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Changing Polar Environments: Interdisciplinary Challenges

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In the past few decades, there has been enormous growth in scientific studies of physical, chemical, and biological interactions among reservoirs in polar regions. This has come, in part, as a result of a few significant discoveries: There is dramatic halogen chemistry that occurs on and above the sea ice in the springtime that destroys lower tropospheric ozone and mercury [*Simpson et al.,* 2007; *Steffen et al.,* 2008], the sunlit snowpack is very photochemically active [*Grannas et al.,* 2007], biology as a source of organic compounds plays a pivotal role in these processes, and these processes are occurring in the context of rapidly changing polar regions under climate feedbacks that are as of yet not fully understood [*Serreze and Barry,* 2011].

Stimulated by the opportunities of the International Polar Year (IPY, 2007–2009), a number of large-scale field studies in both polar environments have been undertaken, aimed at the study of the complex biotic and abiotic processes occurring in all phases (see Figure 1). Sea ice plays a critical role in polar environments: It is a highly reflective surface that interacts with radiation; it provides a habitat for mammals and micro-organisms alike, thus playing a key role in polar trophic processes and elemental cycles; and it creates a saline environment for chemical processes that facilitate release of halogenated gases that contribute to the atmosphere's ability to photochemically cleanse itself in an otherwise low-radiation environment. Ocean-air and sea ice–air interfaces also produce aerosol particles that provide cloud condensation nuclei.

Sea ice is undergoing rapid change in the Arctic, transitioning from a perennial or multiyear ice pack to a thinner, seasonal first-year ice pack, thereby transforming the Artic into a more Antarctic-like system. Most climate models project an ice-free summer Arctic by the end of the century, with some projections indicating considerably sooner. Such changes in critical interfaces will likely have large effects across the system, from habitat loss to dramatic changes in heat and water vapor fluxes and changes in atmospheric chemistry. Arctic changes will teleconnect throughout the globe via induced changes in ocean circulation and concomitant modification of weather systems. The loss of sea ice is likely to alter human behavior on a large scale, including adaptive behavior of subsistence hunters across the Arctic and utilization of new trade routes opening across the Canadian archipelago.

To help humans adapt, improve Arctic climate and weather predictions, and better understand the impacts of a seasonally ice-free Arctic on ecosystems and humans, it is essential that scientists understand interactions among components of the entire ocean-climate-cryosphere-human system and potential feedbacks at their most fundamental levels. In particular, the complexities of polar systems must be properly captured in Earth system models. Although the Antarctic may serve as a model for some aspects of the future Arctic system, its contrasting response to climate change emphasizes that many key processes exhibit differing challenges at both poles. One approach to tackling research questions involving climate change in polar regions is to examine topics for focused study as a thematically organized set. This set, discussed below, parallels some of the major scientific and public interest advances of the IPY.

Sea Ice Processes

Sea ice is both a reservoir and a substrate for biogeochemical compounds. Physical forces interact with chemical and biological processes within the ice in complex ways,

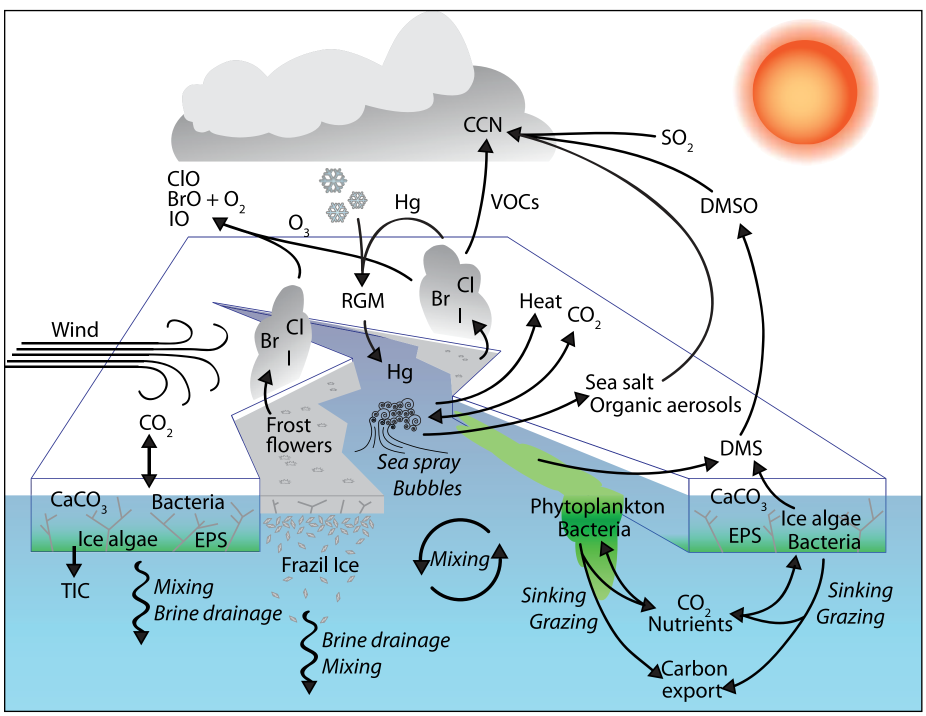

Fig. 1. Schematic of some ocean-atmosphere-sea ice-snowpack interactions among the chemical, physical, and biological processes in polar regions. These include but are not limited to feedbacks involving such chemical species as volatile organic compounds (VOCs), cloud condensation nuclei (CCN), total inorganic carbon (TIC), dimethyl sulfoxide (DMSO), reactive gaseous mercury (RGM), dimethyl sulfide (DMS), exopolymeric substances (EPS), and other molecular exchanges, as shown.

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thereby enforcing limits to the production and consumption of biogenic gases (e.g., oxygen, carbon dioxide, and dimethyl sulfide) throughout the seasonal cycle [*Loose et al.,* 2011]. Gas transport through sea ice pore spaces is temperature dependent and typically minor when the ice is cold, but it increases in warm springtime ice. Subfreezing temperatures inside sea ice can promote calcium carbonate precipitation, driving the carbonate system away from seawater equilibrium, thereby altering the net transport of inorganic carbon between the atmosphere and the deep ocean. However, the magnitude depends on physical rates and pathways that are poorly constrained.

Direct exchange at the air-sea interface also occurs through cracks, leads (long, thin breaks in the ice caused by the combined action of wind and water currents), polynyas (areas of open water surrounded by sea ice), and open water. Sea ice reduces the surface area available for air-sea fluxes, but turbulent ice-ocean and ice-air interfacial stresses, buoyant convection, and wind waves potentially increase gas, aerosol, moisture, and heat transfer above what would be expected over a continuous, quiescent ice cover. Estimates of biogenic material exchanges in the polar ocean and their impact on larger scales will require a good knowledge of constraints on these processes.

The Polar Microbial Loop

Scientific understanding of the flow of energy and material within marine ecosystems and the role of microbes in elemental cycles lags in polar regions. Despite its inherent environmental extremes, sea ice provides a habitat for cryoadapted algae and bacteria, which may catalyze physical changes in the surrounding cryosphere. Exopolymers, proteins, and polysaccharides, produced by microbes as a defense against freezing, alter the microstructure of sea ice and the production of organic aerosols that could act as cloud condensation nuclei. Dense pigment layers not only affect ice albedo but also influence ice structure and stability via solar energy absorption.

In concert with their direct impact on the polar carbon cycle, microbes produce other climatically active species, including dimethyl sulfide and halocarbons, which are precursors of aerosols and reactive oxidizing compounds (e.g., bromine and chlorine atoms). Currently, significant gaps remain in understanding these biologically mediated processes due to the limited number of polar studies fully integrating rate measurements of biological, chemical, and physical processes with good temporal and spatial coverage.

Primary Aerosols

Sea salt aerosol, an important primary aerosol in polar regions, is generated from breaking waves or wind blowing over ice, snow, and frost flowers on the sea ice. Large changes in sea salt aerosol inputs, energy exchange above leads and polynyas, and fluxes of biological and biologically derived material become more likely as the timing and extent of open water are altered. Evidence is clear that organic components from biological activities contribute a substantial fraction of the atmospheric aerosol [e.g., *Orellana et al.,* 2011]. These bio-organic compounds can influence important chemical and physical properties of aerosols, such as their solubility, surface tension, morphology, growth, and oxidation. These physical properties control aerosols' climatic and health effects.

Consequently, understanding the significance of biological particles and associated biogenic volatile compounds (e.g., dimethyl sulfide) for atmospheric processes and air-ice-snow interfaces is of great importance. Key issues to address involve characterizing bio-organic matter and understanding its transformation processes, including its effects on cloud nucleation and climate.

Reactive Halogens in Polar Regions

Many Arctic and Antarctic coastal stations record springtime events of depletion of ground-level ozone and mercury related to halogens released through a complex interplay between gas phase and condensed phase chemistry and meteorology in the lower troposphere. Global Ozone Monitoring Experiment satellite observations of atmospheric backscattered ultraviolet radiation have identified large clouds of bromine oxide (BrO) in springtime over sea ice in both hemispheres. BrO affects the tropospheric oxidizing capacity and is part of a natural biogeochemical cycle leading to the widespread and persistent removal of ground-level ozone and atmospheric mercury, converting the latter into nonvolatile products that reach the surface via either dry or wet deposition. However, exact halogen sources (open water, sea ice, snow, frost flowers, or aerosols) and the mechanisms for halogen release remain a source of controversy.

There is new evidence for extremely active iodine oxide and chlorine chemistry in polar regions, yet their distributions, sources, and magnitudes are also uncertain. Changing sea ice extent and character may significantly affect absolute and relative concentrations of all these reactive halogens; active research and observations via surface measurements from atmospheric platforms and satellites will help to resolve such uncertainties.

Anthropogenic Impacts

As Arctic seasonal sea ice retreats, anthropogenic pressures from sources inside and outside the Arctic will increase. Expanded infrastructure, coupled with increased ship traffic and resource development, will change the chemical nature and concentration of trace gases and particulates in the Arctic boundary layer and will increase pollutant loading to ground and ocean waters. Local effects (e.g., from ship traffic) could include increased sulfur emissions, which will provide cloud-forming particles that alter albedo and precipitation, while increased black carbon emissions will decrease local albedo. Increases in other transportation-related pollutants and long-range transport of Eurasian emissions will alter oxidative chemistry (e.g., via increased inputs of nitrogen oxides).

Anthropogenic impacts on the Arctic will occur on a wide range of scales—from community to regional to pan-Arctic. Human and material infrastructure will be required to mitigate anthropogenic effects and feedbacks at all these levels. Thus, solid scientific understanding of the relationships between anthropogenic pollutants and the physical, chemical, and biological state of the polar environments is necessary to inform decision makers in the development of sound and effective public policy regarding management of polar environments.

Upscaling

A major challenge in understanding and predicting physical, chemical, and biological exchanges among ocean, atmosphere, sea ice, and snow, within the context of a changing ice and climate regime in the polar regions, is in bridging gaps between scale size and scientific issues. Some measurements are done in laboratories at the microscale level, while others are made from satellites. While their key goals are to measure and model small-scale processes driven by or linked to interactions with sea ice, scientists also aim to understand the significance and applicability of these processes on the 1- to 100-kilometer (or larger) scales of satellite observations and Earth system models.

However, a single-model grid cell or satellite footprint often contains a wide range of ice types and states, and the scales of interest depend on the processes studied. Quantifying the system-wide effects of new ice formation or ice deformation requires considering different temporal or spatial scales for biology, chemistry, or physics. Hence, large-scale models currently designed to represent physical air-ice-ocean interactions will require creative approaches to adequately represent such small-scale processes. Tackling these challenges requires connecting effectively across disciplines, developing models in parallel on all scales, and considering scaling and heterogeneity issues when designing field process studies to interpret and evaluate satellite observations.

Effective Organization of Polar Interdisciplinary Research

Perhaps the most important lesson from recent sea ice studies is that physical, chemical, and biological processes interact in distinctive and complex ways and should not be studied independently of one another. Rapidly changing polar environments challenge the scientific community to develop robust and reliable models applicable on both small and system-wide scales for the poles and the entire Earth. A better understanding of how chemical and biological species exchange among all ocean, air, snow, and ice reservoirs is needed to anticipate and understand the effects of sea ice loss in polar environments. With this information, researchers can better prepare community planners and public policy makers for what may lie ahead.

In addition, an effective organizational structure will help the scientific community articulate research priorities and identify optimized and cost-effective approaches during the current period of funding challenges. For example, because individual countries, including the United States, manage few icebreakers and other polar research platforms, an organized research community can play a role in brokering priorities and organizing coordinated field campaigns in both polar regions. Several initiatives have been undertaken to get organized. The International Geosphere-Biosphere Programme's Surface Ocean–Lower Atmosphere Study (SOLAS) has formulated sea ice biogeochemistry as one of its new foci, and the IPY's Ocean-Atmosphere-Sea Ice-Snowpack project (OASIS) [*Shepson et al.*, 2003] has recently decided to continue with a second phase aimed at more effective coordination and approaches that seek to interconnect the necessary disciplines, e.g., meteorology; climate science; atmospheric chemistry; polar ocean biology; and sea ice physics, chemistry, and biology. The SOLAS and OASIS communities will work together through the new Scientific Committee on Oceanic Research working group of the International Council for Science, known as the Biogeochemical Exchange Processes at the Sea-Ice Interfaces, which was formed in late 2011.

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