"Ocean-Atmosphere-Sea Ice-Snowpack Interactions, Changes, and Feedbacks in Polar Regions: A Scientific Challenge for the 21st Century"

I. Introduction

In the past few decades there has been an 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, e.g., that there is dramatic halogen chemistry that occurs on and above the sea ice in spring time that destroys lower tropospheric ozone and mercury (Simpson et al., 2007; Steffen et al., 2007), that the sunlit snowpack is very photochemically active (Grannas et al., 2007), that biology as a source of organic compounds plays a pivotal role in these processes and that these processes are occurring in the context of rapidly changing polar regions, with climate feedbacks that are as yet not fully understood (Serreze and Barry, 2011). Stimulated by the opportunities of the International Polar Year, a number of large-scale field studies in both polar environments have been undertaken, which 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 microorganisms alike, thus playing a key role in polar trophic processes and elemental cycles; and creates a saline environment for chemical processes that facilitate a highly oxidizing (cleaning) atmosphere in an otherwise low-radiation environment. Ocean-air and sea ice-air interfaces also produce aerosol particles that provide cloud condensation nuclei (CCN).

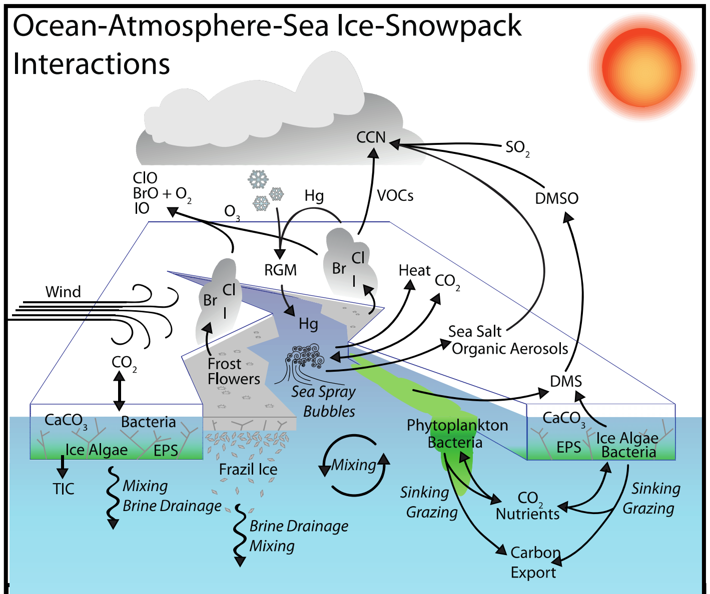

Figure 1. Schematic of interacting chemical, physical and biological processes in polar regions..

Sea ice is undergoing rapid change in the Arctic, transitioning from a perennial or multi-year ice (MYI) pack to a thinner, seasonal first-year ice (FYI) pack, thereby transforming into a more Antarctic-like system. Most climate models project an ice-free summer Arctic by the end of the century, with some projections considerably sooner. Such changes in critical interfaces will likely have large impacts system wide - from habitat loss to dramatic changes in heat and water vapor fluxes to 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 large-scale human behavior, 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 we understand interactions among components of the system and potential feedbacks at their most fundamental levels. In particular, the complexities of polar systems must be properly captured in Earth System Models. The Antarctic may serve as a model for some aspects of the future Arctic system. Yet, its contrasting response to climate change emphasizes that many key processes present differing challenges at both poles. Here we describe our view of a thematically-organized set of topics for research focus, related to ongoing and predicted ice loss in the polar regions, following some of the major scientific and public interest advances of the IPY.

1) Sea ice processes

Sea ice is both a reservoir and substrate for biogeochemical compounds. Physical forces interact with chemical and biological processes in complex ways, thereby enforcing limits to the production and consumption of biogenic gases (e.g. O_2, CO_2 and dimethylsulfide (DMS)) 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 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, polynyas, 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.

2) The polar microbial loop

Our 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 change 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 CCN. Dense pigment layers not only affect ice albedo, but 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 DMS and halocarbons, which are precursors of aerosols and reactive oxidizing compounds (e.g., bromine (Br) and chlorine (Cl) atoms). Currently, significant gaps remain in our understanding of 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.

3) 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 are 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., DMS) 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, the effects on cloud nucleation, and climate modeling.

4) Reactive halogens in Polar Regions

Many Arctic and Antarctic coastal stations record springtime events of depletion of ozone and mercury related to halogen explosions caused by a complex interplay between gas and condensed-phase chemistry and meteorology in the lower troposphere. Global Ozone Monitoring Experiment satellite observations of atmospheric backscattered UV from space have identified large clouds of bromine oxide (BrO) in springtime over sea ice in both hemispheres. However, the exact halogen source(s) (open water, sea ice, snow, frost flowers, or aerosols), and the mechanisms for halogen release, remain a source of controversy. BrO affects the tropospheric oxidizing capacity and is part of a natural biogeochemical cycle leading to the widespread and persistent removal of ubiquitous ozone, and also represents a potentially important sink for atmospheric mercury. There is new evidence for extremely active IO and Cl atom chemistry in polar regions, yet their distributions, sources, and magnitudes are uncertain. The changing sea ice extent and character may significantly impact absolute and relative concentrations of reactive halogens.

5) 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 impact pollution loading to ground and ocean waters. Local impacts could include increased sulfur emissions, which will provide cloud-forming particles that impact 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). Climate-induced changes and anthropogenic impacts on the Arctic will occur on a wide range of scales - from community to regional to pan-Arctic- and human and material infrastructure will be required in response at all these levels.

II. 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 key goals are measuring and modeling small-scale processes driven by or linked to interactions with sea ice, we also aim to understand the significance and applicability of these processes on the 1- to 100-km scales (or larger) 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 impact 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.

III. Conclusions

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. Rapidly changing polar environments challenge the scientific community to develop robust and reliable models applicable on small scales and at the polar/earth-system-wide scale. We need to better understand exchanges of chemical and biological species among all ocean, air, snow and ice compartments to anticipate and understand the impacts of sea ice loss in polar environments, and so better inform public policy. An effective organizational structure is needed to help the community articulate research priorities and identify optimized and cost-effective approaches and research platforms in internationally resource-limited times. Since individual countries, including the U.S., are ice-breaker-limited, 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 IGBP core project SOLAS has formulated sea-ice biogeochemistry as one of its new foci; the IPY project OASIS has recently decided to continue with a 2^{nd} phase. An updated website (www.oasishome.net) contains presentations from the recent workshop held in Telluride that led to this paper and will report future activities. The SOLAS and OASIS communities will work together in a new SCOR working group that will start in 2012.

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