Project Summary

Collaborative Research: The seasonal response of the Arctic and global climate system to projected sea ice loss within the context of GHG-induced climate change

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Dr. Marika Holland, Dr. David Lawrence and Dr. Andrew Slater, Co- Principal Investigators

Intellectual Merit

The most striking evidence of a changing Arctic system is the loss of the sea ice cover. This has a distinctly seasonal component, with the largest ice retreat present during summer months. In turn, this ice loss leads to seasonally dependent changes in the ice-ocean-atmosphere heat and freshwater exchange. In particular, enhanced surface warming and ice melt occur in summer with a decreasing albedo. This excess heat is then lost back to the atmosphere during the cold season. This can be attended by enhanced ice growth in the fall due to the loss of the insulating ice cover. The seasonality of these heat and freshwater flux changes has consequent repercussions for atmospheric circulation, temperature and precipitation, snow accumulation, ocean circulation and mixing, and terrestrial processes such as permafrost thaw, ecosystem dynamics and carbon cycling, with global implications.

The primary goal of this proposed project is to investigate the mechanisms underlying the seasonal response of the climate system to Arctic sea ice loss within the context of anthropogenic climate change. This research will make use of the Community Climate System Model, version 4 (CCSM4), which is a fully coupled global atmosphere-ocean-cryosphere-land model with terrestrial and oceanic carbon-nitrogen cycling capabilities. This version of CCSM has improved cloud microphysics, sea ice albedo, dynamic vegetation, snow parameterizations, and permafrost dynamics among other aspects, which should lead to more reliable polar simulations. The overarching goal of this proposed effort is to investigate the relative roles of sea ice loss versus rising greenhouse gases for changes in the seasonal succession and timing of Arctic processes. This will involve research designed to assess the influence of seasonal sea ice loss on aspects of the marine, terrestrial and atmospheric systems, with a particular emphasis on the seasonal dependence of the responses. This work will include a series of targeted sensitivity integrations to isolate the processes of interest. These experiments will be evaluated within the context of available observations. We will also assess the integrated effects of these various processes and how they in turn feedback onto the seasonality of Arctic sea ice change.

Broader Impacts

Current and projected changes in the Arctic system have repercussions for the global climate system, Arctic wildlife, and socio-economic activities in the region. Improving our understanding and modeling of the factors affecting the seasonal timing and succession of processes within the Arctic system will allow for improved Arctic and global system predictability. This has a direct impact on the ability of society to anticipate, mitigate, and adapt to future change. We envision coordination with other funded CSAS projects that investigate other aspects of Arctic seasonality and will freely provide our climate model integration data for these (and other) projects.

Additionally, we will promote the education of a young scientist through a funded postdoctoral position and the mentoring of an undergraduate student through the Significant Opportunities in Atmospheric Research and Science (SOARS) program, which seeks to broaden participation in the atmospheric and related sciences. The PIs will also participate in numerous outreach activities, including public lectures and educational events.

Results from Prior Support

a. "Climate Response to Future Changes in Arctic Snow Cover and Sea Ice: A New Perspective from the High-Resolution NCAR CCSM3" Clara Deser, P.I.
NSF Arctic System Science Program Award ARC-0629300; $477,948; 8/15/06-7/31/09

This project investigates the seasonal impacts of projected future changes in Arctic sea ice and high-latitude terrestrial snow cover on the global atmospheric circulation and climate by means of atmospheric model experiments with the high resolution (1.4° latitude x 1.4 ° longitude) version of the Community Atmospheric Model version 3 (CAM3) coupled to the Community Land Model (CLM). In these experiments, sea ice cover (concentration and thickness) or snow cover (extent, depth and age) for the present (1980-1999) and future (2080-2099; taken from the fully coupled Community Climate System Model Version 3 under the SRES "A1B" scenario) are prescribed as lower boundary conditions to CAM3/CLM. The results show that the largest atmospheric response occurs in winter despite that the largest sea ice loss occurs in late summer. This is a consequence of the seasonal timing of the response of the net surface energy flux, indicating that the linkages between summer sea ice loss and climate response are not necessarily simultaneous. The winter atmospheric response consists of warming that extends ~1500 km inland over Eurasia and North America, enhanced precipitation and snow cover, as well as circulation changes and associated shifts in stormtracks.

Lawrence, D., A. Slater, R. Tomas, M. Holland, and C. Deser, 2008: Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss. *Geophys. Res. Lett.* L11506, doi:10.1029/2008GL033985

Deser, C., M. Alexander, R. Tomas and D. Lawrence, 2008: Atmospheric circulation and climate response to future Arctic sea ice loss. *In preparation*.

Tomas, R., C. Deser, M. Alexander, and D. Lawrence, 2008: Atmospheric circulation and climate response to future changes in northern hemisphere terrestrial snow cover. *In preparation*.

b. Integrated Analyses of the Arctic Freshwater Cycle and Its Influence on Global Climate. NSF-OPP-0242290, (PI: Marika Holland), 2003-2006. $163,086.

This project improved the understanding of processes that influence the arctic freshwater cycle and examined impacts that changes in this cycle can have on the global climate system. This included the study of processes that modify arctic freshwater budgets in the terrestrial, atmospheric, and oceanic environments, the integration of these processes to produce the exchange of freshwater between the Arctic and North Atlantic, and the influence of these processes on the thermohaline circulation and global climate. We found that climate models consistently show an acceleration of the Arctic hydrological cycle over the 20th and 21st centuries in response to increasing greenhouse gas concentrations. Many of the budget terms show the largest changes from 1975-2025, suggesting that we are in the midst of very large anthropogenically forced change in the Arctic freshwater system (Holland et al., 2006b).

Goosse, H., and M.M. Holland, 2005: Mechanisms of interdecadal Arctic climate variability in the Community Climate System Model CCSM2, *J Climate*, **18**, 3552-3570.

Hack, J.J., J.M. Caron, S.G. Yeager, K.W. Oleson, M.M. Holland, J.E. Truesdale, and P.J. Rasch, 2006: Simulation of the global hydrological cycle in the CCSM Community Atmosphere Model (CAM3): Mean Features. *J. Climate*, **19**, 2199-2221.

Holland, M.M., C.M. Bitz, and B. Tremblay, 2006a: Future abrupt reductions in the Summer Arctic sea ice, *Geophys. Res. Lett.*, 33, L23503, doi:10.1029/2006GL028024.

Holland, M.M., J. Finnis, and M.C. Serreze, 2006b: Simulated Arctic Ocean freshwater budgets in the 20th and 21st centuries, *J. Climate*, 19, 6221-6242.

Finnis, J., M.M. Holland, M.C. Serreze, and J.J. Cassano 2007: Response of Northern Hemisphere extratropical cyclone activity and associated precipitation to climate change, as represented by CCSM3. *J. Geophys. Res.*, 112, G04S55, doi:10.1029/2006JG000286.

Holland, M.M., J. Finnis, A. Barrett and M.C. Serreze, 2007: Projected changes in Arctic Ocean freshwater budgets, *J. Geophys. Res.*, 112, G04S55, doi:10.1029/2006JG000354.

White, D., L. Hinzman, L. Alessa, J. Cassano, M Chambers, K Falkner, J Francis, B Gutowski, M Holland, M Holmes, H Huntington, D Kane, A Kliskey, C Lee, J McClelland, B Peterson, F Straneo, M Steele, R Woodgate, D Yang, K Yoshikawa, T Zhang, 2007: The Arctic freshwater system: Changes and impacts, *J. Geophys. Res*., 112, G04S55, doi:10.1029/2006JG000353.

c.NSF ARC-0229769, "Collaborative Research: A Land Surface Model Hind-Cast for the Terrestrial Arctic Drainage System", 01/03-12/07, $583,755 (PI MC Serreze, Co-PI AG Slater). "Collaborative Research: A Heat Budget Analysis of the Arctic System", NSF ARC-0531040, 10/05-ongoing; $436, 991 [PI M.C. Serreze, Co-PI, A.G. Slater (Univ. of Colorado)]

These projects resulted in numerous findings concerning the state of the Arctic land surface both in the present and for the future. Driving five land surface models with ECMWF Reanalysis data it was shown that no single model was superior to all others when assessed against a variety metrics such as simulation of snow, albedo or runoff. While all models are capable of producing acceptable simulations, there is still considerable uncertainty as to how to partition precipitation between evaporation and runoff (Slater *et al.*, 2007). Over the Yenesi Basin, observations show contrasting trends of decreasing precipitation but increasing streamflow; this mystery remains unresolved. The possible state of permafrost over the next century was investigated (Lawrence and Slater, 2005) and where necessary model improvements were made (Lawrence and Slater, 2008). With the amplified warming expected to occur in the Arctic, the vast majority of near-surface permafrost is vulnerable to degradation. Lastly, the consequences of rapid sea ice loss events for the Arctic land surface were shown as producing in significant increases in warming rates as far as 1500km inland from the Arctic Ocean (Lawrence *et al.*, 2008). Much of the work regarding permafrost garnered large public interest in the subject, indicating the broader impacts of our work.

Slater, A.G., T.J. Bohn, J.L. McCreight, M.C. Serreze, and D.P. Lettenmaier, 2007: A multimodel simulation of pan-Arctic hydrology. *J. Geophys. Res.*, 112, G04S45, doi:10.1029/2006JG000303

Lawrence, D.M. and A.G. Slater, 2005: A projection of severe near-surface permafrost degradation during the 21st century. *Geophys. Res. Lett.*, 32, L24401, doi:10.1029/2005GL025080

Lawrence, D.M. and A.G. Slater, 2008: Incorporating organic soil into a global climate model. *Clim. Dynam.*, 30, 145-160

Lawrence, D.M., A.G. Slater, V.E. Romanovsky and D.J. Nicolsky, 2008: The sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter, *J. Geophys.*, *Res.*,113, F02011, doi:10.1029/2007JF000883

Lawrence, DM., A.G. Slater, R.A. Tomas, M.M. Holland, and C. Deser, 2008: Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss. *Geophys. Res. Lett.,* 35, L11506, doi:10.1029/2008GL033985

Lawrence, D.M., and A.G. Slater, 2008: The contribution of changes in snow conditions to future ground climate. Submitted to *J. Geophys. Res*.

PROJECT DESCRIPTION

1. Introduction and Scientific Background

The Arctic environment is changing at an alarming and unprecedented rate. These changes are present in atmosphere, marine and terrestrial components and encompass the physical, chemical and biological systems. A well documented retreat of the summer sea ice cover (e.g. Serreze et al., 2007) is particularly striking, as was accentuated in 2007 with a new record September minimum that shattered the previous record low by 23% (Stroeve et al., 2008). Accompanying this sea ice loss is a reduction in surface albedo (Perovich et al, 2008) and a warming of the surface ocean (Steele et al, 2008), which have contributed to accelerated ice melt.

While perhaps the most obvious, ice retreat is just one aspect of the changing Arctic environment. Other studies provide evidence for a warming of the Atlantic layer within the Arctic Ocean (e.g. Polyakov et al, 2005), warming of Arctic lands (e.g. ACIA, 2004; IPCC, 2007), increases in Eurasian river runoff (Peterson et al., 2002), increases in shrub abundance and a ‘greening’ of the Arctic (Sturm et al., 2001; Myneni et al., 1997), warming permafrost (e.g. Taylor et al., 2006), and decreases in the mass of small Arctic glaciers (Dyurgerov and Meier, 1997) among others. Studies have documented that these changes are interrelated (e.g. Serreze et al, 2000; Overland et al., 2004; McGuire et al. 2006) suggesting that the Arctic is responding as a coherent system. However the numerous and varied linkages among these different aspects of change are not clearly understood.

Climate models project that Arctic change may accelerate in the next decades (Holland et al., 2006) and that a transition to a seasonally ice covered Arctic Ocean could occur within this century (Zhang and Walsh, 2006; Arzel et al., 2006). Observational records indicate that sea ice is retreating faster than climate model simulations of the late 20th century, and a seasonally ice free Arctic Ocean could occur much earlier if the current pace of retreat continues (Stroeve et al., 2007). Climate models also indicate that rapid sea ice loss, and associated acceleration of warming over land, may increase the vulnerability of Arctic terrestrial systems, including permafrost (Lawrence et al., 2008b). This highlights the immediacy of the need to better understand the effects of Arctic sea ice loss on the atmosphere, ocean, and terrestrial systems.

The observed and projected Arctic changes have a distinctly seasonal component. Observed and projected trends in the ice cover are largest during late summer (Figure 1) and are indicative of an earlier melt onset and later freeze-up (e.g., Deser and Teng, 2008). Climate models project this lengthening of the melt season to continue, with associated effects on the surface energy budget that vary distinctly over the annual cycle (Figure 1). In particular, with retreating sea ice, the surface gains heat in the summer due primarily to a lower surface albedo and enhanced shortwave absorption. This heating contributes to further ice melt and ocean surface warming. The heat is then lost during the cold season by turbulent and longwave exchange which leads to enhanced atmospheric warming during the fall and winter with consequent effects on air temperature, precipitation, snow cover, and circulation over the adjacent continents . This seasonal signature of sea-ice-loss-induced fall and winter warming is beginning to become apparent in monthly land air temperature trends (Figure 2). The changing surface heat budgets are also indicative of changes in the ice melt-growth cycle, with enhanced summer melting followed (at least in the short term) by enhanced ice growth in many regions due to a loss of the insulating ice cover (Holland et al., *in review*). This has important implications for the ocean buoyancy flux and consequent ocean mixing and circulation.

These aspects of the changing surface heat and freshwater fluxes appear to be driven in large part by the changing sea ice conditions and not the direct effects of rising greenhouse gases (GHG) (Deser et al., *in preparation*). The direct influence of rising greenhouse gases is instead

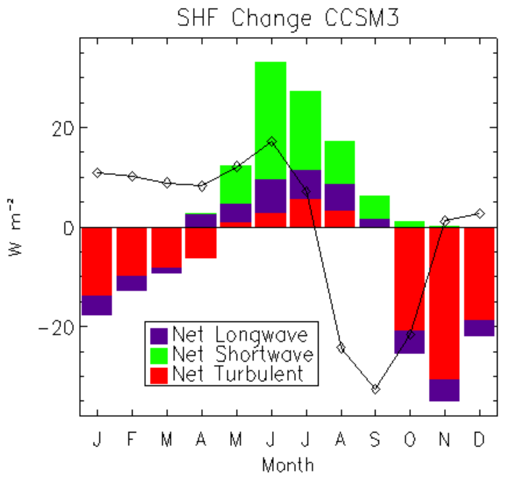


Figure 1: Change in Arctic sea ice extent (thin black curve) and Arctic Ocean surface energy budget (colored bars; positive downward) between 1940-1959 and 2040-2059 as simulated by CCSM3. Ice extent ranges from -6.9 million km^2 in September to -3.3 million km^2 in June.

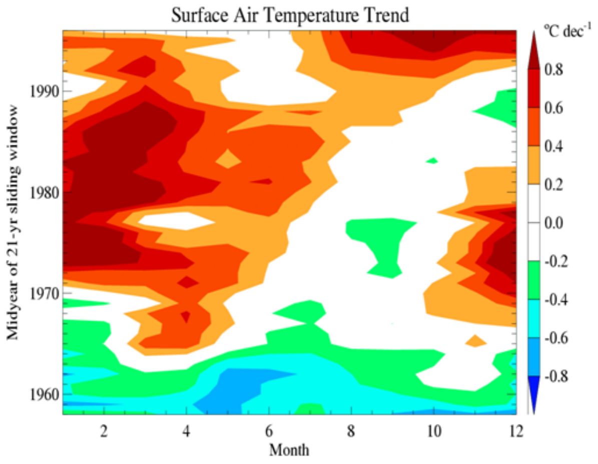


Figure 2: Changing seasonality of Arctic land surface air temperature trend (60°-75°N, excluding Greenland). Data from NCEP/NCAR reanalysis covers the period 1948 to 2007 (Kalnay et al, 1996). Trends are calculated from 21-yr sliding windows for each month of the year.

less regionally and seasonally dependent. This suggests that some of the seasonal changes present in the observational record, which may have a dependence on rising GHG, will be strongly modified in the future as larger seasonal ice loss occurs. In particular, because of non-linearities in atmosphere, ocean and terrestrial processes, the seasonal changes in surface heat and water fluxes associated with ice loss will modulate the response of those systems. More simply put, an excess atmospheric heating during the summer will not have the same net effect as a similar amount of excess heating during winter for numerous processes like cloud formation, circulation response, and downstream terrestrial conditions. Additionally, the seasonally dependent changes in the heat and freshwater budgets will lead to a cascade of effects in the seasonal timing and succession of events throughout the Arctic system, with possible global repercussions.

2. Guiding Research Questions and Approach

The overarching goal of the proposed research is to examine the role of projected Arctic sea ice loss in the seasonal response of the climate system to increased GHG concentrations. In particular, what are the seasonally-dependent local and remote responses to future Arctic sea ice loss, and how do these compare with the fully coupled climate system response to GHG forcing? As such, our proposed work directly addresses two of the broad questions in the proposal solicitation: "how do shifts in seasonal events alter linkages among system components and how do these changes alter the functioning of the arctic system as a whole?"; "how do seasonal changes within the arctic system alter linkages between the arctic and larger scale Earth systems?". We propose a set of experiments with a state-of-the-art climate system model to assess the integrated and interacting effects of projected Arctic sea ice loss on Arctic and global climate system change. In addition, we propose complementary targeted model sensitivity studies to isolate key processes involved in the responses of the atmosphere, terrestrial and marine systems to Arctic sea ice loss.

2.1 Research Tool: CCSM4

Our primary research tool will be the Community Climate System Model, version 4 (CCSM4) scheduled for release by summer 2009. The PI and co-PIs have all contributed to the development and evaluation of CCSM4 and thus are well poised to make effective use of CCSM4 in the proposed experiments. CCSM4 features numerous improvements and new capabilities over previous versions of CCSM, including a number of new or improved representations of polar processes in addition to a generally improved simulation of global climate and its variability (e.g. improved ENSO; Neale et al., 2008). While acknowledging that model biases will remain, experiments with CCSM4 will allow us to directly quantify processes and feedbacks within the modeled system. Observational data will be used to guide our analyses and validate the model response.

Similar to previous versions, the sea ice component of CCSM4 (the Los Alamos National Laboratory’s CICE model) uses the dynamics of Hunke and Dukowicz (1997), multi-layer thermodynamics (Bitz and Lipscomb, 1999) and a subgridscale ice thickness distribution (Thorndike et al., 1975). Improvements from previous versions include the incorporation of a new radiative transfer scheme (Briegleb and Light, 2007) that makes use of inherent optical properties to define the scattering and absorption properties for snow, sea ice and included absorbers. An explicit melt pond parameterization is now incorporated which relates the pond evolution to the surface melt water flux. Additionally, aerosol deposition and cycling within the sea ice component for black carbon and dust species is now included. Taken together, these improvements provide a more sophisticated and complete surface albedo treatment with possible implications for the albedo feedback.

The ocean component of CCSM4 will also include numerous improvements over previous model versions in its physical parameterizations. These include new parameterizations for near-surface eddy fluxes, submesoscale eddies, tidal mixing, gravity current overflows, and langmuir circulation as well as new formulations for anisotropic horizontal viscosity and vertically varying isopycnal and thickness diffusivities. Some of these modifications have documented improvements in the polar regions (Jochum et al., 2007) resulting in a more realistically simulated sea ice edge and ocean heat transport.

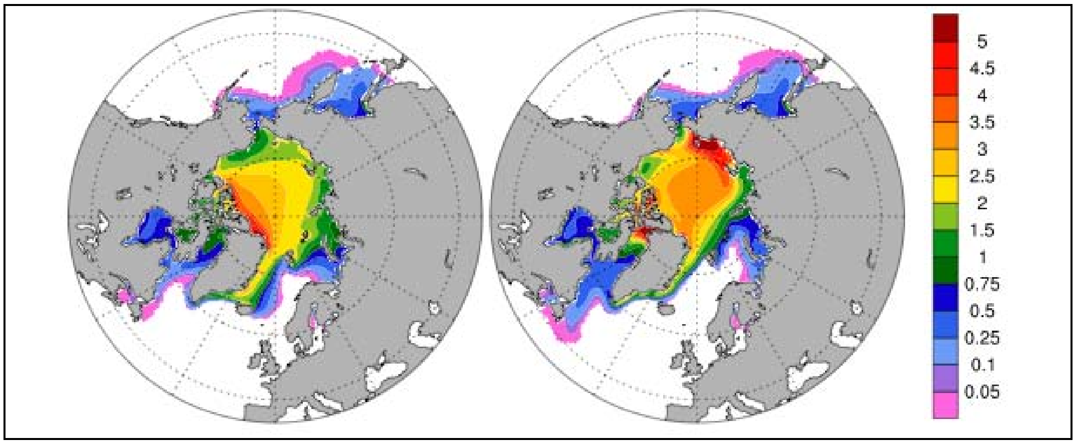
The atmospheric component of CCSM4, the Community Atmosphere Model (CAM) will include updates to virtually every major component of the atmospheric model code including the dynamical core (spectral to finite volume), the convection (Neale et al., 2008) and cloud microphysics schemes (Gettelman et al., 2008; Morrison and Gettelman, 2008), the radiative transfer model, and planetary boundary layer dynamics (Park and Bretherton, 2008) in addition to an improved representation of the aerosol indirect effect. The new cloud microphysics and planetary boundary layer packages, in particular, improve polar climate simulations by reducing the prominent excess low cloud bias present in CAM3. The resulting surface climate simulation is improved, most notably with a more realistic annual cycle amplitude.

The new version of the Community Land Model, the land component of CCSM4, will benefit from a broad range of improved parameterizations and newly represented processes, many of which are directly relevant to Arctic simulations. Improved parameterizations have been incorporated for the soil hydrology scheme (Oleson et al., 2008; Stöckli et al., 2008) including the effects of freezing-point depression and frozen soil permeability (Niu and Yang, 2006). The snow model has been updated with revised snow cover fraction (Niu and Yang, 2007), snow aging (Flanner and Zender, 2006), and snow compaction schemes (Lawrence and Slater, 2008a) and now includes vertically resolved heating of the snowpack (Flanner and Zender, 2005) and aerosol deposition (Flanner et al., 2007). Permafrost dynamics are better represented through explicit representation of the thermal and hydrologic properties of organic soil (Lawrence and Slater, 2008b) and an extension of the soil column from 3.5 to 50m depth (Lawrence et al., 2008a). Fully prognostic terrestrial carbon and nitrogen dynamics are represented through a cascade of vegetation, litter, and soil organic pools (Thornton et al., 2007; Thornton and Zimmerman, 2007).

The seasonal timing of new vegetation growth and litterfall is prognostic, responding to soil and air temperature, soil water availability, and daylength. Dynamic vegetation (DGVM) biogeography is integrated with the carbon and nitrogen dynamics scheme. New for the DGVM is the inclusion of a boreal shrub plant functional type (Zeng et al., 2008).

Taken together, the improvements in CCSM4 relative to previous versions represent an important step forward in our ability to model the global climate system. Although this model is still being assembled, results from interim model versions indicate significant improvements in polar climate, ENSO variability, and terrestrial processes. Of note for this proposal, CCSM3.5 (an interim step to CCSM4) has an improved Arctic sea level pressure distribution, which leads to better sea ice transport and resulting ice thickness simulation (Figure 3). Excessive winter polar cloud cover that was present in CCSM3 (with consequent impacts on surface radiation) is ameliorated in CCSM3.5. Additionally, improved surface land processes contribute to a better simulation of soil temperature and permafrost (Figure 3), cold region hydrology, and snow cover. We fully expect these general improvements to carry over to CCSM4, which is significant given that the previous CCSM model (version 3) had a very reasonable (and in some measures, one of the best) Arctic climate simulation compared to other IPCC-AR4 models (Stroeve et al., 2007; Holland et al., 2006; Chapman and Walsh, 2007). More results and information on the polar climate simulated in CCSM simulations can be found in presentations available from http://www.ccsm.ucar.edu/working_groups/Polar.

Thickness (m) CCSM3.5 CCSM3



Soil Temp OBS CLM3.5 CLM4

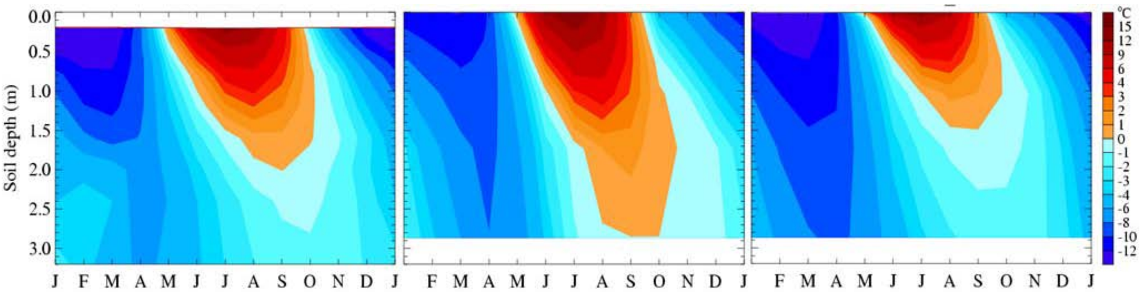


Figure 3. Model improvements in CCSM. Top: Annual mean sea ice thickness (m) in CCSM3 and CCSM3.5 control simulations. Bottom: Soil temperature annual cycle as a function of depth for observations (selected Russian stations from Zhang et al., 2001) and for equivalent model grid boxes in CLM3.5 and CLM4 runs.

2.2 Proposed Experiments

We propose the following set of experiments with CCSM4 and its component models to assess the integrated and interacting effects of projected Arctic sea ice loss on Arctic and global climate system change and to identify key mechanisms for the seasonally-dependent atmospheric, terrestrial and marine responses to projected Arctic sea ice loss. All experiments will be conducted at 1.9° latitude by 2.5° longitude atmosphere/land resolution, and nominally 1-degree ocean/ice resolution on a displaced pole grid.

Experiment 1: *20th and 21st century transient integration* (CCSM4, 200y)

A transient 20th and 21st century integration forced by a complete set of historic natural and anthropogenic forcings and a to-be-determined future scenario of GHGs. It will be conducted as part of the overall CCSM project at no cost to the current proposal and is projected to be completed by late 2009. This experiment contains the full coupled system response to projected future changes in GHG concentrations.

Experiment 2: *Present-day GHG, future sea ice* (CCSM4, 60y)

This experiment is designed to isolate the impact of future Arctic sea ice changes on the coupled system by fixing GHG levels at late 20th century values and forcing near seasonally ice-free conditions by lowering the sea ice albedos. This will result in sea ice conditions that are similar to those obtained in Experiment 1 but in the absence of GHG changes. The integration will be ~ 60 years in length to allow the system to come into quasi-equilibrium with the forcing. The difference between Experiment 2 and Experiment 1 will isolate the impact of future Arctic sea ice loss on the climate system.

Experiment 3: *Present-day sea ice, future GHG* (CCSM4, 60y)

This experiment is similar to Experiment 2 but with GHG levels at 2080-99 values and prescribed seasonally-varying Arctic ice/ocean albedos fixed near late 20th century values in order to retain a perennial ice pack. This will result in enhanced GHG levels in the absence of large sea ice area loss. The difference between Experiment 3 and Experiment 1 (years 2080-2099) will isolate the impact of GHG changes on the system and its seasonal signature.

Experiment 4: *Present-day sea ice freshwater exchange, future GHG* (CCSM4, 60y)

A transient future scenario run that will prescribe the ice-ocean freshwater exchange to remain fixed at the present day annual cycle. The difference between Experiment 4 and Experiment 1 will isolate the role of changing seasonality in sea ice freshwater exchange on ocean conditions and its influence on climate.

Experiment 5: *Prescribed Present-day and Future sea ice* (CAM4/CLM4, 2x60y)

This is a process experiment with CAM4 coupled to CLM4, in which prescribed seasonally-varying Arctic sea ice area and thickness are fixed at either present-day or future levels taken from Experiment 1. SSTs will be fixed at a seasonally-varying present-day climatology. These experiments will isolate the coupled atmosphere-terrestrial response to Arctic sea ice change in the absence of any oceanic feedbacks. Terrestrial carbon cycle and vegetation dynamics will be active in these experiments.

Experiment 6: *Prescribed Future sea ice, Nitrogen fixed present-day* (CAM4/CLM4, 60y)

This experiment is nearly identical to Experiment 5 but with fixed terrestrial nitrogen pools taken from the present-day simulation in Experiment 5**.** Comparison of Experiment 6 and Experiment 5 will isolate the vegetation response to autumn/early winter mineralization of nitrogen by microbial activity.

Experiment 7: *Prescribed Future sea ice, vegetation fixed present-day* (CAM4/CLM4, 60y)

This experiment is nearly identical to Experiment 5 but with vegetation biogeography and phenology in CLM4 fixed at present-day levels taken from Experiment 5. Comparison of Experiment 7 and Experiment 5 will give the impact of dynamical vegetation feedbacks on the coupled atmosphere-terrestrial response to Arctic sea ice change. Note that in all other experiments vegetation is dynamic in the sense that vegetation biogeography and seasonal phenology are allowed to evolve in accord with the simulated climate.

Experiment 8: *Prescribed Present-day and Future sea ice* (CAM4/CLM4/SOM, 2x60y)

This experiment is like Experiment 5 but a simple slab ocean mixed (SOM) layer will be interactive with CAM4/CLM4. Comparison of Experiment 8 and Experiment 5 will isolate the effect of the thermodynamic ocean mixed layer response via SST changes on the coupled atmosphere-terrestrial response to Arctic sea ice change.

Note that although the carbon cycle response to sea ice loss and GHG increases is not a focus of this proposal, where appropriate and technically feasible, the terrestrial and marine carbon cycles will be active in the CCSM4 to allow for assessment by this and other research teams.

2.3 Model Evaluation

The model experiments will be evaluated to the extent possible within the context of available observations. This evaluation will be constrained by limitations in the observational record (e.g., sparse spatial and temporal coverage, especially in the Arctic region) and by the fact that the effects of Arctic sea ice loss and other GHG-induced changes are only just beginning to emerge (e.g., Serreze et al., 2008). Where possible and appropriate, we will evaluate the simulated relationships among different components of the climate system in the various experiments for consistency with those in the observational record. Some examples of the types of model evaluation diagnostics we propose are given below.

- *Linkages between Arctic sea ice concentration and Arctic Ocean surface energy flux anomalies. What are the seasonal relationships in the observed record and how do these compare with those from the proposed experiments (as in, for example, Fig. 1)?* Observed ice cover will be obtained from the HadISST data set (Rayner et al., 2003) for the period 1953-1978 and from satellite passive microwave observations using the NASA Team sea ice algorithm starting in 1979 (Meier et al., 2006). Observed surface energy flux and state components will be compared for a variety of data sources including SHEBA (Persson et al., 2002), ERA40 (Uppala et al., 2005) and NCEP/NCAR (Kalnay et al., 1996) Reanalysis Products, International Arctic Buoy Programme (Rigor et al., 2000) and related Polar Exchange at the Sea Surface (POLES) data, including satellite products such as the TOVS data (Francis and Hunter, 2007).
- *Linkages among Arctic sea ice, terrestrial air temperature, precipitation, snowcover and vegetation anomalies. What are the observed spatial and seasonal relationships and how do these compare with the simulated relationships forced by sea ice cover changes in the proposed experiments?* A variety of observational data sets will be used, in part leveraging from the verification portion of another NSF effort, the "Arctic System Reanalysis", which Co-PI Slater is involved with at the National Snow and Ice Data Center (NSIDC). A new compendium of pan-Arctic station based snow data is being compiled and traditional satellite imagery will be available (e.g. Northern Hemisphere Weekly Snow Cover, derived from visible satellite imagery since 1966; Armstrong and Brodzik, 2005). Precipitation from a newly available dataset of bias-corrected gauge stations north of 45°N (Yang et al., 2005) as well as the gridded Global Precipitation Climatology Project (GPCP) dataset which merges rain gauge stations, and satellite geostationary and low-orbit infrared, passive microwave, and sounding observations to generate monthly rainfall on a 2.5° global grid from 1979 to the present (Adler et al., 2003); gridded monthly surface air temperature based on station data from the Climate Research Unit (CRU, Jones et al., 2006) and NCEP/NCAR Reanalysis (Kalnay et al, 1996). Daily terrestrial precipitation, temperature, and snow data are available through the Global Historical Climatology Network (GHCN, http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/); Vegetation state will be derived from the

global 8-km AVHRR Normalized Vegetation Difference Index (NDVI, Tucker et al., 2005**).** Ground thermal state data will be obtained from the Global Terrestrial Network for Permafrost (GTN-P, Burgess et al., 2000), NSF field campaigns and ongoing data efforts at NSIDC. Although limited in geographical scope, FLUXNET tower site data (Baldocchi et al., 2001) from sites such as Barrow (Alaska), Kaamanen (Finland) and Boreas (Canada) provide the most complete characterization of the surface-atmosphere exchanges of water, energy, and carbon and will be used to evaluate the model (as in Stockli et al., 2008) and to corroborate the large-scale analyses. Surface radiative fluxes, from NSF-ARCSS field programs, are also being compiled at NSIDC.

- *Relationships between Arctic sea ice and ocean conditions.* Large scale observed sea ice cover (as above) will be supplemented by higher resolution (but shorter duration) satellite observations for example from the AMSR-E daily 12.5 km sea ice concentration data (Cavalieri et al. 2004). Relationships with ocean conditions will be evaluated to the extent possible using observed timeseries of ocean salinity and temperature profiles from the Environmental Working Group Arctic Ocean Atlas, which has coarse decadal temporal resolution. This data will be complemented by T/S profiles available through the Arctic Observing Network projects, including the North Pole Environmental Observatory, Naval Postgraduate School Autonomous Ocean Flux Buoys, and Woods Hole Oceanographic Institute Ice tethered profiler data.

Since the proposed work emphasizes the seasonal cycle of the climate response to future Arctic sea ice loss, we shall utilize daily or weekly (as opposed to monthly) model and observational data as much as possible to better define the seasonal character of the response and to gain additional insight into the relative timing of various processes. The need for high temporal resolution is underscored by the rapidity of the simulated warming over the northern hemisphere high latitude continents in response to Arctic sea ice loss (e.g., ~ 6 K from mid-October to mid-November). Another motivation for using daily resolution data is the critical role of high-frequency (synoptic-scale) transient atmospheric motions in mixing heat and moisture out of the Arctic and over the adjacent continents (see Section 2.4.1). It is also becoming increasingly clear that the character of day-to-day weather events and the frequency of extreme events are important in determining the response of ecosystems and society to climate change. Recent studies have documented observed changes in daily climate extremes of temperature and precipitation (Alexander et al, 2006), impacts of El Nino on current and future weather extremes (Meehl et al., 2007), and projected future changes in heat waves and frost days (Meehl and Tebaldi, 2004; Meehl et al., 2004). We therefore propose to examine not only the monthly-mean climate response to future Arctic sea ice loss, but also the response of daily climate extremes including minimum and maximum temperatures, diurnal temperature range, intensity and frequency of daily precipitation, dates of first and last frost, number of frost days, dates of snow onset and melt, and frequency and intensity of cold air outbreaks and heat waves.

2.4 Scientific Rationale for the Proposed Experiments

2.4.1 Background: Previous work

Our proposed work builds on current research aimed at understanding the *direct* impact of projected Arctic sea ice loss in the late 21st century upon the atmospheric circulation and climate using an atmospheric modeling approach (Deser et al., *in preparation*). This approach is designed to isolate the direct impact of sea ice changes upon the atmosphere, and does not account for feedbacks involving the ocean or the terrestrial system. As such, it may be used as a baseline for evaluating the impact of sea ice loss upon the atmosphere, and serves as a useful starting point for the research outlined in this proposal. Preliminary results on the terrestrial surface air temperature response and its seasonal signature were presented in Lawrence et al.

(2008b). We conducted two experiments with Community Atmospheric Model Version 3 (CAM3) coupled to the Community Land Model (CLM) at T85 horizontal resolution (approximately 1.4° latitude x 1.4° longitude; see Collins et al. (2006) for model details). The 'control' experiment consists of a 60-year integration with a specified repeating seasonal cycle of SSTs and sea ice (concentration and thickness) for the period 1980-1999, obtained from the 7-member ensemble mean of 20th century simulations with the fully coupled ocean-atmosphere-land-sea ice Community Climate System Model Version 3 (CCCSM3) at T85 resolution. The 'perturbation' experiment consists of a 60-year integration with a repeating seasonal cycle of Arctic sea ice (concentration and thickness) for the period 2080-2099, taken from the 8-member ensemble mean of 21st century CCSM3 (T85) simulations under the A1B forcing scenario. For the CAM3 experiments with prescribed sea ice conditions for the late 21st century, SSTs are set to those in the control experiment so as to isolate the impact of the sea ice changes. At grid boxes where fractional sea ice cover in the late 20th century is replaced by open water in the late 21st century, SSTs are set to the freezing point of sea water (~ -1.8°C).

One important result from these experiments is the seasonal delay of the peak net surface energy flux response over the Arctic Ocean in October-December with respect to the maximum sea ice loss in August-October (recall Fig. 1). This is due to the fact that the sensible heat loss, the dominant term in the net surface energy budget, is greatest when the air temperatures are coolest relative to the underlying surface (ice or open water). This has important implications for the seasonality of the thermodynamic and dynamic atmospheric responses since the sea ice loss is communicated to the atmosphere *via* the surface energy fluxes. This is evident in, for example, the seasonal timing of the surface air temperature (SAT) response over land, with the largest warming over the high latitude continents in November-December (Figure 4) that is nearly in phase with the net surface energy flux response. A heat budget analysis (not shown) indicates that horizontal advection by sub-monthly transient atmospheric motions is the dominant cause for the high latitude terrestrial warming. In other words, high frequency (e.g., synoptic scale) wind variations advect southward the air that has been anomalously warmed over the Arctic Ocean as a result of reduced sea ice concentrations. Temperature advection by the monthly mean atmospheric circulation acts as a negative feedback, as do all of the other terms in the heat budget except for condensational latent heat release associated with enhanced cloudiness and precipitation. Despite the warming, snow depth increases over Siberia and northern Canada due to increased precipitation in early winter which in turn results from the increased moisture advection out of the Arctic by the sub-monthly transient atmospheric flow variations (not shown). The seasonal dependence of the atmospheric circulation response also follows that of the surface energy fluxes, with the largest magnitudes in early winter and negligible response in summer (see Figure 4).

The results shown above highlight the distinctive seasonal (and spatial; not shown) structures of the climate response to future Arctic sea ice loss. This unique "fingerprint" may serve to distinguish the impact of sea ice changes from other impacts associated with increased GHGs, for example oceanic warming and direct radiative effects. An example of this is given in Figure 4 (left) which compares the high latitude (60º-80º N) terrestrial SAT response in the fully coupled CCSM3 (late 21st century minus late 20th century) with that in the CAM3 specified sea ice experiments. It is clear that almost all of the seasonal dependence of the SAT response over the high latitude continents arises from sea ice forcing. Indeed, removing the ice–induced SAT response from the SAT response in the fully coupled system yields a residual warming that is nearly invariant with season (Fig. 4, left). The precipitation and snow cover responses over the high latitude continents also exhibit some correspondence between CAM3 and CCSM3, although not as high as that for SAT (not shown). With regard to the atmospheric circulation response over the northern high latitudes, the direct impact of future sea ice loss accounts for much of the coupled model's response to GHG forcing in early winter, but it does not explain the coupled model's circulation response in summer (Fig. 4, right).

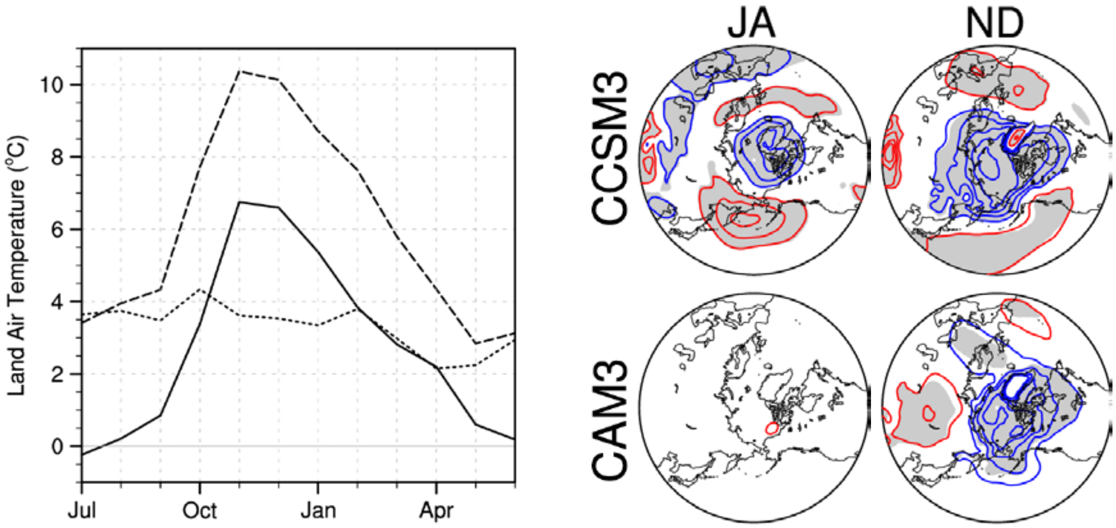


Figure 4. Comparison of the climate response (late 21st century minus late 20th century) in the fully coupled CCSM3 with that in the CAM3 specified sea ice experiments. (Left) Seasonal cycle of the high latitude terrestrial surface air temperature response in CCSM3 (dashed), CAM3 (solid), and their difference (dotted). (Right) Sea level pressure response in summer (July-August; JA) and early winter (November-December; ND) in CCSM3 (top) and CAM3 (bottom). Blue (red) contours indicate negative (positive) values, with contours every 1 hPa and the zero contours omitted; shading indicates values that are statistically significant at the 95% confidence level according to a Student's t-test.

The results shown above raise a number of outstanding issues regarding a) the roles of oceanic and terrestrial feedbacks in the seasonal timing and magnitude of the atmospheric/climate response to future Arctic sea ice loss, and b) the relative importance of future Arctic sea ice loss in the larger context of the integrated climate response to GHG forcing. The proposed model experiments will address these outstanding issues as follows. Experiments 2 and 3 provide the integrated climate system response to Arctic sea ice loss in the absence of GHG increases, and conversely, to GHG increases in the absence of Arctic sea ice loss. The processes and feedbacks contributing to the integrated responses will be evaluated from the remaining set of proposed experiments as described in Sections 2.4.2 and 2.4.3.

2.4.2 Oceanic Feedbacks

a. Mixed layer ocean response

In the results described in the previous section, the net surface energy flux response to future Arctic sea ice loss is such as to warm the Arctic ocean in summer and the high latitude portions of the north Atlantic and Pacific oceans in winter. However, this effect has been deliberately suppressed due to the lack of an interactive ocean. By comparing our proposed Experiments 8 and 5, we will be able to assess the feedback of the thermodynamic ocean mixed layer response. We anticipate that the summer SST response may increase the upward sensible and latent heat fluxes and enhance warming and precipitation over the high latitude continents as well as augment the SLP response. In addition, the winter SST response may alter the atmospheric circulation response since the SST changes may extend far enough south to perturb the middle latitude stormtracks which have been shown to provide a strong positive feedback onto the time-mean atmospheric circulation response (e.g., Peng et al., 1997; Deser et al., 2007).

We also anticipate that tropical SSTs may respond to future Arctic sea ice loss (e.g., Chiang and Bitz, 2005; Kwon et al., 2008) which may in turn force global atmospheric circulation anomalies in the form of preferred teleconnection patterns, thereby communicating the Arctic sea ice signal to remote parts of the globe. However, dynamical ocean processes must also be included when considering the tropical SST response.

b. Dynamical ocean response

What are the global dynamical ocean responses to Arctic sea ice loss? How do changes in the annual cycle of sea ice melt and growth modify the ocean response to climate change, and what are the consequent impacts on atmospheric and terrestrial processes?

We will consider the full global coupled climate response to sea ice loss in Experiment 2. A comparison of this coupled response to the mixed layer ocean response and resulting feedbacks discussed above, will provide insight on the role of dynamical ocean changes and how they modify the coupled climate response to seasonal changes in the Arctic ice cover. This will include an analysis of the causal mechanisms of the tropical SST response.

In addition, we will perform experiments to isolate specific ocean forcing associated with seasonal sea ice change. In low temperature environments, such as the Arctic, ocean density changes are largely determined by salinity variations. As such, seasonal changes in the ice-ocean freshwater exchange are likely to be important in driving local changes in ocean mixing and circulation. Climate projections with the CCSM3 show seasonally and regionally varying changes in the surface ocean freshwater flux associated with ice melt/growth. For projections into the next several decades, an earlier melt season causes larger freshwater fluxes throughout the Arctic basin in May-June. This increased melting continues for the central Arctic through August. However, in regions where sea ice completely melts out (the shelf regions), increased melting is not possible throughout the summer. As such, these regions get larger and earlier freshwater fluxes that are then followed by no sea ice freshwater exchange for the remainder of the melt season. Ice growth initiation is delayed in the future projections, but by November freeze up is in full swing across the Arctic. The ice growth during Nov-Feb is enhanced in the warmer climate likely due to thinner snow cover (with a delayed snow onset), thinner ice, and decreased ice concentration that all reduce the insulating properties of the sea ice cover.

Overall, in the annual mean, there in an increase in Arctic Ocean surface freshening due to ice melt. Based only on this information, one would expect that the surface ocean would stabilize and reduced vertical mixing would result. This would be reinforced by increasing river discharge and local precipitation with the warming climate (e.g. Holland et al., 2007) and the enhanced warming of the surface. However, there are indications that this simple picture is incorrect. An ocean ideal age tracer indicates the time since a parcel of water was last in contact with the surface. As such, younger waters represent increased ventilation. Throughout the Arctic Ocean, there are indications of enhanced ventilation with the warming climate as ideal age drops in the upper water column. While counter-intuitive to the enhanced annual freshening, the reason for this response may lie in the changing annual cycle (and not the changing annual mean) of ice melt/growth and in particular from enhanced brine rejection during fall into winter. The importance of this increased ocean ventilation is uncertain, but it could well modify the upwelling of Atlantic layer heat and general ocean circulation. Indeed, these simulations show an enhanced Atlantic inflow with the warming climate (Bitz et al., 2006) that appears to contribute to amplified polar warming and abrupt summer ice loss (Holland et al., 2006).

To investigate the role that the changing seasonality in surface ice/ocean freshwater fluxes has on climate conditions, we will perform a 21st century scenario integration in which the sea ice freshwater exchange remains fixed at late 20th century conditions (Experiment 4). More specifically, we will diagnose a daily and spatially varying climatology of ice-ocean freshwater exchange from the standard CCSM4 20th century integration for years 1980-1999. This climatology will then be prescribed in a 21st century scenario run providing the ocean component with a constant annual cycle of ice-ocean freshwater exchange and thereby disabling the influence of seasonal changes in ice freshwater discharge and brine rejection on ocean conditions. By comparison to the standard future scenario run (Experiment 1), this will allow us to directly assess the importance of these changing fluxes for ocean ventilation and circulation. We will specifically address how the seasonality of these changes modifies the upwelling of heat from the Atlantic layer and the resulting feedbacks to sea ice loss. Additionally, we will examine the influence on large scale changes in Arctic and North Atlantic Ocean circulation and heat transport from lower latitudes. This will specifically examine linkages of Arctic change to the global system through an analysis of the importance of ice-ocean freshwater change on deep water formation in the Nordic Seas and resulting Meridional Overturning Circulation (MOC) variations. These ocean circulation changes can in turn influence the global SST distribution. For example, reductions in the MOC are associated with less northward heat transport in the Atlantic, with consequent cooling in the Nordic Seas and warming in the south Atlantic (e.g. Stouffer et al., 2006) as well as changes in tropical Atlantic and Pacific SSTs (Okumura et al., 2008). The importance of these remote SST effects for the atmospheric and terrestrial response to the freshwater component of sea ice loss will also be investigated.

2.4.3 Terrestrial Feedbacks

What is the terrestrial response to a shifting seasonality of Arctic climate and how does this response, especially with respect to snow and vegetation, feedback onto the broader Arctic system?

Due to the potential vulnerability of the large stocks of carbon stored in permafrost-affected soils (Schuur et al., 2008) and the possibly substantial reduction in surface albedo associated with a shorter snow season and concomitant ‘greening’ of the Arctic (Myneni et al., 1997; Chapin et al., 2005), there is concern that the integrated Arctic terrestrial response to climate change will be a strong positive feedback that will exacerbate Arctic, and potentially global, climate change (McGuire et al., 2006). Arctic ecosystems are already displaying a propensity for sudden change with recent observations indicating thawing permafrost, earlier melting of snow, increasing shrubbiness, lengthening growing seasons, advancing treelines, shifting migratory bird ranges, and declining caribou herd health (Hinzman et al., 2005). Models indicate that much more change is expected with large-scale permafrost degradation (Lawrence et al., 2008a; Zhang et al., 2008) and widespread changes in snow depth and snow season length (Räisänen, 2008) likely. Alterations to the surface energy, water, and biogeochemical fluxes, therefore, will reflect the combined surface hydrology, snow, and vegetation transitions that are best captured in a process-based land surface scheme such as that in CCSM4.

Observations already reveal a distinctly seasonal character to the Arctic land response to climate change. Increased and earlier spring plant growth has been reported (Myneni et al., 1997) and there is recent evidence that the peak vegetation production may now occur before caribou calves have been born, leading to reduced reproductive success (Post and Forchhammer, 2008). Snow is melting earlier, but the date of snow onset remains essentially unchanged (Dye, 2002). Models suggest, however, that in the future the strongest warming will occur in the autumn and winter, in response to sea ice loss (Lawrence et al., 2008b), and that the date of snow onset will retreat faster than the snow melt date will advance (Lawrence and Slater, 2008a).

In this project, we propose to investigate how a shift in seasonality associated with sea ice loss, both within and outside the context of GHG-related warming, affects vegetation, permafrost, and snow by comparing the response of these systems across Experiments 1 to 3. In particular, we will use Experiments 1 to 3 to assess whether or not projected 21st century increases in snowfall, snow depth, and the timing of snow onset and melt can be attributed to climate change associated with sea ice loss or GHG or both. Our analysis will also focus on the response of Arctic vegetation to seasonal changes in temperature, snow, and permafrost conditions. During the 1980’s and 1990’s, a shift to earlier snow melt contributed to strong spring warming

(Groisman et al., 1994), encouraging an earlier leaf out date and increased plant productivity across much of the northern high-latitudes (Myneni et al., 1997). With sea ice loss, on the other hand, warming is expected to be strongest in autumn and early winter when plants are in their senescent phase. The direct impact of sea-ice-loss-induced warming on vegetation growth is therefore likely be minimal, but warmer autumn and winter temperatures, in conjunction with changes in snow conditions, may increase microbial activity and soil respiration. Microbial activity mineralizes nitrogen which in the nutrient-limited Arctic environment can promote vegetation growth the following spring and summer (Sturm et al., 2005). The role of nutrients in the vegetation response to sea ice loss will be assessed by comparing present-day/future sea ice CAM4/CLM4 experiments (Experiment 5) with equivalent experiments in which terrestrial nitrogen dynamics are turned off (Experiment 6).

We will also investigate how the vegetation and snow responses to sea-ice-loss-induced shifts in seasonality will feedback onto the broader Arctic system. Changes in vegetation and snow alter the surface energy and water balances through their influence on albedo, surface turbulent flux partitioning, and surface roughness. The influence of simulated changes in the distribution (e.g. shrub encroachment into tundra regions) and seasonal phenology (e.g. earlier leaf out or delayed senescence) of vegetation on the atmospheric response to sea ice loss are isolated through Experiments 5 and 7. These experiments will complement ongoing studies with CCSM and CLM that are aimed at evaluating how changes in Arctic snow conditions feedback onto atmospheric (Tomas et al., in preparation) and ground (Lawrence and Slater, 2008a) climate.

3.1 Project Team

As a team, the P.I. and co-P.I.'s bring breadth and depth to the proposed project through their complementary sets of expertise in the atmosphere (Deser), ocean/seaice (Holland), and terrestrial (Lawrence/Slater) systems. Further, the team members are co-chairs for the CCSM Climate Variability (Deser), Polar Climate (Holland) and Land (Lawrence) working groups, bringing their knowledge and expertise of different components of CCSM. Co-PI Slater is at the National Snow and Ice Data Center, providing a direct link to a vast and diverse database of Arctic observations.

3.2 Synergistic Activities

The project will benefit from the leveraged activities of the CCSM Climate Variability, Polar Climate, Land and Biogeochemistry working groups. All model output will be made freely available to the research community via the CCSM project. We will also actively share information with other projects funded under the CSAS program. The project will participate with the SOARS program at UCAR. We will actively engage with researchers from Arctic Observing Network projects, ongoing ARCSS synthesis efforts and SEARCH activities.

3.3 Broader Impacts

Current and projected changes in the Arctic system have repercussions for the global climate system, Arctic wildlife, and socio-economic activities in the region. Improving our understanding and modeling of the factors affecting the seasonal timing and succession of processes within the Arctic system will allow for improved Arctic and global system predictability. This has a direct impact on the ability of society to anticipate, mitigate, and adapt to future change. We envision coordination with other funded CSAS projects that investigate other aspects of Arctic seasonality and will freely provide our climate model integration data for these (and other) projects.

Additionally, we will promote the education of a young scientist through a funded postdoctoral position and the mentoring of an undergraduate student through the Significant Opportunities in Atmospheric Research and Science (SOARS) program, which seeks to broaden participation in the atmospheric and related sciences. The PIs will also participate in numerous outreach activities, including public lectures and educational events.

3.4 Workplan

During the first year, we will focus on analysis of the fully coupled CCSM4 transient 21st century integration which is anticipated to be completed by the CCSM project by the beginning of the funding cycle. We will also begin the additional CCSM4 sensitivity integrations (Experiments 2-4), and assemble and begin analysis of the observational data sets. In the second year, we will analyze the additional CCSM4 integrations and complete the targeted sensitivity runs with the component models (e.g., Experiments 5-8). Year 3 will be devoted to analysis of all model experiments and observations, the results of which will be reported in peer-reviewed publications and presentations.

3.5 Management, budget and facilities

The PI and co-PIs will oversee the design, implementation and completion of all research tasks; lead in the preparation of progress reports; ensure the prompt dissemination of results through conferences and preparation of journal articles, and ensure the distribution of model output through the CCSM project. They will also contribute to the mentoring of a postdoctoral fellow and assist in the SOARS outreach program, including the design of student research projects. The Associate Scientist will be responsible for carrying out all of the model simulations, post-processing of model output, and technical assistance with computing, data analysis and graphics.

Computational resources will be secured through the CCSM Working Group (Climate Variability, Polar Climate, Land, and Biogeochemistry) proposals to the NCAR Climate System Laboratory. Data from all experiments conducted will be archived and shared with the scientific community through the Earth System Grid (https://www.earthsystemgrid.org/).

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