High Latitude Processes and Feedbacks

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The Arctic is changing faster than any other location on Earth; these changes are unprecedented during the observational period and constitute a clear regime shift, for example from permanent toward seasonal sea-ice cover. In contrast, change has been slower to emerge in the Antarctic, but the longer-term changes and impacts may be even more severe. High-latitude Earth system (HLES) change has global implications, for instance through sea level rise, carbon release through permafrost thawing, and the impact of Arctic sea ice decline on mid-latitude weather. Regionally, indigenous communities and ecosystems are being directly affected; but other consequences may be economic (e.g., shipping, tourism, fisheries), or related to resource exploration and national security (e.g., mining, oil exploration, search and rescue, territorial disputes). Research on prediction and predictability of HLES variability and trends on seasonal to multi-decadal time scales is of critical importance. However, observations of the HLES are sparse (both temporally and spatially), and its complexity and strong component interactions make it a challenging system to diagnose and model.

The HLES responds to external forcing but also operates through local processes, and interactions and feedbacks between these processes. Surface heat fluxes respond strongly to changes in sea ice extent as do clouds and upper ocean heat content. Clouds can also respond to varying aerosol concentrations arising from changes in the marine ecosystems. Clouds in turn strongly impact the surface heat budget. Identifying and quantifying these regional controls, processes and feedbacks is critical for understanding and ultimately predicting the state of the HLES, in response to both human changes and natural variability.

The high latitudes are intrinsically coupled to lower latitudes through atmospheric and oceanic circulations, and are modulated by regional feedbacks and global teleconnection patterns. Changes in energy, moisture and momentum budgets at high latitudes can influence atmospheric and oceanic meridional transports globally. Declining Arctic sea-ice can impact lower latitude weather extremes and climate, while glacial freshwater inputs can influence deep-water formation and the meridional overturning circulation (MOC). In turn, changes in the MOC may affect the heat budget of the subpolar North Atlantic and Arctic Oceans, while the high latitude atmosphere responds to modes of variability originating at lower latitudes (e.g., ENSO, MJO, QBO).

Sea level rise driven by land ice mass loss is threatening coastal communities worldwide. The mass balance of ice sheets, ice shelves and glaciers depend critically on interactions with other climate system components, in particular with the atmosphere through surface melt and precipitation, but often (in case of marine terminating glaciers and ice shelves) with the ocean as well.

Permafrost degradation due to warming Arctic climate makes the enormous soil carbon pool vulnerable to accelerated losses through mobilization and decomposition, with potentially significant global climate impacts. The simultaneous greening of high-latitude systems and rapid shifts in vegetation types will also affect the net terrestrial carbon budgets of these systems. Changes to the high-latitude environment may also alter biological productivity of marine ecosystems, affecting sequestration of anthropogenic carbon from the atmosphere through the biological pump. Understanding the high-latitude contribution to the global carbon budget is critical to predict global greenhouse gas concentrations and their radiative impacts.

Grand Challenge Question: *What are the roles of regional processes and feedbacks, atmospheric and oceanic coupling to lower latitudes, in shaping the high-latitude Earth system, its variability and trends and what are the consequences of high-latitude climate change for the regional and global carbon cycle and sea level rise?*

Several components of the Grand Challenge are being addressed by RGMA-funded research projects, often in cooperation with other lab- and university-led projects sponsored by CESD.

Description of Challenges and Current Research in RGMA

Characterization of the sources of water vapor to the high latitudes is investigated in the **HiLAT** project. This project is using tagged water vapor species to produce a better characterization of the sources of water vapor to the high latitudes. This will lead to better understanding of the surface mass balance of the Antarctic Ice Sheet and of changes in Arctic precipitation. It is also exploring the two-way coupling of the Greenland Ice Sheet with the atmosphere in a fully-coupled climate system model. Far-field controls on high-latitude climate are addressed by the **UCAR Cooperative Agreement** team, in particular with a focus of equatorial Pacific variability impacts on Southern Ocean atmosphere through atmospheric (Rossby wave) teleconnections. The dynamics and impacts of AMOC variability are being explored by several projects such as the UCAR Cooperative Agreement, and HiLAT through its collaboration with a **NOAA** project.

Sea-ice synoptic weather interactions are addressed in the **RASM** project. Inertial oscillations in sea-ice (and ocean) generated by synoptic storms are an important component of energy spectra and commonly produce sea-ice deformations; in turn, they are a source of elevated air-sea turbulent heat and radiative fluxes. Such processes and feedbacks are of increasing relevance to Arctic climate, due to a changing sea-ice regime toward thinner and easier deformable first-year sea-ice, as compared to thicker multi-year sea-ice. RASM, in collaboration with **HiLAT**, is also experimenting with new parameterizations of sea-ice roughness through predictive calculation of form drag, to improve representation of horizontal momentum transfer from air to ice. **PAMIP** is evaluating how changes in sea ice cover affect the local and remote atmospheric circulation. In particular, do polar changes impact the frequency, intensity and duration of extreme weather events in mid-latitudes?

Polar amplification is addressed by the RGMA Polar Amplification MIP (**PAMIP**) project. The project examines the causes and consequences of polar amplification in the context of both atmosphere and ocean through a hierarchy of coordinated global climate model (GCM) perturbation experiments in a multi-model framework. In addition to quantifying the relative role of remote SST patterns vs local processes in causing polar amplification, the role of atmospheric moist transport along isentropic surfaces will be quantified, as well as the role of ocean heat transport in polar amplification. Other questions addressed are: 1) What is the role of the stratosphere and forcing of anomalos planetary waves in communicating the response to mid-latitudes. 2) How do polar changes combine with the general response to GHG forcing at the end of the 21st century, and what is the resulting response of the midlatitude atmospheric circulation and extreme weather events? What is the oceanic response to changes in sea ice, and how does it feedback on the atmosphere and its circulation features such as the ITCZ? 3) How can the role of sea ice loss in mid-latitude changes, in the real world and in climate simulations, be separated from tropical influences?

Arctic sea-ice decline impacts on mid-latitude weather is addressed in the **HiLAT** project. Using self-organizing maps (a machine learning technique) and system identification methods borrowed from the engineering literature are being used to tease out the influence of sea-ice losses on local heat and moisture fluxes, and the subsequent impact on clouds and the general circulation.

Oceanic controls on ice sheet disintegration are addressed by several projects. **HiLAT** is exploring the use of low-order models to represent ocean/ice sheet interactions and their uncertainties. The project approaches the problem by configuring global climate models with unprecedented high resolution (mesoscale eddy resolving) around Antarctica and Greenland to more accurately resolve ocean pathways towards ice sheets. Ocean/ice sheet interactions are parameterized. **RASM** is investigating oceanic controls on marine-terminating glaciers on a regional to local scale using eddy-resolving regional ocean model configurations and by explicitly resolving circulation in a fjord in Greenland using a separate model.

Feedbacks involving ocean and sea-ice biogeochemistry are being investigated by the **HiLAT** project, with an emphasis on Southern Ocean marine ecosystems and their impact on clouds through the emission of trace gases and aerosols. HiLAT is also developing knowledge about Arctic deltaic systems as a buffering interface between terrestrial and marine ecosystems, in close collaboration with the TES-funded **NGEE-Arctic** project, and the **RGMA RUBISCO SFA**, which addresses high-latitude biogeochemistry predominantly from a terrestrial perspective. The ultimate goal is a comprehensive description of biogeochemical processes from soil to sea. RASM is also addressing marine and terrestrial biogeochemistry in a regional Arctic and high spatio-temporal context, focusing on the role of ocean stratification, mesoscale eddies, coastal and boundary currents, and shelf-basin interactions on nutrient distribution and biological productivity.

Gaps in Current Research

There are significant gaps in understanding of many processes that are fundamental to HLES variability and change. As understanding improves and model capability expands it will be important to assess the role of these processes in the Earth System.

Marine biogeochemistry at high latitudes. Marine and terrestrial ecosystems are important for the global carbon cycle, and Earth's radiative budget (through surface albedo, energy and water fluxes, and marine aerosol production). The biogeochemistry within sea-ice, and physical exchange processes between sea-ice and the ocean are highly complex, and poorly understood. For example, iron, a major limiting nutrient in the Southern Ocean, accumulates in sea-ice brine to concentrations many times higher than that of the surrounding ocean. Also, Marine organisms (calcifiers) might adapt to ocean acidification, or they might experience tipping points under multiple stressors (warming, acidification, nutrient stress etc.); their response will affect ecosystem structure, and modify their role in the biological pump, and marine aerosol emissions. As better process level understanding of sea and ice ecosystem is achieved, it will be important to assess their impact on the carbon cycle and the Earth's radiative budget, and subsequent implications in a warming world.

Organic macromolecules, byproducts of the oceanic food webs, affect surface tension of the ocean/atmosphere interface. Laboratory studies suggest that these surfactants may lead to a significant reduction in the turbulent transfer of gases, momentum, heat and freshwater. These changes may be particularly impactful at the high-latitudes, where the strong seasonality of light availability leads to intense plankton blooms. The impact of organic material on surface fluxes needs to be quantified, and if it appears significant, its impact on climate should be assessed.

Terrestrial biogeochemistry at high latitudes. At present, distribution, spatial heterogeneity, and quality (decomposability) of soil organic carbon (SOC) are poorly known and account for about half of the total uncertainty that exists in predicting permafrost carbon climate feedbacks. Also, surface organic layer thickness regulates permafrost dynamics and stability, water and nutrient availability, soil respiration, thermal conductivity, and the magnitude of carbon losses from combustion. The lateral transport of moisture through the soil active layer and through the rivers and lakes in the Arctic/boreal regions strongly affect the biogeochemistry of the moisture flux from the land surface into the ocean. These features, and their environmental controls, are poorly understood and not well represented in Earth systems models. As process understanding is improved, exploration of potential feedbacks between terrestrial carbon and other components of the high-latitude and global Earth systems is needed.

Land/ocean/sea-ice coupling. Arctic deltas regulate the flux of water, sediments and nutrients from land to the ocean. They are sensitive to both upstream (land) and downstream (ocean) drivers. Due to sea level rise, permafrost degradation, and changes in landfast sea-ice and terrestrial hydrology, it is likely that the structure and functioning of Arctic deltas will change significantly in the coming decades. As understanding of the structure and functioning of deltas improves and representations of these features are being embedded in Earth System Models, it will be important to assess the fate of terrestrial fluxes in the ocean and the biogeochemical feedbacks of the coastal ocean on these fluxes.

Ice sheet-ocean interactions. One extremely challenging issue of ice sheet/ocean interactions is the problem of scale, as they often take place on spatial scales that are not resolved by the current generation of climate models (for instance in fjords). Another challenge related to ice-sheet/ocean interaction is the representation of a fjord mélange, consisting of sea-ice and calved icebergs, and the persistent lack of observations and knowledge of the behavior of mélange. As new model formulations resolve (for example through regional refinement, or embedded explicit models), or parameterize these features, it will be important to understand their impact on Earth System behavior.

Mesoscale oceanic processes. The large-scale ocean circulation, including the MOC, is strongly influenced by mesoscale processes (localized and intermittent convective events, localized abyssal mixing, geostrophic eddies, narrow boundary currents, and sill overflows). Eddies strongly control the transport of riverine and glacial outflows towards the interior of the Arctic and Southern Oceans and the subpolar basins in the North Atlantic and also deliver warm Circumpolar Deep Water (CDW) to ice shelves around Antarctica, and subpolar Atlantic waters near terminating glaciers around Greenland. Most existing ocean models do not resolve the Rossby radius of deformation in the polar oceans, which limits their ability to realistically represent mesoscale processes in high latitudes. Current intuition about the sensitivity of the MOC to changes in forcing, its internal variability, and ultimately its stability in view of a potential collapse, is based on low resolution model configurations, in which these processes are parameterized. It is not known how mesoscale processes affect the exchange of properties between the pelagic and coastal oceans, or the behavior of the MOC.

Mesoscale atmospheric processes. Mesoscale atmospheric features, such as topographically modified flows (e.g. barrier and katabatic winds) and polar lows, are not resolved in global climate models but can play a vital role in coupled climate system processes. Strong katabatic and barrier winds around the periphery of Antarctica result in persistent polynya formation with implications for deep water formation and sea ice. In the Arctic, barrier winds and tip jets around Greenland, have the potential to impact oceanic convection. The impact of polar lows, with strong localized winds and large surface turbulent fluxes, on oceanic convection is not known. It is unknown how mesoscale wind forcing impact ocean, sea ice, and ice sheet processes in fjords.

River and meltwater runoff. Increased freshwater fluxes from rivers and glacial melt into the Arctic and Southern Oceans is one of the key consequences of climate change in high latitudes, and a key component of most polar feedbacks. Freshwater inputs are poorly represented in many ocean models. Shelf regions are characterized by very small Rossby radius of deformation (<4 km), and processes associated with river and melt water are unresolved in current simulations.

For instance, very few models have river temperature fluxes, which may play a crucial role in the onset of sea-ice melt during spring. High-resolution models with improved river parameterizations are necessary to study freshwater-related processes on the shelf regions.

More than half of the total Arctic Ocean's liquid freshwater is stored within the Beaufort Gyre. Driven by atmospheric anticyclonic circulation the freshwater content of the Beaufort Gyre has increased by >30% over the last decade. Freshwater released from the Beaufort Gyre can inhibit deep convection in the northern North Atlantic reducing the intensity of the ocean meridional overturning circulation and impacting climate. The time scale of freshwater release and its global impacts are currently unknown.

Clouds. Clouds are important participants in the HLESs, but operate very differently in Northern and Southern Hemispheres because of differences in: 1) surface properties (e.g. topographic forcing; fluxes of heat, moisture, and momentum; and atmospheric and oceanic stability); 2) meteorological regime; and 3) sources of aerosol particles. High-latitude clouds are often optically thin, consisting of mixed phases, and they occur in relatively pristine environments, which makes them very sensitive to small changes in anthropogenic or natural emissions. These characteristics make high-latitude clouds very hard to model. Current model treatments are very inaccurate, producing errors in the frequency of occurrence of clouds and cloud properties (geometric and optical thickness, height, and vertical distribution of liquid and ice particle by size and number). These deficiencies introduce errors representing cloud radiative forcing, responses to changing emissions (of gases and aerosols), and cloud feedbacks. Even small changes in cloud properties can produce big changes in land-ice and sea-ice distributions, and other responses in the earth system (e.g. through polar amplification, far field responses in the stratosphere and mid and low latitude teleconnections). High latitude cloud biases in models, the reasons for the biases, and the implications for models if those biases are reduced or removed are not known.

Aerosols. Absorbing aerosols can play an important role in the evolution of sea-ice, land-ice, and snow cover, by changing their surface albedo, and thus their melting. Models show very large biases in virtually all aerosol types measured at high latitudes (sea salt, primary organics, black and brown carbon, dust, and secondary organic aerosols). These biases arise from deficiencies in treating (local and remote) sources, the processes that transport and remove aerosols that originate from lower latitudes, and local processes (e.g., surface wind speeds, turbulence, and high latitude meteorology). It appears that both local and remote aerosol sources are important at high latitudes, and modeled aerosol concentrations often differ by one or two orders of magnitude compared to measurements. A better understanding of the origin of the model errors is necessary, and it is useful to assess the consequences (to modelled climate, and the model response to climate change) that would result from reducing these errors.

Sea-ice. Contrary to atmospheric and oceanic codes, current generation sea-ice models are unable to universally simulate the frozen ocean from the basin scale (106 m) to the floe scale (< 2 km). Continuum sea-ice model dynamics were originally designed to operate well above the so-called multi-floe spatial scale (2-10 km). At smaller scales, continuum rheological and morphological approximations break down. Discrete element models are being developed to resolve coagulations of floes beneath this scale, but it will be some time before these models are able to simulate individual floes, requiring resolutions of <100m. Regardless of development of discrete models, or even high-resolution finite element models, refinements of the physics associated with sub-element or sub-grid scale deformation will be required over the next decade. Combined use of models and observations to assess and test existing theories are needed. This kind of testing framework provides an opportunity to assess existing, and develop better sea-ice rheological and morphological approximations. In addition to having an impact on the physical characterization, improvements to the treatments will affect high latitude biogeochemistry and its impact on the Earth system.

Radiation: Radiative fluxes are key to to the delicate surface energy balance that determines the mass balances of land and sea ice and the deposition of energy into the high-latitude oceans. The cold, dry atmospheres found at high latitudes are among the most extreme conditions found on Earth and so present an unusual challenge for the climate model parameterizations. Advancing modeling and understanding will require characterizing the errors in present-day parameterizations and identifying ways to ameliorate those biases in future representations. A larger issue is that the radiation flows seamlessly through the all components of the earth system, include the atmosphere, land or sea ice, vegetation canopy, and ocean, but is normally modeled within each component independently (and inconsistently). A particular issue at high latitudes is the treatment of melt ponds on sea ice which dramatically change the surface albedo and the amount of radiation transmitted into the ocean.

Future Directions

Short Term (3-5 years) Research Goals

We have begun addressing these longer term goals through immediate shorter term activities that are tied to the components of the Grand Challenge question listed above.

- Study the influence of sea-ice loss on local heat and moisture fluxes, and subsequent impacts on clouds and precipitation.
- Study the spatio-temporal characteristics of Arctic deltas, using satellite observations and numerical modeling.
- Evaluate new or improved parameterizations of momentum and radiation transfer within and between atmosphere and ocean in presence/absence of sea-ice and melt ponds.
- Explore the role of mesoscale processes (e.g. sea-ice deformations, mesoscale ocean eddies) in high-latitude climate processes and feedbacks, by using high-resolution regional and global models.

- Study the impact of glacial and fluvial inputs of freshwater and nutrients on high-latitude marine ecosystems, and the consequences for marine aerosol emissions and clouds in a fully-coupled climate system model.
- Analyze the roles of high-latitude vegetation changes on surface energy budgets, carbon dynamics and greenhouse gas emissions, and interactions with regional and global atmospheric responses.
- What is the role of decadal to multidecadal climate patterns such as the IPV and AMV in forcing polar amplification? What is the role of remote SST warming compared to local feedback processes in polar amplification?
- Study the influence of sea-ice loss on mid-latitude weather and climate, using machine learning and system identification techniques, and water tagging methods.
- Investigate freshwater (river runoff and glacier meltwater) pathways from coast to the shelf and to the deep ocean in order to estimate time scales and influence of freshwater spreading on thermohaline processes in the ocean, using high-resolution coupled ocean-ice models.
- Investigate the climate response to changes in meridional ocean heat fluxes and ocean heat uptake, using fully-coupled models.
- Explore ice-sheet/climate interactions using climate models with partly and fully interactive ice sheets.
- Project sea level rise from the Greenland Ice Sheet, as part of the ISMIP6 project.
- Investigate changes in marine ecosystem productivity on seasonal to multidecadal time scales.
- Study the environmental controls on the surface organic layer in the boreal Arctic system, its spatial heterogeneity, and its role in regulating active-layer thickness and permafrost dynamics.
- Study the effects of expected changes in precipitation on biogeochemical cycles and interactions with climate.

Long Term (10 years) Research Goals

- Quantify process interactions and feedbacks between cryosphere, ocean, land and atmosphere, and identify the distinctive feedbacks operating in the Arctic and Antarctic;
- Explore terrestrial and marine ecosystems responses to HLES change, and potential feedbacks on other components of the climate system;
- Quantify high-latitude climate responses to exogenous (external) factors, e.g., aerosols, in the presence of natural variability.

- Identify and quantify:
    - High-latitude effects on mid-latitude weather and climate; specifically, how do polar changes in sea ice cover affect the local and remote atmospheric circulation? Do polar changes impact the frequency, intensity and duration of extreme weather events in midlatitudes? What is the role of the stratosphere and forcing of anomalous planetary waves in communicating the response to midlatitudes?
    - High-latitude effects on the ocean's wind-driven and meridional overturning circulation, and their implications for global climate (e.g. shifts in ITCZ precipitation);
    - Mid- and low-latitude atmosphere-ocean effects on the high-latitude climate systems.
- Use ice sheet models partly or fully coupled to other Earth system components to:
    - Better understand the dynamics of ice sheets, glaciers, and ice shelves, and their response to external drivers;
    - Improve prediction of land ice mass loss and its impact on global sea level rise.
- Enhance understanding of high-latitude terrestrial and marine ecosystems and their impact on the carbon cycle.
- Quantify regional carbon sinks and sources in the high-latitude regions and their potential changes in a warmer planet.