Earth System Modeling and Field Experiments in the Arctic-Boreal Zone

NASA Workshop Report

22-24 May 2012

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National Aeronautics and
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Executive Summary

Climate model calculations performed in the 1980s predicted that the Arctic Ocean and surrounding circumpolar land masses would warm earlier and faster than other parts of the planet as a result of greenhouse gas-induced climate change, augmented by the sea-ice albedo feedback effect (e.g., Manabe and Wetherald, 1975; Hansen et al., 1981; 1984). These predictions have been largely borne out by observations over the last thirty years (e.g., Stroeve et al., 2012; Screen and Simmonds, 2010). Nonetheless, climate models vary widely in their warming trajectories over the 21st century. In addition, a range of biogeochemical cycle (BGC) models indicate that Arctic-Boreal Zone (ABZ) warming could lead to widespread permafrost thaw, which could contribute around 90 ppm CO_2 to the atmospheric CO_2 burden by 2100 (Schaefer et al., 2011), and lead to significant changes in the vegetation cover in the ABZ (e.g., Lawrence and Slater, 2005). However, the uncertainties associated with these BGC model predictions are even larger than those associated with the physical climate system (PCS) models used to predict climate change.

A workshop was held at NASA/GSFC, May 22-24 2012, to assess the predictive capability of current Earth system models (ESMs), prioritize the critical science questions and make recommendations regarding new field experiments that would contribute to important improvements in model subcomponents. This report summarizes the findings of the workshop and is intended to provide input to agency program managers and others when deciding on priorities and resource allocations for field experiments in the ABZ as well as for model development and other related activities.

I. Key Science Questions

Critical questions to guide model development and measurement priorities were identified:

1. Clouds, radiation and aerosols: Are the observed seasonal changes of Arctic clouds primarily determined by the large-scale circulation or do microphysical and surface processes play a key role? What is the role of downwelling infrared radiation in the surface energy budget of the Arctic Ocean in winter? How does aerosol forcing affect the Arctic climate, and how will aerosol loadings change as a result of changes in land-use, industrial emission, desertification, and fire?
2. Ocean circulation and sea ice: What are the processes involved in melting the sea ice and controlling ocean stratification in the Beaufort Sea?
3. Integrated systems, land surface hydrology, and carbon cycle: What are the linkages between land surface hydrology, vegetation changes and the surface energy budget over the ABZ and how will these influence the evolving climate? How, and how rapidly, is the ocean-land interface changing in the ABZ?
4. Carbon balance: How rapidly, in which direction, and by how much will warming and changing precipitation modify the ABZ net carbon balance? Will the impact on net CO_2 exchange be smaller or larger than the impact on net CH_4 exchange?

II. Model Weaknesses

Physical Climate System

Clouds, radiation and aerosols

- (i) Poor modeling of cloud properties, of cloud fraction in winter, and of the annual cycle of cloudiness.
- (ii) Poor representation of mixed-phase clouds in the Arctic, leading to deficiencies in the calculated surface radiation.

(iii) Inadequate modeling of microphysics, particularly ice nucleation.
(iv) Unreliable modeling of the seasonal cycle of aerosols due to inadequate representation of wet scavenging as well as poor simulation of wintertime low-level liquid clouds.

Oceans and Sea-ice

(i) Models have inadequate resolution in the Arctic Ocean, with resulting impacts on the accuracy and realism of the calculated circulation. The representation of narrow coastal currents and the poleward heat and freshwater transports are particularly affected. Oceanic mixing and heat convergence are under-represented.
(ii) Most models show biases in atmospheric circulation and precipitation, impacting the representation of sea-ice distribution.
(iii) Parameterizations of surface boundary layers and air-sea interactions are deficient, impacting ice melt and deep-water formation.

Land surface climatology and hydrology

(i) The representation of the surface-atmosphere exchanges of energy, momentum, water and carbon remain unvalidated at intermediate (1-10km) and larger (ESM) scales.
(ii) Snow processes could be represented better. In particular, wintertime snowpack simulations are too deep, over-insulating the ground below; the parameterized relationships between unresolved spatial variability and snow water variables are very crude; and albedo parameterizations do not adequately treat snow aging and the effects of deposited constituents (dust, black carbon).
(iii) Permafrost and the subgrid distributions of freezing soil are poorly parameterized.
(iv) Lakes are represented crudely.
(v) No ESMs have incorporated thermokarst processes as yet.

Biogeochemical cycles

(i) The representations of carbon dynamics in BGC models have large uncertainties in their parameter values and they lack credible methodologies for upscaling from the local scale to the scales appropriate to ESMs. The links between the PCS drivers and the modeled BGC processes need to be verified.
(ii) Disturbance is not represented convincingly in any ESM. Few models consider fire emissions. Others do so in simplistic ways that do not capture the full vulnerability of the large surface carbon stocks. Disturbance severity needs to be represented.
(iii) The use of vertically integrated soil organic matter (SOM) pools with first-order decay in ESM soil models fails to capture SOM dynamics at high latitudes.
(iv) Phenology is not well modeled, nor is the treeline. The dynamics and gradients of tree canopy density may need to be addressed.
(v) No ESM has permafrost carbon or peatland carbon or permafrost/peatland-specific processes to mineralize their carbon pools; few include nitrogen availability constraints on the carbon cycle; very few credibly simulate CH_4 or N_2O fluxes.
(vi) The source/sink patterns of CO_2 and CH_4 determined from ESM inversions are very poorly constrained by in-situ atmospheric concentration measurements.

III. Proposed Experimental Activities

The broad goals of the experiments proposed here should be to improve our understanding of the governing processes, advance our interpretation and utilization of the available satellite data, and use these gains to significantly improve ESM performance.

Some specific experimental activities were recommended to address the model weaknesses and key science questions listed above. Note that in some cases these activities could greatly benefit from coordination between PCS- and BGC-focused experiments.

Physical Climate System

Clouds, radiation and aerosols

(i) The DOE ARM observations should be extended, with an emphasis on getting better observations of cloud ice properties and their effects on the radiation budget.

(ii) An aircraft- and ground-based field campaign should be conducted, with some focus on the Russian Arctic-boreal zone if possible, targeting aerosol wet removal by super-cooled liquid, mixed-phase and ice clouds.

Oceans and Sea-ice

(iii) A field campaign should be conducted in the western Arctic (Beaufort Sea) to address the processes involved in melting sea-ice and controlling ocean stratification.

(iv) A long-term SHEBA follow-on experiment, like the proposed multi-year MOSAiC (Multi-disciplinary drifting Observatory for the Study of the Arctic Climate) project, should be conducted with 21st century observing capabilities that sample many different thermodynamic and dynamic environments, clean and polluted situations, and provide insights into the larger-scale controls on cloud cover and cloud properties.

Integrated systems, land surface hydrology, and carbon cycle

(v) Experiments, using flux towers and aircraft campaigns, directed at validating the calculated ESM grid-scale surface-atmosphere exchanges of energy, momentum, water and carbon, and relating these fluxes to variables that are amenable to satellite remote sensing should be conducted. These should be integrated with the experiments proposed in section (i) and (ii) of the BGC section below.

Biogeochemical cycles

A key overall goal is to develop, test, and validate BGC models that can be embedded in ESMs. Most of the surface parameters for these models can be extracted from satellite data and model performance should be validated using in-situ observations (1 – 100 m), local-to-regional up-scaling work (100 m – 1000 km) and inversion models (1000 km – ABZ scale).

(i) Integrated surface-atmosphere and surface processes: A network of tower and surface sites is needed to measure surface-atmosphere fluxes of CO_2 and CH_4 and their governing processes, in addition to those PCS fluxes described above.

(ii) Disturbance and carbon cycle dynamics: A combination of satellite fire mapping, in-situ pre- and post-fire inventories, and atmospheric composition (surface, airborne, satellite) measurements should provide the constraints to support disturbance model development. Some flux towers and aircraft campaigns should focus on abrupt disturbance impacts, such as post-fire recovery or rapidly warming permafrost, to study changes in surface properties and associated BGC dynamics. A series of aircraft-based flux measurements of CO_2/CH_4 and Bowen ratios along long transects would provide data under a wide range of environmental conditions.

(iii) Upscaling: For upscaling from site to region, high-precision and continuous tower-based measurements should be made of the mixing ratios, and fluxes when possible, of CO_2, CH_4 and other gas species. Surface-based atmospheric column measurements could complement these tower measurements and validate satellite trace gas retrievals. Vertical profiles and near-surface fluxes of these gases in the planetary boundary layer could be sampled by aircraft during field campaigns. Satellite and aircraft remote sensing data at various spatial resolutions could also be used to characterize surface heterogeneity of the measurement sites and the pan-ABZ. In combination, these measurements could be used to directly evaluate process models over the range of local to regional scales as well as to constrain downscaling schemes.

(iv) Downscaling: A comprehensive effort should be made to expand the network of atmospheric CO_2 and CH_4 concentration measurements in the ABZ, preceded and accompanied by 4DDA/OSSE work to determine the optimal deployment pattern and schedule for inversion studies. This network should directly complement the surface, tower and airborne process study networks listed above and be used to support a multi-team atmospheric inversion initiative allied to satellite trace gas algorithm development.

All of these studies should be directly linked to remote sensing investigations with a view to scaling up the improved process models to the ESM scale. Previous, current and proposed experiment sites in Alaska and Canada (e.g., ABLE, BOREAS, BERMS, NGEE, etc.) should be assessed for their suitability for embedding in a zonal-scale modeling framework to support this work.

IV. Preparatory activities and next steps

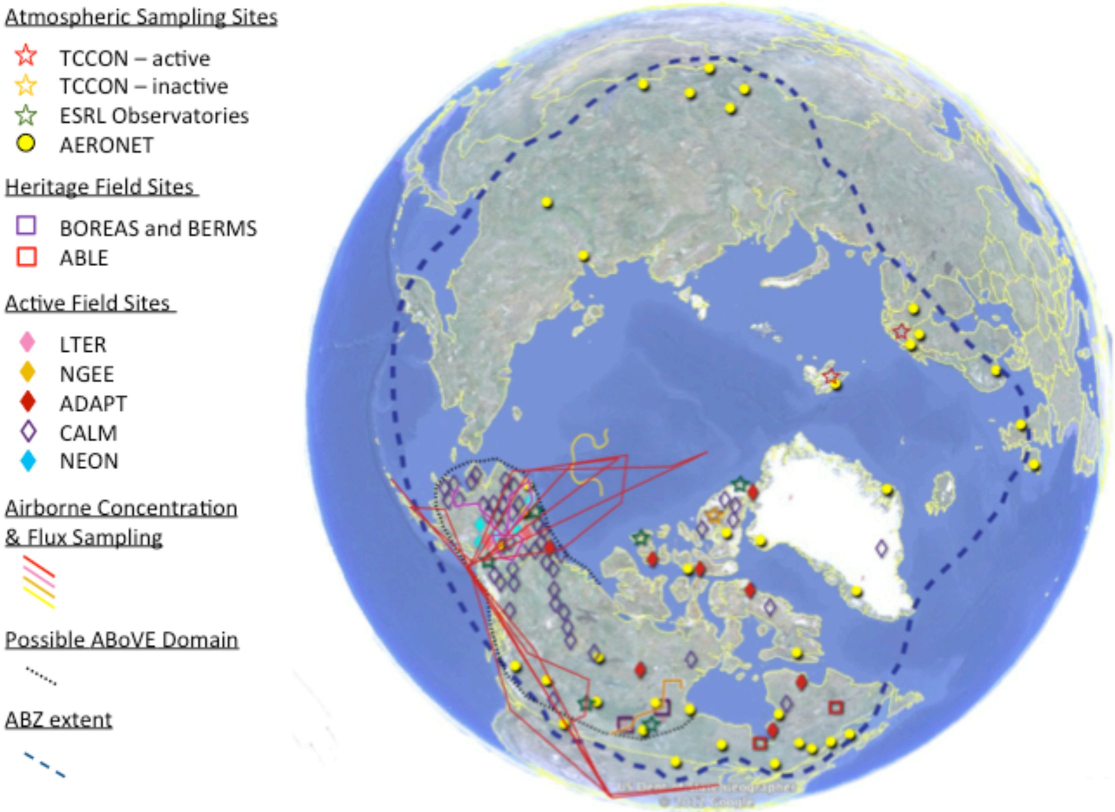
Satellite data and other data sets should be collected and consolidated for the entire ABZ. Model development work, especially cloud and aerosol microphysics developments for mixed-phase and ice clouds, improvements in surface boundary layer parameterizations, and integration of many new elements in land surface modeling of hydrology and BGC, should be a priority. Other activities recommended for early attention include data mining, model support for network and field campaign design, and some integrative work.

Considerable resources and organization will be required to address this research agenda. Inter-agency, international coordination is essential in order to span the physical scales and scientific disciplines involved. The obvious lead players are the US and Canadian federal agencies, but support can be expected from state-level and provincial authorities, and the academic research community. A small interdisciplinary, interagency team should be formed to build on the work of this report and:

1) Assess current and planned activities in the context of this and other study reports; and

2) Assess priorities, feasibility and resources required to conduct the recommended activities.

The structure of this report roughly follows the agenda for the workshop. Section 1 provides an overview of important dynamical, physical and biogeochemical processes in the ABZ. Section 2 summarizes the status of the predictive models and lists those gaps in our understanding that are considered to lead to poor predictive performance. Section 3 itemizes the key science questions that need to be addressed and Section 4 lays out a suggested list of priority experimental activities that could be executed to address those questions. A table in Section 4 summarizes previous, existing and proposed experimental activities in the ABZ.



[illegible], NASA Carbon Cycle & Ecosystems Office

1 Introduction

Early climate modeling studies indicated that the Arctic zone would be a bellweather of anthropogenic global warming (e.g., Manabe and Wetherald, 1975; Hansen et al., 1981; 1984). These early predictions are being realized, as observations now show that the Arctic is warming more than twice as fast as the rest of the planet, (e.g., Hansen et al., 2010), and observations and models indicate that a late-summer ice-free Arctic Ocean could be a reality within two to three decades. This accelerated warming, often referred to as *Polar Amplification*, is mainly attributed to increased solar absorption by the Arctic Ocean as a result of the sea ice-albedo feedback effect (e.g., Serreze et al., 2009; Serreze and Barry, 2011). State-of-the-art models indicate that the Boreal region, the latitude zone immediately to the south of the Arctic, is next in line for accelerated warming due to mid-continental warming and drying, reduced snow cover and hence reduced surface albedo, and reduced cold advection from a warming Arctic.

Changes in the physical climate, biogeochemical systems, and disturbance regimes are expected to generate changes in a wide range of land surface characteristics that will in turn feed back onto physical climate and biogeochemical processes. The combined Arctic-Boreal Zone (ABZ) warming could have significant impacts on regional biogeochemistry and ecology. The Arctic land areas contain deep carbon stores in the permafrost, and the Boreal Zone has large carbon stores in saturated organic soils (peatlands and discontinuous permafrost), mineral soils and the forest biomass. These frozen and saturated soils are expected to release carbon as methane (CH_4) and carbon dioxide (CO_2) as they warm and dry. Warming, longer growing seasons, and permafrost thawing are expected to cause changes in ABZ plant community composition, photosynthesis, and net primary production (e.g., Macias-Fauria et al., 2012). Changing fire frequency and intensity will impact the regional carbon balance (e.g., Turetsky et al., 2011; Mack et al., 2011). The net impact of these changes in productivity and decomposition on the pan-ABZ carbon balance is not known, and system-wide feedbacks are poorly understood and likely to be complex (e.g., Wookey et al., 2009). For CH_4 emissions, the biggest potential increase comes from permafrost thaw, but the magnitude of this effect is quite uncertain, as it depends on whether the thawing/thawed landscapes become wetter or drier (Frolking et al., 2011).

Despite constant improvement, global climate models have greater difficulty in reproducing the current climate in the Arctic than elsewhere (Walsh et al., 2002) and the scatter between projections from different climate models is much larger in the Arctic than for other regions (e.g., Prenni et al., 2007). For example, although all models participating in the Fourth Assessment Report for the Intergovernmental Panel on Climate Change (IPCC AR4) show declining Arctic ice cover from 1953 to 2006, none of the model simulations shows decreases as large as observed. Since 2006 the precipitous decrease in summer sea ice extent has continued, with 2007 and 2012 setting new records (Comiso, 2012). Current observed summer minima are at least 30 years ahead of the consensus model forecast. If these observed changes are due to the increased atmospheric greenhouse gas (GHG) loadings, we can expect an essentially ice-free Arctic Ocean in 20 to 30 years. The models used for the Fifth Assessment Report (AR5) show a similar response. Although the AR5 models are more consistent than the AR4 models when compared with observations over the satellite era (1979–2011), trends from most models remain smaller than observed (Stroeve et al., 2012). Recent studies (e.g., Kay et al., 2011), however, suggest that some of the summer sea ice decline in recent years could be due to natural decadal variability. Partly because of this and partly because of suspected deficiencies in the models' atmospheric parameterizations and their treatment of sea ice, Stroeve et al. (2012) finds that "the CMIP5 models do not appear to have appreciably reduced uncertainty as to when a seasonally ice-free Arctic Ocean will be realized."

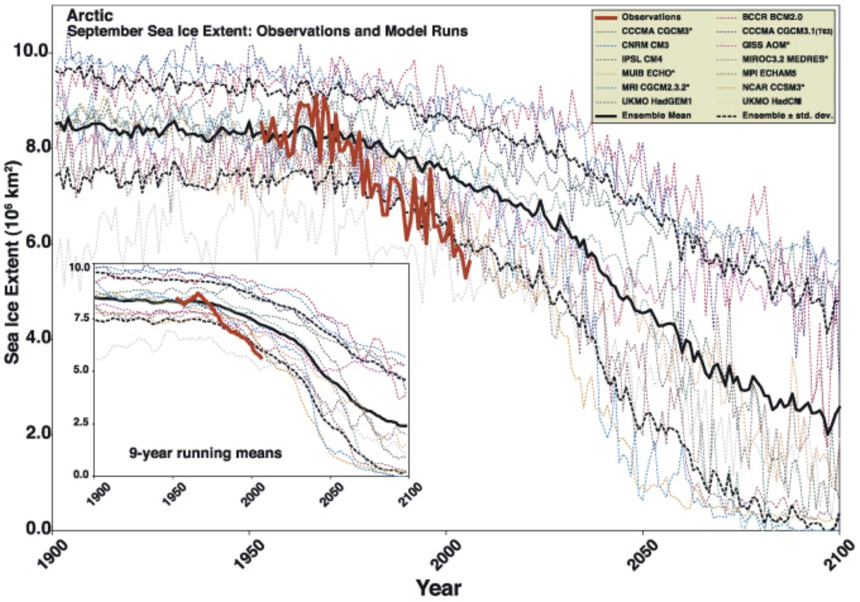


Figure 1a: Arctic September sea ice extent (x 10^6 km^2) from observations (thick red line) and 13 IPCC AR4 climate models using the SRES A1B scenario, together with multi-model ensemble mean (solid black line) and standard deviation (dotted black line). Insert shows 9-year running means. [*From Stroeve et al., 2007*]

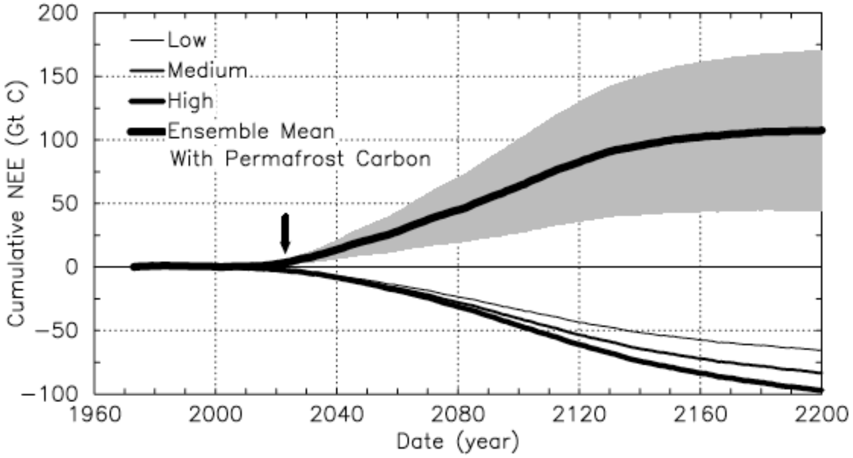


Figure 2: Pan-Arctic total cumulative Net Ecosystem Exchange (NEE, the exchange of CO_2 with the atmosphere, where a positive NEE represents a loss of CO_2 from the land to the atmosphere) for low, medium and high warming rates without permafrost carbon and the ensemble mean with permafrost carbon flux. The grey shading represents uncertainty and the arrow marks the pan-Arctic starting point of 2023 ± 4 years. [*From Schaefer et al. 2011*]

The prediction of likely biogeochemical cycle (BGC) responses in the ABZ, particularly the future trajectory of CO_2 and CH_4 emissions from the thawing permafrost and warming and drying boreal forest, is even more problematic. Several modeling groups have used BGC models in which they have varied the important controlling parameters over the likely range of values in an attempt to bound the uncertainties (e.g., Figure 2; Schaefer et al., 2011; Koven et al., 2011; Schneider von

Deimling et al., 2012). Most of these studies indicate that the ABZ will switch from being a net carbon sink to a source over the next few decades but estimates of the release trajectories vary widely (e.g., Qian et al., 2010). A recent study suggests the evolved CO_2 from thawing Arctic permafrost alone could contribute around 90 ppm CO_2 to the atmospheric CO_2 burden by 2100 (Schaefer et al., 2011). To date, no IPCC model has accounted for this or similar feedback effects associated with changes in the ABZ carbon cycle.

Physical Climate System (PCS) models are becoming more realistic. For AR5, several models aimed to improve model realism by including advanced cloud microphysics parameterizations and explicit modeling of the carbon cycle, i.e., the emergence of Earth System Models (ESMs) with the coupling of PCS and BGC models. The AR5 models do show some improvement relative to AR4, but the issues noted – specifically the limited capability for producing reliable quantitative predictions, especially in the Arctic – are still present. The deficiencies reflect, at least in part, an incomplete understanding of the Arctic climate system and can be related to inadequate observational data or to inadequate analysis of existing data.

Since the sensitivity of the ABZ may well be greater than the models suggest, improving model performance is essential for reliable predictions and projections of the future and for reliable attribution of natural and forced changes. How can we improve the predictive capabilities of models further? To first order, we need observations of particular processes: those related to surface exchanges, including carbon fluxes, and to cloud microphysics, as well as observations that help upscale point observations to the grid-scale of models, both to improve parameterizations and for appropriate evaluation of model performance. The modeling community, therefore, recognized the urgent need to improve ESM performance and to develop a series of field campaigns to support this goal. This idea was used to organize and task this workshop.

1.1 Workshop Organization

The workshop was held at NASA/GSFC, May 22-24 2012, to assess the predictive capability of climate models in the ABZ, identify priorities for development, and make recommendations regarding new field experiments needed to improve model subcomponents. The workshop began with overview presentations of the current state of the PCS and BGC models, presentations on some important recent and planned field campaigns, and a summary of the 2010 report prepared by the Arctic research community for NSF. These presentations provided a focus for breakout sessions – with PCS and BGC discussions in separate groups. The breakout groups were primarily responsible for identifying the most important challenges faced by the model developers and discuss how observations could help. They also identified some priorities that should/could be pursued even without new observations, such as model developments or new data products. Plenary sessions were used to look for synergy and to guide further breakout group discussions.

At the first plenary session, it was decided that model developments and associated field campaigns should be focused towards some key science questions that would then lead to an improvement in predictive capability. These questions were refined at the end of the workshop with a smaller group who were also tasked to provide technical material summarizing discussions as well as additional material on the status of current climate models in terms of the priority areas identified in the breakout discussions.

This report summarizes the findings of the workshop as well as comments received from scientists asked to review the report draft. It is intended to provide input to agency program managers and others when deciding on priorities and resource allocations for field experiments in the ABZ. Here, the ABZ refers to the high northern latitudes, extending from the North Pole down to the southern limit of the boreal forest (~40-50°N, depending on geographical location).

2 Predictive Models - Status and Gaps

In an analysis of IPCC AR4 models, Eisenman et al. (2007) found large inter-model differences in simulating the current climate of Arctic cloud cover that resulted in significant differences in downwelling long-wave radiation and equilibrium ice thickness (Figure 3). In addition to having difficulty in reproducing the current climate in the Arctic, the scatter between projections from different climate models is much larger in the Arctic than for other regions. Much of this uncertainty is related to the inability of current models to accurately represent many of the physical processes and feedbacks involved, especially processes related to Arctic sea ice cover (e.g., Zhang and Walsh, 2006; Stroeve et al., 2007; Eisenman et al., 2007), mixed-phase clouds (Prenni et al., 2007), and near-surface temperature (e.g., Holland and Bitz, 2003). Rind (2008) emphasizes the importance of understanding cryospheric (both sea ice and snow cover) feedback since reduction in surface snow and ice cover, and the corresponding reduction in surface albedo, is the primary reason for the observed high-latitude amplification of surface air temperature (e.g., Serreze et al., 2009; Screen and Simmonds, 2010). Screen and Simmonds (2010) argue that strong positive ice-temperature feedbacks have emerged in the Arctic, increasing the chances of further rapid warming and sea ice loss.

The roles of changes in the cryosphere and changes in atmospheric and oceanic circulation, cloud cover and water vapor in Arctic amplification are still matters for research. A better understanding of the processes responsible for the recent amplified warming is essential for ensuring that our models are capable of predicting any future rapid Arctic warming and sea ice loss.

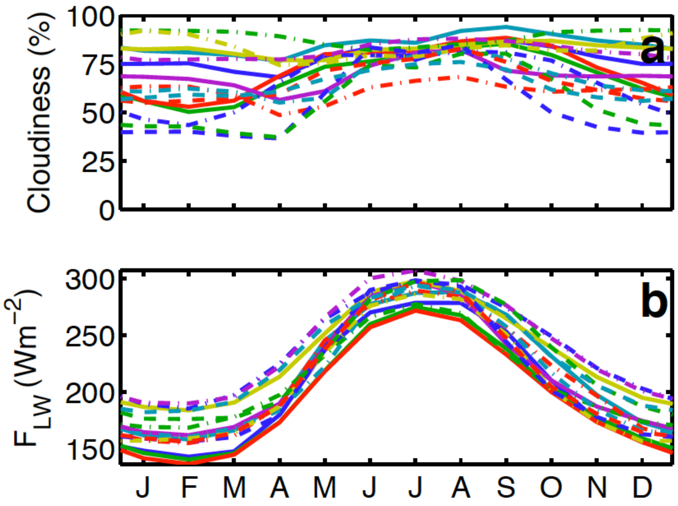


Figure 3: Simulated Arctic (70–90°N) mean seasonal cycle for 1980–1999 from AR4 climate model simulations. (a) Total vertically integrated cloudiness. (b) Surface downward LW radiation. Model attributions are given in Eisenman et al. (2007). [*Figure courtesy of I. Eisenman*]

2.1 Clouds, Aerosols, Radiation, and the Planetary Boundary Layer

Clouds remain the largest source of uncertainty in climate models (IPCC, 2007). They determine the net long-wave (LW) radiation at the surface and also regulate incoming solar radiation in summer. Modeling clouds in the Arctic presents unique challenges because of the frequent occurrence of cloud types and characteristics that are not as common at lower latitudes. Low-level boundary layer (BL) clouds tend to dominate in the Arctic (Shupe et al., 2011), with very high temporal frequencies in all seasons (Intrieri et al., 2002; Vavrus et al., 2009) and somewhat uniform spatial distributions (Vavrus, 2004). Arctic boundary layer clouds are often characterized by the presence of persistent temperature inversions, humidity inversions, and strong, stably stratified layers (Sedler et al., 2012).

A key finding from Arctic atmospheric observatories is that shallow, near surface Arctic clouds are commonly mixed-phase (where ice and liquid are present between about -35 and -5°C), moderately super-cooled and very long-lived (e.g., Shupe, 2011). Accurate modeling of cloud water phase is particularly important for determining the radiation balance at the surface: water phase clouds tend to be optically thicker than ice clouds, resulting in considerably larger downwelling LW radiative fluxes at the surface (e.g., Shupe and Intrieri, 2004), and increases in both the surface air temperature (SAT) and cloud top radiative cooling (e.g., Morrison and Pinto, 2006).

Seasonal variation in cloud response to sea ice loss is due to changes in stability and air-sea temperature gradients. During the melt season, Arctic cloud cover is controlled by large-scale atmospheric circulation patterns, near-surface static stability, and surface conditions (Kay and Gettelman, 2009). The low-cloud increases observed by MISR and CALIOP support the positive cloud-temperature-ice feedback hypothesis that has been proposed as a cause of accelerated surface air temperature increase in the past decade (Wu and Lee, 2012).

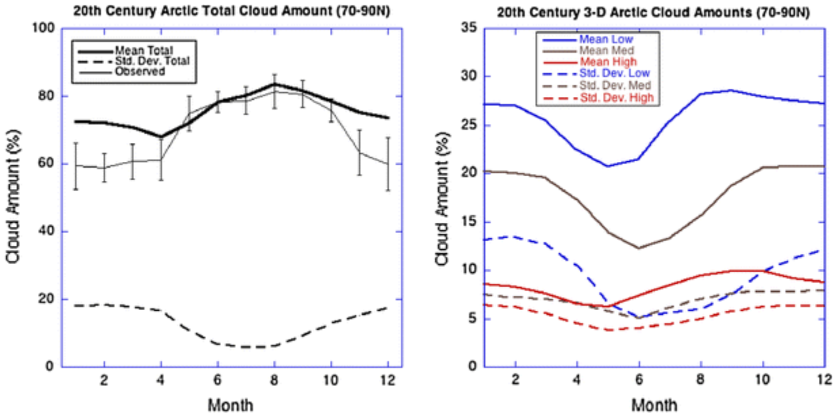


Figure 4: Annual cycle of simulated mean cloudiness (thick solid lines) and intermodel standard deviation (dashed) areally averaged over the Arctic (70°–90°N): (left) Total cloud amount, (right) Low, medium, and high cloud amounts. The observations (thin line) are the average of four surface-based and eight satellite-derived data sets described in Vavrus and Waliser (2008) with error bars representing the upper and lower quartile of reported values. [*From Vavrus et al., 2009*]

Vavrus et al. (2009) found that the AR4 models correctly simulated Arctic cloudiness as a strong function of surface type. Models agree on simulating very cloudy conditions over the ice pack during summer, but disagree in the simulations over Greenland in all seasons and during winter above the ice pack and Canadian Archipelago. The models simulate summertime Arctic cloud amount well, but perform poorly in simulating cloudiness during winter, when they overproduce clouds and exhibit the greatest amount of inter-model spread (Figure 4). Low clouds are correctly modeled as the prevailing cloud type in the Arctic. However, models disagree in the simulated magnitude of low cloud amount, particularly during winter. One-third of the models simulated an inverted annual cycle (more clouds in winter than summer). These differences may relate to biases in the sea ice distribution or circulation patterns and are clear targets for model improvement.

Whereas the models consistently simulate similar fairly small increases in summer temperatures, the autumn peak in low-level warming is not represented in all models (Serreze et al., 2009).

An issue for observations used in model evaluations is that cloud detection using satellite data over the Arctic can be difficult because of the poor contrast between clouds and icy/snowy surfaces. Depending on the threshold being used to identify a cloud (e.g., the minimum optical depth), a sensor can yield a number of possible cloud amounts, especially during the dry winter months when only the infrared channels can be used for cloud characterization. Inconsistencies in cloud characterization derived from different cloud sensors (e.g., Aqua/MODIS, CloudSat/CPR and CALIPSO/CALIOP) have also been reported (Liu et al., 2010; Chan and Comiso, 2011). Some surface-based measurements are also suspect because the temperature sensors can be covered by snow. The climate model community has more recently undertaken comparisons, not only in terms of cloud fraction but also in terms of more direct comparisons with measurements through simulators. The Cloud Feedbacks Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP) produces climate model diagnostics that can be compared with satellite data products from ISCCP, MISR, MODIS, CloudSAT, CALIPSO, and PARASOL. Simulator-facilitated evaluation of cloud properties, such as amount by vertical level and optical depth, can expose large, and at times radiatively-compensating, climate model cloud biases (e.g., Kay et al., 2012).

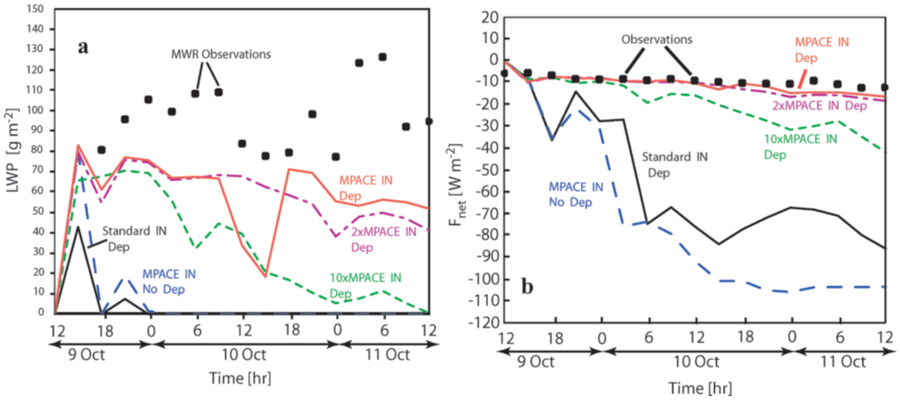


Figure 5: Time series for a two-day simulation plotted over Oliktok Point for Standard IN and M-PACE IN concentrations: (a) liquid water path (g m^{-2}) and (b) net infrared surface flux (W m^{-2}, negative values indicate surface cooling by infrared emission). The solid black points represent observed values: (a) microwave radiometer measurements, and (b) surface infrared flux measurements. Multipliers in front of M-PACE IN indicate the factor by which the M-PACE IN concentrations were increased in the model. "Dep" indicates that IN were depleted by ice precipitation whereas "No Dep" indicates that IN were not depleted. [*From Prenni et al. (2007)*]

Even current state-of-the-art cloud-resolving models have serious difficulties reproducing observed cloud fields from field campaigns (Klein et al., 2009; Morrison et al., 2011; Avramov et al., 2011). Some of the difficulties in modeling Arctic clouds result from inaccuracies in microphysical parameterizations, particularly ice nucleation parameterizations (Figure 5; Prenni et al., 2007). The interaction of aerosols and clouds is critical to these parameterizations.

Aerosols act as Cloud Condensation Nuclei (CCN) and Ice Nuclei (IN), affecting the formation of cloud droplets and ice crystals, which then may alter cloud radiative processes and cloud lifetime by changing precipitation processes. Higher concentrations of ice particles generally lead to rapid glaciation of a mixed-phase cloud. These drastic changes in microphysics affect the radiation balance in the cloud layer as well as at the surface, but they also alter cloud dynamics and macrostructure (e.g., Ovchinnikov et al., 2011).

An issue for modeling Arctic clouds is that Arctic aerosol properties are different from those at lower latitudes (Prenni, 2007). While IN only represent a small fraction of the total aerosol population, their net impact on clouds remains highly uncertain. To improve models, it is important to understand how CCN and IN together impact cloud microphysical properties, phase partitioning, and evolution. Unfortunately, the measurements of ice nucleus properties and ice crystal properties that are needed are not yet available (Fridlind et al., 2012). Substantial instrument development is needed to measure ice nucleation spectra in various modes and to measure ice single-particle properties (McFarquhar et al., 2007; Fridlind et al., 2007) to support validation of their representation in microphysics parameterizations (e.g., Barahona, 2012).

Development of cloud microphysics parameterizations to model super-cooled liquid, mixed-phase and ice clouds in GCMs is a priority. Because of the many known gaps in our knowledge of cloud processes, comprehensive field experiment case studies are required to evaluate simulation fidelity.

Despite some local seasonal natural and anthropogenic sources (e.g., Law and Stohl, 2007), aerosol pollutants in the Arctic lower troposphere (Arctic haze) originate from a mixture of lower-latitude forest fires, agricultural fires (e.g., Hegg et al., 2010; Wang et al., 2011) and industrial activities (Rahn et al., 1977). During winter the polar front expands equatorward as far as 40°N, so aerosols from major source regions in Asia, Europe and North America can be rapidly transported to the Arctic (e.g., Fisher et al., 2011) and impact Arctic climatology (Menon et al., 2008) and ecological systems (Muir et al., 1992). They perturb solar reflection and thermal radiative emission by clouds and they directly scatter sunlight back to space. While the more abundant sulfate and organic matter particles in the Arctic haze likely cool air at the surface, light-absorbing black carbon (BC), a minor but important component of the Arctic haze (Sharma et al., 2006), can directly heat the haze layer and subsequently warm the surface through enhanced downward LW radiation (Quinn et al., 2007). In addition, absorbing aerosol particles deposited onto snow and ice surfaces can enhance absorption of shortwave (SW) radiation at the surface, resulting in a warming of the lower atmosphere and more rapid melting of snow and ice (Warren and Wiscombe, 1980; Flanner et al., 2009).

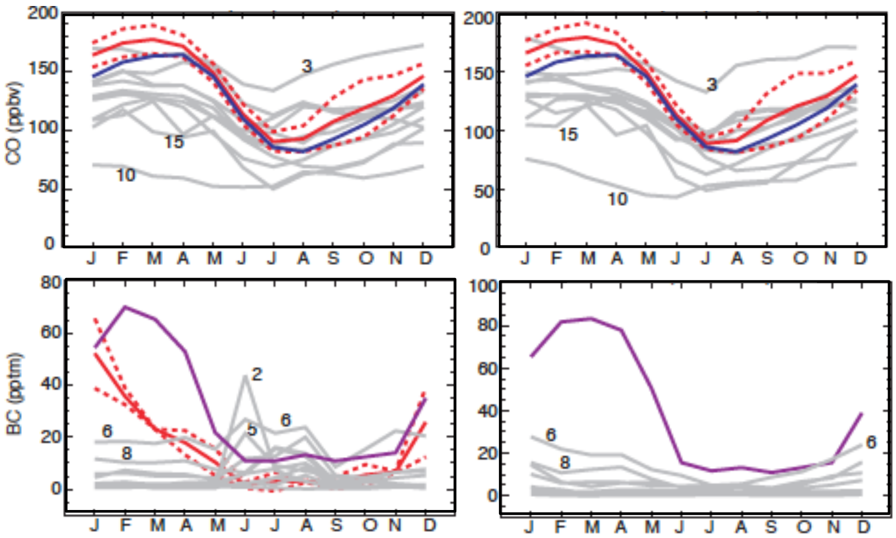


Figure 6: Observed and modeled seasonal cycles of CO (upper) and BC (lower) surface concentrations at Barrow (left) and Alert (right). Results from 17 models are in grey. Plots for CO show observations from the NOAA Global Monitoring Division, with 1992-2006 means and standard deviations in red and 2001 in blue. BC data are from Barrow during 1996-1998 (red), and from Sharma et al. (2006) using equivalent BC over 1989-2003 (purple). [*From Shindell et al. (2008)*]

Garrett et al. (2011) showed that the seasonal cycle of Arctic BC is primarily driven by wet scavenging of lower-latitude sources en route to the Arctic at near-freezing temperatures. Models struggle to reproduce the observed Arctic aerosol seasonality (Figure 6), perhaps because fast processes such as wet scavenging are exceptionally difficult to parameterize within the coarse spatial grid of climate models (Shindell et al., 2008). In addition, climate models tend to overestimate low clouds in the Arctic region, particularly wintertime low-level liquid clouds (e.g., Vavrus and Waliser, 2008; Qian et al., 2012). This can be a potentially important contributor to the under-prediction of BC and other aerosol species in the Arctic by climate models (e.g., Wang et al., 2012; Koch et al., 2009).

A field campaign targeting aerosol wet removal by super-cooled liquid, mixed-phase and ice clouds, along with observations from CloudSAT, CALIPSO and other A-train sensors, would be very helpful to increase the understanding of aerosol transport to the Arctic from lower latitudes and subsequent deposition onto snow and ice within the Arctic, and to improve the representation of these processes in global models.

Longwave radiation dominates the surface energy balance of the Arctic Ocean during all seasons and plays a major role in the climate feedback (Curry et al., 1996, 1997), yet downwelling LW radiation is still poorly known over both land and ocean, especially in winter. Many climate models overestimate surface absorption of solar radiation partly due to problems in the parameterizations of atmospheric absorption, clouds and aerosols (Randall et al., 2007). Difficulties in simulating absorbed solar and infrared radiation at the surface leads inevitably to uncertainty in the simulation of surface sensible and latent heat fluxes.

The DOE ARM observations should be extended, with an emphasis on getting better observations of cloud ice properties and their effects on the radiation budget. The satellite remote sensing component should be well supported. A long-term follow-on to SHEBA (Surface Heat Budget of the Arctic Ocean), like the proposed multi-year MOSAiC (Multi-disciplinary drifting Observatory for the Study of the Arctic Climate) project, should be conducted with 21st century observing capabilities that sample many different thermodynamic and dynamic environments under clean and polluted situations, providing insights into the larger-scale controls on cloud cover and cloud properties.

In addition to examination of Arctic cloud distributions, climate model evaluations have also considered the representation of surface boundary layer temperature inversions, which are ubiquitous in the lower Arctic atmosphere. The inversions occur frequently in the lowest few hundred meters above the surface throughout all seasons and are most persistent and strongest during the winter months when surface solar heating is minimal or absent. Boé et al. (2009) demonstrated that temperature inversions in the lower-Arctic atmosphere regulate heat content of the upper-Arctic Ocean through modification of outgoing LW radiation. CMIP3 models over-predicted atmospheric inversion strength, and some models were found to exaggerate stable and underestimate unstable regimes (Medeiros et al., 2011). An examination of CCSM4 found the atmospheric boundary layer in the model is too stable as compared to ERA-40 and ERA-Interim, particularly during spring over both land and ocean surfaces. The surface inversions were still too strong (by nearly a factor of two) and too numerous. Thus, *boundary layers continue to be challenging for models, particularly in the highly stratified Arctic, and should be a priority for future model development.*

Climate sensitivity to planetary boundary layer (PBL) depth has been shown to be largest for shallow stable boundary layer regimes (Knight et al., 2007), such as would be found at night or in wintertime. Model overestimation of stable PBL heights may contribute to underestimation of climate sensitivity (Esau et al., 2010). *In-situ measurements of PBL height, for example using LIDAR,* *over an expanded area are needed to confirm this hypothesis. To identify the causes for the apparent overestimate in PBL depth, moisture and wind profile measurements and surface enthalpy flux measurements are needed. These would answer questions about whether models respond incorrectly to wind shear or whether the surface enthalpy flux is overestimated. Raman LIDAR for moisture profiles should be added to any backscatter lidar measurements.*

2.2 Ocean and Sea Ice – Physical Climate System

Both ocean and sea-ice processes represent critical components of the Arctic and the global climate system. The formation of North Atlantic Deep Water (NADW) is an important factor in maintaining the thermohaline circulation that transports heat from the tropics through the Atlantic Ocean to the Arctic. An important element in NADW formation is the freshwater export from the Arctic Ocean to the North Atlantic subpolar seas, where a freshwater cap can effectively stabilize the water column.

Sea ice cover is particularly important because it buffers air-sea heat fluxes and strongly influences Earth’s absorption of solar radiation through ice-albedo feedback. As the climate warms, the summer melt season lengthens and intensifies, leading to less sea ice at summer’s end. Summertime absorption of solar energy in open water areas increases the heat content of the ocean. Ice formation in autumn and winter, important for insulating the warm ocean from the cooling atmosphere, is delayed. This promotes enhanced upward heat fluxes, seen as strong warming at the surface and in the lower troposphere.

A unique feature affecting the freshwater content within and export from the Arctic Ocean is the Beaufort Gyre freshwater reservoir, comprising a set of specific atmospheric, sea ice, and oceanic conditions and interactions that have significant influence on Arctic and global climate. Besides the disappearing sea ice cover, the Beaufort Gyre freshwater reservoir is the next largest entity in the Arctic Ocean where we expect to find sensitivity to global climate change.

Investigation of Beaufort Gyre dynamics and change requires a comprehensive long-term measuring and monitoring system and careful analysis of both observational data and numerical model results to examine conditions, mechanisms and variability of freshwater accumulation and release. A field campaign could help to answer the question: What are the processes involved in melting the sea-ice and controlling the ocean stratification, especially in the western Arctic (Beaufort Sea)?

Unfortunately, the majority of models used for climate projections have significant limitations in their representation of past and present sea ice variability in the Arctic. Most current climate models do not reproduce observed multi-decadal sea ice variability and trends in the pan-Arctic region (Stroeve et al., 2007; Figure 1). The ensemble multi-model mean trend in September Arctic sea ice extent from 1953 to 2006 is much too conservative, being about 30 years behind the observed trend. CMIP5 models yield similar, yet somewhat more conservative, results to the CMIP3 predictions of Arctic sea ice decline noted above (Maslowski et al., 2012; Stroeve et al., 2012). Some of the models have quite unrealistic distributions of sea ice thickness for this period; others have unrealistic extent. Model representation of sea ice thickness presents additional challenges as it involves not only thermodynamic interaction with the ocean below, but also the dynamic and thermodynamic effects from the atmosphere above. An unrealistic sea ice–thickness distribution will affect the modeled ice extent and area as well as volume, which in turn may delay (or accelerate) predicted changes in seasonal sea ice cover in the Arctic Ocean. *Detailed analyses of changes in sea ice thickness and volume are needed to determine the actual melt rate of Arctic sea ice.*

The seasonal evolution of Arctic sea ice albedo undergoes a number of distinct phases including dry snow, melting snow, melt pond formation, pond evolution, and fall freeze-up (Perovich et al., 2002).

Because of the importance of surface albedo parameterizations, CCSM4 (one of the models for CMIP5/AR5) included a parameterization of melt pond effects and the deposition and cycling of aerosols (e.g., Holland et al., 2012). Melt ponds can form and expand rapidly, reducing the surface albedo, but then suddenly drain and cause the surface albedo to rise. The CCSM4 melt pond parameterization is simple and further developments are needed. Distinguishing large melt ponds from open water in the Arctic using satellites is not trivial (e.g., Steffen et al., 1992), so the most detailed assessment of melt pond evolution over the summer occurred during SHEBA. *Further research with remote-sensing observations and a SHEBA follow-on campaign (like the proposed multi-year MOSAiC) are needed to improve the melt pond parameterizations and support model evaluations.*

Maslowski et al. (2012) list critical deficiencies in current climate models: sea ice thickness distribution, deformation, variability and export, air-ice-sea interactions, northward oceanic and atmospheric heat convergence, and freshwater content and export into the North Atlantic. Due to deficiencies in parameterizing the effect of ocean eddies, ocean models significantly under-estimate oceanic mixing and heat convergence in the Arctic Ocean. Atmospheric biases in climate models, particularly in the patterns of sea level pressure and precipitation, are key contributors to deficiencies in sea-ice simulations. Vavrus et al. (2003) infer that deficiencies in simulating ice cover in turn impacts the simulation of high-latitude vegetation by affecting the atmospheric circulation and thus the patterns of temperature and precipitation over land.

Further model development and comparison with observations are needed. Observations of thickness distribution, deformation and export have improved in recent years with the advent of ICESat and CryoSat 2 data (Kwok, 2011). For completeness, *model development should also emphasize getting the right distribution of sea ice that survives the summer and of multiyear ice*. These ice types are measured well and are showing large interannual declines (Comiso, 2012).

2.3 Ocean and Sea Ice – Biogeochemistry

The workshop did not address ocean and sea-ice BGC models. However, Drs Kevin Arrigo, Jeff Bowman, Clara Deal, and Scott Elliott provided input after the workshop.

Marine net primary productivity (NPP) is a key process in the global carbon cycle, controlling the uptake of dissolved inorganic carbon (DIC) in the sunlit surface waters of the ocean and its transformation into organic carbon (OC). However, neither absolute values for global annual NPP and exported particulate OC (EP) nor their spatial and temporal variability are well known from direct observations (Schneider et al., 2008). Ocean circulation and mixing, which transport nutrients into the euphotic zone, control nutrient availability for marine biological production. The melt of sea ice in spring and summer also affects the occurrence of phytoplankton blooms near the ice edges since low-density meltwater provides a stable environment that is ideal for photosynthesis because of the presence of abundant sunlight (Smith and Comiso, 2008).

Current estimates of NPP on Arctic continental shelves may be drastically underestimated (Arrigo et al., 2012). Recent observations from an ICESCAPE (Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment) field campaign suggest that under-ice blooms are widespread, consistent with earlier observations (e.g., Alexander and Niebauer, 1981). Arrigo and van Dijken (2011) showed that NPP in the Arctic has increased 20% over the last decade in response to reduced ice cover and longer open water seasons. Processes that could increase the availability of surface nutrients to support increased NPP include increased river runoff, increased shelf break upwelling, enhanced eddy activity, and greater vertical mixing as the surface ocean is increasingly exposed to wind forcing. Unfortunately, these processes are poorly represented in current models (Seferian et al., 2012; Popova et al., 2012) and have only been sampled sporadically during field campaigns.

Popova et al. (2012) compared five externally forced coupled physical-biological ocean-only models of the Arctic domain that participated in the Arctic Ocean Model Intercomparison Project (AOMIP). Whereas the models showed similar distributions of present-day vertically integrated NPP and were broadly in agreement with in-situ and satellite-derived data, the physical factors controlling this distribution differed between models. There was substantial variation in the depth of winter mixing, one of the main mechanisms supplying inorganic nutrients over the majority of the Arctic Ocean. Although these five models manifested similar levels of light limitation owing to general agreement on the ice distribution, the amount of nutrients available for plankton utilization differed between models. Thus the participating models disagree on the fundamental question of whether light or nutrient availability controls present-day Arctic productivity.

Evaluations of the ocean carbon cycle component in ESMs show discrepancies from available observations, primarily remotely sensed ocean color observations (Schneider et al., 2008). In a comparison of four ESMs, Steinacher et al. (2010) found disagreement among the models in the Arctic where three models project an increase in NPP over the 21st century, while one model (the one that agrees best with observations on a global basis) projects a decrease (Figure 7). Results from the Coupled Climate–Carbon Cycle Model Intercomparison Project (C^4MIP) (e.g., Friedlingstein et al., 2006) suggest that more complete treatments of ocean ecosystems (e.g., resolving more than one phytoplankton functional type), micronutrient limitation, and ocean acidification impacts on the calcium carbonate cycle are needed. In addition to improvements in the physical climate model, ocean and sea-ice BGC model developments under consideration include the nutrient-sulfur cycling due to sea ice biology (Elliott et al., 2012) to improve the simulation of dimethylsuflide (DMS), an important aerosol precursor.

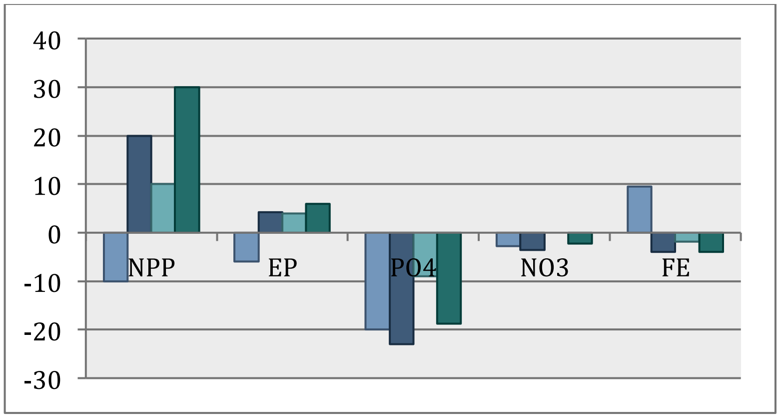


Figure 7: Long-term trends of NPP, EP and related properties in the Arctic as projected by the four models under SRES A2 in Steinacher et al. (2010). The projected changes are with respect to preindustrial conditions (average 2090–2099 minus average 1860–1869). Changes in NPP and EP are in units of mgC $m^{-2}day^{-1}$; PO_4 is 10 µ mol m^{-3}; NO_3 is mmol m^{-3}; and Fe is 10 nmol m^{-3}.

An issue for model development and evaluation is that our current knowledge of Arctic Ocean ecosystems is limited by under-sampling since existing observations are very sparse and biased toward summer. Yet it is during the spring and fall transition periods that ice-ocean exchange processes strongly influence ice algae and phytoplankton that uptake CO_2, as well as zooplankton and bacteria all of which cycle and redistribute C, N and DMS.

Year-round time series measurements of biological and chemical concentrations, parameters, and distributions, such as for biomass, nutrient concentrations, and biological rates are needed. Observational networks and multi-scale field observations should be coordinated with complementary modeling to facilitate sampling over a broad range of scales and upscaling information from fine-scale observations to global-scale ESMs.

2.4 Land Surface – Climatology and Hydrology

ESMs do not represent the energy budget over the Arctic region well, and variations in the Arctic freshwater budget are not well understood (e.g., Kattsov et al., 2007). Variations in hydrologic processes in the ABZ impact terrestrial and marine ecosystems as well as the cryosphere and ocean circulation through the impact on ocean stratification. Landscape (soil) moisture status appears to be important not only for some physical climate system processes but also to the generation of CO_2 and non-CO_2 GHGs (e.g., Khvorostyanov et al., 2008; Qian et al., 2010; Grosse et al., 2011).

2.4.1 Land surface energy and freshwater budgets

The range of historical and future surface temperature increase in CMIP5 ESMs is similar to the range generated by the CMIP3 coupled general circulation models (CGCMs). Thus, ESMs still have significant biases in the prediction of ABZ surface climate parameters, such as seasonal and diurnal temperature and precipitation ranges and interannual variability, the precipitation distribution, and downwelling LW radiation (e.g., Randall et al., 2007; Kattsov et al., 2007; Lawrence et al., 2008, 2012). The implications of these biases for ABZ land processes need to be assessed.

Snow cover and depth play a significant role in the surface energy budget due to albedo and thermal insulation effects and they exert a major control over permafrost distribution pattern in discontinuous and sporadic permafrost zones, particularly in areas of complex terrain. Vegetation influences all components of the land-surface energy budget. In winter, the presence of forest reduces albedo by at least 60% relative to nearby snow-covered grassy areas (Betts and Ball, 1997) and thus is critical in determining surface albedo, the surface energy budget and planetary boundary layer (PBL) temperatures and depths. In summer, vegetation again influences the surface radiation budgets, but latent heat fluxes from forest have been observed to be strongly dependent on soil temperatures (e.g., the so-called "green desert" observed in BOREAS-94 (Betts et al., 2001)).

In general, the surface energy budgets of Arctic and Boreal ecosystems are not well represented in ESMs owing to the difficulties in modeling fluxes over spatially variable landscapes. This issue was addressed in BOREAS and other experiments but an assessment of what is done well and what is done poorly in ESMs, and why, is warranted.

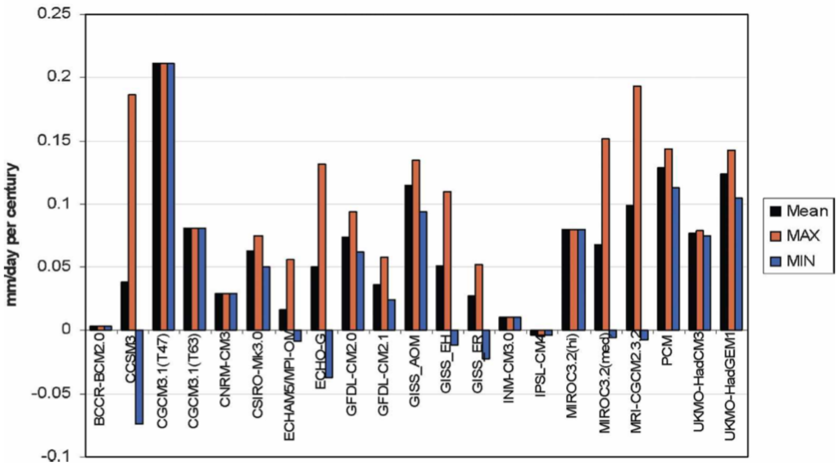


Figure 8: P–E linear trends (mm day^{-1} per century) in CMIP3/AR4 models: maximum (MAX) and minimum (MIN) values for each model ensemble, and values for the ensemble means (Mean) over the entire Arctic Ocean terrestrial watershed for 1965–99. [*From Kattsov et al. (2007)*]

In examining the Arctic freshwater budget simulated by AR4 climate models, Kattsov et al. (2007) noted that evaluation of model simulations of the Arctic hydrologic variables is complicated by uncertainties in observational estimates. However, they found that the biases are at least partly attributable to the spatial variability and complexity of the surface and to biases in large-scale atmospheric circulation and sea ice distribution. There was significant model variability in simulated trends in P-E over the Arctic Ocean terrestrial watershed for 1965-1999 (Figure 8). The models were more similar in their projected 21st century precipitation increases, with a 17-model mean annual precipitation increase of 33% in the Arctic, much higher than the 4.5% global mean increase. *More comprehensive evaluations of the terrestrial surface moisture fluxes, both simulated and observed, are a priority for assessments of the robustness of the projected changes of the hydrologic budget of the Arctic.*

2.4.2 Snow

Virtually all the ABZ land surface is snow-covered for part of the year. Land surface models, which are forced to represent the large-scale behavior of snow with a limited number of prognostic variables, require parameterizations that account realistically for unresolved snow processes. A key example is the impact of the spatially varying snow cover extent and snow water equivalent, which can strongly affect the land surface energy balance through their impact on albedo. In nature, this spatial variability is controlled by topography (e.g., due to altitudinal temperature effects), wind (e.g., the build-up of wind-swept snow in lowland areas), vegetation (e.g., the ability of tall trees to stick out of the snow, reducing the snow's impact on albedo), and by other factors, such as the spatial variability of the precipitation itself. Such variation in snow properties leads to important differences in permafrost characteristics and potential for carbon cycle feedbacks (Gouttevin et al., 2012). The CMIP5 models show a wide range of snow insulation effects, resulting in a wide range of simulated distributions of current permafrost. Improved treatment of thermal insulation by snowpacks (which strongly influences soil freeze-thaw processes) is needed.

Models require parameterized relationships between the unresolved spatial variability of snow and the available diagnostic variables. These relationships are very crude in current models, largely due to the lack of adequate surface observations to support the development of more sophisticated (and presumably more accurate) parameterizations. Satellite data are mostly adequate for the characterization of snow cover extent but *more work needs to be done to retrieve snow water equivalent and surface albedo*. The uncertainties in snow water equivalent are usually associated with snow aging and freeze-thaw processes that affect the dielectric property and emissivity of the surface. Albedo is also affected by grain size, melt/thaw processes and deposited constituents (dust, black carbon). *More basic research with in-situ measurements targeted towards improvement of macroscale model algorithms is needed.*

2.4.3 Permafrost

Permafrost exerts strong controls on hydrologic and biophysical processes over much of the ABZ. Processes that are affected include surface and subsurface runoff, evapotranspiration (especially from trees with roots in the seasonally thawed active layer) and surface biogeochemical fluxes, e.g. of CH_4 and CO_2, which are strongly temperature dependent. Permafrost also represents a major source of largely immobile stored water, the availability of which for river runoff can change if thawing occurs. Permafrost processes are strongly linked with seasonal snow cover, since snow is a strong insulator. The active layer depth is influenced by the date of first snow and snow depth distribution through the winter season. ESMs will require careful treatment of snowpack properties (depth, density, and thermal conductivity) to successfully predict changes in active layer depth and permafrost thickness and distribution.

Climate warming will reduce the spatial extent of permafrost and hence modify the hydrological regime in the ABZ, as lateral water redistribution driven by topographical variation can be greatly enhanced with reduced permafrost areas and increased active layer thickness. This lateral water redistribution not only modifies the local plant growth, grass-shrub-forest distribution, heterotrophic respiration, and other biogeochemical processes, but also the landscape averages of the net carbon and other gas fluxes as represented at the ESM grid scale (Sonnentag et al., 2009; Govind et al., 2011).

Most modern land surface models (LSMs) include a representation of frozen soils and permafrost, but, in climate models, these are applied to relatively large grid cells (~100 km), and hence either ignore or parameterize spatial variability. While the thermodynamics of freezing soil moisture are relatively straightforward, representation of even the direct thermodynamic freezing processes differ greatly amongst the CMIP5 ESMs. Furthermore, large-scale model treatments are necessarily limited by their inability to explicitly resolve subgrid distributions of freezing soil, which in nature are controlled by variations in topography, soil type (through its impact on water transport), vegetation, topographic aspect, and other factors. Local subgrid disturbances such as thermokarst are not incorporated (Grosse et al., 2011). Attempts have been made to base parameterizations on comprehensive in-situ measurements. However, comparisons of model predictions of permafrost-related variables like active layer depth with observations (e.g., from the Circumpolar Active Layer Monitoring program – CALM) usually show large scatter (Lawrence et al., 2012; Figure 9). In analogy with the snow problem, *models may need to parameterize permafrost spatial variability as a function of the physical characteristics of the land surface*.

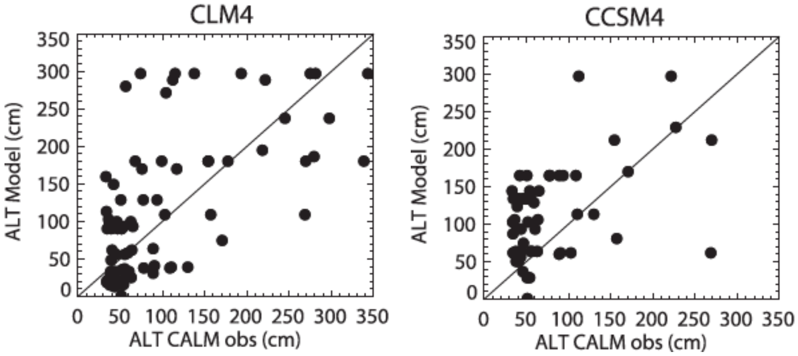


Figure 9: Scatterplot of active layer thickness for CALM sites vs model for CLM4 and CCSM4. Model data are from ensemble mean climatological average for the period 1980–99. CALM site data are climatological average, but with each site containing a different number of years of data. [*From Lawrence et al. (2012)*]

SMAP freeze-thaw measurements may allow the generation of relevant relationships using satellite data, at least for the upper few cm of the soil column. Other remote sensing techniques may prove useful for large-scale monitoring of subsurface freeze-thaw processes as well. Liu et al. (2012) demonstrate that vertical soil displacements due to seasonal freeze-thaw processes, detectable through InSAR, can be related to active layer thickness, although key parameters needed for this inversion, such as soil porosity, currently need to be assumed. *Establishing baseline measurements for longer-term monitoring of settling due to permafrost ice loss and thermokarst may prove a crucial way of detecting changes to permafrost.* Minsley et al. (2012) used airborne electromagnetic (EM) imaging to monitor permafrost distribution in a zone of discontinuous permafrost in Alaska. *Such techniques, or other ways of remotely sensing the ABZ subsurface (or extending the surface measurements to infer subsurface properties through data assimilation), may prove critical in the upscaling of permafrost properties from point measurements to regional scales.*

2.4.4 Lakes, wetlands and rivers

Much of the Arctic land area has a relatively high density of lakes and wetlands with a wide range in size. Lakes represent a major water storage reservoir for the local land system, helping to define the evaporative regime. Differences in lake and wetland areas are thought to account for substantially different runoff ratios among the major Arctic rivers. Hydrologically, lakes, wetlands and floodplains are a complex set of systems that have very different properties (e.g. surface versus groundwater dominated, connected versus unconnected to river systems, thermally stratified versus well-mixed). The thermal properties and surface fluxes of lakes are usually quite different from those of the surrounding land area. Surface fluxes over frozen lakes are usually much smaller than over open water, so the dates of lake freeze and thaw can exert a strong influence on local climate (Samuelsson et al., 2010; Subin et al., 2012a). During summertime, net radiation in high latitudes is high, and as the surrounding landscape dries a large contrast in latent heating can arise (e.g., Subin et al., 2012a).

Most climate models at present represent lakes only crudely and typically lump multiple lakes into an "equivalent" fractional grid cell lake with a static area. Efforts are underway to refine the lake model components included in climate models (e.g., Subin et al., 2012b). A good representation of surface lakes, wetlands and floodplain inundation in ESMs depends on the incorporation of high-resolution topographic data into the lower-resolution structure of the land surface model (statistically or explicitly).

The Arctic contains some of the largest rivers and watersheds on Earth and one-half to two-thirds of the total freshwater flux to the Arctic Ocean is estimated to originate as river runoff. Most GCMs include a river routing scheme, and although there are undoubtedly improvements that are needed, the primary deficiency in modeling the freshwater transport to the Arctic Ocean lies in modeling precipitation and other inputs rather than the river routing scheme itself. *Gravity remote sensing (e.g., GRACE) of surface water dynamics over large watersheds could help detect macroscale changes in lake storage and river runoff and provide some validation of the PCS models.*

2.4.5 Sub-grid heterogeneity

Currently, the most sophisticated treatments of sub-grid heterogeneity in land components of ESMs assume that a model grid cell can be represented as fractional areas of lake, bare ground, and multiple plant functional types. Sub-grid fractional areas are combined linearly to arrive at grid cell fluxes and states. Many LSMs represent processes as acting in independent one-dimensional columns; this may not be sufficient to deal with redistribution of water and energy across landscapes (e.g., Koster et al., 2000) and the resulting effects on soil climate and biogeochemical fluxes. This is likely to be particularly important in environments such as Arctic polygonal ground and peatland microtopography. DOE's Next Generation Ecosystem Experiments (NGEE) project aims to develop a high-resolution 3-D LSM that includes land surface deformation for the Alaskan North Slope, as well as a framework for bringing a statistical treatment of these dynamics to the ESM scale. NGEE will examine whether adequate representation of biogeochemical and biophysical dynamics in these systems depends on a more sophisticated representation of the fine-scale covariance of vegetation, hydrology, and thermal regime as structured by geomorphology (e.g., Grosse et al., 2011). If results from NGEE over limited spatial domains confirm the hypothesis, then *a more extensive effort to map fine-scale geomorphological variability at pan-Arctic scales should be a priority*.

A critical focus should be on the testing of parameterizations at the ESM scale. Surface energy budget calculations based on statistical representations of the land surface variability – perhaps best *obtained from remotely-sensed data – must be rigorously evaluated at regional (10 – 1000 km) scales as well as at the scale of individual process study sites (10 m – 10 km).* A direct additive scaling-up approach from process study site to grid area is not feasible as almost all the landscape variability is expressed at length scales much smaller than ESM grid areas.

2.5 Land Surface – Biogeochemistry

2.5.1 Soils

About one-third of the world's soil organic carbon occurs in the Arctic, much of it in peatlands and in the deep permafrost soils of Siberia (McGuire et al., 2010). Most of this storage has accumulated because of wet and cold physical conditions that are not conducive to the decomposition of soil organic matter (SOM). The biogeochemical soil models in ESMs have typically been conceptualized as vertically integrated box models with first-order decay of SOM and transfer among multiple pools (e.g., Friedlingstein et al., 2006). This approach fails at high latitudes for a variety of reasons:

- Steep vertical gradients in environmentally determined soil turnover, with extremely low decomposition in permafrost layers, leads to buildup of labile material deep in mineral soils.
- Organic layers, which build up in saturated and/or cold soils, contain large amounts of carbon that could be mineralized or combusted during fires under changing environmental conditions. Since organic soils have very different physical properties, permafrost organic soils are likely to thaw much more slowly than mineral soils with climate warming.
- Anoxic decomposition, and the production and consumption of CH_4 and N_2O are poorly or not represented in the current generation of ESMs.
- Microbial dynamics might be particularly important in places with very dynamic changes in soil microenvironment, such as the active layer/permafrost interface or oxic/anoxic zones in saturated soils.

To address these issues, models need to use sufficient representation of the vertical structure in soil biogeochemistry to assess the effects of permafrost thaw on the overall soil carbon budget; account for both thermal and hydrologic properties of SOM; improve the treatment of shallow water tables, and the production, consumption, and transport of trace gases; and include microbial dynamics.

Recent modeling studies (Lawrence et al., 2008; Koven et al., 2009, 2011; Schneider von Deimling et al., 2012) used a vertically discretized soil carbon module, where decomposition rates are calculated for each soil level, to dynamically model the steep vertical gradient in soil carbon residence time that occurs at the permafrost table in permafrost-affected soils. Lawrence et al. (2008) account for both thermal and hydrologic properties of SOM and model the effect of SOM on active layer thickness. These model improvements lead to better agreement with observations, as seen in the comparison from Koven et al. (2011) (Figure 10). However, initial carbon stocks are still substantially underestimated, particularly those in western Siberia and Canada, because the model does not include the buildup of organic matter peatlands or forests on sites with permafrost. Khvorostyanov et al. (2008a) found the mobilization of frozen carbon to be particularly sensitive to heat produced by soil microorganisms, but the strength of this feedback mechanism and the realism of the simulations remain unclear (Heimann and Reichstein, 2008). Harden et al. (2012) show important differences in carbon form, vertical distribution, content, and potential mechanisms of vulnerability across different permafrost soil types. Mapable soil units may be a way of upscaling from point measurements to regional scales to address these issues.

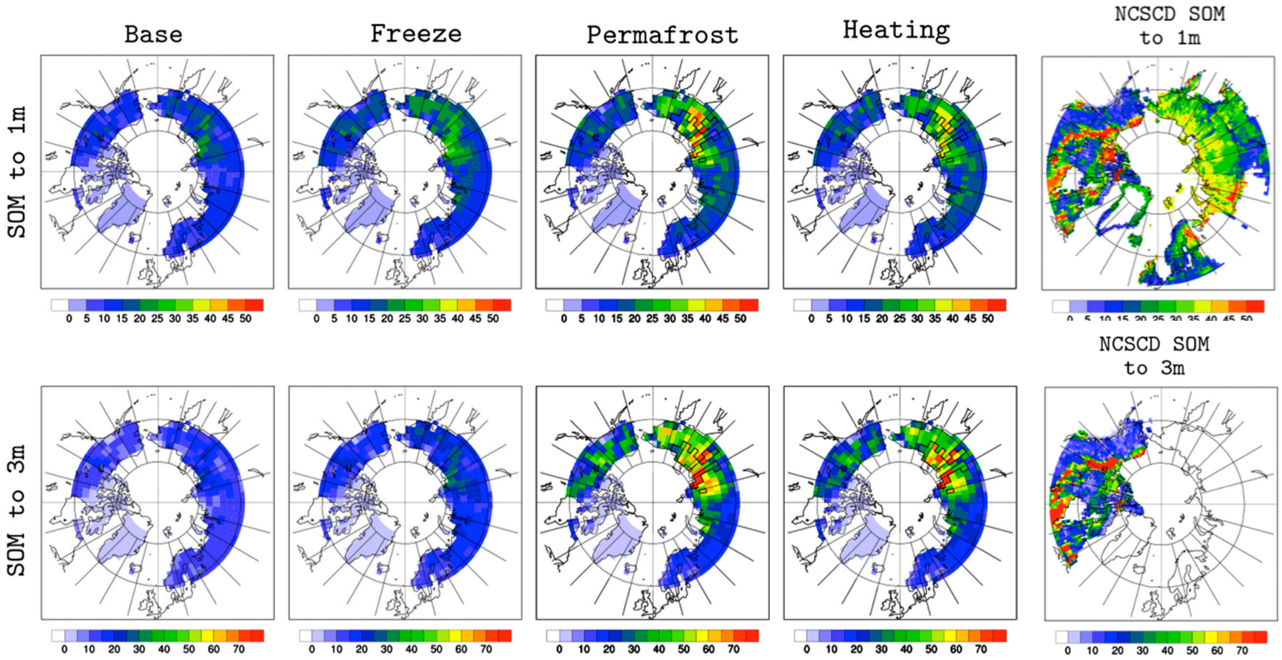


Figure 10: Maps of initial soil carbon (kg C m^{-2}) to depths of 1 m and 3 m for sensitivity experiments, and for comparison, observations from the northern circumpolar soil carbon database (NCSCD). The four experiments are (i) base, in which soil carbon is vertically resolved but no additional processes are added; (ii) freeze, inhibition of decomposition in seasonally frozen soil layers, but no soil carbon in permafrost soil layers; (iii) permafrost, inclusion of permafrost carbon through vertical mixing and soil organic insulation; and (iv) heat, inclusion of microbial heat release by decomposing microbes to the soil thermal budget. [*From Koven et al., 2011]*

Priority should be given to mapping permafrost and soil properties across the ABZ using satellite data and available in-situ data sets, with a significant effort to correlate soil, vegetation and hydrological attributes to remotely-sensed data using sophisticated soil-vegetation models. Field campaigns designed to investigate surface hydrology and land-atmosphere fluxes should consider this goal when designing the experiment. A key aspect will be to use observations gathered over a range of spatial scales – surface site, airborne sensors and satellite sensors – to credibly account for scaling effects.

2.5.2 Disturbance

The ABZ will be subjected to both press-type disturbance (relatively slow but persistent, large scale impacts like warming-induced top-down permafrost thaw, gradual climatic drying, pollution or N-deposition), and pulse-type disturbances (abrupt, often localized impacts like fires, flooding, thaw slumping) (e.g., Grosse et al. 2011). These disturbances can interact, e.g., fire leading to (multi-year) surface warming causing accelerated permafrost thaw.

Disturbance varies considerably between Arctic tundra and boreal biomes, but fire is common to both and is ubiquitous in the latter. The disturbance regime has intensified in recent decades in both North America and northern Eurasia (e.g., Kasischke and Turetsky, 2006; Goetz et al., 2007). Fires of anthropogenic origin account for a portion of wildland area burned, but a substantial fraction are of natural origin. Increased convective activity in the ABZ has produced more frequent lightning strikes in both tundra and boreal zones, increasing the likelihood of fire ignition. Ignition probability is amplified in the boreal zone as a result of warmer conditions and associated tree mortality from drought and insect pests. The latter are highly episodic and difficult to predict but are typically associated with stress brought on by drought and also increased pest survival during warmer winter months. Separation of longer-term disturbance regimes from the current, intensifying regime has a high level of uncertainty and needs attention for realistic model evaluation.

Insects and pathogens are biotic agents of disturbance that may affect up to 45 times the area of wildfire. Climate is an important driver of insect and disease outbreaks and potential feedbacks exist between climate change and biotic disturbances through the carbon cycle. According to Kurz et al. (2008a, b), mountain pine beetle outbreaks in western Canada have had a dramatic impact on carbon cycling. Hicke et al. (2012) found that biotic disturbances (insects, disease, and forest dieback) can have major impacts on forest carbon stocks and fluxes and can be large enough to affect regional carbon cycling. They identified significant knowledge gaps, including a limited understanding of carbon cycle impacts among different biotic disturbance types (particularly pathogens) and their impacts at landscape and regional scales. The capacity to predict disturbance events and their consequences for carbon cycling is limited by the lack of knowledge of the life history, traits and drivers that can be incorporated into predictive modeling and the lack of a predictive capability for invasions by exotic species. In addition, interactions with other disturbances are not well quantified.

Disturbance processes are inadequately incorporated in the LSM-BGC component of ESMs. Hicke et al. (2012) note that most carbon cycle models do not include biotic disturbances. Removal of surface organic matter by fires may further destabilize permafrost, exposing underlying carbon to further fire vulnerability (positive feedback). These processes are poorly constrained in models because of the short and sparse record of actual fire emissions from the Arctic. Therefore few models consider fire emissions or do so in simplistic ways that do not capture the full vulnerability of this large carbon store. To remedy this, *a combination of satellite fire mapping, in-situ pre- and post-fire inventories, and atmospheric composition (surface, airborne, satellite) measurements can provide the needed constraints to allow development of models that capture the current situation* and that can provide predictions of future carbon emissions from this important carbon stock. Fire observations are accurate and routine from satellites. What is uncertain is the amount of fuel consumed.

Recovery from disturbance in the ABZ is also highly variable and strongly influenced by the intensity of disturbance (e.g., Goetz et al., 2012). Disturbance intensity produces non-linear trajectories of post-disturbance carbon and energy exchange. This is true of all disturbance types - whether fire, insects, logging or the interaction of these – but the time scale of their legacy effects differ. Progress is also needed with respect to modeling the indirect effects of disturbances on how soil hydrological, thermal, and biogeochemical dynamics co-vary during succession following disturbance. In addition to changing post-disturbance vegetation succession, more severe fire disturbance produces greater microbial respiration, and can change the balance of the components of net exchange. *Better remote sensing methods are needed to map disturbance severity (e.g. for fire disturbance this is defined by SOM consumption), and disturbance severity needs to be represented in LSM-BGC models. Temporal and spatial scaling of these non-linear disturbance effects on carbon, energy and water is a high priority and would benefit from coordinated and focused field experiments.*

Realistic predictions of future BGC in the ABZ requires realistic simulation of changes in vegetation functional types as mediated by disturbance – not simply climate envelopes of species presence/absence projected into the future. *Better records of past disturbance are needed – perhaps from the Landsat record – particularly for northern Eurasia.* Ideally these should be “wall to wall” rather than sampling-based, and available annually as far back as possible.

Predictive Disturbance Modeling and ESMs: ESMs and related BGC and/or submodels (e.g., Hicke et al., 2012) need to be able to predict how climate will change the distribution, frequency, seasonal timing, and severity of disturbances common to the ABZ (e.g., fire, thermokarst, and biological disturbances – insects and pathogens). Currently, relationships between fire frequency and climate are based on comparisons of burned area in large geographic regions and variables that are derived from weather data, including a set of fuel moisture indices derived from weather variables (e.g., Balshi et al., 2009a, b). *Further research is needed to determine how variations in vegetation cover, fuel amounts and fuel conditions influence fire occurrence so that these effects can be included in ESMs.*

Liu et al. (2011) review how disturbances and their impacts are treated and modeled in process-based state-of-the-art carbon cycle models at the stand level and how disturbances and their impacts are scaled up from stand to continental scales. Grosse et al. (2011) noted the need for subgrid-scale processes related to all disturbances to be meaningfully integrated with macro-scale models. To model the stochastic nature of disturbances, probability distributions of frequency, severity, and spatial coverage for different types of disturbances can be constructed from regional databases. The challenge is to upscale these relationships to the continental scale of ESMs (e.g., Weng et al., 2012). In order to capture spatial heterogeneity of landscape-scale processes, more detailed spatial scales must be integrated mathematically into the coarser scales required for regional and global models. However, it is not clear which processes and properties are critical at a given temporal or spatial scale, and which can be simplified.

It is probably not necessary, or efficient, to try to incorporate a coupled mechanistic climate-vegetation-fire frequency relationship into the ESMs themselves. However, one approach might be for ESMs to generate good output drivers for an ensemble of disturbance/BGC models that could be run offline to get a good statistical set of model outcomes. The results could then be summarized to calibrate a simpler parameterization that could be integrated into the ESM itself.

2.5.3 Ecosystem dynamics

Terrestrial ecosystems are a major player in the carbon-climate system: they can release or absorb globally relevant greenhouse gases such as CO_2, CH_4 and nitrous oxide, they emit aerosols and aerosol precursors, and they control exchanges of energy, water and momentum between the atmosphere and the land surface. A multitude of climate–ecosystem feedbacks might amplify or dampen regional and global climate change. The rather wide spread of CO_2 fluxes among ESM models in both historical simulations and future projections of carbon-climate feedbacks (Friedlingstein et al., 2006) demonstrates the very poor understanding of processes in functioning ecosystems as represented in these models (Heimann and Reichstein, 2008).

Dynamic global vegetation models (DGVMs) were developed to simulate the coupling between climate and vegetation in transient simulations. Levis (2010) summarizes DGVMs and processes (e.g., inclusion of fire or nitrogen cycle, the level of complexity of the representation of plants) that vary between them. The second-generation DGVMs simulate a suite of ecosystem properties, from half-hourly carbon and water exchange, through daily growth and tissue turnover, to longer-term processes of reproduction, competition, and mortality (e.g., Fisher et al., 2010). Sitch et al. (2008) evaluated five DGVMs, forced with observed climatology and atmospheric CO_2.They found large uncertainties associated with the response of boreal ecosystems to elevated temperatures and changing soil moisture status. For the most extreme emission scenario tested, cumulative land uptake over the 21st century differed among DGVMs by 494 Pg C, an uncertainty equivalent to over 50 years of anthropogenic emissions at current levels.

Ongoing assessments of ecosystem models include the NACP-led MsTMIP (Multi-scale Synthesis and Terrestrial Model Intercomparison Project). Their early evaluations show that there is a lot of room for model improvement. For example, Schaefer et al. (2012) showed that the models do not simulate gross primary productivity (GPP) very well, with none of the models included in the study matching estimated GPP within observational uncertainty. They suggest that *improving simulated GPP requires better leaf-to-canopy scaling and better values of model parameters that control the maximum potential GPP (such as light use efficiency).* Richardson et al. (2010, 2012) reveal several other deficiencies. The models differ in the calculated magnitude of peak fluxes, phenology (timing) of seasonal changes, and high-frequency sensitivity to drivers (Figure 11). They do not represent interannual variability in the start/end of the growing season and show large model biases for GPP during phenological transition periods. *Multi-year, spatially extensive observations are needed to help develop better phenological models.*

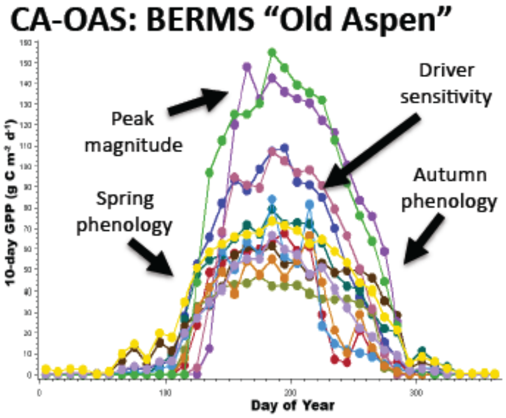


Figure 11: The 10-day GPP (g C m^{-2} day^{-1}) for deciduous broadleaf forest at the Old Aspen Site in Canada from 14 ecosystem models participating in MsTMIP. [*From Richardson et al., 2010*]

Invasion of shrubs into tussock tundra areas is widespread in northern Alaska. Tree line expansion is documented for northwestern Alaska, and is often associated with permafrost degradation and soil drainage. Expansion of forests into tundra will lead to significant heating of the lower atmosphere through a reduction of albedo, especially in winter (e.g., Betts and Ball, 1997; Chapin et al., 2000). Jin et al. (2012) also highlight the importance of vegetation succession and snow cover duration in modulating the latitudinal patterns of annual albedo change and surface shortwave forcing averaged over the decades following fire. Neilson et al. (2005) discuss many of the challenges associated with including migration in DGVMs, particularly the importance of sub-grid processes, and the limitations introduced by the use of plant functional types. Perhaps the biggest challenge is the lack of useful data on which to build mechanistic and empirical models.

To understand ABZ ecosystem transient responses, including boundary shifts, a better description of the treeline which incorporates gradients of tree canopy density rather than discrete class boundaries, is needed for a more realistic model representation of the biophysical characteristics of the transition between Arctic tundra and the boreal biomes and associated changes in albedo and radiative forcings. *DGVMs may also need improved treatment of plant diversity and mechanistic treatment of migration and competition among these plants.*

2.6 Integrated Systems, Carbon Cycle, and Scaling Methodologies

The carbon cycle in the ABZ has the potential to influence the climate system through feedback pathways involving responses in both terrestrial and marine systems. Observational and model component enhancements proposed below will lead to increased understanding of small-scale carbon flux processes and improve the ability of ESMs to integrate, simulate and predict such processes.

2.6.1 Land surface hydrology and carbon cycle

Processes in the terrestrial ABZ that are sensitive to change on a 10- to 20-year timeframe are those that are primarily sensitive to changes in atmospheric variables (e.g., temperature, precipitation, CO_2 concentration) and include surface hydrology, photosynthesis and fire. The net direction of the photosynthesis and fire feedbacks depends substantially on landscape wetness and dryness. For example, photosynthesis may be decreased more by dry conditions than it will be promoted by a longer growing season. Also, dry conditions may result in the release of substantial carbon through fire. Riverine chemistry is impacted by permafrost thaw due to large-scale fire disturbance. On the 50-to-100-year timeframe, processes responding slowly to climate include slow ecological processes (e.g., increase in shrub tundra, changes in tree species, treeline advance, and forest degradation) and decomposition responses associated with the thawing of permafrost. Once permafrost thaws, the direction of feedbacks to the climate system depends largely on landscape wetness and dryness. *To facilitate ESM evaluation and improvements, improved characterization and reduced uncertainty in ABZ physical (e.g., permafrost distribution) and biogeochemical (e.g., carbon in peatlands) properties are needed. In-situ measurements of riverine chemistry could contribute to BGC model validation.*

Several model developments are needed to improve representation of the impact of land surface hydrology on the carbon cycle. For example, sub-surface leaching and surface mobilization of C, N, sediments, P, etc., should be represented in ESMs. This requires representation of complex Arctic soil mineral and organic properties, explicit representation of linked nutrient-carbon-water cycles, and improving simulations of surface and sub-surface properties, among other things. The physical properties of lakes and wetlands, especially their thermal structure, can also have important implications for biogeochemical fluxes. For instance, there is some evidence that lakes are responsible for much of the flux of methane from western Siberia (Walter et al., 2006). Sub-models of chemical processes (e.g., CH_4) need to be linked to prognostic hydrological properties (e.g. T, depth, O_2). *Observations are needed to test the ability of the simple approaches used to represent lakes and wetlands in ESMs to capture the fluxes of greenhouse gases accurately.*

One of the significant uncertainties in ESMs is how future changes to peatland hydrology will impact these large carbon reservoirs (e.g., Wania et al., 2009). The accumulation of peat, which is partially decomposed organic matter, depends on water table position, soil temperature, and net primary production, with water table position being most important (Rouse et al., 1997). Permafrost presence in peatlands strongly affects vegetation structure and soil drainage characteristics, and thus SOC accumulation rates (Robinson and Moore, 2000). Whether permafrost thaw in peatlands leads to a positive or negative feedback to atmospheric greenhouse gas concentrations will depend on spatial and temporal variation in water table position as well as soil temperature, which both serve as important controls on methane release in peatlands (Grosse et al., 2011). Peatlands in some situations may be resistant to drought due to the high water holding capacity of some moss species. Hence *it is important for ESMs to have explicitly modeled peatlands and peatland hydrology along with soil freezing and thawing and permafrost dynamics. Thermokarst and other disturbances like fire and cryoturbation should be integrated into permafrost models to better quantify and predict the impact of disturbances on high latitude SOC pools* (Grosse et al., 2011).

2.6.2 Marine processes, land-ocean exchanges and carbon cycle

For marine systems, processes sensitive to changes in surface conditions like sea ice cover and near surface water temperature could have substantial responses on the 10-to-20-year timeframe. Decreasing sea ice cover could increase CO_2 sequestration by increasing the physical transfer of dissolved inorganic Carbon (DIC) to the surface layer and the biological uptake of CO_2 in the surface layer through more light and nutrients. It could also decrease CO_2 uptake through the creation of a stable photic zone. In contrast, increases in water temperature also have the potential to enhance the release of CO_2 and CH_4 through enhanced decomposition and methanogenesis of organic carbon in the water column.

It is estimated that one-half to two-thirds of the total freshwater flux to the Arctic Ocean originates as river runoff. However, there are major uncertainties in riverine fluxes because important areas of the Arctic basin are essentially without gauges. *Measurement of riverine fluxes is important to evaluate the model estimates of land-ocean BGC fluxes.*

The Arctic land-ocean interface is in a very dynamic transition. Receding sea ice has changed the seasonal climatology of the coastal zone with significant consequences for both land and ocean ecosystems. Ice-free conditions have resulted in the generation of extreme coastal erosion (e.g., Overeem et al., 2011), acceleration of permafrost thaw, and other changes in coastal maritime environments and upland hydrologic changes in the major deltaic ecosystems (e.g., Mackenzie and Yukon-Kuskokwim deltas). With an anticipated trend toward stronger extreme Arctic cyclones, the associated greater wave activity would promote even further coastal erosion (Vavrus et al., 2012).

Key questions related to the carbon cycle associated with marine processes and land-ocean exchanges include: How are land-to-ocean fluxes of water, heat, carbon, nutrient, and sediment fluxes through both riverine transport and coastal erosion changing? How will ocean trophic levels respond to reduced ice cover, and, coupled with changes in nutrient runoff from the land, influence the Arctic Ocean carbon budget? Addressing these questions requires both observations and model developments to improve representation of ocean and sea-ice processes and the links between land surface processes and the coastal ocean. As mentioned in sections 2.2 and 2.3, *models need to represent sea-ice distributions better and include more complete treatments of ocean ecosystems, micronutrient limitation, and ocean acidification impacts on the calcium carbonate cycle as well as improvements to sea-ice biology.*

2.6.3 Trace gas concentrations and fluxes

Comprehensive atmospheric measurements of CO_2 and CH_4 are needed to assess ABZ carbon fluxes and their representation in models. The current observing network leaves major gaps in understanding CO_2 and CH_4 distributions and flux processes in the ABZ. Comparison of surface-only CO_2 and CH_4 measurements with atmospheric transport models is particularly susceptible to errors in vertical mixing and boundary layer processes, which remain a challenge for ESMs. Column CO_2 measurement comparisons are less affected by these types of model error but lack a long data record and are challenged in various ways. Ground-based operational networks provide information over Europe and Canada but coverage is sparse and no ground-based observations exist over Eurasia.

Satellite data from AIRS and GOSAT provide the most comprehensive available regional view of CO_2 and CH_4 but these data remain limited by several factors. AIRS observations primarily reflect the middle and upper troposphere, making connection to small-scale surface source/sink processes difficult. GOSAT observations (and planned OCO-2 measurements) provide sparse sampling of CO_2 in the ABZ only over land during summer months. Future satellite missions, such as ASCENDS, will employ active remote sensing techniques, providing improved ability to observe CO_2 in the ABZ. Because of the limited lifetimes of such missions, these types of observations will be most useful in characterizing variability in fluxes on seasonal to interannual scales.

Overarching measurement needs for improved characterization of ABZ CO_2 and CH_4 fluxes are (i) *improvements in trace gas concentration and flux measurements through a combination of ground-based, aircraft, and satellite observations, and (ii) improvements in understanding local scale processes. An expansion of existing ground-based networks is necessary to characterize changes in the regional carbon budget on longer timescales. Aircraft field campaigns are essential for validating satellite observations and providing the link between surface site observations and inverse modeling retrievals. Necessary model improvements include improved surface boundary layers, better characterization of model transport error in the ABZ and development and evaluation of improved up- and downscaling techniques appropriate for the region (see section 2.6.5).*

2.6.4 Flux estimation and evaluation: inverse modeling, upscaling and downscaling

Inverse modeling techniques are used to estimate surface fluxes using information contained in trace gas observations. The majority of inversion studies to date have used CO_2 data collected by the NOAA ground-based network and estimated fluxes for large areas (e.g. boreal Asia or North America, ~5 or 10° latitude × longitude boxes). The multi-phase TRANSCOM experiment has helped to quantify uncertainty in CO_2 inversion methods using a number of global atmospheric transport models; results indicate large differences in boreal summer flux estimates among models due to differences in the timing of vegetation CO_2 uptake. Considerable uncertainty remains regarding total CO_2 flux from the ABZ and few attempts have been made to apply inversion techniques to sub-regional scales in this area. Efforts to use GOSAT CO_2 observations in inversions are underway by a number of groups. Chevallier et al. (2011) used ground-based remote sensing data from a sparse network to estimate CO_2 fluxes globally, but were not able to reduce flux uncertainty over the North American boreal region due to a lack of data. Results for CH_4 are less advanced than those for CO_2.

In recent years, considerable effort has focused on estimating CO_2 fluxes over a densely sampled region (e.g., North America) on finer resolution spatial resolutions (e.g., 4-12 km, up to 50 km) using regional transport models (e.g., Göckede et al., 2010; Gourdji et al. 2010). These efforts combine regional models with Lagrangian particle dispersion models to diagnose upstream influence on atmospheric measurement locations. Such methods provide a promising path forward for estimating ABZ fluxes at sub-regional scales but require a denser observing network than currently exists. In addition, inversions at both regional and global scales are still challenged by the difficulty in estimating atmospheric transport model error; lack of accurate transport model characterization contributes to continuing flux uncertainty and can cause errors in source/sink attribution if not properly quantified in the inversion framework. Work is ongoing to develop better transport model error estimates.

Upscaling methods extrapolate knowledge of fluxes gained from high-resolution process models or direct observations over limited areas (10 m – 1 km) to larger scales (1 – 1000 km) using models in which the land surface or ecosystem properties are derived from remotely sensed data. Airborne eddy correlation measurements (e.g., Desjardins et al., 1997) provide a very powerful means of bridging the scale interval between flux towers, regional surface/atmosphere models, and the retrievals provided by ESM inversions. These "bottom-up" spatially coherent flux estimates can be compared with the fluxes retrieved from ESM inversions, which would be anchored by a sparse network of trace gas concentration measurements.

Techniques are being developed to estimate large-scale land biosphere CO_2 fluxes from sparse flux tower observations but the results remain subject to large uncertainties. While regional-scale fluxes appear reasonable, in some cases these techniques lead to global net flux estimates that are inconsistent with atmospheric CO_2 concentration observations. In order to apply such techniques successfully to the ABZ, improvements in local carbon flux estimates are needed through improvements in process models, increases in the flux tower network density and/or increased use of airborne eddy correlation. Improved characterization of spatial heterogeneity of land surface and ecosystem properties in the ABZ is also needed for proper extrapolation to larger scales; it is expected that planned and proposed field campaigns and analysis of relevant remote sensing observations can contribute significantly to this goal.

Forward model scaling approach*:* Spatial heterogeneity in ABZ landscapes and coupling of physical, biological, and BGC processes at multiple spatial scales present special problems for climate-scale predictive modeling. The lack of a solid theoretical foundation to address these scaling problems is one reason for the diversity in model formulation and parameterization and the resulting scatter in large-scale predictions of permafrost dynamics for the 21st century. One approach for reducing prediction uncertainty at the climate-modeling scale is to construct, initialize, and execute fine-scale models that represent Arctic landscape processes explicitly, and to use these process-resolving high-resolution models as a basis for parameterizing implicit or statistical representations of important processes at larger spatial scales. This concept is the basis for NGEE.

Downscaling techniques translate larger scale flux estimates produced by global models or inversions to finer spatial scales, using information about surface properties or statistics about high resolution variability from higher resolution models or dense observations (satellite or aircraft). These methods are essential for evaluation of coarse resolution flux estimates with the higher resolution estimates described above. Such methods could be applied to existing observations and models to estimate small-scale variability for planning future field campaigns and measurement network deployments. Knowledge of realistic regional flux estimates and variability in the context of global flux estimates could require a hierarchical model approach that integrates contributions with small-scale process models (~ 1 km) with regional (~10 km) and global models (~100 km).

3 Key questions to be addressed

The critical questions that should guide model development and measurement priorities are summarized from Section 2 as follows:

1. Clouds, radiation and aerosols: Are the observed seasonal changes of Arctic clouds primarily determined by the large-scale circulation or do microphysical and surface processes play a key role? What is the role of downwelling infrared radiation in the surface energy budget of the Arctic Ocean in winter? How does aerosol forcing affect the Arctic climate, and how will aerosol loadings change as a result of changes in land-use, industrial emission, desertification, and fire?

2. Ocean circulation and sea ice: What are the processes involved in melting the sea ice and controlling ocean stratification in the Beaufort Sea?

3. Integrated systems, land surface hydrology, and carbon cycle: What are the linkages between land surface hydrology, vegetation changes and the surface energy budget over the ABZ and how will these influence the evolving climate? How, and how rapidly, is the ocean-land interface changing in the ABZ?

4. Carbon balance: How rapidly, in which direction, and by how much will warming and changing precipitation modify the ABZ net carbon balance? Will the impact on net CO_2 exchange be smaller or larger than the impact on net CH_4 exchange?

4 Proposed Field Experiments and Studies

The discussion in Sections 1 and 2 and the key science questions of Section 3 provided the basis for laying out a set of recommended field experiment activities. Each activity is designed to address important weaknesses in the process models that make up the subcomponents of ESMs. The problem of scaling, that is, the development and validation of process models and global ESMs, is also addressed.

4.1 Field campaigns – requirements and initial ideas for new activities

4.1.1 Clouds, aerosols and radiation

(i) **Cloud ice properties and the radiation budget**: Development of cloud microphysics parameterizations to model mixed-phase and ice clouds in global climate models is a priority. Because of the many known gaps in our knowledge of cloud processes, comprehensive field experiment case studies are required to evaluate simulation fidelity. Participation in and extension of DOE ARM observations, with an emphasis on getting better observations of CCN and cloud ice properties and their effects on the radiation budget, is recommended.

(ii) **Aerosols**: A field campaign targeting aerosol wet removal by super-cooled liquid, mixed-phase and ice clouds, along with observations from CloudSat, CALIPSO, MODIS, and MISR, is recommended to increase scientific understanding of aerosol transport to the Arctic from lower latitudes and deposition onto snow and ice within the Arctic, and to improve the representation of these processes in global models.

Previous field campaigns in the Arctic have focused on the North American and European sectors. Whereas there is value in additional campaigns in those regions, an aircraft- and ground-based field campaign from bases in Siberia would be of considerable value for better understanding aerosol-climate interactions and biogeochemical processes of critical relevance for the Arctic. However, since field observations in the Russian Arctic will likely remain limited in the future because of the difficulty of access, satellite observations will play a crucial role for monitoring the future evolution of this critical region. Opportunities for participating in field campaigns there should nevertheless be explored.

4.1.2 Ocean circulation and sea ice

(iii) **Sea-ice melt in the Western Arctic and surface energy budget of the Arctic Ocean**: Climate models melt the ice in the eastern Arctic (Laptev Sea) rather than the western Arctic (Canadian Basin, Beaufort Sea). A field campaign should be conducted to address the processes involved in melting the sea-ice and controlling the ocean stratification in the western Arctic (Beaufort Sea).

(iv) A long-term experiment like SHEBA is needed (but with 21st century observing capability) that samples many different thermodynamic and dynamic environments, clean and polluted situations, and gives us insights into the larger-scale controls on cloud cover and cloud properties. If an icebreaker were used as an observational platform, as in SHEBA, it would be possible to operate instrumented unmanned aerial vehicles (UAVs) from the ship, providing greatly extended areal coverage of measurements over the central Arctic Ocean. This would be a major advance over what could be achieved during the 1990s. Participation in MOSAiC (Multi-disciplinary drifting Observatory for the Study of the Arctic Climate), a proposed activity under the auspices of the International Arctic Science Committee (IASC), would be an effective way to meet this observational need.

4.1.3 Integrated systems, land surface hydrology, and carbon cycle

(i) **Surface-Atmosphere Interactions**: Experiments should be designed and conducted to validate the calculated ESM grid-scale surface-atmosphere exchanges of energy, momentum, water and carbon, and to relate these fluxes to variables that are amenable to satellite remote sensing. This will require in-situ measurements of radiation components, momentum, sensible heat, latent heat, CO_2 and CH_4 (where possible) preferably measured at multiple nested scales, by short and tall towers, and from aircraft. As part of this, the data collected over the "heritage" ABZ sites - Hudson Bay Lowland (1990), BOREAS (1994 & 1996), BERMS and Mackenzie Basin (1999), etc. – should be re-examined, and some of these data should be revisited to ascertain how the land surface climatology, hydrology and carbon cycle have changed.

4.1.4 Biogeochemical cycles

The overall goal is to develop, test and validate zonal-scale BGC models that can be embedded in ESMs. Most of the surface parameters for these models are to be extracted from satellite data and model performance is to be validated by in-situ observations (1 – 100 m), local-to-regional up-scaling work (100 m – 1000 km) and inversion models (1000 km – ABZ scale). The specific experimental activities that are considered to be most useful are outlined below.

(i) **Integrated surface-atmosphere and surface processes**: A network of tower and surface process study sites is needed to measure surface-atmosphere fluxes of CO_2 and CH_4 and their governing processes, in addition to those PCS fluxes described above. Processes and pools that dominate short-term BGC response (i.e., fast flux pools) may be different from those that dominate long-term responses (large, slow flux pools, permafrost, ecosystem shifts or state changes), and these will likely require different observations. Expanded ground-based monitoring capabilities would support observations of long-term changes needed for model validation and source/sink inversion studies. Clearly, PCS and BGC requirements can and should be meshed at some sites. These studies should be directly linked to remote sensing investigations with a view to scaling up the improved process models to the ESM scale.

As in subsection 4.1.3, the data collected over the "heritage" sites should be re-examined. Some of these sites could be revived to ascertain how the hydrological properties and associated surface-atmosphere energy, momentum, water and carbon fluxes have changed. This effort should be meshed with any proposed work to be conducted at "new" sites. New measurements that would be useful include response of vegetation growth and heterotrophic respiration to changes in temperature and soil moisture, allocation of plant growth above and below ground, and response of allocation to changes in temperature, moisture, and vegetation community structure. Data on stable isotope content (e.g., ^{13}C) of vegetation and soil organic matter will be useful in evaluating predicted water use efficiency.

The development of new CH_4 sensors has made it feasible to measure CO_2/CH_4 fluxes from an airborne platform, thus increasing the flux footprint of tower-and chamberbased CO_2/CH_4 measurements. This represents an important step between very small-scale (process study, flux tower) measurements and the very large scale relevant to ESMs. Flux measurements should be obtained with aircraft-based systems along several transects as well as during grid flights. The field campaigns augmented with CO_2 and CH_4 measurement capabilities and future satellite missions would provide a more comprehensive regional picture of trace gases to complement the long-term record provided by ground-based networks.

Cooperation with Siberian work for validation purposes and to anchor some model predictions for this part of the ABZ should be continued. The West Siberian Lowlands are the largest boreal wetland ecosystem in the world and could play an important role in the global emission of CH_4, but we presently have no direct observations of such emissions from this region.

(ii) **Disturbance and carbon cycle dynamics**: A combination of satellite fire mapping, in-situ pre- and post-fire inventories, and atmospheric composition (surface, airborne, satellite) measurements should provide the constraints to support disturbance model development. Short-term processes (including interannual variability) need to be studied with observations such as flux towers and aircraft campaigns with a focus on abrupt disturbance impacts such as post-fire. Aircraft-based flux measurements along several long transects (200 km) with a substantial temperature gradient would be useful. A series of aircraft-based flux measurements of CO_2/CH_4 and Bowen ratios along long transects, with a wide range of environmental conditions, have the potential to provide the data necessary to evaluate whether the physical, chemical and biological mechanisms in the ESMs are accurately modeled.

Decadal/century trends need to be investigated through analysis of long-term data records (stream gauges, remote sensing records, Long Term Ecological Research (LTER) data, etc.). Field sites studied one or more decades ago (as noted above) should be revisited using a combination of flux tower and aircraft-based flux measurements to identify the significance of any changes in ecosystem properties. In addition, processes associated with post-fire recovery can be studied using the aircraft to measure CO_2 exchange 1, 10, 20, 30 years after a fire.

(iii) **Upscaling**: A combination of flux towers, flux aircraft and remote sensing data collection and validation efforts should all be used to address the scale gap between the in-situ process studies and the ESM scales. For the purpose of upscaling from site to region, high-precision and continuous tower-based measurements should be made of the mixing ratios, and fluxes when possible, of CO_2, CH_4 and other gas species. Surface-based atmospheric column measurements will complement these tower measurements and validate satellite trace gas retrievals. Vertical profiles and near-surface fluxes of these gases in the PBL can be sampled by aircraft during field campaigns. Satellite and aircraft remote sensing data at various spatial resolutions can also be used to characterize surface heterogeneity of the measurement sites and the global ABZ. In combination, these measurements can be used to evaluate process models directly over the range of local to regional scales and can help to constrain the atmospheric inversion work described in (iv) below.

(iv) **Downscaling**: A comprehensive effort should be made to expand the network of atmospheric CO_2 and CH_4 concentration measurements in the ABZ, preceded and

> accompanied by four-dimensional data assimilation (4DDA) and observing system simulation experiments (OSSEs) to determine the optimal deployment pattern and schedule for inversion studies. This network should directly complement the surface, tower and airborne process study networks listed above and be used to support a multi-team atmospheric inversion initiative allied to satellite trace gas algorithm development.

All of these studies should be directly linked to remote sensing investigations with a view to scaling up the improved process models to the ESM scale. Previous, current and proposed experiment sites in Alaska and Canada (e.g., ABLE, BOREAS, BERMS, NGEE, etc.) should be assessed for zonal-scale embedding.

4.2 Remote sensing contributions

Remote sensing provides the only viable option for obtaining high spatial and temporal sampling in the remote regions of the ABZ. Many observations are available almost contemporaneously from the A-train sensors and the operational NOAA satellites to help improve climate models. Much work remains to be done to use these observations effectively.

A more complete picture of the ABZ meteorology can be obtained by integrating in-situ and satellite observations through model reanalysis (4DDA). The satellite sounding measurements of humidity and temperature (AIRS, AMSU, AMSR, CrIS, ATMS, etc.) are particularly important. The EOS platforms, and the A-Train in particular, have provided unprecedented observations of clouds and aerosols (CloudSat, CALIPSO, PARASOL). Observations of cloudiness and the atmospheric radiation budget are provided by AVHRR, MODIS, VIIRS, MISR and CERES to give a record from the late 1970s onward. MISR measurements are particularly valuable for cloud observations over the Arctic Ocean where icy and snowy surfaces are problematic to other sensors that are sensitive to radiometric/thermal calibration and the contrast between surface and cloud radiances (Wu and Lee, 2012). MISR has been operating almost continuously since March 2000 except for a ~16-day gap in October 2008. However, high optically thick clouds prevent satellite sensors from seeing lower clouds, and the vertical resolution of MISR prohibits it from detecting clouds lower than ~500 m from the surface. Whereas the lidar active remote sensing technique used for CALIPSO has advantages in vertical accuracy and insensitivity to lack of sunlight or thermal contrast, the main disadvantage is its limited spatial coverage (e.g., Palm et al., 2010).

CALIPSO, MODIS and MISR provide information on aerosol profiles and column-integrated aerosol optical depth, respectively. With data assimilation systems, these observations can provide constraints on aerosol transports from lower latitudes to the ABZ. Field campaigns can then be used to evaluate those estimates and provide details on their distribution within the ABZ. The combination of field campaign and satellite data is then useful for evaluating model transport estimates, including wet deposition during transport. In conjunction with in-situ observations from the ARM program, the combination of CloudSat and CALIPSO data, with their high-resolution representation of cloud and aerosol structures, will provide important metrics to evaluate new parameterizations of ice and mixed-phase cloud microphysics

Large-scale information about the sea ice cover, water vapor and precipitation has been available almost continuously from passive microwave data (ESMR, SMMR, SSM/I and AMSR-E) since the 1970s. Seasonal and interannual variability in the extent and distribution of ice has been derived primarily from these data. Radarsat and other radar satellites launched since the mid-1990s provide information on surface type, sea ice cover and freeze-thaw extent. The SMAP mission includes a freeze/thaw component that could be highly relevant to an ABZ field experiment. SMAP is slated for launch in late 2014 and, for at least three years, will provide binary freeze/thaw state information at a resolution of 3 km every two days, with a classification accuracy of 80%. Pilot investigations, using airborne microwave instruments, should be conducted over the ABZ before and during the SMAP mission. Gravity remote sensing (e.g., GRACE) of surface water dynamics over large watersheds could help in detecting macroscale changes in permafrost thaw, active layer thickness, soil water storage, and runoff.

Satellite data from AIRS, IASI and GOSAT provide the most comprehensive available regional view of CO_2 and CH_4 but these data remain limited by several factors. AIRS observations primarily reflect the middle and upper troposphere, making connection to small-scale surface source/sink processes difficult. GOSAT observations provide sparse sampling of CO_2 columns in the ABZ only over land during summer months. OCO-2, scheduled for launch in December 2014, will provide CO_2 measurements in the ABZ from spring to fall. AIRS, IASI, and TES provide observations of partial columns of CO and MLS upper tropospheric CO. Making most use of these observations requires the use of data assimilation systems. The advantage of using these observations in an assimilation framework is that a view of atmospheric trace gases that is consistent across platforms, and also consistent with the concurrent meteorology, emerges. Field campaigns provide invaluable evaluation metrics.

Satellite observations of ocean color (SeaWiFS, MODIS, VIIRS) have been important to studies of phytoplankton abundance and net primary production, including model evaluation. These observations can be difficult to use in the Arctic because of the large solar zenith angles, persistent cloud cover, and high riverine fluxes into its coastal margins (Arrigo et al., 2011). In addition, depth-integrated rates of NPP that are calculated from satellite-based measurements will be underestimated in regions of the Arctic Ocean that have a well-developed subsurface chlorophyll maximum. In-situ observations are essential to quantify the uncertainties in remote sensing estimates; comparisons and uncertainty quantification should be pursued whenever possible.

Grosse et al. (2011) enumerate many ways that remote sensing data can be used to improve or evaluate land surface disturbance models. Spatial monitoring of aboveground organic carbon stocks and vegetation-soil-water interactions using remote sensing including hyperspectral, SAR and LIDAR sensors, coupled with dedicated field campaigns, could greatly improve our understanding of SOC input dynamics related to terrestrial land surface dynamics under disturbance regimes. Since thermal and hydrological regimes are critical to vulnerability and resilience of SOC, remote sensing applications aimed at quantifying these regimes in the ABZ would enhance our capability to characterize, quantify, and potentially predict disturbances and their impacts on SOC at large scales. Relevant existing or upcoming missions include soil moisture and surface water satellite missions (e.g., SMOS, SMAP, SWOT (2020 launch)), spaceborne SAR missions to detect aboveground biomass, and existing thermal satellite measurements (e.g., AVHRR, MODIS, VIIRS).

Several optical (Visible, NIR) satellite data sets have been used to study land surface changes and processes in the ABZ (e.g., Frolking et al., 2009). These data could also be used to characterize surface variability and specify surface parameter fields for models. The AVHRR archive extends back to 1979 and is currently being used to study the progressive “green-up” of the Arctic tundra over the last 30 years (Bhatt et al., 2010; Raynolds et al., 2012). Landsat data, extending from the 1970’s onwards, has been used to track disturbance in several ABZ regions (e.g., Hall et al., 1991; Kasischke et al., 2010). MODIS data, starting from 1998, offers great enhancements over the AVHRR data set, and VIIRS will extend the MODIS data set forward.

4.3 Proposed and Related Ongoing Activities and Leveraging Opportunities

Atmosphere

Observational Activity	Details	Proposed Supplements (shown in blue) and New Activities (shown in red)	Reference
Clouds-Aerosols-Radiation			
DOE ARM Program	ARM Climate Research Facilities at Barrow (coastal) and Atqasuk (inland). **Campaigns**: Barrow Black Carbon Source and Impact Study, July 2012 – June 2013: combination of air monitoring, snow collection and radiative measurements.	Conduct analyses of existing observations of CCN and IN to characterize the probability distribution of ice particle properties. Obtain more observations (including at new sites in the ABZ) of CCN and cloud ice properties and their effects on the radiation budget. Spring aircraft campaign; add aerosol component targeting aerosol wet removal.	§2.1 §4.4.1
ICECAPS (NSF AON)	A field campaign adding cloud, atmosphere, and precipitation measurements, and associated higher-order data products, to Summit, Greenland at the top of the Greenland Icesheet.		§2.1 §4.1.1
CALIPSO, CloudSAT, MISR, MODIS	Cloud and aerosol profiles; column-integrated AOD.	Conduct analyses related to ABZ.	§2.1 §4.2
AEROCAN	19 sites across Canada – part of AERONET.	Augment network in ABZ.	§2.1
CO_2, CH_4			
NOAA ESRL surface observatories	Ground-based observing network for surface observations of CO_2, CH_4, etc.; 10 locations (6 in Canada and Alaska, 1 in Greenland, and 3 in Europe north of 60°N (Iceland, Finland, and Sweden/Norway).	Augment network with new surface observations (~10-20 stations). Use 4DDA/OSSE to define the network. Assess other cheaper methods for measuring concentrations and columns in the ABZ.	§2.6.1 §2.6.5 §4.5.3
TCCON	Ground-based Fourier Transform Spectrometers recording direct solar spectra in the near-IR for column-averaged CO_2, CH_4, CO, etc. Three sites are north of 60°N, but only 2 are operational.		
ABoVE	RS and field-based measurements to understand how land surface processes interact to regulate the atmospheric GHGs; will add eddy covariance towers, and provide the opportunity to extend CARVE. CO_2 and CH_4 flux measurements using flux auto chambers.	Embed ABoVE within US-Canadian downscaling effort. Evaluate requirements for US airborne flux measurement capability for CO_2 and CH_4.	§2.6.5 §4.1.4

CARVE (2012-2015)	Airborne mission to quantify correlations between atmospheric concentrations of CO_2 and CH_4 with surface-atmosphere carbon fluxes and surface state control variables.	Augment coverage, extend duration. Assess adding airborne flux measurement capability to follow-on campaigns.	§2.6.1 §2.6.5 §4.1.3 §4.1.4
Satellites (AIRS, IASI, MLS, GOSAT, OCO-2)	Combined with 4DDA provides information on transport into ABZ.	Use 4DDA/OSSE to contribute to future mission (ASCENDS) planning to ensure the measurements meet requirements for ABZ.	§2.6.5 §4.2

Land Surface

Observational Activity	**Details**	**Proposed Supplements (shown in blue) and New Activities (shown in red)**	**Reference**
Permafrost and thermokarst scaling studies			
NGEE	Phase 1 – field observations, lab experiments, modeling activities – Permafrost degradation and its impact on water, N, C, and energy-related processes across a hierarchy of scales. Locations: North Slope (Barrow) and Seward Peninsula (Council).	Augment upscaling approach using flux aircraft and additional remote sensing studies.	§2.4.5
ABoVE	Field measurements to understand driving processes and agents to develop inputs to physical models to predict spatial and temporal patterns and future conditions for soil active layer depth and permafrost status.	Coordination with NGEE, extending the domain, incorporating heritage sites and scaling studies.	§2.4.3
NSF AON	Long-term permafrost temperature observations and active layer thickness in the NH; over 300 sites.	Conduct analyses of existing observations	§2.4.3
ADAPT (2011-2015)	Many observational sites across northern Canada to identify the impacts of rapid environmental changes underway in the North caused by thawing permafrost.	Conduct analyses of existing and new observations.	§2.4.3
Hydrology			
DOE ARM Program	**Campaign**: Barrow Webcam for ITEX, Sept 2009-Aug 2012: Daily ground views to observe seasonal surface changes such as onset and melt of snow cover.	Conduct data analyses.	§2.4.2

ABoVE	Field measurements, watershed scale: soil moisture, precipitation, snow depth and SWE; tower eddy covariance measurements of land-atmosphere water/energy fluxes; water isotopes; stream flow; fine scale topography; vertical and lateral runoff and groundwater flows; water chemistry.	Upscale with remote sensing (RS) and flux aircraft.	§4.1.3
Satellite-retrieved Snow products (MODIS)	Products available from NSIDC.	Upscale characteristics (density, spatial variability). Develop better estimates of SWE.	§2.4.2
SMAP (2014)	Soil moisture, freeze/thaw state	Use observations to help derive parameterizations of permafrost spatial variability as a function of the physical characteristics of the land surface.	§2.4.3
Biogeochemistry			
NGEE	Examining whether adequate representation of biogeochemical and biophysical processes requires sophisticated representation of fine-scale covariance of vegetation, hydrology, and thermal regime as structured by geomorphology.	Upscale, high-resolution as function of plant type. If results from NGEE over limited spatial domains confirm their hypothesis, extend effort to map fine-scale geomorphological variability.	§2.4.5
ABoVE	LIDAR and SAR characterize vegetation structure and biomass changes following disturbance. Field measurements study factors controlling plant community structure and response to variations in permafrost and surface hydrology. Regional soil mapping; use RS to quantify linkages between in situ soil C patterns and overlying vegetation, terrain and microclimate.	Couple to pan-ABZ RS effort to characterize ABZ vegetation, soils, hydrology, etc., in ESMs.	§2.4.5
Heritage sites (e.g., BOREAS, BERMS, ABLE-3A, 3B)	Previous field experiment sites in Canada and Alaska	Revisit using a combination of flux tower and aircraft-based flux measurements; add some “new” sites - determine how to do temporal and spatial scaling of non-linear disturbance effects on carbon, energy and water. Assess changes since previous studies.	§4.1.3 §4.1.4

Ocean & Sea Ice

Observational Activity	Details	Proposed Supplements (shown in blue) and New Activities (shown in red)	Reference
SHEBA (1997-1998)	Concurrent measurement of the atmosphere, sea ice and upper ocean, including air-ice, ice-ocean, and air-ocean fluxes.	Contribute to MOSAiC, particularly with observations focused on the Western Arctic. Coordinate multi-scale ecosystem observations with complementary modeling to facilitate upscaling information from small-scale observations.	§2.1 §2.3 §4.1.1 §4.1.2 §4.1.3
MOSAiC (~ 2017) (Follow-up to SHEBA)	Scientific emphasis: processes that transfer heat, moisture, density, and momentum through the system. Proposed observations: a manned, transpolar drifting observatory for intensive observations of atmospheric, oceanic, and sea-ice properties over 1-2-year timeframe. Expand to larger spatial scales with a network of buoys, unmanned aerial systems, autonomous underwater vehicles, ships, aircraft, and satellites.		
Satellite-derived sea-ice extent (AMSR-E; SSMI/S)	Products available from NSIDC.	4DDA products for integrated view of variations and surface flux estimates.	§4.5.1 §4.5.4
CryoSAT-2, IceSAT-2 (2016)	Satellite-derived sea-ice thickness.	Use IceBridge measurements of opportunity for validation.	§2.2

Integrated Systems

Observational Activity	Details	Proposed Supplements (shown in blue) and New Activities (shown in red)	Reference
Global Rivers Project	Characterize the sources, pathways and timescales of riverine export of organic and inorganic carbon from land to ocean. Two rivers (Lena, Kolyma) in Arctic basin.	Extend to rivers in Canadian Basin.	§4.4
NSF-OPP Soil fluxes (water, C, N…)	Fluxes of water, carbon, nutrients from soils as function of climate and land surface	Upscale with RS/flux aircraft.	§2.6.2
DOE ARM Program	**Campaign**: Sea Ice Effect on Arctic Precipitation, 2011-2013: oxygen and hydrogen isotopic compositions in precipitation collected at Barrow and Atqasuk.	Compare with integrative reanalyses.	§4.5.4

4.4 Other Activities

4.4.1 Model development, diagnostics, and assimilation

Even before targeted field campaigns are planned, it is important to recognize that there are deficiencies in models that can and should be addressed with model development activities. Examples include the development of cloud microphysics parameterizations, the better representation and parameterization of small scale terrestrial geomorphology for the relatively larger scale atmospheric model grids, improvements of old parameterizations or the introduction of new parameterizations to keep up with the continuing evolution of models toward higher horizontal and vertical resolution, and the need for improvements in the representation of both the atmospheric and oceanic planetary boundary layer. The models undoubtedly need much increased vertical resolution, but this will only be useful with improved parameterizations of turbulence and clouds.

Cloud and aerosol microphysics

Development of cloud microphysics parameterizations to represent super-cooled liquid, mixed-phase and ice clouds, and of cloud-aerosol interactions at the microphysical level is a priority. The ARM program aims to get better observations of ice properties (see draft white paper on Ice Physical and Radiative Properties focus group at http://asr.science.energy.gov/science/working-groups/focus-groups). As a first step, they plan analysis of existing observations, including new observations at Barrow, to characterize the probability distribution of ice particle properties in terms of other properties (such as temperature, cloud type, etc.). Activities like this need to be given priority and new observational needs must be identified.

Land Surface Model Developments

Land surface models aim to produce an accurate large-scale description of snow behavior using only a handful of snow variables; this is made difficult by the fact that in nature, the evolution of a snowpack is strongly affected by spatial variability in snow at scales not resolved by the model. Similarly, land models attempt to reproduce the surface and energy water balances accurately at the large scale without resolving explicitly key spatial variations in soil water and temperature variables. In principle, the models can function adequately with their coarse resolution by properly parameterizing the effects of the unresolved variability. The parameterizations in models today, however, are very crude, largely due to a paucity of the surface observations needed to support their development. More basic research based on in-situ measurements is needed to improve macroscale land surface model representations of energy, water, and snow processes. Better BGC component models are also needed, e.g., a better phenological model and improved ability to represent the treeline. DVGMs may also need improved treatment of plant diversity and a better mechanistic treatment of migration and competition among plant types. Fire emissions and disturbance severity need to be represented. Improving permafrost models by integrating thermokarst and other disturbances is necessary to better quantify and predict the impact of disturbances on northern high-latitude SOC pools. Several model developments are needed to improve the representation of the impact of land surface hydrology on the carbon cycle. Surface lakes/wetlands/floodplain inundation should also be included in the land models.

Vertical resolution in AGCMs

Observations show that the Arctic atmosphere has many important structures that are very thin vertically. These include the turbulent boundary layer, cloud layers, and inversions. High vertical resolution is needed in a model that resolves these features, but high vertical resolution is useful only when the physical parameterizations are sufficiently realistic. Therefore increasing vertical resolution should be accompanied by improvements in parameterizations.

Horizontal resolution in OGCMs and Sea-Ice Models

Maslowski et al. (2008) show that significant improvements in ocean and sea-ice models are realized by increasing resolution. Better representation of bathymetry due to higher resolution both in the horizontal and vertical improves the simulation of topographically steered flows, which in the case of the Barents Sea and other coastal areas can change the representation of ocean circulation as well as regional distribution and transformation of water masses. Validation of model results against observations (Maslowski and Walczowski; 2002; McGeehan and Maslowski, 2012) indicate that high horizontal resolution is required to properly represent buoyancy-driven narrow coastal currents (e.g., Alaska Coastal Current or Norwegian Coastal Current), small-scale bathymetry (e.g., Bering Strait Barrow Canyon), and land futures (e.g., passages through the Canadian Arctic Archipelago).

4DDA Analyses

Analyses generated through data assimilation are an important part of the tool set for advancing understanding of the Arctic region. With adequate observations, assimilation analyses help to characterize the state of the ABZ and provide an assessment of the quality and consistency of model components with respect to the observations. Through the direct confrontation of models with observations, assimilation also has the potential for guiding model development or improving parameter choices. It can also help determine the optimal choice of field experiments (surface and aircraft observations) to help evaluate and constrain the uncertain model processes.

4.4.2 Observations: analyses, data products and data mining

A comprehensive satellite collection and analysis effort should be implemented for the entire ABZ. These data (including the complete available historical data archive) will be used for a better characterization of PCS and BGC parameters in ESMs and for experimental validation. This applies particularly to land surface parameters.

A survey of other available data sets should be a priority, with provision of a central access site to those data that will be used by models either for ingestion or validation. New data products as well as analyses of existing products should be undertaken to bring new insight to ABZ questions. Providing easy access to model output for analysis or comparison by interested parties will also be necessary. A valuable addition would be a data repository specifically for model calibration and validation with site-specific data in complementary formats of all available biophysical variables.

New data products that would be useful include:

- Improved vegetation data sets;
- Map of soil properties across the ABZ using satellite data, the available sparse in-situ data sets, and modeling;
- Better records of past disturbance – perhaps from the Landsat record – particularly for northern Eurasia;
- Change and disturbance mapping;
- Near-surface hourly weather drivers, at the highest resolution possible, for multiple decades;
- Characterization of fresh snow density.

4.4.3 Model input to planning of new observations and field campaigns

Modeling studies, either unconstrained simulation or data-constrained assimilation analyses, can help to refine measurement needs. For example, simulations that quantify the uncertainty in transport and the relation to surface emissions and spatiotemporal variability can be used to identify the requirements (number and sites) for an expanded ground-based network to monitor long-term changes in carbon flux and storage. Data assimilation, which can be used to infer unobserved parameters from limited observations (such as column-integrated CO_2), can be used with samples extracted from high-resolution simulations to determine the satellite measurements best suited to observing spatial and shorter term (seasonal to interannual) variability in CO_2 and CH_4 fluxes and concentrations. Sampling studies using high-resolution simulations could also be used to identify the types of field campaigns that best support model testing and what observations are needed to provide a comprehensive, short term view of regional carbon fluxes, examining (for example) the benefits of potential UAV observations versus conventional in-situ aircraft sampling.

4.4.4 Integrative assessments

The balance between the opposing processes of increased carbon capture and release will determine future changes in the carbon feedbacks from Arctic-Boreal ecosystems to global climate. However, there are large uncertainties in calculating this balance across permafrost, terrestrial soil, vegetation, ocean, and freshwater systems. Integrative assessments are urgently needed to advance state-of-the-art modeling. An important step forward would be to establish an Arctic-Boreal System Synthesis Center. At a minimum, having a devoted multi-year program to synthesize and integrate the numerous previously funded Arctic-Boreal projects would yield an advanced understanding of feedback and scaling processes and interactions. The effort would include ABLE, BOREAS, ICESCAPE, IceBridge, ARCTAS, etc., the integration of multiple remotely sensed products from the EOS satellites, and other resources. In either case, it would be a very reasonable investment to integrate the many existing parts into a whole and discover that we know more than we realized.

5 Next steps

This report is the outcome of a small, focused workshop funded by NASA/HQ and held at the Goddard Space Flight Center. The workshop benefited from the insights gained from a few recent workshops and/or planning activities, some initiated by other agencies. The recommendations for activities – field campaigns, data analysis, and model developments – are priorities identified as necessary for a major advance in our predictive modeling capabilities. However, it is clear that these proposed activities have to be considered in the light of activities funded by other agencies and would both leverage those activities and potentially contribute to them. Thus, one of the desired steps forward is the formation of a small interdisciplinary, interagency team to

1) Assess current and planned activities in the context of this and other study reports, and
2) Assess priorities, feasibility and resources required to conduct the recommended activities.

NASA has the expertise – satellite data, field campaigns, and models – to lead the formation of such a team. Although careful consideration has to go into the development of a phased plan of activities and the required funding profiles, several activities could be initiated early since they are relatively low-cost tasks that can proceed without new observations and can provide information for planning campaigns and new observational sites. These tasks inlcude data mining and analysis, new product development, data assimilation synthesis of existing observations, observing system design, and model development.

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Appendix A: Acronyms

3-D	Three-dimensional
4DDA	Four-Dimensional Data Assimilation
ABLE	Arctic Boundary Layer Expedition
ABoVE	Arctic-Boreal Vulnerability Experiment
ABZ	Arctic-Boreal Zone
ADAPT	Arctic Development and Adaptation to Permafrost in Transition
AEROCAN	AERONET Canada
AERONET	AErosol RObotic NETwork
AGCM	Atmospheric General Circulation Model
AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System
AOD	Aerosol Optical Depth
AOMIP	Arctic Ocean Model Intercomparison Project
AON	Arctic Observing Network
AR4 (5)	Fourth (Fifth) Assessment Report of the IPCC
ARCTAS	Arctic Research of the Composition of the Troposphere from Aircraft and Satellites
ARM	Atmospheric Radiation Measurement
ASCENDS	Active Sensing of CO_2 Emissions over Nights, Days, and Seasons
ASOF	Arctic/Subarctic Ocean Fluxes
ATMS	Advanced Technology Microwave Sounder
AVHRR	Advanced Very High Resolution Radiometer
BC	Black carbon
BERMS	Boreal Ecosystem Research and Monitoring Sites
BGC	Biogeochemical
BL	Boundary Layer
BOREAS	Boreal Ecosystem–Atmosphere Study
CADIS	Cooperative Arctic Data and Information Service
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarisation
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CALM	Circumpolar Active Layer Monitoring program
CARVE	Carbon in Arctic Reservoirs Vulnerability Experiment
C^4MIP	Coupled Climate–Carbon Cycle Model Intercomparison Project
CCN	Cloud Condensation Nuclei
CCSM4	Community Climate System Model version 4
CERES	Clouds and Earth's Radiant Energy System
CFMIP	Cloud Feedbacks Model Intercomparison Project
CGCM	Coupled General Circulation Model
CliC	Climate and Cryosphere
CLM4	Community Land Surface Model, Version 4
CMIP3(5)	Coupled Model Intercomparison Project, Phase 3 (5)
COSP	CFMIP Observation Simulator Package
CPR	Cloud Profiling Radar
CrIS	Cross-track Infrared Sounder
DIC	Dissolved Inorganic Carbon
DMS	Dimethylsulfide
DoE	Department of Energy
DGVM	Dynamic Global Vegetation Model

EM	Electro-Magnetic
EP	Export of POC
ERA	ECMWF Re-Analysis
ESM	Earth System Model
ESMR	Electrically Scanning Microwave Radiometer
ESRL	Earth System Research Laboratory
GCM	Global Climate Model
GHG	Greenhouse Gas
GOSAT	Greenhouse gases Observing SATellite
GPP	Gross Primary Productivity
GRACE	Gravity Recovery and Climate Experiment
IASC	International Arctic Science Committee
IASI	Infrared Atmospheric Sounding Interferometer
ICECAPS	Integrated Characterization of Energy, Clouds, Atmospheric State, and Precipitation over Summit
ICESCAPE	Impacts of Climate on EcoSystems and Chemistry of the Arctic Pacific Environment
IMPROVE	Interagency Monitoring of Protected Visual Environments
IN	Ice Nuclei
InSAR	Interferometric Synthetic Aperture Radar
IPCC	Intergovernmental Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Project
ITEX	International Tundra Experiment
LIDAR	Light Detection and Ranging
LSM	Land Surface Model
LTER	Long Term Ecological Research
LW	Longwave
MISR	Multi-angle Imaging SpectroRadiometer
MLS	Microwave Limb Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MOSAiC	Multi-disciplinary drifting Observatory for the Study of the Arctic Climate
M-PACE	Mixed-Phase Arctic Cloud Experiment
MsTMIP	Multi-scale Synthesis and Terrestrial Model Intercomparison Project
NACP	North American Carbon Program
NADW	North Atlantic Deep Water
NASA	National Aeronautics and Space Administration
NCSCD	Northern Circumpolar Soil Carbon Database
NEE	Net Ecosystem Exchange
NGEE	Next Generation Ecosystem Experiments
NH	Northern Hemisphere
NIR	Near Infra-Red
NOAA	National Oceanic and Atmospheric Administration
NOWES	Northern Wetlands Study
NPP	National Polar-orbiting Partnership
NPP	Net Primary Productivity (context provides the distinction from the above)
NSA	North Slope of Alaska
NSIDC	National Snow and Ice Data Center
NSF	National Science Foundation
OC	Organic Carbon
OCO	Orbiting Carbon Observatory
OGCM	Ocean General Circulation Model

OPP	Office of Polar Programs
OSSE	Observing System Simulation Experiment
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a lidar
PBL	Planetary Boundary Layer
PCS	Physical Climate System
PP	Primary Productivity
RS	Remote Sensing
SAR	Synthetic Aperture Radar
SAT	Surface Air Temperature
SEARCH	Study of Environmental Arctic Change
SeaWIFS	Sea-viewing Wide Field-of-view Sensor
SHEBA	Surface Heat Budget of Arctic Ocean
SLP	Sea Level Pressure
SMAP	Soil Moisture Active Passive mission
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity mission
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SRES	Special Report Emissions Scenario
SSMI/S	Special Sensor Microwave Imager / Sounder
SW	Shortwave
SWE	Snow Water Equivalent
SWOT	Surface Water Ocean Topography mission
TCCON	Total Carbon Column Observing Network
TES	Tropospheric Emission Spectrometer
TransCom	Atmospheric Tracer Transport Model Intercomparison Project
UAV	Unmanned Aerial Vehicle
VIIRS	Visible Infrared Imaging Radiometer Suite
WWRP	World Weather Research Program
YOPP	Year of Polar Prediction

Appendix B: Relevant Field Campaigns and Measurement Programs

ABoVE – the Arctic-Boreal Vulnerability Experiment (NASA)

http://cce.nasa.gov/terrestrial_ecology/scoping.html#above

ABoVE will be an international research initiative led by NASA. ABoVE is designed to produce new knowledge needed to understand how climate change impacts ecosystems in the High Northern Latitude region, and how these changes produce feedbacks to climate and are influencing ecosystem services. ABoVE was scoped to focus on *processes, feedbacks and interactions* that are regulated by climate and influence the *vulnerability and resilience* of Arctic and Boreal ecosystems and landscapes. Particular focus is placed on the roles of and interactions between disturbance, permafrost, and surface hydrology – processes that are key to high northern latitude biomes.

ABoVE is designed around intensive study sites located in areas that (a) represent major ecosystem/landscape types; (b) span gradients in permafrost and surface hydrology; (c) include areas where disturbances are common; and (d) include ongoing intensive and/or long term research projects (such as LTERs) sponsored by the Canadian, Japanese, and U.S. agencies. These intensive study sites will be located along three N-S transects (western Alaska, central Alaska and western Canada. The field campaign will focus on collection of a similar suite of measurements and observations in each intensive study area to enable the improvement and validation of key models. The field campaign will also include experiments and studies of key processes. Many of experiments and studies at intensive sites will be based on research being sponsored by collaborating agencies and organizations. Secondary study sites will be established to address knowledge gaps that focus on a specific area (e.g., impacts of insects).

AERONET (AErosol RObotic NETwork)

http://aeronet.gsfc.nasa.gov/

AERONET is a network of ground-based sun photometers, which measure atmospheric aerosol properties, providing continuous cloud-screened observations of spectral aerosol optical depth (AOD), precipitable water, and inversion aerosol products in diverse aerosol regimes. For more than a decade the AEROCAN sun photometry network has generated aerosol concentration and size information at sites across Canada.

Arctic Boundary Layer Expedition (ABLE-3 A, ABLE-3B, NASA), July-August 1988 and 1990

The Arctic Boundary Layer Expeditions (ABLE) 3A and 3B were conducted in arctic and boreal North America. ABLE-3A used ground, aircraft and satellite measurements to characterize the chemistry and dynamics of the lower atmosphere during July-August 1988, with research areas in Alaska's North Slope and Yukon-Kuskokwim Delta regions. ABLE-3B was focused on the north central and northeastern regions of Canada during July-August 1990, co-incident with the Northern Wetlands Study (NOWES) in the Hudson Bay Lowlands (Glooschenko et al. 1994). A latitudinal study of tropospheric trace gas and aerosol composition was also conducted along the east coast of North America from 37°N to 65°N. The expedition used ground, aircraft, and satellite measurements to study source, sink, and transport processes that influence the chemical climate of subarctic and Arctic regions of Canada. Intensive studies, involving coordinated ground and aircraft measurements, were centered on Kinosheo Lake in the Hudson Bay lowlands on and forest/wetland sites near Schefferville, Quebec. The emphases placed in the experimental design included (1) biosphere-atmosphere interactions on the atmospheric biogeochemical cycles of CO_2, CO, CH_4 and other chemical species, and (2) the importance of long-range transport as a source of airborne pollutants. More information on ABLE-3A and ABLE-3B is available in Harriss et al. (1992, 1994).

Arctic Observing Network (AON, NSF)

http://www.arcus.org/search/aon

AON is an integral part of the SEARCH program, as an NSF initiative growing out of the International Polar Year (IPY) to improve observational capabilities in the Arctic and leave a long-term legacy for the benefit of science and society. AON data will contribute to scientific research leading to (1) increased knowledge and understanding of the regional and global causes and consequences of present-day environmental arctic change, (2) scenarios for and prediction of the course of future arctic change and its regional and global consequences, and (3) the development of adaptive responses to arctic change. AON currently consists of 51 projects funded by the NSF Office of Polar Programs. The AON projects fall into the following SEARCH Implementation Plan categories: Atmosphere; Ocean and Sea Ice; Hydrology/Cryosphere; Terrestrial Ecosystems; and Human Dimensions. The Cooperative Arctic Data and Information Service (CADIS) supports AON by providing portal for data discovery, provide near-real-time data delivery, a repository for data storage, and tools to manipulate data.

ADAPT

http://www.cen.ulaval.ca/adapt/index.php

The Canadian ADAPT mission is to produce an 'Integrated Permafrost Systems Science' framework that will be used to help generate sustainable development and adaptation strategies for the North in the context of rapid socio-economic and climate change. It will work at numerous sites across northern Canada, from Yukon to Labrador, to study the impact of changing permafrost and snowfall on landscapes, wildlife, northern communities and northern industries. ADAPT is organized as four interlocking research modules to address a broad, representative spectrum of natural science and engineering issues within the Integrated Permafrost Systems framework:

(1) Permafrost dynamics in natural and engineered environments;
(2) Permafrost and aquatic ecosystems;
(3) Microbes and biogeochemical fluxes of nutrients and carbon; and
(4) Tundra ecosystems: vegetation and wildlife.

The project, funded under NSERC's Discovery Frontiers initiative, is led by Université Laval ecologist Warwick Vincent.

Arctic/Subarctic Ocean Fluxes (ASOF)

http://www.asof.awi.de/en/home/

ASOF is an international program on the oceanography of the Arctic and Subarctic seas and their role in climate. ASOF focuses on ocean fluxes of mass, heat, freshwater, and ice in the Arctic and subarctic oceans. The program was established in 2000 and the first phase from 2000-2008 coordinated novel measurements in novel places in order to produce a baseline freshwater flux budget for Arctic inflows and outflows. Since 2008, the second phase, ASOF II, still has a focus on fluxes, but now has a charge to apply the knowledge gained during the first phase to broader issues of high scientific and societal importance. ASOF has strong links to SEARCH (ASOF is a sub-program of International SEARCH), CLIVAR (an endorsed program), CliC (an endorsed program), and DAMOCLES (which has substantial overlap with ASOF).

Atmospheric Radiation Measurement (ARM, DOE)

http://www.arm.gov

ARM's North Slope of Alaska (NSA) site is providing data about cloud and radiative processes at high latitudes. Centered at Barrow and extending to the south (to the vicinity of Atqasuk), west (to the vicinity of Wainwright), and east (towards Oliktok), the NSA site has become a focal point for atmospheric and ecological research activity on the North Slope. The principal instrumented facility was installed near Barrow in 1997, followed by a smaller remote site in Atqasuk in 1999, which operated through 2010.

Ongoing ARM campaigns in the ABZ are:

- Arctic Cloud Infrared Imaging, 2012.07.16 - 2013.09.30, at or close to the Great White facility at the North Slope of Alaska site
- ARM Radiosondes for NPOESS/NPP Validation, 2012.07.09 - 2015.12.31
- Barrow Black Carbon Source and Impact Study, 2012.07.01 - 2013.06.30
- Lidar support for ICECAPS at Summit, Greenland, 2010.04.15 - 2014.10.31

Boreal Ecosystem Research and Monitoring Sites (BERMS, Canada)

http://berms.ccrp.ec.gc.ca/Overview/e-overview-about.htm

The BERMS program is a joint initiative of Canadian government agencies, universities and other research partners. Their main objective is to study the role that Canadian boreal forest plays in the global carbon budget and climate change. From 1996 to 2006, the program continued where the field phase of BOREAS left off. New research projects were conducted at the three previous study sites in the southern boreal forest of Saskatchewan (Old Aspen, Old Jack Pine, Old Black Spruce). Younger forest sites associated with the main sites have been included. The BERMS sites are the flagship sites in the Fluxnet-Canada network.

Boreal Ecosystem-Atmosphere Study (BOREAS)

http://daac.ornl.gov/BOREAS/boreas.shtml

BOREAS was a large-scale experiment initiated in 1990 to investigate interactions between the boreal forest biome and the atmosphere. Surface, airborne, and satellite-based observations were collected at representative sites in the boreal forest of central Canada from 1993 through 1996 to study the biological and physical processes and conditions that govern the exchanges of radiative energy, water, heat, carbon, and trace gases between boreal forest ecosystems and the atmosphere, particularly those processes that may be sensitive to global change. The objectives of the BOREAS project were: (1) to improve process models that describe the exchanges of radiative energy, water, heat, carbon, and trace constituents between the boreal forest and the atmosphere; and (2) to develop methods for applying the process models over large spatial scales using remote sensing and other integrative modeling techniques.

The BOREAS Follow-On project extended and built upon the original BOREAS goal of investigating interactions between the boreal forest biome and the atmosphere to clarify their roles in global change. A common set of existing BOREAS in situ and remote-sensing data from 1993-1996 was compiled at point, study area, and regional scales for use by Follow-On investigators. In addition new data were compiled for 1997-1998.

Circumpolar Active Layer Monitoring (CALM, NSF)

http://www.gwu.edu/~calm/

The primary goal of the CALM program is to observe the response of the active layer and near-surface permafrost to climate change over long (multi-decadal) time scales. The CALM observational network, established in the 1990s, observes the long-term response of the active layer and near-surface permafrost to changes and variations in climate at more than 200 sites in both hemispheres. CALM currently has participants from 15 countries. Majority of sites measure active-layer thickness on grids ranging from 1 ha to 1 km^2, and observe soil temperatures. Most sites in the CALM network are located in Arctic and Subarctic lowlands. The CALM program began in 1991. It was initially affiliated with the International Tundra Experiment. Since 2009 CALM is part of the NSF Arctic Observing Network (AON) Program.

CARVE (NASA)

http://science.nasa.gov/missions/carve/

The Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) is one of the first of NASA's Earth Ventures (EV-1) investigations. CARVE is a 5-year mission designed to quantify correlations between atmospheric concentrations of CO_2 and CH_4 with surface-atmosphere carbon fluxes and surface state control variables (soil moisture, freeze-thaw state, inundation state, surface soil temperature) and elucidate the sensitivities of Arctic carbon cycle processes to climate change. CARVE will use the Arctic-proven C-23 Sherpa aircraft to fly an innovative airborne remote sensing payload. It includes an L-band radiometer/radar and a nadir-viewing spectrometer to deliver the first simultaneous measurements of surface parameters that control gas emissions (i.e., soil moisture, freeze/thaw state, surface temperature) and total atmospheric columns of carbon dioxide, methane, and carbon monoxide. The aircraft payload also includes a gas analyzer that links greenhouse gas measurements directly to WMO standards. Deployments will occur during the spring, summer and early fall when Arctic carbon fluxes are large and change rapidly. Further, at these times, the sensitivities of ecosystems to external forces such as fire and anomalous variability of temperature and precipitation are maximized. Continuous ground-based measurements provide temporal and regional context as well as calibration for CARVE airborne measurements. Science operations are scheduled for 2012-2015.

Global Rivers Project

http://www.whoi.edu/page.do?pid=19735

This is an NSF-funded effort of WHOI and WHRC to characterize the sources, pathways and timescales of riverine export of organic and inorganic carbon from land to the ocean. This is accomplished by integrating detailed geochemical information on temporal and spatial changes in the composition of the dissolved and particulate river loads with spatially and temporally resolved data on relevant ecosystem, hydrologic, geologic, geomorphologic and climatologic characteristics derived from remote sensing and GIS mapping. The study is conducted on six large river basins. Rivers relevant to the ABZ are the Lena and Kolyma Rivers that feed the Arctic and Eastern Siberian Sea, respectively.

IceBridge (NASA)

http://www.nasa.gov/mission_pages/icebridge/index.html

Operation IceBridge images Earth's polar ice in unprecedented detail to better understand processes that connect the polar regions with the global climate system. IceBridge utilizes a highly specialized fleet of research aircraft and the most sophisticated suite of innovative science instruments ever assembled to characterize annual changes in thickness of sea ice, glaciers, and ice sheets. In addition, IceBridge collects critical data used to predict the response of earth's polar ice to climate change and resulting sea-level rise. IceBridge also helps bridge the gap in polar observations between NASA's ICESat satellite missions.

ICECAPS (NSF)

The Integrated Characterization of Energy, Clouds, Atmospheric State, and Precipitation over Summit (ICECAPS) project, funded through NSF's Arctic Observing Network, is deploying a suite of remote sensors at Summit, Greenland, for four years, beginning May 2010. The instrument suite includes a millimeter-wave cloud radar, Atmospheric Emitted Radiance Interferometer, microwave radiometer profiler, a high-frequency microwave radiometer, microwave precipitation sensor, and other instruments. The project also includes twice-daily radiosonde launches. ARM is contributing to this campaign with a micropulse lidar and Vaisala ceilometer to gather information about optically thin clouds commonly found above the Summit site. Combined measurements from these sensors and instruments will result in a comprehensive data set of cloud properties, atmospheric state, precipitation, and radiation. Data from ICECAPS data will provide a complementary data set to ongoing measurements gathered at ARMs North Slope of Alaska site in Barrow, and the SEARCH site in Eureka, Canada.

ITEX – International Tundra Experiment

http://www.geog.ubc.ca/itex/

The International Tundra Experiment is a scientific network of experiments focusing on the impact of climate change on selected plant species in tundra and alpine vegetation. Currently, research teams at more than 24 circumpolar sites carry out similar, multi-year plant manipulation experiments that allow them to compare annual variation in plant performance with respect to phenological response to climate conditions.

MOSAiC - Multi-disciplinary drifting Observatory for the Study of the Arctic Climate

http://www.iasc.info

MOSAiC is an activity being organized under the auspices of the International Arctic Science Committee (IASC). It will be fashioned after SHEBA, but the goal is to substantially improve on SHEBA in terms of spatial context, and observations of aerosols, boundary layer structure, and measurement technology. There will be intensive measurements in the atmosphere, sea-ice, ocean, and biosphere. An initial deployment, targeted for the 2017 timeframe, is being coordinated with the WWRP Year of Polar Prediction (YOPP) activities. MOSAiC Overview Statement: "Multi-year, detailed, and comprehensive measurements, extending from the atmosphere through the sea-ice and into the ocean of the central Arctic Basin are needed to improve our understanding and modeling of Arctic climate and weather, and enhance Arctic sea-ice predictive capabilities. These observations will be designed to provide a process-level understanding of the new central Arctic climate system, consisting of dramatically less and thinner sea-ice than in the recent past, as well as a more detailed understanding of the processes leading to these sea-ice changes. Scientific emphasis will be placed on processes that transfer heat, moisture, density, and momentum through the system. To obtain the needed measurements, a manned, transpolar drifting observatory is proposed, wherein an ice-hardened ship serves as a central hub for intensive observations of atmospheric, oceanic, and sea-ice properties over 1-2 years' time. The comprehensive information from this central facility will be expanded to larger spatial scales using a coordinated network of distributed measurements made using buoys, unmanned aerial systems, autonomous underwater vehicles, additional ships, aircraft, and satellites. A broad consortium of nations and funding agencies is needed to facilitate, coordinate, and support such a constellation of central Arctic observations."

NGEE-Arctic (DOE)

http://ngee.ornl.gov/

The Next-Generation Ecosystem Experiments (NGEE) project will use observations and models to quantify the response of physical, ecological, and biogeochemical processes to climatic change across molecular to landscape scales. Their approach addresses how permafrost degradation in a warming Arctic, and the associated changes in landscape evolution, hydrology, soil biogeochemical processes, and plant community succession, will affect feedbacks to the climate system. Field and lab research will focus on interactions that drive ecosystem-climate feedbacks through greenhouse gas fluxes and changes in surface energy balance.

NGEE Phase 1 includes a series of integrated field observations, lab experiments, and modeling activities. Permafrost degradation and its impact on water, nitrogen, carbon, and energy-related processes will be investigated across a hierarchy of scales, including the pore/core, plot, and landscape scales. Field research will be conducted in Alaska on the North Slope (Barrow) and Seward Peninsula (Council). Phase 1 modeling efforts will focus on application of existing models to evaluate their predictive capability across a range of spatial scales, from single-column to plot to landscape scales. Model results will be compared with laboratory experiments and field observations at the Barrow and Council sites.

NGEE is sponsored by the Office of Biological and Environmental Research within the U.S. Department of Energy's Office of Science.

SEARCH – Study of Environmental Arctic Change – Arctic Atmospheric Observatories (NOAA)

http://www.esrl.noaa.gov/psd/arctic/observatories/

The NOAA Atmospheric Observatory program has established long-term, intensive measurements of clouds, radiation, aerosols, surface energy fluxes and chemistry in Eureka/Alert Canada and Tiksi, Russia. These measurements allow comparison with similar observatory measurements in Barrow, Alaska.

SHEBA – Surface Heat Budget of the Arctic Ocean, September 1997-October 1998

The SHEBA (Surface Heat Budget of the Arctic Ocean) project, which was sponsored jointly by the National Science Foundation's Office of Polar Programs Arctic System Science program and the Office of Naval Research's High Latitude Dynamics program, included a field experiment from September 1997 through October 1998. SHEBA was governed by two broad goals: understand the ice–albedo and cloud–radiation feedback mechanisms and use that understanding to improve the treatment of the Arctic in large-scale climate models. A unique aspect of the field program was the concurrent measurement of characteristics and physical properties of the atmosphere, sea ice and upper ocean, including the fluxes that occur at the air-ice, ice-ocean, and air-ocean interfaces.

TCCON – the Total Carbon Column Observing Network

http://tccon-wiki.caltech.edu/

TCCON is a network of ground-based Fourier Transform Spectrometers recording direct solar spectra in the near-infrared spectral region. From these spectra, accurate and precise column-averaged abundance of CO_2, CH_4, N_2O, HF, CO, H_2O, and HDO are retrieved. The web site lists 19 operational sites; three sites are north of 60°N, but only two are operational.

TransCom

http://transcom.project.asu.edu/index.php

The Atmospheric Tracer Transport Model Intercomparison Project (TransCom) was created to quantify and diagnose the uncertainty in inversion calculations of the global carbon budget that result from errors in simulated atmospheric transport.

Appendix C: Contributors to this Report

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Appendix D: Workshop Agenda

May 22

9:00 AM	Welcome	(R. Harriss and D. Wickland)
9:15 AM	Logistics	(D. Adamec)
9:20 AM	Physical Climate System Overview	(D. Randall)
10:00 AM	Biogeochemical Climate System	(S. Frolking)
10:40 AM	BREAK	
11:00 AM	ABoVE	(S. Goetz)
11:15 AM	NGEE	(P. Thornton)
11:30 AM	ARCTAS	(D. Jacob)
11:45 AM	Report for NSF	(W. Maslowski)
12:00 PM	Charge to Working Groups	(P. Sellers)
12:15 PM	LUNCH	

Breakout Sessions

1:15PM	Biogeochemical & Physical Climate Breakout Session
2:45PM	BREAK
3:00PM	Biogeochemical & Physical Climate Breakout Session
4:30PM	Plenary Discussion – Summary, Issues and concerns
5:00PM	Adjourn
5:30PM	Social at GSFC Recreational Center

May 23

9:00 AM	Biogeochemical & Physical Climate Breakout Session
10:20 AM	BREAK
10:40 AM	Biogeochemical & Physical Climate Breakout Session
11:30 AM	LUNCH
1:30 PM	Plenary Discussion - Progress Report, Q&A
2:30 PM	BREAK
3:00 PM	Biogeochemical & Physical Climate Breakout Session
5:00 PM	Adjourn

May 24

9:00 AM	Report Writing (Breakout session leads and all interested parties)
10:20 AM	BREAK
10:40 AM	Report Writing (Breakout session leads and all interested parties)
11:40 AM	Final Issues and Assignments
12:00PM	Workshop Adjourns

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