High Latitude Earth System Processes and Feedbacks

A White Paper for DOE's Regional and Global Climate Modeling (RGCM) program

Lead authors: Wilbert Weijer (LANL), Wieslaw Maslowski (NPS), and Phil Rasch (PNNL)

With input from: John Cassano, Wei Cheng, Gokhan Danabasoglu, Dmitry Dukhovskoy, Scott Elliott, Jeremy Fyke, Diana Gergel, Sarah Gille, Joe Hamman, Aixue Hu, Elizabeth Hunke, Bill Lipscomb, Bart Nijssen, Julie McClean, Umakant Mishra, Bill Riley, Andrew Roberts, Hansi Singh, Steve Smith, Hailong Wang.

Grand Challenges and Long-Term Goals

The Arctic is changing faster than any other location on Earth; these changes are unprecedented and constitute a clear regime shift, for instance from permanent toward seasonal sea-ice cover. In contrast, signals have been slower to emerge in the Antarctic, but the longer-term changes and their consequences may be even more severe. High-latitude Earth system (HLES) changes have 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 energy security (e.g. natural resource exploitation) and national security (e.g. search and rescue, territorial disputes). Research on prediction and predictability of HLES variability and trends on seasonal to multi-decadal time scales is hence important. However, observational records of the HLES are sparse, and its complexity and strong component interactions make it a difficult system to model. So the HLES is a relatively poorly understood part of the global Earth system.

We have identified below four Grand Challenges with long-term (5-10 year) goals designed to guide RGCM-funded research that will enhance our understanding of HLES processes and feedbacks, in order to reduce uncertainties in model predictions and enhance model predictive capability. The next section discusses short-term (3-5 year) goals.

Grand Challenge 1: What are the roles of regional processes and feedbacks in shaping the high-latitude Earth system, its variability and trends?

The HLES responds to external agents (like heat, moisture, and momentum transports, or pollution imported into these regions) but also operates through local feedbacks and interactions between processes. For example, clouds and upper ocean heat content respond to sea ice decline. Clouds can also respond to varying aerosol concentrations arising from changes in marine ecosystems, as a result of increased nutrient and freshwater inputs. 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 (internal) variability. The associated long-term goals are:

GC1.1. Quantify process interactions and feedbacks between cryosphere, ocean, land and atmosphere, and identify the distinctive feedbacks operating in the Arctic and Antarctic;

GC1.2. Explore terrestrial and marine ecosystems responses to HLES change, and potential feedbacks on other components of the climate system;

GC1.3. Quantify high-latitude climate responses to exogenous (external) factors, e.g., aerosols, in the presence of natural variability.

Grand Challenge 2: How are high- and lower latitudes coupled through atmospheric and oceanic circulation cells? Will changes in high latitudes affect the coupling itself?

The high latitudes are intrinsically coupled to lower latitudes through atmospheric and oceanic circulation cells, and modulated by regional feedbacks. Changes in energy, moisture and momentum budgets at high latitudes can influence atmospheric and oceanic meridional transports globally: for instance, 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., NAO, ENSO). Our long term goals for understanding and quantifying these global interactions are to identify and quantify:

GC2.1. High-latitude controls on mid-latitude weather and climate;

GC2.2. High-latitude controls on the ocean's meridional overturning circulation, and their implications for global climate (e.g. shifts in ITCZ precipitation);

GC2.3. Mid- and low-latitude atmosphere-ocean controls on the high-latitude climate systems.

Grand Challenge 3: What are the roles of interactions between land ice (i.e. ice sheets, ice shelves, and glaciers) and atmosphere and ocean on sea level rise?

Sea level rise driven by land ice mass loss is threatening coastal communities worldwide. The mass balance of ice sheets, ice shelves and glaciers depends 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. Our long term goal is to use ice sheet models partly or fully coupled to other Earth system components to:

GC3.1. Better understand the dynamics of ice sheets, glaciers, and ice shelves, and their response to external drivers;

GC3.2. Improve prediction of land ice mass loss and its impact on global sea level rise.

Grand Challenge 4: What are the consequences of high-latitude climate change for the regional and global carbon cycle?

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. Associated long-term goals are:

GC4.1. Enhance understanding of high-latitude terrestrial and marine ecosystems and their impact on the carbon cycle;

GC4.2. Quantify regional carbon sinks and sources in the high-latitude regions and their potential changes in a warmer planet.

Short-Term Goals

We have begun addressing these longer term goals through immediate shorter term activities that are tied to the Grand Challenges listed above. More detail about how we are pursuing these goals is provided in the subsequent section (Current Research and Capabilities).

GC1:

- Study the influence of sea-ice loss on local heat and moisture fluxes, and subsequent impacts on clouds and precipitation (GC1.1);
- Study the spatio-temporal characteristics of Arctic deltas, using satellite observations and numerical modeling (GC1.1);
- Evaluate new or improved parameterizations of momentum and radiation transfer between atmosphere and ocean in presence/absence of sea-ice (GC1.1);
- 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 (GC1.1 and 1.3);
- 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 (GC1.2 and 1.3);
- Analyze the roles of vegetation changes on surface energy budgets and interactions with regional and global atmospheric responses (GC1.1 and 1.3);
- Distinguish between natural and forced climate variability and long term trends by designing and analyzing climate model experiments by prescribing various forcing agents or process interactions (GC1.3);

GC2:

- Study the influence of sea-ice loss on mid-latitude weather and climate, using machine learning and system identification techniques, and water tagging methods (GC2.1);
- 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 (GC2.2);
- Investigate the climate response to changes in meridional ocean heat fluxes and ocean heat uptake, using slab-ocean and fully-coupled models (GC2.3);

GC3:

- Explore ice-sheet/climate interactions using climate models with partly and fully interactive ice sheets (GC3.1);
- Project sea level rise from the Greenland Ice Sheet, as part of the ISMIP6 project (GC3.2);

GC4:

- Analyze the roles of vegetation changes on carbon dynamics and greenhouse gas emissions (GC4.1);

- Investigate changes in marine ecosystem productivity on seasonal to multidecadal time scales (GC4.1);
- 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 (GC4.2);
- Study the effects of expected changes in precipitation on biogeochemical cycles and interactions with climate (GC4.2).

Current Research and Capabilities

High-latitude biogeochemistry. 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 **RGCM BGC 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.

Ocean/Cryosphere interactions. 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 led by **J. McClean** 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.

Atmosphere/Ocean/Cryosphere Interactions. HiLAT 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. HiLAT is also exploring how (1) feedbacks local to the high latitudes, (2) the large-scale dynamics, and (3) synergies between local processes and large-scale dynamics drive polar climate change; these analyses will also highlight differences and similarities in how the Arctic and Antarctic each respond to anthropogenic forcing. **RASM** resolves inertial oscillations in sea-ice (and ocean) generated by synoptic storms, which 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.

High-Latitude Teleconnections. HiLAT is addressing Arctic sea-ice decline impacts on mid-latitude weather**.** 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. **RASM** is also investigating troposphere-stratosphere linkages and local to regional effects of a diminishing sea-ice cover on air-sea fluxes, atmospheric circulation patterns, and precipitation over land. 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, among which the project led by **A. Fedorov**; the **UCAR Cooperative Agreement** through the work of **A. Hu**; and HiLAT through its collaboration with the NOAA project led by **W. Cheng**.

Validation and Verification: Our team is focusing on **metrics** that characterize seasonal evolution of variables important at high latitudes. **RASM** has established that simulations of sea-ice extent, concentration and thickness distribution can serve as a benchmark for the Arctic surface climate: discrepancies with respect to sea-ice observations point to biases in other model components (e.g. atmosphere or ocean) related to specific processes (e.g. clouds) or feedbacks (e.g. cloud-radiation feedback). **RASM** is implementing a satellite simulator in its sea-ice component (CICE) to allow accurate comparisons of sea-ice freeboard measured from existing and future satellites. Dual relevance of this approach lies in the need for accurate model constraints of the state and variability of sea-ice cover and the large uncertainty in observational estimates of sea-ice thickness based on freeboard. **HiLAT** is developing special datasets of composited surface winds, sea level pressure, and satellite products to better establish the role of meteorology; aerosol production, transport, and removal; and cloud features for the Southern Ocean clouds, where biases in current earth system models are very large. The project is also exploring approaches to objectively quantify model skill in simulating sea-ice variables, that are multi-variate, and account for uncertainties in a statistically robust way. The **RGCM BGC SFA** has developed metrics in its ILAMB infrastructure to evaluate high-latitude carbon cycling (e.g., permafrost and vegetation carbon, surface fluxes). The project is also working to integrate and study experimental manipulation meta-analyses and soil radiocarbon metrics.

Gaps

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. Polar lows, with strong localized winds and large surface turbulent fluxes, can impact oceanic convection. It is unknown how mesoscale wind forcing impact ocean, sea ice, and ice sheet processes in fjords. *Assessment of mesoscale atmospheric processes on sea ice, ocean, and ice sheet processes is needed and can be addressed using high-resolution coupled models such as RASM or ACME.*

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*). There are many opportunities for progress through better characterizations of high latitude cloud biases in models, the reasons for the biases, and the implications for models if those biases are reduced or removed.* Progress will improve understanding of the Earth system and its response to humans.

Aerosols. In addition to the roles of aerosols as cloud and ice nuclei, they also scatter and absorb energy directly (in the long and shortwave), changing the energy budget of the atmosphere and surface. Scattering aerosols (e.g., sulfate, some organics, sea spray) are important over ocean surfaces. 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 (10^6 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.*

Research Needs and Opportunities

Observations. Understanding of HLES processes is severely hampered by scarcity and strong seasonal biases in observations, in all Earth System components. Significant progress is mitigating the most severe restrictions of the traditional observing systems. Recent developments in ice-avoiding technologies for Argo floats, and the use of elephant seals mounted with sensors, allow for autonomous observations under sea-ice, enhancing understanding of the hydrography of the high-latitude oceans. The launch of ICESat-2 in 2018 offers an excellent opportunity to evaluate both land-ice and sea-ice models, as well as other simulated terrestrial components. Similarly, NASA's ECOSTRESS and JEDI missions will give an unprecedented level of information on land surface structure and function.

The RGCM program has significant opportunities to engage with DOE high latitude observational programs (e.g., NGEE-Arctic, the ARM facility program, and M-PACE, etc), to ensure a synergy between theory development, observations, and model development and analysis. Other relevant programs are the international project MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate); the European Space Agency's project GlobPermafrost; the NSF-funded SOCCOM (Southern Ocean Carbon and Climate Observations and Modeling); NASA's Arctic-COLORS (COastal Land Ocean inteRactionS in the Arctic); the German project "Arctic Amplification: Climate Relevant Atmospheric and Surface Processes and Feedback Mechanisms"; the Horizon 2020 project Blue-Action, a project in the context of the Transatlantic Ocean Research Alliance (Galway agreement); and the UK/USA trans-Atlantic RAPID/MOCHA and OSNAP arrays.

Model Resolution. Relatively low resolution (> ~25 km) of global climate models limits progress because many high latitude processes require higher resolution. Cross-shelf transport of heat and biogeochemical agents in coastal and shelf regions occurs through eddies scaling with the Rossby radius (a few kilometers in the Arctic and Southern Oceans). Very high resolution models reach resolutions closer to 6 km, but are prohibitively expensive at uniform resolution on the globe. Regional models like RASM operate at these resolutions (2-10 km). The ACME model includes the capability for arbitrary refinement of the grid in regions where required or desired. This capability provides an opportunity to refine the resolution in the coastal zone, where the ocean and sea-ice interface with land (deltas and estuaries) and land-ice (fjords, ice shelves); or in the atmosphere to better resolve details of the atmospheric circulation and physical processes over the strong gradients imposed by the ocean/land/ice boundaries, improving representations of process interactions and feedbacks.

Fully interactive ice-sheets. The next phase of CMIP will feature models that incorporate fully dynamic ice sheets, e.g. CESM, which includes a dynamical ice sheet component for the Greenland Ice Sheet, with two-way coupling to the atmosphere. ACME's pending version 1 release has the capability to resolve circulation underneath static Antarctic ice shelves, while two-way coupling of marine terminating glaciers and ice shelves to the ocean is a capability that is envisioned for future releases. This new generation of models provides opportunities for more comprehensive study of the role of ice sheets in the Earth System.

Model validation and verification of polar climate. A major RGCM theme involves "diagnosing model systems that are cause for uncertainty in regional climate projections." The HiLAT project has begun developing diagnostics as a means to better understand and represent sea-ice variability, and identify current high latitude biases in Earth System models. Two of the three major foci of the ACME activity do not have a high-latitude theme, and it is possible that RGCM could complement ACME's current activities, and provide a synergy for DOE by:

- Assessing the fidelity of ACME climate at high latitudes, and identifying current deficiencies;
- Identifying parameterizations responsible for those deficiencies, and possibly, alternate choices of parameter settings or treatments that produce better high latitude fidelity;
- Exploring the consequences of tuning or parameterization changes to the simulation, and the primary scientific features (feedbacks, and responses to forcings) that result from reductions in climate biases.

Hindcasting capabilities provide a mechanism for validating model behavior (on daily to decadal timescales), and opportunities for interactions with other programs (NWP, USGCRP, etc).

Methods for understanding the complexity of the Earth System. The steady increase in number and complexity of processes included in Earth System models may increase internal variability, and high latitudes also have a lot of natural variability. It is more difficult to assess model responses involving interactions across many variables and processes in this situation; individual realizations become less meaningful, and it is important to analyze ensembles of simulations. Analyzing and interpreting model behavior will hence require a stronger emphasis on data reduction strategies. *We see opportunities and need for: new methods to diagnose nonlinear feedbacks; model reduction methods to convert diagnosed dynamics and feedbacks into predictive stochastic models; and uncertainty quantification techniques that can effectively synthesize scientific information from a collection of diverse models of varying resolution and process fidelity with incomplete observations and measurement systems.*

We also believe simpler models (e.g. slab ocean models, or models of intermediate complexity) can be particularly useful in teasing out component interactions. The RASM project has demonstrated the usefulness of **regional models**. The ability to focus on the high-latitude climate system allows researchers to optimize process representations for these regions, and to increase the resolution of the model, making the solution less reliant on parameterizations.

Cross-topical synergies

RGCM's High-Latitude Climate Processes and Feedbacks activity can contribute to several cross-cutting themes:

- Many of our activities are engaged in the **detection and attribution** of climate change, the study of **feedbacks and process interactions** involving high-latitude climate system components, and **the quantification of their uncertainties**. There are obvious opportunities for activity to engage with the **cloud feedbacks** activities within RGCM, and with other DOE projects;
- Our target of **Improved fidelity of climate models,** provides many opportunities to work with other RGCM components (CAPT, Cloud feedbacks, climate extremes) and other DOE projects;
- Land and marine biogeochemistry studies in high latitudes are complementary to and natural extension of the ongoing BGC focus area;
- Important **tipping points** exist in the climate system, for instance related to sea-ice decline, the retreat of marine-terminating glaciers, the collapse of ice shelves, the stability of the Atlantic Meridional Overturning Circulation, or the release of carbon from permafrost or methane hydrates on shallow Arctic shelves. An emerging field is the casting of tipping points in terms of Cumulative Carbon Emissions, which is increasingly recognized as the most pertinent metric of human forcing for many aspects of anthropogenically-forced change. As such it provides a direct link between climate science and decision-making;
- Ice provides a significant buffer in the climate system against climate variability, and reduction of ice cover at high latitudes (sea-ice, permafrost, land-based ice) will likely lead to more **extreme events**, potentially with global consequences.

Impacts and Metrics of Success

The High-Latitude Earth System Processes and Feedbacks activity of the RGCM program can be considered successful if it produces impactful *integrative HLES science* that demonstrably leads to better system understanding and enhanced predictive ability. Our projects already have world-class status in component modeling, as DOE scientists continue to be leaders in modeling of the ocean, land-ice and sea-ice systems, terrestrial processes, marine and sea-ice biogeochemistry, high-latitude atmospheric dynamics, and aerosol-cloud interactions. Our challenge is to integrate the diverse set of capabilities within the RGCM program to explore interactions between multiple Earth system components.

The activity will have an optimal impact if the project engages in productive collaborations with other programs, for instance by evaluating and applying numerical tools developed by the ACME project; and in successful collaborations with academic partners, for instance by sharing model simulations for interdisciplinary and collaborative research, and for guiding field work.

Natural metrics of the impact of the program are the number and quality of publications, the number of invited presentations, and the number of leadership positions assumed by RGCM scientists. Another important metric of success is the number of students and postdocs that are being engaged in climate research.