The aim of SOLAS is to continue providing a framework to encourage fully integrated multi-national, regional, and national efforts in its scientific activities. SOLAS does not impose a rigid template on the nature of these efforts. However, it does endorse specific funded projects that conform to the SOLAS SPO and will energetically encourage this practice in the coming decade.

## 3.2 Communication, Capacity Building, and Global Networking

### Communication

SOLAS will continue to promote science communication via e-bulletins, newsletters, a website, and a Twitter account. The e-bulletin is an e-mail message circulated every two months, informing the SOLAS community of relevant present and future activities, meetings, workshops, and courses. Initiated in 2004, the Newsletter is now distributed to 2,200 individuals across 70 countries. It is published annually and communicates syntheses of SOLAS science and reports on workshops, activities, campaigns, and network activities. The website will continue to be a key source of project news and information, and a repository for publications. The Twitter account will allow fast diffusion of SOLAS project news with a higher visibility of science highlights. The scientific results of SOLAS will primarily be published as scientific papers in international journals, and the SSC and IPO will encourage and facilitate the production and distribution of summaries for policy-makers. Going forward, SOLAS will also utilize the Future Earth media lab to increase the effectiveness of knowledge transfer to social scientists and policy-makers.

SOLAS will continue to promote science communication via open science conferences (OSCs). The biennial SOLAS OSCs foster communication within the SOLAS community, the generation of new research ideas, and the engagement of early career scientists and researchers from developing countries. The IPO will continue to raise funds specifically to support the meeting and attendance by students and scientists from under-represented nations.

## Capacity Building and Global Networking

Professional capacity building and networking are integral elements of SOLAS. The first six international SOLAS Summer Schools trained more than 420 young scientists in a range of topics covering fundamental and integrative SOLAS science, as well as professional development. The success is well documented by the testimonials and career paths of our alumni. There is high demand for participation in these capacity-building activities and the quality of students participating has been excellent. Going forward, SOLAS will also establish links with the Future Earth Early Career Network to extend our capacity-building efforts to audiences we have not yet been able to reach, as well as help expose both young and mature SOLAS scientists to new fields.

For its next decade, SOLAS will explore an innovative capacity-building concept: the Network of Early Career SOLAS Scientists (NECSS). This will combine traditional capacity building of early career scientists with a new level of institutional networking. The ultimate goals are to support, train, and interconnect the next generation of SOLAS scientists, and to foster enduring institutional interactions that support addressing the scientific challenges of SOLAS 2015-2025. SOLAS will also facilitate other training and professional development workshops and programmes, such as those funded by the Marie Skłodowska Curie Innovative Training Network.

The NECSS was inspired by the success of the Scientific Short-Term Missions (STSM), funded by the SOLAS/COST Action 735 ([www.cost.eu/COST\\_Actions/essem/735](http://www.cost.eu/COST_Actions/essem/735)) and the GAME training programme developed and coordinated by GEOMAR for master students. NECSS will be composed of short-term research projects and/or measurement campaigns carried out by PhD-level students from around the globe on a different predetermined topic every couple of years. These topics will address the SOLAS 2015-2025 themes and will be selected by the SSC through an international call to the SOLAS community. A local host and a group of remote experts will supervise the projects, supporting the development of the institutional network. Formal training for the fellows will utilise e-learning technology such as edX or Coursera; a SOLAS course to introduce technologies and techniques could be envisioned via the company Mooc. Building on the success of the SOLAS Summer School and its companion textbook “Surface Ocean-Lower Atmosphere Processes”, SOLAS is in an excellent position to develop useful on-line courses for its scientific community. To ensure and foster interactions among students and supervisors during each project, regular videoconferences and a blog or ‘project’ in the scientist social network *ResearchGate* will be organised.

NECSS activities will be linked to activities at the SOLAS OSC to present and discuss project results with the wider SOLAS community during dedicated sessions. This will also help them appreciate how their doctoral work fits into the larger canvas of SOLAS science. The expected outcomes of the projects will be scientific deliverables such as reports or peer-reviewed white papers archived in an open-access database. Ideally, peer-reviewed journal articles should be the goal. The long-term outcomes will include a cohort of young scientists with the resources to develop inter- and trans-disciplinary global research activities in Earth System science. The professional development workshops (oral/written communication, ethics, policy, media), which were viewed by the alumni as among the most valuable aspects of the SOLAS Summer Schools, will also be incorporated into future SOLAS OSCs as side events, optimally two or three days before and after the conference. We intend to give the students the basic understanding and tools to engage in Responsible Research and Innovation (RRI). This means teaching them to anticipate and assess potential implications and societal expectations with regard to research and innovation, with the aim of fostering the design of inclusive and sustainable research and innovation, that is, to better align both the research and innovation process and its outcomes with the values, needs and expectations of society.

As a first attempt, a workshop was organised for early-career scientists at the 2015 SOLAS OSC in Kiel, Germany. The hands-on workshop helped the students present themselves with

impact to peers and interact effectively within a conference environment. The course was composed of a session before the conference began, some hands-on practice during the conference, in particular poster sessions and breaks, and a session after the conference, to exchange feedback and assess potential improvements.

Funding for the NECSSs will be sought from a range of sources and stakeholders supporting training and networking measures worldwide, to maximise participation by students from across the globe. We will collaborate with the Global Change System for Analysis, Research and Training (START), the Inter-American Institute for Global Change Research (IAI), the Partnership for Observation of the Global Oceans (POGO) and the Asia-Pacific Network for Global Change Research (APN), as well as with similar programmes of the National Committees of the sponsors. We can also envision partially funding this programme through COST (European Cooperation in Science and Technology) and Future Earth proposals as well as European Marie Skłodowska Curie funding opportunities. To establish the NECSS fellowship procedure and secure the necessary funding, a committee will be formed of mid-career scientists, namely alumni from the first and second SOLAS Summer Schools, from multiple natural and social disciplines across the SOLAS 2015-2025 domain.

### 3.3 Data Management

Data and model management are critical logistical tasks for SOLAS. The overall objective of the SOLAS data management strategy is to ensure the security, accessibility, publication, and free exchange of data collected or used as part of SOLAS scientific research. SOLAS data include measurements of biological, physical, and chemical parameters collected from process studies and experiments (field and laboratory), time-series studies, and large-scale surveys collected through national and international projects. Remote sensing data from operational satellites and operational infrastructures (e.g., AERONET) are available from space agencies, but those associated with experiments (e.g., overflights) should be archived similar to other field data. Similarly, SOLAS uses a hierarchy of modelling approaches. The data and scientific conclusions from SOLAS projects must be made available for independent assessment.

Project endorsement by International SOLAS requires a commitment to data management. The research community is strongly encouraged to submit data rapidly to existing international data centres and provide information about the data to the SOLAS metadata base ([www.solas-int.org/solas-metadata-portal.html](http://www.solas-int.org/solas-metadata-portal.html)). Data management within SOLAS can only be effective with full cooperation from relevant international data centres. Data are not archived by SOLAS, but by a distributed system involving scientists and data centres around the world, such as the CLIVAR and Carbon Hydrographic Data Office (CCHDO), and PANGAEA.

SOLAS is also committed to data intercomparison and intercalibration activities (e.g., DMS: Bell et al. 2011; Halocarbons: Butler et al. 2010; Jones et al. 2011) and to establishing recommended protocols for 'standard' SOLAS measurements (e.g. CO<sub>2</sub>: Dickson 2010; DMS: Bell et al. 2011; Stefels et al. 2012; Ocean Acidification: Riebesell et al. 2010, Sea-ice biogeochemistry: Miller et al. 2015). In most cases, the utility of SOLAS data extends beyond the projects themselves, and significant benefits result from combining data and model output from multiple projects. For example, community-led, integrative work during the first phase of SOLAS produced global climatological air-sea flux products for CO<sub>2</sub> (Pfeil et al. 2013; Bakker et al. 2014), dimethyl sulphide (Lana et al. 2011), halogenated compounds (Ziska et al. 2013), and nitrous oxide (Freing et al. 2009; Zamora et al. 2012). The second phase of SOLAS will actively encourage further global synthesis products.

## 3.4 Linkages to other Projects and Activities

SOLAS science, with its emphasis on biogeochemical, chemical, and physical processes and their respective interactions across the air-sea interface, is inherently interdisciplinary. From its onset, the SOLAS community has embraced interdisciplinarity, abandoning traditional boundaries. In its first decade, SOLAS was sponsored by IGBP, SCOR, iCACGP, and WCRP, and several activities carried out by these past and current SOLAS sponsors are relevant to SOLAS science. Therefore, SOLAS has created strong linkages with the other projects sponsored by these organisations. In particular, SOLAS and IMBeR have an operational joint group on carbon research activities, in cooperation with the SCOR-IOC International Ocean Carbon Coordination Project (IOCCP) and the Global Carbon Project, which has led, among other things, to the development of the Ocean Acidification International Coordination Centre (OA-ICC) and the Surface Ocean CO<sub>2</sub> Atlas (SOCAT) data product. IGAC and SOLAS have had joint efforts on Air-Ice Chemical Interactions (AICI) and on Halogens in the Troposphere (HitT). SOLAS and the European Space Agency (ESA) have conducted three successful OceanFlux projects and jointly organised two well-attended conferences. SOLAS has also established collaborations with SCOR working groups, the WCRP Data Advisory Council (WDAC), and IGBP Fast Track Initiatives.

SOLAS will reinforce and open up new collaborations with other projects for its five core themes and cross-cutting themes during the upcoming decade 2015-2025. Core science themes as well as cross-cutting themes should provide a mechanism for fostering interactions between international projects on co-designed and co-produced knowledge in marine sciences at large to fulfil the Future Earth 2025 Vision. Additional working groups for activities and initiatives will be launched with partners when necessary to progress specific topics. We note that expanding our activities and initiatives beyond the realm of natural sciences to explore linkages with the human sphere will require dedicated resources and funding from Future Earth and other sources.

### Linkages via SOLAS Core Themes

**Core Theme 1** “Greenhouse gases and the oceans”: SOLAS will maintain its strong interconnections with IMBeR, IOCCP, the Global Carbon Project, the SOLAS/IMBeR WGs on ocean carbon (Surface Ocean Systems, Interior Ocean, Ocean Acidification). Core Theme 1 is linked to the IMBeR Grand Challenges I and II, namely, ‘Understanding and quantifying marine ecosystems state and variability’, and ‘Improving scenarios, predictions and projections of future ocean-human systems at multiple scales’. Theme 1 is also linked to the WCRP Grand Challenge on ‘Carbon feedbacks in the climate system’.

**Core Theme 2** “Air-sea Interface and fluxes of mass and energy”: SOLAS will continue its involvement within the WDAC and will work with the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS), and the WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM). In particular, SOLAS would welcome a new initiative that integrates knowledge produced by CLIVAR, SPARC, IMBeR and SOLAS on air-sea exchanges. An action is being developed within the newly established Surface Heat Flux Task Team.

**Core Theme 3** “Atmospheric deposition and ocean biogeochemistry”: SOLAS will keep the SOLAS ADOES (Asian Dust and Ocean EcoSystem) Activity operative and will foster new collaborations with organisations such as the International Society for Aeolian Research (ISAR) and the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection working group on Atmospheric Input of Chemicals to the Ocean (GESAMP WG38). The topics ‘Impact of ocean acidification on fluxes of atmospheric non CO<sub>2</sub> climate-active species’ and ‘Changing atmospheric nutrient solubility’ were recently endorsed by SOLAS.

**Core Theme 4** “Interconnections between aerosols, clouds and marine ecosystems”: SOLAS will encourage links with the Global Energy and Water Cycle Experiment (GEWEX) Radiation Panel, the International Commission on Clouds and Precipitation (ICCP), and the atmospheric chemical transport and climate modelling communities (i.e., CLIVAR Climate Dynamics Panel) to further advance research on atmospheric topics.

**Core Theme 5** “Ocean biogeochemical control on atmospheric chemistry”: SOLAS has invited the Air Ice Chemical Interactions/Ocean-Atmosphere Sea Ice Snowpack (AICI/OASIS) community to join in an effort to propose new activities involving halogens and air-ice chemical interactions, preferably incorporating a wider community, for example, linking to iCACGP via IGAC and WCRP (including SPARC). In particular, collaborations with the Climate and Cryosphere (CliC) fora on Arctic and Antarctic sea ice, the Southern and Arctic Ocean Observing Systems, and Biogeochemical Exchange Processes at Sea Ice Interfaces (BEPSII, a joint SOLAS-CliC Activity) hold potential to benefit air-ice-ocean research. Following up on the SOLAS-IGAC HitT joint effort of the first decade of SOLAS, a new initiative on halogens is being developed jointly between SOLAS, IGAC, and SPARC.

### Linkages via SOLAS Cross-Cutting Themes

SOLAS research on environmental impacts of geoengineering could be integrated in a broader multidisciplinary framework such as, for instance, a Geoengineering Knowledge-Action Network within the Future Earth programme. Among the SOLAS Integrated Topics (see 2.2.1), SOLAS has targeted ‘*Extreme events in eastern boundary upwelling systems*’ and ‘*Changes in the Arctic: threat or opportunity?*’ for further development across international large-scale projects. These two topics were circulated among a number of global environmental change communities for feedback and discussed during meetings of the Future Earth Scientific and Engagement Committees.

**Extreme events in eastern boundary upwelling systems (EBUS).** These regions have low oxygen and pH values that affect nearly all aspects of ecosystem structure and functioning in the water, and play critical roles in atmospheric chemistry and climate. Such areas appear to be expanding in tropical and subtropical regions as a result of climate change, potentially affecting neighbouring countries reliant on marine resources for protein and employment. These regions also feature extensive stratocumulus cloud decks that play a pivotal role in the response of the climate system to greenhouse gas forcing and are the target of controversial proposals for cooling the global climate through marine cloud brightening ‘climate engineering’ (or ‘geo-engineering’) activities. It is proposed that SOLAS, IMBeR, CLIVAR, IGAC, Future Earth Coasts (former LOICZ), ecoSERVICES and GEOTRACES join efforts to adopt an integrative approach coupling atmosphere, ocean, continents and socio-economic dimensions. Such an initiative also relates to the CLIVAR-IMBeR Working Group on Upwelling Systems. In December 2015, IOC/UNESCO launched the Global Ocean Oxygen Network (GO<sub>2</sub>NE) to globally foster sustained measurements of global ocean oxygenation state and rates of deoxygenation, and to refine predictive capabilities of regional and global Earth system models. GO<sub>2</sub>NE will also become a natural partner of SOLAS on this topic.

**Changes in the Arctic: threat or opportunity?** The Arctic is undergoing swift environmental change, including significant potential marine changes due to warming, melting ice, ocean acidification, permafrost thawing, coastal erosion, increased shipping traffic and ship-based emissions, and industrial development. Increase in nutrients and invasive species from ballast water discharges might also affect marine ecosystems. The increasing commercial and industrial activity and investment in the Arctic will probably have major consequences with important implications for indigenous peoples and other Arctic inhabitants. It is proposed that IGAC, SOLAS, IMBeR, CliC, Future Earth Coasts, Earth System Governance, and other rele-

vant international projects join efforts to develop knowledge for assessing the social and economic impact of observed and projected climate change and to implement policies to balance the needs of human development in the Arctic with environmental protection. It could be helpful to build on the existing Future Earth cluster ArcticSTAR Polar Science Network.

Another topic that could well address the Future Earth co-design and co-production of knowledge concept is '**Atmospheric chemistry services**'. It will highlight the environmental functions and benefits played by the natural environment. Topics on volcanic emissions and on megacities in the coastal zone and their links to atmospheric and marine pollution have already been proposed by SOLAS.

**Volcanic emissions** are important sources of atmospheric gases, aerosols and ash. Volcanic gas emissions consist of H<sub>2</sub>O, CO<sub>2</sub>, SO<sub>2</sub>, HCl, HF and other compounds. These gases and their oxidation products (i.e., sulfate aerosols) may play an important role in tropospheric and stratospheric chemistry and can impact terrestrial and oceanic ecosystems and human health and activities (e.g., air travel). Volcanic ash and aerosols can be transported over long distances to remote parts of the ocean. Upon deposition in the ocean, volcanic ash can release nutrients and toxic substances into seawater and may affect marine ecosystem structure and functioning. On average, 50-70 volcanoes erupt every year, one moderate to large eruption occurs every year, and extreme eruptions like Pinatubo and El Chichón occur every decade or so. Civil aviation can be seriously perturbed by large eruptions, causing major communications disruption and leading to severe global economic loss (e.g., the massive disruption to air travel across western and northern Europe by eruptions of the Icelandic volcano Eyjafjallajökull in 2010).

**Air pollution in megacities** in the coastal zone has impacts locally and regionally on human well-being, for example, health and agriculture. The recent idea of floating cities on seawater in architecture and urban planning to mitigate sea level rise might accelerate further the need to find responses to the complex interactions amongst air and water pollution, ecosystem services, and human well-being.

It is proposed that SOLAS, IGAC, IMBeR, ecoHEALTH and other relevant international projects join efforts to develop research on atmospheric chemistry 'services' that would combine process (laboratory) studies, in situ observations, space observations, and global/regional modelling. This development would offer an excellent opportunity to play a long-term scientific/research role in support of new needed operational activities. As an example of such an integrated approach, prototype systems could be developed and tested that could monitor volcanic eruptions by predicting the evolution of plumes, measure and monitor them and inform stakeholders (e.g., civil aviation) of the evolving situation. Such analyses could also be used to assess the impact of ocean fertilization by volcanic eruptions on marine ecosystems. Similarly, the possibilities of increased coastal water-based urbanism call for a proper environmental assessment of development pathways, such as floating cities.

Last but not least, SOLAS will explore additional links to projects and organisations for new avenues into transdisciplinary research and additional connections to stakeholders. SOLAS will develop co-operative activities to take advantage of the unique expertise of these different groups and to avoid unnecessary duplication.

## 3.5 Outlook

This SPO represents the natural evolution from the first decade of SOLAS into priorities for future research. Numerous activities from the first decade of SOLAS are continuing, including the mid-term strategy initiatives, SOCAT, and the OA-ICC.

A synthesis of the first decade of SOLAS research was completed in 2013 and published in an open access book (Liss & Johnson 2014). This book has been followed by a publication of a synthesis article in the journal *Anthropocene* at the end of 2015, contributing to the IGBP synthesis effort (Brévière et al. 2015). This science plan and organisation was distributed and promoted at the SOLAS Open Science Conference that took place on 7-11 September 2015 in Kiel, Germany. This conference was used as a platform to shape the Implementation Plan with input from the SOLAS community. This implementation plan will be maintained as a living document on the SOLAS website. In addition, a priority for 2015 was to secure long-term funding for SOLAS activities and for the IPO. Going forward into 2017, particular emphasis is on polar oceans and atmospheres, although concurrent development of all other aspects of the science plan is also necessary. GEOMAR Helmholtz Centre for Ocean Research Kiel will remain the host institution of the IPO until December 2020 and will continue its financial support with the Executive Officer's salary. Additional sources of funding for SOLAS operations and the Project Officer's salary continue to be relentlessly pursued.

## 4 Acronyms

ADEOS	Advanced Earth Observing Satellite
AGU	American Geophysical Union
AICI	Air-Ice Chemical Interactions
AIMES	Analysis, Integration and Modeling of the Earth System
AMAP	Arctic Monitoring and Assessment Programme
APN	Asia-Pacific Network for Global Change Research
ArcticNet	Network of Centres of Excellence of Canada on the Arctic
ArcticSTAR	Solution-oriented, transdisciplinary research for a sustainable Arctic
AUV	Autonomous Underwater Vehicle
BATS	Bermuda Atlantic Time-Series Study
CARINA	Carbon Dioxide in the Atlantic Ocean
CBD	Convention on Biological Diversity
CCHDO	CLIVAR & Carbon Hydrographic Data Office
CCMI	Chemistry-Climate Model Initiative
CCN	Cloud Condensation Nuclei
CCS	Carbon Capture and Storage
CDIAC	Carbon Dioxide Information and Analysis Center
CDR	Carbon Dioxide Removal
CLAW	First letters of authors' names: Charlson, Lovelock, Andreae, Warren
CliC	Climate and Cryosphere
CLIVAR	Climate Variability and Predictability
CMIP	Coupled Model Intercomparison Project
CRM	Cloud Resolving Models
CSIR	Council for Scientific and Industrial Research
CTM	Chemical Transport Models
CVOO	Cape Verde Ocean Observatory
DMS	Dimethyl sulfide
DOALOS	UN Division for Ocean Affairs and Law of the Sea
DYFAMED	Dynamique des flux de matière en Méditerranée
ECRA	European Climate Research Alliance
EGU	European Geosciences Union
EPOCA	European Project on Ocean Acidification
ESA	European Space Agency
ESM	Earth System Models
ETP	Eastern Tropical Pacific
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FOO	Framework for Ocean Observing
GCM	Global Climate Models
GCOS	Global Climate Observing System
GCP	Global Carbon Project
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection
GHG	Greenhouse gas
GLODAP	Global Ocean Data Analysis Project
GOOS	Global Ocean Observing System
GOSAT	Greenhouse Gases Observing Satellite
HitT	Halogens in the Troposphere
HOT	Hawaii Ocean Time-series
IAI	Inter-American Institute for Global Change Research

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iCACGP	International Commission on Atmospheric Chemistry and Global Pollution
ICES	International Council for Exploration of the Sea
ICSU	International Council for Science
IGAC	International Global Atmospheric Chemistry
IGBP	International Geosphere-Biosphere Programme
iLEAPS	Integrated Land Ecosystem-Atmosphere Processes Study
IMBeR	Integrated Marine Biosphere Research project
IMO	International Maritime Organization
IN	Ice Nuclei
IOC	Intergovernmental Oceanographic Commission of UNESCO
IOCCP	International Ocean Carbon Coordination Project
IPCC	Intergovernmental Panel on Climate Change
IPO	International Project Office
ISAR	International Society for Aeolian Research
JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology
LES	Large Eddy Simulation
LNLC	Low Nutrient Low Chlorophyll
LOICZ	Land-Ocean Interactions in the Coastal Zone
MAIRS	Monsoon Asia Integrated Regional Study
MBL	Marine Boundary Layer
MEMENTO	Marine Methane and Nitrous Oxide
MIP	Model Intercomparison Projects
MLD	Mixed Layer Depth
MODIS	Moderate Resolution Imaging Spectroradiometer
NECSS	Network of Early Career SOLAS Scientists
OA-ICC	Ocean Acidification International Coordination Centre
OCB	Ocean Carbon and Biogeochemistry
OMZ	Oxygen Minimum Zone
OSC	Open Science Conference
OSPAR	Oslo-Paris Convention on Marine Pollution
PACIFICA	Pacific Ocean Interior Carbon
PAGES	Past Global Changes
PAH	Polycyclic Aromatic Hydrocarbons
PANGAEA	Data Publisher for Earth & Environmental Science
PICES	North Pacific Marine Science Organization
POC	Particulate Organic Carbon
ROV	Remote Operated Vehicle
SA	Secondary Aerosol
SCOR	Scientific Committee on Oceanic Research
SEATS	South East Asian Time Series Station
SeaWiFS	Sea-viewing Wide Field-of-view Sensor Project
SEEDS II	Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study II
SHIVA	Stratospheric Ozone: Halogens in a Varying Atmosphere
SML	Sea Surface Microlayer
SOCAT	Surface Ocean CO <sub>2</sub> Atlas
SOCOM	Surface Ocean pCO <sub>2</sub> Mapping Intercomparison
SOPRAN	Surface Ocean Processes in the Anthropocene
SPARC	Stratospheric Processes and their Role in Climate
SRM	Solar Radiation Management
SSA	Sea Spray Aerosol
SSC	Scientific Steering Committee
SSiRC	Stratospheric Sulfur and its Role in Climate
START	System for Analysis Research and Training
UNEP	United Nations Environment Programme

UNESCO	United Nations Educational, Scientific and Cultural Organization
VOC	Volatile Organic Compound
VSLS	Very Short-Lived Substance
WCRP	World Climate Research Programme
WDAC	World Climate Research Programme Data Advisory Council
WG	Working Group
WHO	World Health Organization
WMO	World Meteorological Organization
WWF	World Wildlife Fund
XLD	Mixing Layer Depth

## 5 Appendices

### 5.1 Outcome of selected Scientific Synthesis Activities

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## 5.2 'Added value' of SOLAS

### 2015

- SOLAS Open Science Conference 2015. 7-11 September 2015, Kiel, Germany, incl. SOPRAN final meeting, SOCAT/SOCOM meeting, early career scientist workshop, Nordic SOLAS meeting
- SOLAS/CLIVAR session on 'The earth's energy imbalance and exchanges at the atmosphere-ocean interface' at the conference on 'Our common future under climate change'. 7-10 July 2015, Paris, France

### 2014

- SOLAS/ESA/EGU conference on 'Earth observation for ocean-atmosphere interactions science 2014: Responding to the new scientific challenges of SOLAS'. 28-31 October 2014, Frascati, Italy
- SOLAS workshop on 'SOLAS into the Future: Designing the next phase of the Surface Ocean-Lower Atmosphere Study within the context of the Future Earth Program' at the PICES 2014 annual meeting. 16-26 October 2014, Yeosu, South Korea
- Swedish SOLAS Science Symposium. 27-28 August 2014, Gothenburg, Sweden
- SOLAS France meeting. 7-8 July 2014, Paris, France
- SOLAS Symposium Day Israel. 19 June 2014, Rehovot, Israel
- SOLAS at the Ocean Sciences Meeting 2014 (sharing a booth with other projects, poster presentation, SOLAS session). 23-28 February 2014, Honolulu, USA
- SOLAS workshop on 'Future SOLAS'. 9-10 January 2014, Galway, Ireland

### 2013

- SOLAS workshop for early career scientists on 'Future SOLAS'. 3-5 December 2013, Plymouth, UK
- Swedish SOLAS workshop. 18-19 November 2013, Stockholm, Sweden
- SOLAS co-sponsored topic session on 'The changing carbon cycle of North Pacific continental shelves and marginal seas'. 11-20 October 2013, Nanaimo, Canada
- Science workshop of the 'Oceanflux greenhouse gases project'. 24-27 September 2013, Brest, France
- SOLAS Summer School 2013. 23 August - 2 September 2013, Xiamen, China
- SOLAS co-sponsored PICES Summer School 2013. 19-23 August 2013, Newport, USA
- SOLAS/IMBER Carbon group / subgroup 3 'Ocean Acidification' (SIOA) annual meeting. 13-14 May 2013, Monaco
- SOLAS Symposium Day Japan. 31 May 2013, Tsukuba, Japan
- SOLAS/IMBER session on 'Sensitivity of marine ecosystems and biogeochemical cycles to global change' at EGU General Assembly 2012. 7-12 April 2013, Vienna, Austria

### 2012

- SOLAS workshop on 'The role of marine gel for the emission of primary organic aerosols from the ocean'. 11-13 December 2012, Kiel, Germany
- SOLAS workshop on 'HiT - Climate impact of seasalt-derived Cl atoms'. 17-19 December 2012, Kiel, Germany
- SOLAS workshop on 'Towards an integrative regional coupling in the eastern boundary upwelling system'. 26-28 November 2012, Lima, Peru
- SOLAS at 'The ocean in a high-CO<sub>2</sub> world/Ocean Acidification'. 24-27 September 2012, Monterey, USA
- SOLAS Open Science Conference 2012. 7-10 May 2012, Cle Elum, USA

### 2011

- SOLAS/ESA/EGU Conference on 'Earth observation for ocean-atmosphere interactions science'. 29 November - 2 December 2011, Frascati, Italy

- Joint 6<sup>th</sup> workshop on 'ADOES with Asian SOLAS'. 5-9 October 2011, Qingdao, China
- SOLAS/IMBER/IOCCP 'Carbon synthesis meeting'. 14-16 September 2011, Paris, France
- SOLAS Summer School 2011. 29 August - 10 September 2011, Corsica, France
- COST Action 735 sub-working group 1 & 3 meeting on 'Sea-ice biogeochemistry and interactions with the atmosphere'. 12-14 April 2011, Amsterdam, Netherlands
- COST Action 735 working group 2 & 3 meeting on 'What is the sea surface microlayer? Towards a unified physical, chemical and biological definition of the air-ocean interface'. 25-26 January 2011, Plymouth, UK

## 2010

- SOLAS/COST Action 735 workshop on 'Atmospheric versus land based controls of nutrient cycling and production in the surface: From fieldwork to modelling'. 8-9 December 2010, Istanbul, Turkey
- 7<sup>th</sup> COST Action 735 Management Committee meeting and working groups meeting. 8 December 2010, Istanbul, Turkey
- Joint 5<sup>th</sup> workshop on 'ADOES with Asian SOLAS/WESTPAC/METMOP/SALSA'. 29 November - 2 December 2010, Nagasaki, Japan
- SOLAS workshop on 'Air-sea gas fluxes at eastern boundary upwelling and oxygen minimum zones systems'. 8-10 November 2010, Lima, Peru
- COST Action 735 sub-working group 1 & 3 meeting on 'Upper ocean nutrient limitation: Processes, patterns and potential for change'. 3-5 November 2010, Southampton, UK
- SOLAS co-sponsored session on 'Understanding the role of iron in regulating biogeochemical cycles and ecosystem structures in the North Pacific Ocean' at the PICES 2010 annual meeting. 22-31 October 2010, Portland, USA
- COST Action 735 sub-working group 3 meeting on 'Experimental, typological and modelling approaches to evaluate at global and regional scales horizontal and vertical fluxes from land to open ocean through rivers, estuaries and the coastal ocean'. 4-5 October 2010, Liege, Belgium
- SOLAS co-sponsored workshop on 'Sea change: Charting the course for ecological and biogeochemical ocean time-series re- search'. 21-23 September 2010, Honolulu, Hawaii
- COST Action 735 sub-working group 1 meeting on 'Trace metal speciation data in COST Actions 735 and 801'. 16-17 August 2010, Kiel, Germany
- 6<sup>th</sup> COST Action 735 Management Committee meeting. 25-26 May 2010, Hamburg, Germany
- SOLAS/IMBER session on 'Understanding biogeochemical-physical interactions and physical oceanographic control on marine species' at the EGU General Assembly 2010. 2-7 May 2010, Vienna, Austria
- COST Action 735 sub-working group 1 meeting on 'Marine secondary organic aerosols (SOA) formation'. 26-28 April 2010, Bologna, Italy
- COST Action 735 sub-working group 1, 2 & 3 meeting on 'Identification of the scientific themes potentially leading to a collaboration between SOLAS and the European Space Agency (ESA)'. 30-31 March 2010, Toulouse, France
- UK SOLAS final meeting 'Modelling, observational and experimental legacy from coordinated UK programme'. 23 March 2010, Exeter, UK
- COST Action 735 sub-working group 1 meeting on 'Iron bioavailability in the surface ocean'. 1-2 February 2010, Kiel, Germany

## 2009

- SOLAS/IMBER Carbon group / subgroup 3 'Ocean Acidification' (SIOA) 1<sup>st</sup> meeting. 1-3 December 2009, Paris, France
- 5<sup>th</sup> COST Action 735 Management Committee meeting. 19 November 2009, Barcelona, Spain
- SOLAS Open Science Conference 2009. 16-19 November 2009, Barcelona, Spain
- SOLAS session on 'Southern African SOLAS science' at the 'International conference on planetary boundary layers and climate change'. 26-28 October 2009, Cape Town, South Africa
- SOLAS Summer School 2009. 3-14 August 2009, Corsica, France
- COST Action 735 sub-working group 1 meeting 'SOCAT Atlantic-Indian-Southern Ocean regional meeting'. 25-26 June 2009, Norwich, UK
- COST Action 735 sub-working group 1 meeting on 'Processes controlling O<sub>3</sub> in the marine boundary

layer'. 12 May 2009, York, UK

- SOLAS session on 'SOLAS and sensitivity of marine ecosystems and biogeochemical cycles to climate change' at EGU General Assembly 2009. 20-24 April 2009, Vienna, Austria
- COST Action 735 sub-working group 2 meeting on 'Surfactants and the microlayer gas exchange'. 18-19 March 2009, Plymouth, UK
- COST Action 735 sub-working group 1 meeting on 'Aerosol iron solubility and database'. 23-24 February 2009, Norwich, UK
- COST Action 735 sub-working group 1 meeting on 'Halocarbon database'. 11-12 February 2009, Kiel, Germany
- COST Action 735 sub-working group 3 meeting on 'Coastal CO<sub>2</sub>/N<sub>2</sub>O/CH<sub>4</sub> data'. 22-23 January 2009, Kiel, Germany

## 2008

- SOLAS Ireland national workshop. 17 December 2008, Galway, Ireland
- 4<sup>th</sup> COST Action 735 Management Committee meeting. 28 November 2008, Barcelona, Spain
- COST Action 735 workshop of working group 2 on 'Understanding of the process of parameterization of air-sea fluxes and toward the development of recommendations to the larger community as to the adequacy and caveats of particular parameterizations'. 6-7 February 2008, Norwich, UK
- SOLAS/COST Action 735 workshop on 'Halocarbon intercalibration'. 4 February 2008, London, UK

## 2007

- SOLAS Summer School 2007. 22 October - 3 November 2007, Corsica, France
- 3<sup>rd</sup> COST Action 735 Management Committee meeting and working group meetings. 16-17 October 2007, Brussels, Belgium
- UK SOLAS annual science meeting. 25-27 September 2007, Leeds, UK
- 2<sup>nd</sup> COST Action 735 Management Committee meeting and working groups meeting. 29-30 May 2007, Brussels, Belgium
- SOLAS co-sponsored workshop on 'Surface ocean CO<sub>2</sub> variability and vulnerability'. 11-14 April 2007, Paris, France
- SOLAS Open Science Conference 2007. 6-9 March 2007, Xiamen, China
- SOLAS co-sponsored workshop on 'SOLAS/QUEST/ACCENT Cape Verde'. 8-10 January 2007, Mindelo, Cape Verde

## 2006

- SOLAS session on 'SEAREX to SOLAS: 30 years of air-sea exchange research' at AGU fall meeting. 11-15 December 2006, San Francisco, USA
- SOLAS workshop on 'Comparison of ocean dimethylsulfide models'. 4-8 December 2006, Brussels, Belgium
- SOLAS Ireland meeting. 1 December 2006, Galway, Ireland
- 1<sup>st</sup> COST Action 735 Management Committee meeting. 25-26 October 2006, Brussels, Belgium
- SOLAS co-sponsored workshop on 'Modelling iron biogeochemistry and ocean ecosystems'. 13 October 2006, Yokohama, Japan
- SOLAS session on 'Reactive chemistry and exchanges between the marine boundary layer and the ocean mixed layer' at the 'Atmospheric chemistry at the interfaces symposium'. 17-22 September 2006, Cape Town, South Africa
- SOLAS Focus 2 meeting. 4-8 September 2006, Heidelberg, Germany
- SOLAS/IMBER joint workshop. 9-10 March 2006, Nagoya, Japan
- SOLAS sessions on 'Sea surface science and marine boundary layers' and 'Aerosols in the marine atmospheric boundary layer' at the Ocean Sciences Meeting 2006. 20-24 February 2006, Honolulu, USA

## 2005

- SOLAS co-sponsored 'Iron' workshop. 30 October - 3 November 2005, Wellington, New Zealand
- SOLAS co-sponsored workshop on 'Asian dust and ocean ecosystems (ADOES)'. 12-13 October 2005, Weihai, China
- Asian SOLAS meeting. 1-3 June 2005, Tokyo, Japan
- SOLAS Summer School 2005. 29 August - 10 September 2005, Corsica, France

## 2004

- SOLAS Open Science Conference 2004. 13-16 October 2004, Halifax, Canada

## 2003

- SOLAS Summer School 2003. 30 June - 11 July 2003, Corsica, France

## 2002

- Meeting of National SOLAS Representatives. 10-14 June, Amsterdam, Netherlands

## 2000

- SOLAS Open Science Conference 2000. 20-24 February 2000, Damp, Germany

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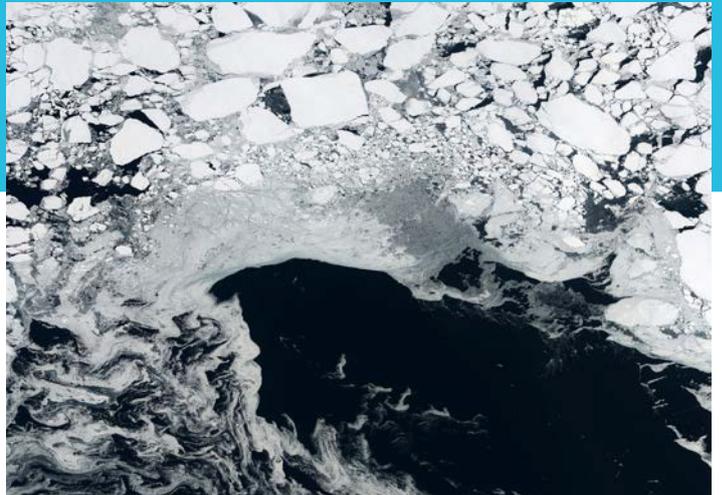
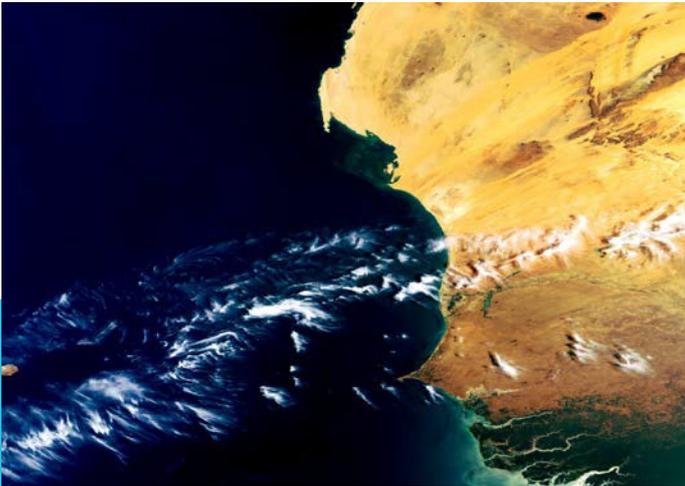
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