Sea ice biogeochemistry and interactions with the atmosphere

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1. Background and significance

a) Significance

Near-future climate change is predicted to have its strongest impact in polar regions due to direct changes in surface area of polar oceans and ice sheets and to subsequent feedback processes. At both poles, climate change is already apparent in reduced sea ice extent. In the Antarctic, reductions in sea-ice cover are observed in the Bellingshausen/Amundsen seas (Cavalieri and Parkinson 2008). In the Arctic region, both ice extent and thickness are reducing rapidly, with a record low summer ice extent in 2007. The observed reductions appear to be ahead in time of current model forecasts (Perovich and Richter-Menge 2009), illustrating both the rapidity of the observed change and the difficulty of understanding and modeling all the feedbacks involved in the change.

Current global models include the seasonal wax and wane of sea ice, but restrict associated properties to only a few physical features. In such models, sea ice's main impact is on Earth's radiative balance through its albedo, on deepwater formation and on air-sea-exchange processes of gases. The latter impact refers to sea ice as a "cap" on the ocean surface (Stephens and Keeling 2000). Emerging views indicate, however, that sea ice itself plays an important role in the biogeochemical cycling and exchange of climate gases. A better understanding of these processes is warranted in order to improve climate change models and associated feedbacks. It is important to realize that sea ice may not completely disappear from polar regions, but will definitively experience a profound change in its dynamics and properties.

Sea ice as a habitat, reaction surface, source, sink and barrier for gas exchange
Sea ice is not only an active site for important and specific conversion processes, but also a source and sink for climate gases. Although the mechanism remains enigmatic, sea ice is involved in the photochemical production of reactive halogen species and subsequent destruction of ozone in the boundary layer. This has important implications for the oxidative capacity of the atmosphere and influences the atmospheric composition of trace gases (Simpson et al. 2007). In addition, sea ice is a potential major source for the climate-cooling gas dimethylsulfide (DMS), containing concentrations of DMS and associated compounds that are 3 orders of magnitude higher than observed in the water column (Trevena and Jones 2006; Stefels and Tison manuscripts in prep.). Recent evidence also shows that sea ice can be an important sink for CO_2 through physical ($CaCO_3$ precipitation as ikaite crystals (Dieckmann et al. 2008)) and biological processes (Delille et al. 2007). Several other trace gases have been measured in high concentrations at the ice edge, but the exact processes, in-ice and in-water, are largely unknown.

By definition, biology is the source of (volatile) organic compounds and the important role of sea ice can at least partly be explained by the high algal biomass found within confined ice layers. In Antarctic sea ice, high biomasses may be due to high in-ice iron concentrations, with concentrations an order of magnitude higher than in the underlying water (Lannuzel et al. 2007). Especially in the Arctic were sea ice is formed close to land, sea ice can become in important vehicle for capturing and concentrating material that originates from land and is transported through the atmosphere. This highlights another important role of sea ice in biogeochemical cycles, namely the seeding of surface waters with nutrients, iron and potentially other trace elements upon seasonal ice melt. As a result, such sea ice-influenced surface waters act as a CO_2 sink, which is irrespective of the sink within the ice itself (Arrigo et al. 2008).

Apart from the need for a better understanding of the biogeochemical cycles in sea ice for future climate models, this is also important for unraveling palaeoclimatology. Sea ice extent is an important indicator for past climate. Proxies in Antarctic ice cores are used to reconstruct regional sea ice extent. One of these proxies is methane sulfonic acid (MSA), an atmospheric oxidation product of DMS. The current idea is that extensive winter sea ice results in high plankton productivity and associated DMS production in surface waters during seasonal ice melt, with subsequent increased MSA levels deposited in nearby snow. The mechanisms that relate marine DMS to MSA in snow are however enigmatic (Preunkert et al. 2008) and both positive and negative MSA-sea ice correlations have been observed (Röthlisberger and Abram 2009). An explicit contribution from sea ice itself so far has not been considered, which seems unrealistic given the observed high DMS levels in ice.

Recently, also the previously mentioned hydrated carbonate crystal, ikaite, has been found in Antarctic ice cores (Sala et al. 2008). It is hypothesized to be derived from the sea ice surface, where ikaite typically forms at the early stages of sea ice formation. Combining knowledge on sea-ice related processes involved in the formation of both MSA and ikaite with data analyses from firn, will improve our understanding of palaeoclimate.

b) Background information stated in the SOLAS Science Plan and Implementation Strategy

Understanding the coupling between ice physics and biogeochemical processes at the sea-ice-atmosphere interfaces is a prerequisite to quantify the role of ice-covered oceans in climate change scenarios, in the past, present and future. This directly links to SOLAS' main goal as documented in the SOLAS Science Plan and Implementation Strategy, but with a focus on ice-covered areas: "In the horizontal dimension, SOLAS research can be focused anywhere over the ocean, extending into coastal areas and estuaries, as well as ice covered areas… Processes that occur at ice edges and in ice covered seas are important for emission of trace gases such as DMS and organo-halogens, and each focus in SOLAS includes important research in these regions."
More specific, this action is relevant for the following SOLAS foci and activities:
Activity 1.1 Sea-salt Particle Formation and Transformations
Activity 1.2 Trace Gas Emissions and Photochemical Feedbacks
Activity 1.3 Dimethylsulphide and Climate
Activity 1.4 Iron and Marine Productivity
Activity 2.1 Exchange Across the Air-Sea Interface
Activity 2.3 Processes in the Atmospheric Boundary Layer
Activity 3.2 Surface Layer Carbon Transformations in the Oceans: Sensitivity to Global Change

2. Questions to be addressed

More specific, though by no means exclusive, questions that need to be addressed are:

- What are the main climate-relevant compounds and processes associated with sea ice?
  Until now, the main focus of the published studies was on DMS and CO2, but very little is known about other VOC's.
- How can we compare and quantify the relative contribution of different pathways of the main climate gases in time and space?
  Pathways to distinguish are direct ice/snow-atmosphere interactions, direct water-atmosphere interactions and indirect impact of ice melt on surface waters and subsequent sea-air fluxes.
- What is the difference between first-year ice and multi-year ice with respect to their quantitative contributions to gas fluxes?
  With ongoing climate warming, the relative contribution of multi-year ice will reduce, especially in the Arctic.
- How will major and minor elemental cycles influence in-ice food web structure and how will this feed back on ice structure and stability?
  Relevant topics are pigment layers that influence ice structure and stability via internal absorption and energy deposition; porous flow/transport of nutrients; the effects of organics and polymers on freezing; and special upper level habitats which cannot be captured in one dimensional models (rafting).
- What are the major differences in biogeochemical fluxes between the Arctic and Antarctic?
  There are distinct differences between Arctic and Antarctic sea ice, with respect to physical, chemical and biological features that can be largely attributed to difference in snow cover. With the expected increase in precipitation in the Arctic, this may change in the future.
- What is the relative contribution of sea ice and surface water to MSA and ikaite deposited on land?

In order to improve a proxy-based reconstruction of past sea-ice extent, a mechanistic understanding of the transportation of ikaite and the flux of DMS and derived compounds from ice and water is needed.

- Can we derive parameterisations for modelling ice and water contributions to atmospheric gas budgets? Parallel efforts should be performed to develop 1D-(eco)system models of sea ice, coupling of ice-water-atmosphere systems and implementation into global climate models.

3. What needs to be done to address the questions?

- A series of workshops is needed to make an inventory of existing and missing knowledge and data and to bring together experimentalists and modellers. Ideally, a working group should be devoted to:

- explore existing knowledge on the role of sea ice in influencing fluxes of climate-relevant gases,
- discuss and formulate the relevant biogeochemical processes and specify gaps in our knowledge,
- explore and compile available field data needed for model validation, and
- stimulate integrated model development.

- SOLAS should stimulate interdisciplinary field campaigns, ideally both in the Arctic and in the Antarctic. These field campaigns should cover different ice types and seasons. The programme should include at least the following compounds: CO_2, DMS and related compounds, methane. Other halogenated and non-halogenated VOC's need to be discussed. Measurements should include ice, water and atmosphere and emphasize flux studies within and between these compartments. Assessing the role of volatile compounds in determining cloud properties and the oxidative capacity of the atmosphere are also important aspects. Biological and ice-physicochemical parameters are needed to describe the different compartments and to understand the underlying processes.

- Sea-ice modelling. Currently, several sea-ice models are under development with very different approaches. SOLAS can bring together both modellers and experimentalists to improve integrated model development.

4. What is planned, possible and missing?

In the modelling community, at least one effort is underway to organize international projects around high latitude climate change issues, including ice and the related biogeochemistry. The International Arctic Research Center in Alaska is working with European and Asian counterparts to coordinate the development of Arctic Systems Models, as subsets of global scale Earth Systems Models. All the groups involved are considering detailed coupling of biogeochemistry with numerical models of ice-ocean-atmosphere interaction, and some of these are relatively advanced.
To further improve the exchange of information between experimentalists and modellers, a proposal is out for establishing a SCOR Working Group on Sea Ice Biogeochemistry in order to facilitate a series of workshops. We will seek additional support for organising workshops from other sources such as the SOLAS-related European COST Action 735 (‘Tools for Assessing Global Air–Sea Fluxes of Climate and Air Pollution Relevant Gases’).
It is important to mention that this Working Group intends to benefit from the momentum generated by the IPY programs; not to re-invent the wheel. Collating existing programs and projects is one of the first tasks of the WG.

5. Needed co-ordination and planning tasks

During the SOLAS OSM in Barcelona, 16-19 November 2009, a preparatory meeting will be organised to discuss the opportunities for collaboration and interaction within this theme.
From 2010 onwards a series of workshops is needed to collate existing knowledge and discuss open questions.
Interaction between modellers and experimentalists can further be used to formulate directional questions for field campaigns to be undertaken in the coming years.

Field campaigns that address such questions should receive SOLAS endorsement and be invited to share their data with the sea-ice modelling community.

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