Advancing Understanding of Variability, Predictability, and Change Across Spatiotemporal Scales

A Whitepaper Synthesizing Current and Future Earth System Science Research

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Executive Summary

The Earth and Environmental Sciences Division (EESD) within the U.S. Department of Energy (DOE) Office of Biological and Environmental Research (BER) recently released a strategic plan for the period 2018—2023 that outlines 5 grand challenges in: the integrated water cycle, biogeochemistry, high latitudes, drivers and responses in the Earth system, and data-model integration. This strategic plan specifically aims to "make a special effort to exploit DOE facilities and capabilities". Within EESD, the Regional and Global Model Analysis (RGMA) component of the Earth and Environmental System Modeling Program supports a diverse set of projects that have developed expertise and capabilities uniquely poised to address topics that cut across several of these grand challenges.

As part of the 2018 Earth and Environmental Sciences Modeling Integrated Principal Investigator Meeting[1], investigators from across RGMA attended multiple working sessions related to variability and change at synoptic to multidecadal timescales to: (1) summarize current research efforts across RGMA, (2) enumerate and describe gaps in research in this topic and related to the EESD grand challenges, and (3) identify ways to effectively and efficiently address these research gaps. As a result of this process, six themes were identified (each with a cross-cutting grand challenge question) where RGMA expertise and capabilities could readily be leveraged to address research gaps, these cross-cutting grand challenges, and ultimately the EESD grand challenges:

- **Convection and surface-atmosphere interactions**: *How do cloud microphysics, atmospheric dynamics, surface fluxes and their multiscale interactions influence the predictability of mesoscale convection and its impact on surface conditions and land-atmosphere interactions from synoptic to interannual time scales?*
- **Synoptic to Intraseasonal Scale Interactions:** *How do synoptic-scale disturbances and intraseasonal modes of variability emerge from—and feed back onto—the seasonal mean land-atmosphere-ocean-ice state and how will these interactions evolve in a changing climate?*
- **Extremes and Impacts:** *What interactions across spatial and temporal scales drive extreme and impactful events, and how can understanding of such interactions be leveraged to better comprehend, quantify, and predict extreme and impactful events?*
- **Multi-year Earth system variability, predictability and prediction**: *What is the interplay between internal variability (from extreme weather to low frequency modes) and external forcing (both anthropogenic and natural) that affects predictability and prediction of near-term regional climate in decadal climate predictions and what critical processes limit our ability to improve predictability and predictions of multi-year Earth system variability?*
- **Ecosystem responses and feedbacks**: *How do land vegetation, terrestrial, oceanic and marine ecosystems respond to changes in the frequency, intensity, and extent of natural*

[1] Convened November 5-9, 2018 at the Bolger Center in Potomac, MD

and anthropogenic disturbances (extreme weather and hydrological events, land cover change, reactive transport and deposition of aerosols, etc) and influence regional and global environmental conditions?

- **High Latitude Processes and Feedbacks**: *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?*

All six of these themes draw on RGMA strengths – improving fundamental understanding by integrating research across disciplines that include atmospheric physics, climate dynamics, statistics, and computational science using observational, analytic, and theoretical approaches. Research around these themes will address four EESD grand challenges: the Integrated Water Cycle Scientific Grand Challenge, the Drivers and Responses in the Earth System Scientific Grand Challenge, the Data-Model Integration Scientific Grand Challenge and the High Latitudes Scientific Grand Challenge. There is a strong potential for investment in these areas to efficiently and effectively address several EESD grand challenges.

Convection and Surface-Atmosphere Interactions

Section Lead Authors: Ruby Leung (PNNL) and Gabriel Kooperman (UGA)

Atmospheric convection plays important roles in the Earth's water cycle. Through the release of latent heat, convection is a major driver of atmospheric circulations that redistribute heat, moisture, and momentum in the atmospheric column and between the tropics, extratropics and polar regions. Organized convection, particularly when manifested as mesoscale convective systems (MCSs), is often associated with heavy precipitation and strong winds and is thus linked to extreme events worldwide. Through its impacts on radiation, winds, and precipitation, convection can alter surface-atmosphere interactions and processes such as precipitation recycling and ocean mixing. Likewise, land- and ocean-surface conditions can influence the triggering and strength of convective events. Hence convection is a major element of the regional and global water cycle, with important implications for understanding and predicting precipitation and floods on weather time scales, and water cycle changes and cloud-feedbacks on longer time scales.

Changes in atmospheric composition and land-use–land-cover are expected to have impacts on convection, which can modulate the climate system's response and have significant implications for the water cycle. For example, changes in convective storms, such as the intensity, frequency and areal coverage, can influence the characteristics of precipitation and surface-atmosphere interactions, with consequences for the statistics of flooding. As an important driver of large-scale circulation systems, particularly monsoon and Hadley circulations, changes in convection can influence the climates of large populated regions. Our ability to predict how drivers and responses in the Earth system will affect convection is hampered by significant gaps in understanding and modeling convection and its role in surface-atmosphere interactions and large-scale circulation. Advances in observation, modeling, and computing present important opportunities for improving predictive understanding of convection and its regional and global consequences.

Grand Challenge Question: *How do cloud microphysics, atmospheric dynamics, surface fluxes and their multiscale interactions influence the predictability of mesoscale convection and its impact on surface conditions and land-atmosphere interactions from synoptic to interannual time scales?*

Addressing this grand challenge question will require improved capabilities for observing and modeling mesoscale convection and associated cloud, dynamical, and surface processes. Model-data fusion (e.g., ModEx) and modeling experiments that leverage existing BER investments will play a key role in hypothesis-driven modeling and analysis.

Expertise across existing projects within RGMA offers a unique opportunity to advance our understanding of convection and surface-atmosphere interactions by organizing research on the following science questions:

- How do cloud microphysical processes influence the macro-physical properties and lifecycle of mesoscale convection?
- How do the spatial and temporal variability of surface fluxes influence mesoscale convection and its predictability during the warm season?
- How do mesoscale convection and atmospheric circulation interact locally and remotely to limit the predictability of precipitation from synoptic to interannual time scales?
- How does the frequency, intensity, and timing of precipitation from mesoscale convection impact the surface water balance and its influence on surface temperature and runoff?

Description of Challenges and Current Research in RGMA

RGMA has been supporting research on convection with an increasing focus on organized MCSs because of their relatively larger impacts on precipitation and atmospheric circulation compared to isolated convection and the larger challenges for Earth system models to simulate MCSs. RGMA funded research has been investigating the role of the coupled energy and water cycles in the warm season over the Central U.S. to determine why global Earth system and numerical weather prediction models overestimate regional surface temperatures. Through studies such as the CAUSES (Clouds Above the United States and Errors at the Surface), (Morcrette et al. 2018), the ubiquitous warm bias was linked to too much solar radiation at the surface and too little evaporation, both related to the lack of MCSs simulated in models with parameterized cumulus convection.

RGMA has also been supporting research to understand observed and future changes in MCSs. Statistically significant increases in MCS mean and extreme precipitation and MCS lifetime have been identified east of the Rocky Mountains for the past 35 years (Feng et al. 2016). These results motivated the need to understand robust, long-lived MCSs that contribute importantly to extreme precipitation and their past and future changes. Convection permitting simulations suggested a positive feedback between MCSs and atmospheric circulation that enhances the lifetime of MCSs. Studies are investigating the large-scale environments that support the development of robust MCSs over the Central U.S. in the warm season (Song et al. 2019), which aid in understanding model biases and projections of multidecadal changes in MCSs. Ongoing research is also assessing the impacts of wildfires and urbanization on severe convective systems through changes in aerosols and heat fluxes (Chen et al. 2020).

Through RGMA, studies have been evaluating several different approaches for improving the ability of models to represent MCSs. These include convection permitting regional models, non-hydrostatic global variable resolution models with the capability for convection permitting modeling through regional refinement, and global models with superparameterization to capture different aspects of convective systems including MCSs, their interactions with the land surface, and their impacts on surface hydrology. Advances have also been made in developing methods to track MCSs, and metrics and diagnostics to quantify and understand model biases.

Research Gaps and Future Directions

Current research supported by RGMA is making great strides in improving understanding and modeling of convection and surface-atmosphere interactions. To address the grand challenge and science questions identified above, more research highlighted below is needed to bridge major remaining gaps in order to transform our predictive understanding of mesoscale convection and related surface-atmosphere processes:

Short Term (3- 5 years) Research Goals

- Improve the availability and synergistic use of a variety of measurements from field campaigns to in-situ and remote sensing platforms of microphysical processes, latent heating, dynamics, and thermodynamics environment to understand convective microphysics feedbacks on cloud-scale and large-scale dynamics.
- Leverage Atmospheric Radiation Measurement (ARM) and other BER investments in observation (e.g., data from Next Generation Ecosystem Experiments) with data-fusion techniques to improve estimates of surface fluxes of energy and water in order to better constrain observation and modeling of surface-atmosphere interactions and their roles in the development and evolution of mesoscale convective systems over land and ocean through local and non-local processes including feedbacks.
- Improve understanding of the key microphysical, surface, dynamic and thermodynamic processes that influence the development of MCSs during spring and summer and differentiate the predictability of different types of MCSs in the two seasons.

Long Term (10 years) Research Goals

- Develop a modeling hierarchy, including single-column models, limited area models, and multiscale and uniform/variable resolution global models for the atmosphere coupled to land-surface models with simple-to-complex representations of processes to improve understanding of model biases in the simulation of MCSs and land-atmosphere coupling, and to test hypotheses of convection-surface and convection-circulation interactions.
- Improve the characterization of MCSs, including their three-dimensional structure, across a variety of different climate regimes, and hence understanding of the roles of MCSs in the global and regional water and energy cycles.

- Elucidate the roles of different MCS characteristics (e.g., size, intensity, and propagation speed) and land-surface conditions in the development of convective events that are most conducive to extreme precipitation and flooding.
- Develop a better understanding of the major mechanisms that control how MCSs respond to warming and the implications for the global and regional water cycles and hydrologic extremes.

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Synoptic to Intraseasonal Scale Interactions

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Much Earth system variability manifests as transfers of energy, momentum, and mass between processes occurring on an extremely broad range of temporal and spatial scales. Yet interactions between the synoptic, intraseasonal, and interannual scales set some of the most prominent patterns of variability of the atmosphere, the upper ocean, and the land surface. For example, moisture transport by synoptic-scale atmospheric rivers sets the seasonal mean surface hydrology of much subtropical land and is in turn modulated by the months-long eastward propagation of moisture anomalies across the Indo-Pacific Oceans associated with the Madden-Julian Oscillation (MJO; Madden and Julian, 1971). Interannual variations of seasonal-mean, planetary-scale winds induced by the El Niño-Southern Oscillation (ENSO) alter the MJO and the hydrodynamically unstable basic state out of which monsoon depressions and easterly waves emerge; the MJO and synoptic-scale westerly wind bursts in turn alter the initiation and evolution of ENSO events. The existence of such interactions has been known for decades, yet only now are numerical methods and computational resources available to enable more accurate simulation of these interactions down to the synoptic scale, thus enabling a new era in the study of the eddy-mean flow interactions that dominate the hydrological cycle. For example, a horizontal grid spacing of around 25 km in global atmospheric models is beginning to represent many convectively coupled atmospheric vortices and waves, blocking events, atmospheric rivers, and other weather phenomena. The coming decade is thus an opportune time to address longstanding questions of eddy-mean flow interactions across this range of scales.

Grand Challenge Question: *How do synoptic-scale disturbances and intraseasonal modes of variability emerge from—and feed back onto—the seasonal mean land-atmosphere-ocean-ice state, and how will these interactions evolve in a changing climate?*

Implicit in this challenge is the question of how synoptic to intraseasonal variability, and its relationship with the seasonal mean background state, will evolve as climate changes. Here we set our sights on new sources of predictability and novel understanding that will enable us to project secular changes in synoptic-scale and intraseasonal variability.

Expertise across existing projects within RGMA offers a unique opportunity to advance our understanding of synoptic to intraseasonal scale interactions by organizing research across the following science questions:

- How does synoptic to intraseasonal variability shape (and feed back on) the background mean state? How do changes in Earth system drivers impact this variability?
- What are the modes of atmospheric variability that have yet to be tapped for extending the forecast beyond the typical weather range? For those already identified, what are the mechanisms of the added predictability?

- What are the first-order dynamic and thermodynamic constraints on the subseasonal to seasonal evolution and poleward reach of monsoons, which control climate over nearly all low-latitude land, including the southwestern US?
- What are the foundational building blocks for the MJO? What is the origin of MJO predictability and how does this manifest as predictability for subtropical to mid-latitude extremes?
- To what extent can sea ice melt be considered a forcing for midlatitude variability and extremes in the context of the coupled Earth system?
- What are the respective roles of polar and extra-polar forcings in driving changes at high latitudes?
- How do land surface processes interact with synoptic and intraseasonal atmospheric disturbances?

Description of Current Challenges and Research in RGMA

Existing lines of research in the RGMA portfolio address a wide range of topics on synoptic to interannual variability.

Modes of Subseasonal Variability: Internal modes of variability are the result of deterministic dynamics and feedbacks from constituent processes and hence of unique predictability beyond the typical weather range; external climate forcings often drive the climate by projecting on these internal modes. Considerable activities are centered around understanding the formation mechanisms of poorly understood modes (e.g., the MJO and the Baroclinic Annular Mode [BAM]; Thompson and Barnes, 2014) through phenomenon-focused diagnostics and hypothesis-driven modeling. Activities also focus on understanding the possible influence of these modes on tropical and subtropical extremes, such as tropical cyclones (TCs) and atmospheric rivers (ARs).

Detection and Statistical Characterization: Effort is also ongoing to statistically characterize daily-to-seasonal precipitation variability and detect the change of hydrological extremes in the past and future under climate change. A good example is the Atmospheric River Tracking Method Intercomparison Project (ARTMIP; Shields et al., 2018) for ARs that characterizes uncertainty in AR science associated with uncertainty in the tracking methods.

Monsoons: Recognizing that monsoons are multi-scale phenomena involving interactions across a wide range of scales from the convective (1 km) to the planetary (10^4 km), and also recognizing that large uncertainties exist in projections of future monsoon rainfall, effort has focused on fundamental dynamic and thermodynamic constraints on the seasonal evolution of tropical precipitation, as well as on the sensitivity of synoptic disturbance genesis and intensification to the background seasonal mean state.

Polar-Extra-polar Interactions: There has been considerable interest in the scales between synoptic to decadal on two themes: i) High- or variable-resolution modeling for capturing the fine-structured processes of the polar climate system itself and polar-extra-polar interactions; ii) identifying/understanding the robust impacts of Arctic sea ice melt on midlatitude weather and extremes and the associated teleconnection mechanisms through development of metrics and hierarchical modeling.

Research Gaps and Future Directions

The search for fundamental understanding remains—and should remain—the central driving force for research within RGMA, especially for subjects such as the MJO, BAM, TCs, ARs, etc. For example, gaps in understanding of the fundamental formation and propagation mechanisms of the MJO hamper advances in simulation of the MJO by the model development community, initialization of the MJO by the numerical weather and subseasonal prediction communities, and projection of long-term changes in MJO activity by the climate change community. This lack of understanding is rooted in the multi-scale, multi-component nature of these phenomena. Process-based approaches are still valuable in this regard: e.g., process/feedback/component denial experiments that leverage the modeling hierarchies developed within RGMA. Understanding of the energy and enstrophy cascades may give insights into the limit of prediction of certain phenomena (e.g., mesoscale convective systems).

There are two general research approaches that, when combined with existing expertise and investments within RGMA, are most likely to advance fundamental understanding leading to predictive understanding of the Earth system: holistic modeling and analysis approaches that emphasize inter-scale, inter-component, tropics-to-extratropics, and polar-extra-polar interactions; and statistically oriented analyses that are explicitly merged with physical principle-based diagnostic approaches (e.g., physics-guided machine learning approaches). The following research directions will advance our ability to understand synoptic to intraseasonal interactions in the Earth system.

Short Term (3-5 years) Research Goals

- Determine where, when, and for what applications high resolution is necessary to accurately represent synoptic and intraseasonal modes, and their interactions, in Earth system models; attention should especially be focused on attribution of bias in low-resolution simulations to unresolved processes and to bias in large-scale boundary conditions and forcings.
- Develop new statistically advanced and computationally efficient analysis frameworks to understand and assess the fidelity of cross-scale interactions in upcoming exascale Earth system simulations; these frameworks should explicitly be designed to digest exabytes of data and should leverage existing RGMA investments in statistics and machine learning to enable new scientific understanding.
- Improve the synergistic use of high-resolution remote sensing data, modern ensemble atmosphere-ocean reanalyses, and operational atmospheric state estimates (e.g. from

numerical weather prediction) to create process-based diagnostics of synoptic-scale and intraseasonal phenomena. Emphasize use of ensembles to characterize uncertainty, as well as novel estimates of atmospheric state tendencies due to radiation, latent heating, surface drag, and other subgrid-scale processes typically parameterized in global Earth system models.

- Systematically characterize the causal relationship between synoptic-scale disturbances, intraseasonal modes of variability, and extreme events.
- Develop model hierarchies to assess the sensitivity of synoptic-scale and intraseasonal phenomena to the seasonal-mean background state. E.g., combine regional cloud-resolving models that employ imposed lateral boundary conditions with global model ensembles, land- or ice-surface models, or atmosphere-ocean state estimates; Bayesian frameworks and data assimilation techniques may be useful here.
- Expand the use of *in situ* data, especially from ARM facilities and other BER platforms, in the assessment of synoptic-scale and intraseasonal phenomena in global models; employ direct observations of surface fluxes of radiation, water, and heat to expand understanding of the role of these fluxes in synoptic-scale and intraseasonal variability.

Long Term (10 years) Research Goals

- Understand the physical processes responsible for interactions between synoptic-scale disturbances, intraseasonal modes, and the seasonal-mean background state by addressing questions of how and where hydrodynamic instability of the background state causes synoptic variability, how upscale momentum and energy transfers allow the ensemble of synoptic variability to influence the seasonal mean, and how intraseasonal modes (e.g. the MJO) undergo two-way interactions with the seasonal mean state and with the ensemble of synoptic disturbances.
- Understand how the above cross-scale interactions set regional Earth system variability and teleconnections and how they affect predictability and prediction of the long-term statistics of synoptic and intraseasonal variability.
- Create new projections, and better constrain existing projections, for the response of synoptic-scale and intraseasonal phenomena to warming, with specific focus on implications for regional hydrologic change over land.
- Develop simple models—conceptual, statistical, and theoretical—that augment and validate future projections of synoptic-scale and intraseasonal variability made by exascale Earth system models. Empirically constrained, physically motivated simple models provide a way to confirm and expand on results from much more complex Earth system models.

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Extremes and Impacts

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Extreme events in the climate system take many forms and vary with location and time of year. These are often associated with severe weather, including extratropical and tropical cyclones (TCs), mesoscale-convective systems, atmospheric rivers (ARs), and snow storms. These phenomena and others drive precipitation extremes, wind extremes, drought, heat waves and cold air outbreaks, marine heat waves, and floods.

Impacts on human life and health, energy production, property and infrastructure, water, agriculture, ecosystems, and the environment can be driven by climatically extreme events; and they can also be driven by events that are more mundane by some measures, yet still correspond to, but represent a confluence of factors co-occurring in space and/or time.

Extreme events are, by definition, rare – they are sometimes defined as the statistical tail of climate system variability, which is influenced by interactions across timescales and by interactions among the atmosphere, land, ocean, ice, and human components of the Earth system. Impactful events are those that have repercussions for people, infrastructure, or the environment – and may or may not be associated with extreme events. Measuring and modeling drivers and responses to changes in extremes is central challenge of Earth system science, and of the RGMA program. In order to facilitate research on extremes and impacts, we propose framing it around the following grand challenge.

Grand Challenge Question: *What interactions across spatial and temporal scales drive extreme and impactful events, and how can we leverage understanding of such interactions to better understand, quantify, and predict extreme and impactful events?*

Addressing this grand challenge question requires leveraging expertise across multiple disciplines and through research across multiple spatial and temporal scales. BER investments in Earth system models, and model hierarchies, will play a key role. Expertise across existing projects within RGMA offers a unique opportunity to advance our understanding of extremes and impacts by organizing research around the following science questions:

- What factors (including modes of variability) have contributed to extreme and impactful events in the historical record?
- How do interactions across time and space scales influence extreme and impactful events?
- To what degree and on what timescales are extreme events predictable?
- What is required to achieve such predictability of extreme events?
- How do interactions across different components of the Earth system (atmosphere, land surface, ocean, ice, and humans) influence extreme and impactful events?

- How well do existing model simulations capture and reproduce extreme and impactful events, and what is needed to improve simulations of these events?

Description of Current Challenges and Research in RGMA

Current work in RGMA addresses a number of interesting and important aspects of extreme and impactful events. Tropical cyclones represent a large focus in RGMA, given their role as one of the most destructive events driven by the climate system impacting the U.S. This includes understanding processes that influence TC characteristics, quantifying TC characteristics in climate models, through the use of high-resolution and variable-resolution capabilities, as well as attributing observed and projected changes in TCs. RGMA investments have resulted in new techniques for tracking and characterizing TCs in large climate datasets to allow for novel investigations of these events and improved understanding, such as the role of the ocean in storm intensification. ARs play an important role in western U.S. hydrology, and recent research within RGMA has started to explore the drivers, impacts, and uncertainties in these extremes. For example, RGMA support enabled the Atmospheric River Tracking Method Intercomparison Project (ARTMIP; Shields et al., 2018), which is designed to explicitly and systematically quantify uncertainties associated with different choices for defining atmospheric rivers. RGMA work has also investigated and quantified extremes in the integrated water cycle more generally, to evaluate their response to drivers of change in the Earth system.

Beyond TCs and ARs, research across RGMA has sought to understand how large-scale forcing and natural variability impacts the statistics and characteristics of a variety of extreme event types. These analyses include detailed studies into numerical model design, including resolution, on the characteristics of these extreme events (e.g., Leung et al., 2013, EOS). Such analyses have recently broadened beyond TCs and ARs, to tackle precipitation from mesoscale convective systems, hail events, and drought and aridity, with impacts from wildfire and human activities such as urbanization and irrigation.

Research Gaps and Future Directions

Improving fundamental understanding should remain the main driver for research within RGMA. That said, given the current research in RGMA and the overarching research goals described above, there are some specific research gaps that could be addressed through leveraging existing expertise and capabilities within RGMA. These research gaps fall within two main categories: gaps in our quantitative understanding of the drivers of extremes in the integrated water cycle, and gaps in our ability to effectively utilize Earth system models to simulate extremes and connect them to impacts. The following research directions will advance our ability to understand, quantify, and predict extremes and their impacts:

Short Term (3- 5 years) Research Goals

- Expand research to a broader portfolio of extremes, such as extreme wind events, drought and aridity, and heat waves (including marine heat waves).
- Synthesize extreme event tracking efforts across RGMA to enable a broader and more effective quantification and comparison of observations to models.
- Understand what spatiotemporal aspects of precipitation are important for translating into flood events, and develop diagnostic metrics that enable insightful evaluation of model fidelity.
- Continue efforts to define extreme and impactful events from a stakeholder-informed, use-inspired perspective, with an emphasis on efforts that are interdisciplinary, and that leverage expertise across EESD (e.g., Multi-Sector Dynamics) and other parts of DOE– and even other agencies.

Long Term (10 years) Research Goals

- Document observed extreme events (e.g., precipitation extremes) to enable meaningful evaluation of extremes in simulations, such as those in climate model intercomparisons.
- Continue to emphasize building basic physical understanding of extreme events and the environmental conditions they are associated with.
- Expand research on extremes in the coupled Earth system, especially their interactions with various components (e.g., ocean and land), with an emphasis on understanding the role of surface-atmosphere interactions in driving synoptic to interannual variations in weather extremes and our ability to simulate such variations.

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Multi-year Earth system variability, predictability and prediction

Topical Leads: *Benjamin Kirtman, Gerald Meehl, Christina Patricola*

Individual weather events are generally not predictable more than a couple of weeks in advance. This is because the atmosphere is chaotic, so that errors in the initial conditions grow over a few days into large-scale disturbances. However, the atmosphere can also be influenced by external factors. This is clearly illustrated by the annual cycle. For example, we expect more mid-latitude storms during winter than summer, although the precise time and location of each winter storm cannot be predicted more than a couple of weeks in advance.

Predicting the annual cycle is, of course, trivial. Furthermore, there are other natural factors that can cause particular seasons, or even years or decades, to be abnormal. The combination of natural variability along with forced changes will be felt most acutely through changes in the frequency and intensity of extreme events, including droughts, floods, storms, fires and heat waves. There is therefore an increasing need to know how likely climate events with large societal impact will be in the coming seasons to decades. This section of the white paper *very* briefly reviews the current scientific understanding and challenges, and some of the near-term and longer term research goals of multi-year Earth system variability, predictability and prediction.

Grand Challenge Question: *What is the interplay between internal variability (from extreme weather to low frequency modes) and external forcing (both anthropogenic and natural) that affects predictability and prediction of near-term regional climate in decadal climate predictions and what critical processes limit our ability to improve predictability and predictions of multi-year Earth system variability?*

Addressing this Grand Challenge question will require understanding limit of predictability, and implicitly mechanisms, of phenomena operating at interannual to multi-decadal time scales such as El Niño-Southern Oscillation (ENSO), Atlantic Multidecadal Variability (AMV), Pacific Decadal Variability (PDV). A current overview of these topics and references related to initialized prediction is given in Meehl et al. (2020).

Description of Challenges and Current Research in RGMA

a) Multi-Year ENSO

The largest source of seasonal forecast skill is ENSO, which is a coupled mode of variability in the tropical Pacific. ENSO grows through positive feedbacks between sea surface temperature (SST) and winds: a weakening of the easterly trade winds produces a positive SST anomaly in the eastern tropical Pacific which in turn alters the atmospheric zonal (Walker) circulation to further reduce the easterly winds. ENSO influences seasonal climate almost everywhere either by directly altering the tropical Walker circulation, or through Rossby wave trains that propagate to mid and high latitudes. The strongest impacts occur in Indonesia, North and South America, east and South Africa, India, Australia and East Asia. There is also a notable influence on the NAO, especially in late winter. ENSO also modulates the vertical wind shear and stability in the tropical Atlantic atmosphere, leading to fewer (more) hurricanes during El Niño (La Niña) years. ENSO's heat discharge can fuel intense hurricanes in the East North Pacific and these hurricanes may impact the south west US and Hawaii islands.

Observed El Niño and La Niña events are mostly not opposites of one another. For example, most El Niño events last a few seasons and frequently transition quickly into La Niña. From time to time El Niño events tend to reach extreme intensities. In contrast, one out of two observed La Niña events lasts 2 years or longer. Moreover, very few La Niña events transition directly into El Niño as expected from oscillatory behavior. Instead, the great majority of La Niña events slowly decay, oftentimes taking several years of near-neutral conditions until the next El Niño event is triggered. These observational findings suggest that there is multi-year predictability associated with La Nina events and frequent El Niño to La Niña transitions also implies potential predictability. Not all these observed characteristics of ENSO are simulated by climate models, and improving the simulation and thus prediction remains a challenge. For example, the diversity in ENSO's spatial pattern is largely missing in all climate models. The asymmetry between El Niño and La Niña amplitude and duration are not well captured by many models.

b*) Atlantic and Pacific Multi-Year Mid-Latitude Variability*

Atlantic Multidecadal Variability (AMV) is likely to be a major source of decadal predictability. Observations and climate models indicate that north Atlantic SSTs fluctuate with a period of about 30–80 yrs., linked to variations of the Atlantic Meridional Overturning Circulation (AMOC). Climate models suggest that the AMOC and AMV can vary naturally or through external influences including volcanoes and greenhouse gases. Idealized model experiments suggest that natural fluctuations of the AMOC and AMV are potentially predictable at least a few years ahead. If skillful AMV predictions can be achieved, observations and modelling studies suggest that important climate impacts, including rainfall over the African Sahel, India and Brazil, Atlantic hurricanes and summer climate (e.g., heat waves, droughts) over Europe and America, might also be predictable.

Pacific decadal variability (PDV) is also associated with potentially important climate impacts, including rainfall over America, Asia, Africa and Australia. The combination of PDV, AMV, and trends appears to explain nearly all of the multi-decadal US drought frequency, including key events like the American dust bowl of the 1930s.

c) Prediction and Predictability

In terms of the state-of-the-science in multi-year system prediction, Kirtman et al. (2013) provides a comprehensive review largely based on studies that analyze the experiments made as part of the Coupled Model Intercomparison Project phase 5 (CMIP5). The upshot of the Kirtman et al. (2013) review was there is considerable and more recently, mounting evidence for skillful predictions of temporally averaged temperatures up to ten years in advance particularly in the North Atlantic, Indian, and western subtropical Pacific Oceans. The skill in predicting terrestrial surface temperatures was considerably more modest. All of the models participating in the CMIP5 decadal prediction experiments used eddy-parameterized ocean components. More recently there have been numerous follow on multi-model studies and detailed analysis based on a specific models and experimental designs, and, in particular, ocean eddy-permitting models. A comprehensive review is beyond the scope of this white paper.

Finally, we note that initialization of the current state of the climate is essential for seasonal to decadal forecasts. Here we note an important distinction between initialization and assimilation. There are a number of data assimilation methodologies (e.g., Kalman filter techniques, optimal interpolation techniques, coupled vs. uncoupled) and these primarily focus on how to combine observational estimates with models whereas, initialization emphasizes how the results of these various data assimilation methodologies (or other approaches) are used to actually initialize predictions. In this white paper we focus on the initialization issue. There are a number of possible initialization strategies but in the broadest terms they fall into one of four categories, and all have various strengths and weaknesses:

1) Unified initialization. This can include separate assimilation in the various components of the climate system or fully coupled earth system models. The assimilation is viewed as unified in the sense that the assimilation system uses the component models from the prediction system for the data assimilation.

2) Disparate data assimilation and prediction systems. In this category, assimilation products from a specific data assimilation system involving a particular model is used to initialize predictions made with a completely different model.

3) Anomaly assimilation whereby ocean observations are introduced into the model by relaxing the fully coupled model towards gridded ocean analysis.

4) Ocean only simulation where the initial state comes from a forced ocean - sea-ice hindcast simulation driven by, for example, the Coordinated Ocean-Ice Reference Experiments (CORE) atmospheric data sets. One challenge is the typically-used atmospheric data suitable for forcing coarse-resolution ocean simulations has been demonstrated to introduce substantial errors in high-resolution ocean simulations.

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Gaps in Current Research

Improving fundamental understanding should remain the main driver for research within RGMA. That said, given the current research in RGMA and the overarching research goals described above, there are some specific research gaps that could be addressed through leveraging existing expertise and capabilities within RGMA. These research gaps fall within three main categories: 1) gaps in our quantitative understanding of predictability sources of multi-year variability, 2) gaps in models' ability to simulate and predict the multi-year variability, and 3) gaps in methods for skill assessment.

1) *Sources of multi-year predictability*

- The time between El Niño events is typically about 2–7 years, but the mechanisms controlling the initiation of the warm phase and the reversal to the opposite cold phase are not understood completely.

- Mechanisms underlying AMV and to a greater extent for PDV have yet to explain what are the key underlying processes that control their prolonged persistence and their phase transitions.

- AMOC is believed to be driven to some extent by the NAO which does not have a long memory of its own from the underlying atmospheric dynamics alone. Improved predictions of the evolution of the AMOC and associated climate will therefore likely require low frequency variations of the NAO which to be predicted – the predictability in this regard has not been fully assessed.

- There is clear evidence that seasonal forecasts are more skillful when ENSO is active. Not only is ENSO itself more predictable once established, but climate in teleconnected regions is more strongly constrained, and therefore more predictable, when ENSO is active. Idealized experiments also suggest that the predictability of AMV depends on the initial state. Regime dependence of skill could therefore be exploited further to increase confidence in predictions under certain circumstances. These windows of opportunity during which very skillful predictions could be achieved could therefore be used to give forecasts with higher (but conditional) skill. This could arise, for example, if the effects of several different sources of skill align to produce a particularly strong signal. Finally, the importance of multiple constructive and compensating sources of variability in driving the statistics of extreme events highlights the need to understand future changes in joint probabilities of leading modes of variability.

- There has been substantial research on climate variability and on climate change, however, the interplay between variability and a changing background state has received less attention. Understanding the two jointly is important for two reasons. First, modes of variability shape the statistics of extreme events, and second, the response of extremes to patterns of variability depends on the background state, sometimes non-linearly and with threshold behavior. Variations in background state can arise not only from mean climate change (e.g., changes in interhemispheric, interbasin, and intrabasin SST gradients), but also from changes in spatial patterns of variability and the seasonal cycle. For example, the importance of considering ENSO from such a perspective is highlighted by the non-linear relationship between SST and deep convection, together with the strong background SST gradients associated with the West Pacific warm pool and East Pacific cold Tongue. An additional important consideration is how variability in a changing background state can influence the interactions between thermodynamic and dynamic factors important for extremes.

2) *Model errors*

- Model biases remain one of the most serious limitations in the delivery of more reliable and skillful predictions. Biases in the mean tropical-subtropical SST, land-atmosphere coupling, and precipitation are among the most persistent throughout generations of climate models and problematic in terms of impacting simulated extreme events. Many of these deficiencies stem from a poor representation of sub-grid processes, particularly in the atmosphere - namely those associated with the representation of clouds, convection, and precipitation. The current practice of model mean state bias correction is unphysical and neglects entirely the non-linear relationship between the climate mean state and modes of weather and climate variability. In addition, the AMIP simulations often used to circumvent SST biases in coupled models, while informative, lack important coupled processes and feedbacks. Reducing model bias is arguably the most fundamental requirement going forward. A key activity must be the evaluation of model performance with a greater focus on processes and phenomena that are fundamental to reducing model bias and for delivering improved confidence in the predictions.

- In addition to mean state biases, there are other systematic errors related to feedback processes. For example, in some instances coupled models can simulate ENSO events with the correct amplitude for the wrong reason, owing to strong cancellation of coupled thermodynamic and dynamic feedbacks. What is the cause of errors in feedbacks and how these errors affect models' ability to simulate ENSO asymmetry, extreme events, and ENSO predictability are open questions.

- Likewise, the potential predictability in the climate system for monthly to decadal timescales is probably underestimated because of model shortcomings. For example, ENSO's spatial pattern diversity is largely missing in all climate models thus far. The asymmetry in amplitude and duration between El Niño and La Niña events are not well captured in many models. Improving the simulation and thus prediction of ENSO remains a challenge. There is therefore considerable scope for improved skill through model development aimed at reducing biases and improving the simulation of teleconnections. This will be achieved both by increased resolution as computers become more powerful, and improved parameterization of unresolved processes. Progress in model development may accelerate by studying the development of errors in seamless seasonal to decadal predictions. This is particularly relevant for ocean model errors (e.g. tropical SST errors) that develop with time scales longer than those in the atmosphere, for which it is possible to determine if erroneous atmospheric forcing given realistic SSTs is causing the SST errors.

- One key focus of model improvement efforts should be the representation of clouds, convection, precipitation, and radiation - processes which do not always improve over the range of resolutions in the global models used for multi-year predictions. While it is well-known that errors in these processes contribute to mean-state biases, there is increasing evidence that these errors in these processes also contribute to errors in the simulated variability. In particular, recent studies have demonstrated how low cloud processes contribute to errors in the amplitude of AMV, PDV and ENSO. While low clouds are particularly important for variability because their impact on solar radiation reaching the surface systematically varies with SST itself (i.e. the cloud feedback), the latent heat release in deeper clouds and convection drives atmospheric circulation anomalies that can affect surface wind stress and hence impact climate variability. Spatial gradients in the response of radiative fluxes to changes in composition have similar impacts on circulations and climate variability; errors in the representation of radiation and especially its sensitivity to composition changes (the "radiative forcing") may hamper predictability.

- Ocean and atmosphere model resolution may play an important role in simulating a stronger forcing of the atmosphere from the ocean than is achieved in most climate models, and indeed, there is some evidence that the atmosphere is more strongly coupled to the ocean in higher resolution models.

3) *Evaluation and skill assessment methods*

- The process of forecast calibration and skill assessment using hindcasts presents some serious challenges, however, when the lead time of the predictions extends beyond days to months, seasons and decades. That is because to have a high enough number of cases in the hindcast set means testing the system over many realizations, which can extend to many decades in the case of decadal prediction. Given the limited observational record, forecast calibration and skill assessment continues to require careful consideration.

Future Directions

Based on these gaps identified in our current knowledge, we formulate 3-5 year and 10 year research goals to address these gaps in the context of the Grand Challenge.

Short Term (3- 5 years) Research Goals

- Use the CMIP6 DCPP simulations to better quantify regional prediction skill on different timescales especially from the known predictability sources (MJO, ENSO, land surface, sea ice, stratosphere).

- Perform and analyze process experiments to determine interaction among ocean basins on decadal timescales, as well as to elucidate processes and mechanisms that could be producing decadal climate variability and define the role of the effects of volcanic eruptions in decadal climate prediction.

- Perform large ensemble hindcast simulations (30 ensemble members of 10 years each for each start date) with 1 degree class earth system models, and a moderately large ensemble (10 members of 10 years each for each start date) with ¼ degree class earth system models to determine the relative contributions of natural and anthropogenic forcing agents in the initialized hindcasts.

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- Explore of the benefits and limitations of high resolution on synoptic weather events that produce extreme precipitation in a set of initialized hindcasts at 1 degree and ¼ degree and examine processes connected with synoptic systems that produce precipitation extremes ranging from daily to seasonal to interannual in the initialized hindcasts of the DCPP CMIP6 simulations.
- Study how earth system processes will be affected by short-lived climate forcers to better understand how storms could change in initialized hindcasts due to changes in forcing.
- Study predictability of extremes in a changing climate and establish a benchmark of present-day predictability of extremes to establish reliability bounds for initialized predictions.
- Understand how climate model biases influence the predictability of extreme events using coarse and fine resolution and atmosphere-only and coupled atmosphere-ocean simulations from HighResMIP.
- Quantify how decadal-timescale base state changes affect interannual phenomena such as MJO, ENSO, and monsoons.
- Use the CMIP6 RFMIP and CFMIP simulations to understand how the total response to composition changes is partitioned between variability in forcing and variability in sensitivity.
- Analyze CMIP6 simulations to identify the role of specific atmospheric and oceanic processes in Earth system variability. Advanced multi-model diagnostic techniques such as emergent constraints should be used. The goal is to provide information how these processes affect the character of model simulated variability. Example processes to be considered include clouds, convection, precipitation and fresh water forcing of the ocean, boundary layer mixing (in both the atmosphere and ocean), and oceanic upwelling.

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- Use the latest in new observations (both satellite and ground-based from programs such as the DOE Atmospheric Radiation Measurement (ARM) program) to evaluate the model representation of processes (e.g., clouds, precipitation, surface wind stress, soil moisture, sea-surface height) that are critical to simulation of the mean state and multi-year variability of the Earth System. A key goal is the determination of which critical processes are not improving with increases in model resolution, in order that model developers may be made aware of where their focus should be placed.

- Utilize a hierarchy of models (e.g. aqua-planet, non-linear oscillators, models with specific dynamics or diabatic processes) to illustrate and understand the multi-scale nature of Earth-System variability. A key goal is to the determination of the impact of small-scale processes (e.g. boundary layer mixing, clouds) on Earth-system variability and its predictability as well as the feedback of variability back onto the small-scale processes.

Long Term (10 years) Research Goals

- Elucidate mechanisms that produce decadal climate variability in concert with external forcing, and apply these directly to decadal climate predictions using models from low resolution to high resolution.

- Improved understanding of processes and better quantification of impact that can provide a springboard for developing practically useful decadal prediction system beyond the upper ocean heat content.

- Formulate probabilistic climate information from initialized predictions, and quantify the reliability of such predictions, for regional and local space scales and from seasonal to decadal timescales. This will heavily rely on observations to help characterize model processes and mechanisms that produce regional and local decadal climate variability.

- Analyze high resolution global cloud-permitting model simulations that will be suitable for studies of near-term regional climate predictability without deficiencies of cumulus parameterization.

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- Analyze earth system models of the ¼ degree class for a suite of hindcasts with more frequent start dates larger ensembles for each start date to compile better statistical distributions of storm characteristics involving midlatitude and tropical systems.

- Study initialized hindcasts and predictions of regional/local sea level rise and storm surge with ¼ degree class to ⅛ degree class earth system models with consequent improved representations of midlatitude and tropical cyclones in the models, and the input from ice sheet melt from the next generation coupled ice sheet models.

- Quantify the characteristics of near-term earth system predictability associated with MJO, ENSO and decadal variability phenomena in high resolution initialized hindcasts with changes in short-term climate forcers, GHGs, volcanoes, and solar variability.

- Provide strong constraints on the past temporal evolution of radiative forcing to which the Earth itself has been subject to sharpen interpretation of this historical record.

Ecosystem responses and feedbacks

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Plants respond to changing atmospheric CO_2, humidity, radiation and energy, precipitation, temperature, and nutrient availability in complex ways that affect biological and abiotic interactions with the atmosphere. Similarly, soil ecosystems and permafrost also respond to changes in temperature, precipitation, and nutrients and directly interact with the plants they host. Large uncertainties exist in the biogeophysical and biogeochemical formulations of these vegetation, soil, and hydrological responses in Earth system models (ESMs). The strength and timescale of carbon cycle responses in models are linked to the size of initial carbon pools representing vegetation and soil components at pre-industrial equilibrium. High latitude and tropical ecosystems, which store and cycle vast quantities of carbon, are particularly important since they are poorly represented in ESMs and could release large stores of carbon to the atmosphere in response to environmental change, further accelerating the carbon cycle and fueling greater changes in the Earth system. Rigorous identification and quantification of ecosystem response mechanisms that lead to biogeophysical and biogeochemical feedbacks to the Earth system are critical to advancing understanding of the Earth system and improving predictions of climate variability and change. Measurements from experiments designed to evaluate these ecosystem responses are needed to benchmark multi-scale and validate simulated vegetation/soil moisture feedbacks on atmosphere, in terms of mean climate and especially climate extremes.

There is an emerging model capability to represent extreme events such as hurricanes, windstorms, floods, droughts, etc, in Earth system models. Despite growing evidence in the literature that atmospheric-generated extremes produce significant biogeophysical, biogeochemical and climate feedbacks—from local to regional scales and from immediate to long lasting time scales—the coupling of these extreme events with simulated terrestrial ecosystems has received very little attention. In order to properly represent this important aspect of coupling between the atmosphere and land surface, it will be necessary to develop schemes that provide direct representations of atmosphere-drive disturbance (type and severity). Given the ubiquity and unique biogeophysical characteristics of managed lands, these schemes will also need to represent management activities. Progress on this Grand Challenge will enable new capabilities for mitigating the effects on ecosystems and society, and minimize uncertainties in climate prediction.

Weather and climate extremes (WCEs) are single or compound events that impact ecosystem structure or function and society, and they typically have feedbacks to the atmosphere or Earth system. WCEs are occurrences of weather or Earth system variables above (or below) a threshold value near the upper (or lower) end ("tails") of the observed range (Seneviratne et al., 2012). Compound extreme events may amplify impacts (e.g., heavy rains that follow persistent drought and wildfire, and lead to flooding and erosion that have long-term effects on vegetated ecosystems). Models lacking full vegetation dynamics parameterizations can represent only short-term responses to extremes (e.g., reduced productivity and mortality induced by WCEs), and shifts in community composition or structure cannot be captured. Data sets for evaluating long-term responses to extreme events are severely limited. A deeper understanding of the ecological vulnerability to droughts at a range of time scales is needed, including flash drought episodes and multi-year events, along with assessments of their impact representation in ESMs compared to observations (e.g., remotely sensed vegetation indices, citizen science data, monitoring plots). Characterizing and quantifying ecosystem responses to extreme events is required to improve predictions of future impacts and to inform carbon management strategies.

Land use and land cover change directly affect ecosystem structure and function and alter hydrological, biogeophysical, and biogeochemical feedbacks to the Earth system. Natural disturbances (e.g., effects of wildfire, pest infestation, wind throw, tornadoes, hurricane landfall) may be a normal part of maintaining an ecosystem or may dramatically change functioning of an ecosystem in response to changes in extreme events linked to environmental change. Anthropogenic disturbances (e.g., land clearing, agriculture, mining and resource extraction, urbanization) often have a more direct and immediate effect on natural ecosystems and their feedbacks to the Earth system. While basic land cover information is accounted for in ESMs, and rudimentary vegetation dynamics (e.g., over-generalized plant functional types, no treatment of plant migration, oversimplified plant hydraulics, static rooting depths, limited effort to evaluate vegetation feedbacks with observations) are increasingly incorporated into land surface model parameterizations, most disturbance and recovery processes are poorly captured by or completely absent from ESMs. Initial carbon pool sizes, which are typically highly uncertain, strongly influence the strength and timing of carbon fluxes related to disturbance and recovery over longer timescales. Moreover, observational disturbance data are difficult to obtain and use in models. Improved understanding of land use and land cover change processes and their influence by and on the Earth system are needed to enhance representation of biogeochemical processes in ESMs, reduce uncertainties in predictions, and inform land management practices. Better characterization of disturbance history and land cover dynamics is required to evaluate model performance.

Emissions of aerosols and aerosol precursors (e.g., biogenic volatile organic compounds) from land can come from desert dust, fires, or vegetation and can be modulated by regional processes and in turn alter local radiation properties, including changing the distribution between direct and diffuse radiation or reducing photosynthetically active radiation or changing precipitation or temperature patterns. Aerosols and their precursors often react as they are transported by the atmosphere, sometimes over long distances, and influence cloud formation and precipitation. Aerosols are later deposited onto land or ocean surfaces, or directly onto biota, where they lead to a range of effects, from fertilization to mortality. Thus, these dust and aerosol processes impact the global carbon cycle with consequent feedbacks to the Earth system. Large uncertainties are associated with emission and deposition processes, and most of them are poorly parameterized in or completely absent from today's ESMs. While aerosol observations in air are routinely made, measurements of natural source and deposition processes and their effects on ecosystems are needed to drive development and benchmarking of models.

The world's oceans and sea ice, covering two-thirds of the planet, host diverse biota and provide a sink for about 26% of anthropogenic carbon emissions annually. While both ocean and land sinks have grown with increasing emissions, they are expected to weaken and consequent Earth system changes are realized (Le Quéré et al., 2016). Like their terrestrial counterparts, marine ecosystems are affected by nutrient availability and long-term weather; however, atmospheric and ocean circulation play key roles in supporting biota through nutrient upwelling and aerosol/dust deposition. The structure and function of life in the ocean and sea ice has strong feedbacks to the Earth system through changes in albedo, sea spray, and primary and secondary aerosol generation. Today's ESMs capture some ecosystem processes, but typically lack sufficient cross-component coupling (e.g., dynamic river outflows of water and nutrients or dust/iron deposition from the atmosphere lofted from dynamic land–atmosphere interactions) and feedbacks to the Earth system.

Grand Challenge Question*: How do land vegetation, terrestrial, oceanic and marine ecosystems respond to changes in the frequency, intensity, and extent of natural and anthropogenic disturbances (extreme weather and hydrological events, land cover change, reactive transport and deposition of aerosols, etc) and influence regional and global environmental conditions?*

Knowledge acquired in empirical studies will be fundamental to address some of the components of the Grand Challenge. For instance, studies using extensive field work have addressed the impacts of hurricanes on U.S. forested ecosystems (e.g., Negrón-Juárez et al., 2010). These studies have produced models associating hurricane wind speeds with tree disturbance and tree mortality (e.g., Negrón-Juárez et al., 2014). Therefore the coupling of simulated hurricanes and simulated terrestrial ecosystems is straightforward.

Remote sensing can help reveal species specific responses to atmospheric extremes, like droughts of varying intensity/duration.

Improved understanding of cross-component coupling (e.g., dynamic river outflows of water and nutrients or dust/iron deposition from the atmosphere lofted from dynamic land–atmosphere interactions) and feedbacks to the Earth system, particularly at high latitudes, is required to advance ESM performance skill, and more data are needed to constrain marine ecosystem dynamics and to benchmark model fidelity.

Description of Challenges and Current Research in RGMA

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.

Terrestrial ecosystem energy, water, and carbon fluxes. Surface fluxes of carbon, water, and energy are key inputs from land to atmosphere models, and observations of these variables have been used to benchmark carbon cycle, land surface, and ESMs for several decades. Routine observations of these fluxes come primarily from eddy covariance flux measurement tower sites. Networks of these sites, such as **AmeriFlux** and the **FLUXNET** network-of-networks, have expanded rapidly over the last 25 years, and the data and metadata they collect have been used in numerous model intercomparison and model–data comparison studies. Long-term observations (>15 years) are available from an increasing number of sites, offering the opportunity to consider new studies of interannual to decadal variability, long-term flux trends, ecological succession, multivariate Earth system response, and regional to global upscaling.

Soil carbon and nutrient biogeochemistry. Earth's soil holds roughly 2,000 Pg C, and soils have sequestered a significant fraction of CO_2 emissions from fossil fuel burning and human land use change since the start of the industrial era. Soil sequestration strength is determined by turnover rates, which are functions of plant inputs from litter and losses via microbial decomposition, which are both regulated by nutrient availability. Research shows that soil carbon stocks produced by current ESMs are in only fair agreement with global soil carbon distributions, and the models are unable to reproduce local to regional scale spatial soil carbon patterns or to quantify bulk carbon stocks. While research on processes affecting soil carbon turnover are ongoing in **TES** (e.g., **ORNL TES SFA**, **LBNL TES SFA**, **NGEE Arctic**, **NGEE Tropics**, **SPRUCE**) and **RGMA** (e.g., **RUBISCO SFA**) projects, the largest integration of such data comes from the **International Soil Carbon Network (ISCN)**, which organizes and distributes a community-driven soil carbon database and advocates for large-scale synthesis.

Tropical biogeochemistry and hydrology. Tropical ecosystems represent many processes that overlap with those of other biomes but also have additional complexity that makes modeling and benchmarking a distinct challenge. High biodiversity and its role in buffering ecosystem responses to perturbations, above and belowground traits that relate water use and carbon metabolism, and nutrient cycling that limits the rapid carbon turnover and large net annual fluxes are all poorly represented in current ESMs. The need to improve representation of these processes and to benchmark model performance led to the focus for the **NGEE Tropics** project to develop and synthesize key datasets of tropical forest dynamics. Related research is focused on seasonally dry tropical forests and on the heterogeneity of land–atmosphere interactions related to hydrology. These efforts complement and offer valuable data for RGMA projects (e.g., **RUBISCO SFA**) focused on simulation and analysis of vegetation and soil responses to changing environmental conditions in the tropics.

High latitude biogeochemistry and climate. Northern high latitude soils contain vast stores of carbon that are vulnerable to accelerated losses through mobilization and decomposition under continued anticipated warming, with potentially large impacts on global carbon and the Earth system. Many processes control the response of this carbon pool to changing environmental conditions, including active-layer dynamics associated with permafrost, thermokarst formation, thermal erosion, shrub expansion, fire disturbance, soil moisture heterogeneity, and the overall rate of wetting and drying that may accompany warming. The **RUBISCO SFA** and the **NCAR Cooperative Agreement** projects within the **RGMA Program** study and evaluate permafrost responses to environmental change through simulation and analysis. The **NGEE Arctic** project is focused on many of these processes and is developing an understanding of the heterogeneity of polygonal tundra ecosystems, representing that heterogeneity in ESMs, and developing data for benchmarks to test land model performance at high latitudes. Research in the **HiLAT** project emphasizes high-latitude biogeochemistry in Southern Ocean marine ecosystems and their impact on clouds and developing understanding about Arctic deltaic systems as a buffering interface between terrestrial and marine ecosystems. The **RASM** project is also addressing terrestrial and marine biogeochemistry in the Arctic region through high resolution modeling focused on the roles of ocean stratification, mesoscale eddies, coastal and boundary currents, and shelf-basin interactions on nutrient distribution and productivity.

Process-specific and ecosystem perturbation experiments. To become more robust, ESMs require structural improvements to better represent real world processes. Given the enormous complexity of Earth system processes, spanning many spatial and temporal scales, it is still challenging to specify which processes are more critical than others in regulating Earth system dynamics and to evaluate the representation of processes that have been parameterized differently in various models. Process-specific (e.g., **ORNL TES SFA**, **LBNL TES SFA**, **NGEE Arctic**, **NGEE Tropics**) and perturbation experiments (e.g., **FACE**, **SPRUCE**, nutrient addition, water exclusion, soil and/or air warming) offer the opportunity to evaluate ecosystem responses to individual changes in forcing or nutrient and water status. **RGMA Program** activities (e.g., **RUBISCO SFA**) are focused on investigating and improving model representations of these responses and designing process-level benchmarking metrics from experimental observations.

Extreme events. Weather and climate extremes (WCEs) can induce significant impacts on terrestrial ecosystems, including floods, streamflow and soil moisture droughts, vegetation dieback or community shifts, and wildfire. Many of these impacts have significant feedbacks to the atmosphere, and compound extreme events may amplify impacts and feedbacks. As model representations of both WCEs and their ecosystem effects (e.g., mortality and succession) improve, observational data and metrics for assessing these impacts are required. A key focus of **NGEE Tropics** has been on the development of the model structures (**ELM-FATES**) that enable the representation of extremes on ecosystem structure, as well as the key benchmarking data, such as growth and mortality responses to droughts, to test those model structures. The **CASCADE** project is focused on investigation of extreme events and design of statistical frameworks for characterizing WCEs from ESMs, including the **E3SM** model.

Atmosphere and aerosol interactions. Aerosol biogeochemical interactions induce Earth system changes that are comparable in magnitude to forcing from indirect and direct aerosol effects. ESMs (e.g., **E3SM** and **CESM**) simulate fire and dust aerosol distributions using aerosol optical depth and other observations from DOE’s **ARM Program** and other measurement and monitoring efforts. Of particular interest to **RGMA Program** activities (e.g., **RUBISCO SFA** and **Cloud Feedbacks SFA**) are E3SM simulations of concentrations and deposition of iron, nitrogen, and phosphorus nutrients across the open ocean, as well as aerosol effects on diffuse solar radiation and nitrogen deposition on land. Contributions to the aerosol loading from land and ocean sources, including through secondary organic aerosols, are also simulated by the **E3SM** model and are the subject of analysis and benchmarking in the **RGMA Program**.

Gaps in Current Research

Gaps in understanding, model representations, and observational data limit the ability to accurately simulate Earth system responses to drivers of environmental change. Here, we highlight a few of the most serious gaps that address the Grand Challenge listed above and suggest possible paths forward to bridging these gaps.

Influence of energy and water on soil carbon turnover time. Recent research indicates that ESMs dramatically underestimate the mean age of soil carbon, which can have large impacts on climate–carbon cycle feedbacks (He et al., 2016). These uncertainties have driven development of microbially-explicit soil organic matter (SOM) decomposition modules and multi-layer belowground carbon dynamics modules that include permafrost processes like cryoturbation (Koven et al., 2013). Additional research is needed to improve soil dynamics in models (e.g., **ELMv1** and **CLM5**) and to develop benchmarks for SOM dynamics from ^{14}C observations, **ISCN** synthesis data, and soil warming perturbation experiments. Some of the needed soil measurements could be available from **NGEE Arctic** and similar field activities.

Vegetation physiological responses to increasing CO_2, surface energy budgets, nutrients, and atmospheric forcing. Plants respond to changes in atmospheric CO_2, humidity, precipitation, temperature, and nutrients in complex ways, and these responses will affect biological and abiotic interactions with the atmosphere. Recent research has highlighted the large uncertainty in current ESM formulations of these plant responses (Swann et al., 2016; Ghimire et al., 2016), while new observational data and new model formulations have been developed (e.g., in **ELMv1** and **CLM5**). Although perturbation experiments like **FACE** and **SPRUCE** provide direct, short-term measurements of vegetation responses and feedbacks to changes in atmospheric CO_2 and temperature, useful data are also contained in **AmeriFlux**, **FLUXNET**, and **NGEE Tropics** observations. Given the importance of these responses to future atmospheric CO_2 levels and their complex feedbacks with the Earth system, additional research in this area is critically needed to improve and evaluate models, particularly for CMIP6.

Earth system feedbacks from vegetation cover change. Current literature suggests significant biogeochemical, hydrological, and surface energy budget changes result from conversion of forests to grasslands or shrublands, or from grasses to shrub-dominated landscapes in the Arctic or semi-arid regions. Such changes can have strong and varied feedbacks on the Earth system. Relevant processes are poorly characterized by measurements and poorly represented in ESMs such as **E3SM**. Because of the significance of these feedbacks, connections with data coming from the **NGEE Arctic** and **NGEE Tropics** projects, new model formulations in **ELMv1** and **ELM-FATES**, and availability of key observational data from **AmeriFlux** and **FLUXNET**, new analyses and data constraints on models can now be developed and assessed. New models should be used to investigate the coupled and uncoupled atmospheric responses resulting from such significant land cover changes.

Impact of extremes on terrestrial ecosystems. Models lacking full vegetation dynamics parameterizations can represent only short-term responses to extremes (e.g., reduced productivity and mortality induced by WCEs), and shifts in community composition or structure cannot be captured. Data sets for evaluating long-term responses to extreme events are severely limited. Characterizing and quantifying ecosystem responses to extreme events is required to improve predictions of future impacts and to inform carbon management strategies. For some WCEs (e.g., wildfire, severe storms, ice storms), observational data from **AmeriFlux** and **FLUXNET**, in addition to remote sensing, could be used to constrain model results as such response processes are incorporated into models (e.g., **ELMv1**, **ELM-FATES**). It may be possible to use simulations and statistics developed by the **CASCADE** project to evaluate ecosystem responses, particularly from atmospheric rivers and tropical cyclones.

Marine ecosystem responses to warming and oxygen reduction. Marine ecosystems are strongly influenced by ocean circulation, which controls nutrient distribution through upwelling and surface transport, temperature and stratification induced by warming, and carbon uptake and loss. Thus, models like **E3SM** must faithfully reproduce major circulation features, and these must be evaluated using tracers such as radiocarbon and chlorofluorocarbons (CFCs). Only then can models accurately simulate the three-dimensional structure of anthropogenic carbon and trends in primary production, nutrients, and sub-surface oxygen. Research is needed to understand the drivers and long-term impacts of oxygen reduction and ocean acidification. A multi-scale modeling approach, like that employed by the **RASM** project, and model experiments performed in the **HiLAT** project can help improve understanding of underlying mechanisms in critically important regions like the Arctic.

Deposition of iron, nitrogen, and phosphorus on ocean and land ecosystems. While cross-component biogeochemical coupling in **E3SM** and **CESM** has improved, rigorous evaluation of prognostic fire and dust emissions, coupled transport by the atmosphere and deposition onto land and oceans, is not yet in the default version of either model. The concentration and deposition of iron, nitrogen, and phosphorus nutrients across the open ocean and on land, as well as the aerosol effects of diffuse radiation on terrestrial ecosystems, should be assessed. Observational data could come from measurements made at **ARM** permanent and mobile facilities as well as from remote sensing products from **MISR** and **MODIS**, which offer valuable data for evaluating model emissions, transport and aerosol optical depth (AOD). An integrated effort between **RGMA** and **ASR** researchers could address model evaluation of aerosol-ecosystem interactions that would leverage **ESM Program** investments in **E3SM's** aerosol biogeochemistry development.

Land–atmosphere interactions. Feedbacks from changing vegetation abundance/distribution and soil moisture content to the atmosphere remain poorly understood, largely relying on deficient model-based investigations with insufficient observational foundation, and are a major source of uncertainty in future projections. Several recent and ongoing projects have made peripheral attempts to elucidate the role of land–atmosphere interactions, with need for more focused explorations. The **Land Use Model Intercomparison Project (LUMIP)** is exploring the effects of land-use / land cover change (LULCC) on the Earth system and biogeochemical cycles, along with the impacts of land management on surface fluxes of water, energy, and carbon. The **Clouds Above the United States and Errors at the Surface (CAUSES)** intercomparison project is evaluating the role of cloud, precipitation, and radiation processes in contributing to surface temperature biases in models, while exploring the surface energy balance in order to evaluate the representation of evaporation and soil moisture in models. An ongoing **LLNL** project, supported by the **RGMA Program**, is exploring the impacts of intensified radiative forcings and plant physiological effects on terrestrial aridity. Another ongoing **RGMA**-supported university project is statistically quantifying vegetation feedbacks to the atmosphere for evaluation of coupled models and development of process-based weights for environmental change projections.

Future Directions

The Grand Challenge described above supports the overall objective of the Biogeochemical Processes and Feedbacks topical research area for the RGMA Program to advance understanding of the global Earth system and improve predictions of climate variability and change. This research uniquely unifies CESD Programs by leveraging TES and ASR Program field and laboratory experiments and measurements to evaluate and benchmark ESMs, including the E3SM modeling framework, and by informing future model development in the ESM Program. Employing DOE's growing data cyberinfrastructure and Leadership Computing Facility (LCF) resources, RGMA research activities develop new analysis methods and rigorous metrics for examining model performance to address each of components of the Grand Challenge.

Short Term (3-5 years) Research Goals

To make progress in the short term (3–5 years), observational data and ESM simulation results should be used in the following research activities:

- Investigate biophysical responses to vegetation cover change and the resulting coupling with hydrology and other components of the Earth system using best-available surface observations.
- Evaluate plant physiological and land surface responses to changing atmospheric CO_2 levels, surface energy budgets, nutrient availability, and regional environmental conditions.
- Characterize and evaluate soil dynamics (e.g., decomposition, nutrient cycling, cryoturbation) to better understand distributions of soil organic matter and influences of turnover time using isotope data and advanced tracer methods.
- Study ecosystem dynamics, including demography, growth, migration, and mortality of land and ocean ecosystems, the influence of nutrient availability, and two-way interactions with the Earth system.

- Investigate the three-dimensional structure of anthropogenic carbon and its relationship with ocean circulation tracers, and explore impacts of changing atmospheric CO_2 levels and environmental forcing on marine oxygen, carbon, and nutrients.
- Assess aerosol biogeochemical interactions with marine and terrestrial ecosystems, including fire and dust aerosol distributions, emissions of biogenic primary aerosols and secondary aerosol precursors, reactive transport in the atmosphere, dry and wet depositions processes, and direct and indirect feedbacks to the Earth system.
- Evaluate interannual and decadal-scale ecosystem prediction and the resulting moisture and energy feedbacks for phenomena such as El Niño-Southern Oscillation (ENSO).
- Develop and distribute model benchmarking tools employing novel metrics for evaluating model fidelity of ESMs in terms of representation of biogeochemical processes and feedbacks to the Earth system.
- Conduct simulation experiments using the E3SM modeling framework in support of hypothesis-driven research and organized model intercomparison project (MIPs); and
- Perform rigorous evaluation of model performance for MIP activities using the model benchmarking tools developed in the Program. There would benefits from running a MIP focused on the atmospheric responses to regionally modified land surface conditions (e.g. LAI, soil moisture, snowpack) compared to observations.

Long Term (10 years) Research Goals

Over the long term (5–10 years), systematic research progress can be made through the following activities:

- Convene small, well-structured working groups focused on specific ecosystem processes and feedbacks, involving model developers, observationalists, and remote sensing experts, to improve process understanding and derive new model metrics.
- Design and conduct new model–model and model–data intercomparison experiments to elucidate mechanisms influencing future biogeochemical cycling and climate; and
- Accelerate Earth system science by creating a user facility centered around the E3SM modeling framework and RGMA benchmarking and analysis tools to enable DOE and university scientists to perform societally relevant simulation experiments.

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High Latitude Processes and Feedbacks

Topical Leads: *Wilbert Weijer, Gudrun Magnusdottir, Hailong Wang*

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.

Commented [6]: Not my expertise, but my colleagues here at UCI would argue that the most critical interaction goes on where the landfast ice meets the ocean. This is a later point here, but should be front and center

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.