Web: http://dust.ess.uci.edu/prp/prp_ids/prp_ids.pdf
NASA International Polar Year (IPY) Proposal — Submitted: April 17, 2006
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Black Carbon Impacts on Cryospheric Climate Sensitivity and Surface Hydrology

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News/Preface:

9. 20070914: Received award contract. This is NASA Grant number NNX07AR23G. Acknowledge this number in publications with, e.g., "Supported by NASA NNX07AR23G".
8. 20070907: Award package completed. Award performance dates are 20070802–20100801. Annual Progress Report (APR) deadlines are 20080601, 20090601, 20101101. Submit APRs to Technical Officer (TO) Hal Maring and to NASA Grant Officer (GO) via e-mail (nssc-contactcenter@nasa.gov). Include the grant number (NNX07AR23G) in the subject line.
7. 20070805: Posted opportunities for Graduate Student Researchers and Postdocs on CRYOLIST and on ESS Website.
6. 20070723: Registered for SPAC Workshop in Kjeller (stay in Lillestrom).
5. 20070709–20070712: Attended cryospheric sessions at IUGG/Perugia.
4. 20070614: Posted opportunities for Graduate Student Researchers and Postdocs on group website.
3. POLARCAT organization and planning at Paris meeting. Online presentations. Need to register project/join.
2. 20070517: This proposal was one of 33 funded (of 92 submitted) by the NASA IPY06 program. The public announcment of these NASA IPY awards is here. The entire IPY06 budget is $18M for about 33 awards, which averages out to $545k per award, and to $182k per award-year. Our request for $677725 was reduced $\sim$ 10% to $607k ($200k, $202k, $205k).
1. Program manager is Hal Maring.

Background:

1. 20061206: Proposal was not selected by IDS program. IDS program managers thoughtfully reclassified this as an IPY06 proposal in response to NNH06ZDA001N-IPY (i.e., ROSES 2006 appendix A-16).
2. 20060417: Proposal was submitted to IDS program in rough form. Still needs work. May re-write and submit proposal to ROSES A-15, "Earth System Science Research using Data and Products from Terra, Aqua, and ACRIMSAT satellites". Letters of intent due 5/1/2006, full proposals due 7/18/2006.

3. 20060312: This NASA proposal originally responded to the 2006 NASA Research Opportunities in Space and Earth Sciences (ROSES) announcement, NNH06ZDA001N-IDS, ROSES 2006 appendix A-16. The annual IDS-wide budget was planned to be $11M for about 35 awards, or $314k per award per year. I think this was later cut (to $8M?). The proposal was submitted to the Interdisciplinary Science (IDS) Program subelement 5: Aerosol Impacts on Clouds, Precipitation, and the Hydrologic Cycle. The cognizant Program Manager is Phil DeCola `pdecola@nasa.gov`, (202) 358-0768.

Information for potential collaborators/contributors:

1. Use CVS to obtain source to this proposal:
   `cvs -d :ext:esmf.ess.uci.edu:/u/zender/cvs co -kk prp_ids`
2. Use instructions here (http://dust.ess.uci.edu/doc/tex/index.shtml) to build proposal

Suggestions for current proposal:

1. Beef up specific hypotheses to test with satellite data
2. Zong-Liang Yang for snow extent and vegetation interactions?
3. New Science questions:
   (a) Quantify "dangerous" BC levels for polar regions
   (b) Learn about snow extent/melt by combining AMSR-E and MODIS/MISR
   (c) BC vs. GHG impact on permafrost
   (d) Ghan Barrow ARM/IOP for arctic haze
4. Incorporate new references:
   (a) Hansen et al. (2005): dirty snow has greatest efficacy of all forcing agents
   (b) Alley et al. (2005): dirty snow speeds up worst case scenarios presented here
   (c) Hall and Qu (2006): Using seasonal SAF to estimate GCC SAF
   (d) **?**: dust deposition on snow
   (e) Peltier and Marshall (1995): dust-ice sheet connections
   (f) Lawrence and Slater (2005): permafrost
   (g) Stroeve et al. (2005): MODIS-albedo biases
   (h) Pirazzini (2004): Antarctic station albedo measurements
   (i) Grenfell et al. (1994): Antarctic reflectance albedo-modeling
   (j) Green et al. (2002): Role of liquid water in surface reflectance
   (k) Barnett et al. (2005): Global warming and water availability
   (l) Syed et al. (2007): Arctic freshwater discharge
   (m) Large-scale snow-fraction representations: Yang

Contents

0.1 Summary of Proposal Personnel and Work Efforts

Percentage of nominal work years 1, 2, and 3 spent on project. (Percentages differ from budget request).

1. PI Zender: 25%, 25%, 25%
2. Co-PI Famiglietti: 10%, 10%, 10%
3. Co-PI Randerson: 10%, 10%, 10%
4. Graduate Student I (initially Mark Flanner): 100%, 100%, 100%
5. Graduate Student II (TBD): 100%, 100%, 100%
6. Scientific Programmer/Analyst Chao Luo: 25%, 25%, 25%

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0.2 Project Summary

The prevalence of bright surfaces (snow, glaciers, sea-ice, and clouds) make the cryosphere uniquely susceptible to radiatively induced effects of black carbon (BC) such as ice-albedo feedback amplification. We will advance current understanding of cryospheric BC climate impacts by integrating effects of post-deposition BC (i.e., dirty snow) with the direct effects of atmospheric BC. This project's primary objective is to understand BC effects on cryospheric climate sensitivity and surface hydrology.

We have integrated satellite-derived BC emissions into a unified modeling framework, where we will forecast and hindcast contemporary and 21st century climate with and without atmospheric and surface BC effects. These simulations rely on our SNow, ICe, and Aerosol Radiative model (SNICAR) embedded in the Community Climate System Model (CCSM) forced by the MODIS-derived Global Fire Emissions Database (GFED). We ask three types of questions:

First, how do timing and location of BC emissions affect Arctic surface reflectance and atmospheric processes? BC increases atmospheric absorptance in clear and cloudy conditions and this helps warm and thus darken snowpack. However, snowpack is also very sensitive to temperature feedbacks triggered by the vertical distribution of soot in the snowpack itself. Using alternating years of high and low boreal soot emissions from the GFED, we will test how atmospheric and surface soot contribute to improving model agreement with MODIS-derived spectral surface reflectance.

Second, what are the relative roles of surface and atmospheric BC forcing on Arctic climate sensitivity including sea-ice? Atmospheric BC cools the surface by backscattering and absorbing incident sunlight. Snowpack BC heating compounded by snow-albedo feedback can exceed atmospheric BC surface cooling in strong fire years. We will assess how BC mixing state affects top-of-atmosphere albedo (from CERES), surface spectral reflectance (from MODIS), and sea-ice extent (from AMSR-E).

Third, how does BC alter surface water seasonality such as soil moisture, snowpack depth and extent, depth to permafrost, and runoff to the Arctic? Concentration and scavenging of seasonally deposited BC within snowpack can significantly alter partitioning of spring thaw processes between sublimation to the atmosphere and melt/percolation to surface water. We will use in situ snowpack BC profiles measured during IPY activities to improve BC scavenging in SNICAR and CCSM. Snow water equivalent, extent, and liquid surface soil moisture (from AMSR) and spring discharge to the Arctic Ocean (from gauge data and GRACE) will test our global simulations.

Relevance to NASA's Strategic Objectives: The project outcomes meets NASA Strategic Goal 3.1 ("Study planet Earth from space to advance scientific understanding and meet societal needs") and IDS Subelement 5 objectives by using **space-based remote sensing** and **global models** to improve understanding and prediction of the **role of black carbon in affecting clouds,**

precipitation, and the hydrologic cycle. Our improved understanding and predictions of the cryospheric hydrologic cycle will be incorporated via CCSM into the IPCC AR5 report to help society understand, plan for, and mitigate BC effects on cryospheric climate.

Black Carbon Impacts on Cryospheric Climate Sensitivity and Surface Hydrology

1 Introduction

Surface and atmospheric concentrations of black carbon (BC) are highly variable and slowly increasing in the Arctic (Penner et al., 2001; ACIA, 2005). Bright surfaces (snow, glaciers, sea-ice, and clouds) make the Arctic uniquely susceptible to radiatively induced effects of BC such as ice-albedo feedback amplification (Warren and Wiscombe, 1980; Clarke and Noone, 1985; Holland and Bitz, 2003). Understanding both surface and atmospheric BC effects is important in the Arctic because surface albedo variability dominates planetary albedo variability there (Qu and Hall, 2005), and ice-albedo feedbacks arguably dominate long-term Arctic climate sensitivity, e.g., to greenhouse gas forcing. This project will advance current understanding of cryospheric BC climate impacts by integrating effects of post-deposition BC (i.e., dirty snow) with the direct effects of atmospheric BC in coupled models which can quantify, test, and evaluate hypotheses against satellite, in-situ, and laboratory measurements.

Soot is an important component of Arctic haze (Tsay et al., 1989) which interacts with clouds and snowfall (Noone and Clarke, 1988), and thus has the potential for causing significant direct and indirect effects (Valero et al., 1989; Ackerman et al., 2000). Dirty snow/ice feedbacks (described in Section 1.1) change throughout the aerosol lifecycle in the complex Arctic environment of cloud, snowfall, snowpack aging, snow-melt, drainage, and analogous sea-ice processes (e.g., Light et al., 1998; Aoki et al., 2003; Flanner and Zender, 2006). Ice-albedo feedbacks make dirty snow more efficacious (per unit forcing) than greenhouse gases at changing atmospheric temperature (Hansen and Nazarenko, 2004). Large scale interannual variability in BC emissions related to ENSO and boreal fires modulate BC delivery to the Arctic (van der Werf et al., 2004; Koch and Hansen, 2005). Our project uses models to integrate BC processes across these spatial and temporal scales, and NASA satellite and IPY in situ observations to help constrain and evaluate model fidelity.

We use the terms soot and BC interchangeably to denote the light absorbing component of carbonaceous aerosol (Bond and Bergstrom, 2005). Recent noteworthy studies suggest that anthropogenic soot may have caused one quarter of last century's observed warming (Hansen and Nazarenko, 2004), and significant reductions in Northern hemisphere albedo and sea-ice extent (Jacobson, 2004). Our mid-latitude and polar snow studies show that such estimates are extremely sensitive to accurate treatment of snowpack aging and soot optical properties (Flanner and Zender, 2005; Flanner et al., 2005), two areas where this project will devote significant attention. Our interdisciplinary research team includes experts in aerosols and clouds, surface hydrology and remote sensing, snowpack radiation and aging, and biomass burning emissions and variability.

Relevance to NASA's Strategic Objectives: The project outcomes meet NASA Strategic Goal 3.1, "Study planet Earth from space to advance scientific understanding and meet societal needs". The direct and indirect effects of BC on climate are mediated by sunlight, whether in the atmosphere, clouds, or surface snowpack. Annual runoff north of 40 °N is predominantly snowfall-generated (Barnett et al., 2005). Hence improved understanding and predictions of the cryospheric hydrologic cycle will help society understand, plan for, and mitigate the effects of BC on high latitude climate change.

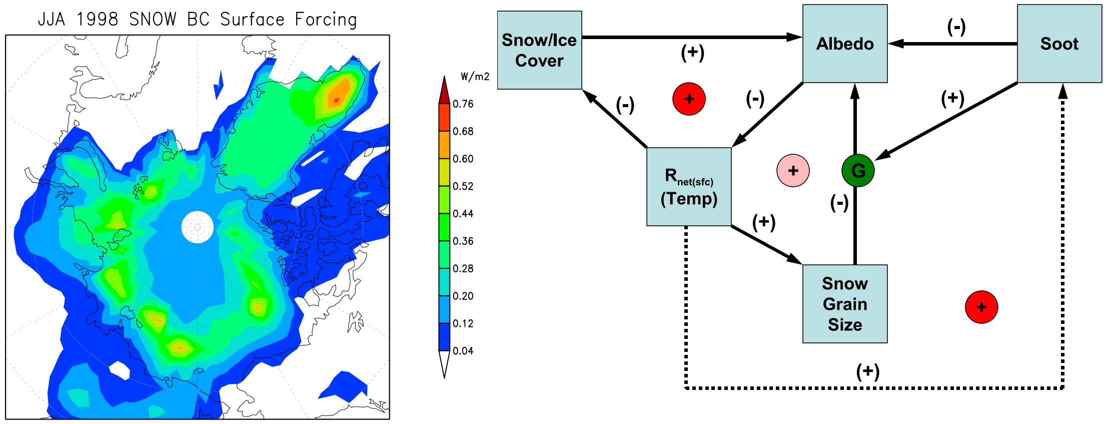

Figure 1: (a) Summer-mean surface direct radiative forcing [W m^{-2}] by soot in snowpack during 1998, a strong boreal burn year. (b) Soot amplifies snow-albedo feedback via multiple paths. Analogous feedbacks occur in clouds and sea-ice.

Note that four letters of support/collaboration and a complete list of acronyms and abbreviations appear as supplementary documents to the main proposal.

1.1 BC Role in Ice-Albedo Feedback

Snow-albedo feedback is triggered by any forcing mechanism (e.g., solar absorption by soot) which changes the areal extent of snow cover (Figure 1). A weaker, positive feedback associated with changes in net surface radiation is the change in growth rate of snow grains. Soot in the snowpack directly lowers snow albedo and increases the growth rate of snow grains, lowering albedo of the ice grains themselves. Furthermore, the instantaneous perturbation of soot is greater in larger-grained snowpack, effectively increasing the gain (G) on feedback involving grain growth. Finally, a fourth mechanism of perturbation may result from accumulation of hydrophobic impurities at the surface during melt events (Clarke and Noone, 1985; Conway et al., 1996).

Of course, BC in clouds and sea-ice causes direct and indirect effects too (e.g., Valero et al., 1989; Chýlek et al., 1996; Ackerman et al., 2000). The feedbacks are analogous to Figure 1, with additional complexities introduced by the dynamic nature of clouds and sea-ice. In polluted marine environments, for example, soot solar absorption appears to reduce cloud albedo and lifetime by reducing net cloud top radiative cooling, boundary layer mixing, and cloud moisture supply (Ackerman et al., 2000).

2 Scientific Objectives and Hypotheses

Our studies of BC effects on cryospheric climate and surface hydrology will utilize NASA satellite observations to improve understanding and simulation of BC effects on polar climate amplification in Nature, and thus improve the potential for more informed mitigation of such effects. Key scientific questions we will address include:

Objective 1: Discover Arctic climate sensitivity to timing and location of Arctic soot events

Hypothesis: *Boreal fires outweigh tropical BC effects on Arctic climate sensitivity. Both amplify* *the ice-albedo feedback.*

Seasonality and location modulate the net solar forcing of Arctic BC. BC of tropical and sub-tropical provenance (van der Werf et al., 2003) deposits more continually than mid-latitude and sub-arctic boreal fire BC (Koch and Hansen, 2005). Low zenith angles reduce the Arctic forcing efficacy (response per unit mass BC) of winter relative to summer BC. How spatio-temporal soot emission patterns affect Arctic climate sensitivity is important in the context of wildfire management and changing fire regimes, yet is nearly completely unexplored. We will inventory relative effects of Asian, American, and tropical, and fossil fuel BC sources on Arctic climate sensitivity.

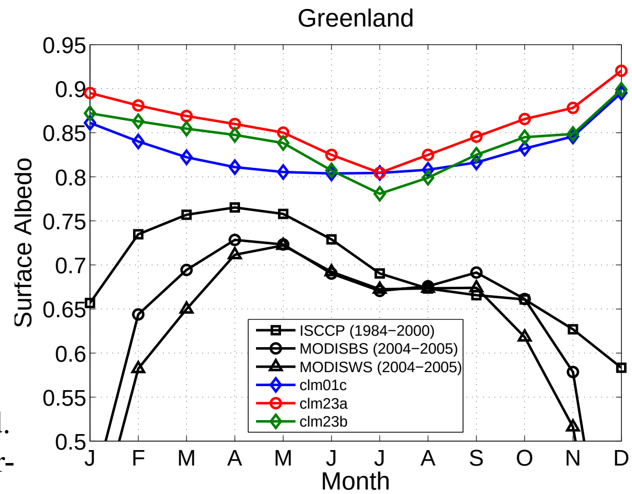

Figure 2: Seasonal cycle of modeled (Flanner et al., 2005) and retrieved surface albedo in Greenland. Experiments clm23a and clm23b include soot and snow-aging effects neglected by experiment clm01c.

We expect soot to amplify the positive ice-albedo feedback and accelerate Arctic albedo change during Spring and Fall transitions, especially during strong boreal fire years. Models currently overestimate surface reflectance relative to satellite retrievals all year, even at relatively high zenith angles (i.e., summer) (Figure 2).

Since Arctic albedo change during spring is dominated by melt processes (Qu and Hall, 2005, 2006) so the efficacy of winter deposition will depend strongly on meltwater scavenging of soot in snowpack. During spring thaw weak scavenging may concentrate hygrophobic soot at the surface (Clarke and Noone, 1985; Noone and Clarke, 1988) and cause additional melt. Our preliminary investigations (Figure 2) show that representing snow aging and soot deposition improves springtime albedo response. Scavenging measurements to be made during IPY will help reduce the uncertainty in these processes (Sections 3.2.1–3.2.3).

Objective 2: Relative roles of surface and atmospheric BC forcing on Arctic climate sensitivity.
Hypothesis: *BC warms Greenland in strong boreal fire years and cools Greenland in weak fire years. Increasing soot will amplify 21st century polar climate sensitivity.*
Atmospheric BC cools the surface by backscattering and absorbing incident sunlight. Snowpack BC heating compounded by snow-albedo feedback can exceed atmospheric BC surface cooling in strong fire years (Flanner et al., 2005) (cf. Figure 4). The net effect of BC on Greenland surface will depend on the balance of atmospheric and surface BC forcing.

Surface and atmospheric BC concentrations are highly variable and slowly increasing in the Arctic. Most emission scenarios project anthropogenic BC emissions will increase 30–250% in the 21st century (Nakićenović et al., 2000; Koch and Hansen, 2005). The seasonal cycle of surface albedo is, in models at least, a good proxy for Arctic climate sensitivity to 21st century GHG forcing (Hall and Qu, 2006). Hence reducing model biases with current observed albedo variability will also reduce uncertainty in 21st century climate forecasts.

Ice core analyses and model simulations (Koch and Hansen, 2005; Flanner et al., 2005) agree that boreal fires are the primary source of BC deposition to Greenland in strong fire years. BC preserved in snow and ice records will allow us to ask how the strongest Boreal events may have affected Greenland on longer timescales.

Objective 3: Assess Arctic BC impacts on sea-ice
Hypothesis: *Arctic BC amplifies polar climate sensitivity by reducing summer sea-ice thickness and extent during strong burn years. Inter-hemispheric asymmetry in polar BC deposition contributes to the significant differences between Arctic and Antarctic sea-ice trends.*
Multiple lines of evidence support the first hypothesis: First, representation of thin sea-ice amplifies polar climate sensitivity (Holland and Bitz, 2003; Holland et al., 2006). Second, internal snowpack heating amplifies mid-latitude climate sensitivity (Flanner and Zender, 2005). Third, aging and absorbing aerosol content increase polar climate sensitivity (Jacobson, 2004; Hansen and Nazarenko, 2004; Flanner et al., 2005). Moreover our preliminary investigations with slab ocean models and simple sea-ice models suggest a summertime Arctic sea-ice response to boreal soot in strong fire years.

In spite of globally-uniform greenhouse forcing, summertime Arctic and Antarctic sea-ice show asymmetric trends over the last 25 years (Folland et al., 2001), likely related to greenhouse gas-induced warming (Serreze et al., 2003; Stroeve et al., 2004). While Antarctic sea-ice has shown little trend, summertime Arctic sea-ice has retreated by more than 15%. Has non-GHG forcing such as snow-aerosol interactions contributed to this trend? To what extent does the asymmetry between northern and southern hemisphere polar BC deposition explain this phenomena? We will search for connections between BC emissions (Randerson et al., 2005) and recent accelerations in Arctic sea-ice reduction.

Objective 4: Role of BC forcing on Arctic surface hydrology.
Hypothesis: *BC-induced positive temperature feedbacks alter Arctic surface hydrology in strong fire years. Changes include wetter, moister soil beneath snowpack, accelerated spring melt, and increased active layer depth to permafrost.*
Snow insulates the underlying surface Arctic from the atmosphere for much of the year so BC-induced changes in snow extent and melt alter surface hydrology. Snowpack thickness and seasonal phasing respond strongly to snowpack opacity (Flanner and Zender, 2005). Our preliminary investigations show that soil moisture, active layer depth to permafrost (not shown), and phasing of freshwater drainage to the Arctic are also sensitive to snowpack opacity (Figure 3). Since BC alters snowpack opacity, we will examine how BC events affect Arctic surface hydrology. If this hypothesis is true, then recent projections of 21st century permafrost degradation (Lawrence and Slater, 2005) may be too conservative.

3 Methods: Arctic Models and Observations

To achieve our objectives we will use NASA satellite products, in situ measurements, and community models. We will also create products useful to NASA in validation and development of satellite retrieval algorithms. This project will not develop any Arctic climate model components from scratch.

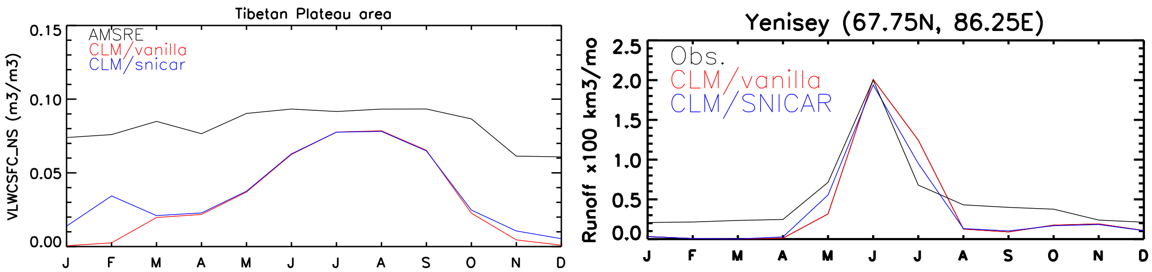

Figure 3: (a) Seasonal cycle of surface soil moisture in the Tibetan Plateau from models (Flanner and Zender, 2005) and AMSR-E retrievals. (b) Impact of SNICAR snow-aerosol treatment on predicted seasonal runoff from Yenisey basin. Earlier spring thaw due to SNICAR improves agreement with observations.

3.1 Climate sensitivity to timing and location of Arctic soot events

3.1.1 BC/OC emissions

The principle sources of BC and Organic Carbon (OC), biomass burning and combustion of fossil- and bio-fuels, have distinct spatial distributions, annual cycles, and interannual variability. We incorporate BC/OC distributions into our models (Flanner et al., 2005) based on two main sources. Fossil and biofuel BC and OC sources are from Bond et al. (2004). Co-PI Randerson's group assembled the Global Fire Emissions Database (GFEDv2) including extra-tropical BC/OC fire emissions based on MODIS-derived fire counts (van der Werf et al., 2003, 2004; Randerson et al., 2005) from 1997–2005. Randerson's group will continue to improve, interpret, and update GFEDv2.

Using emissions factors Andreae and Merlet (2001) to obtain BC/OC aerosols, we estimate that biomass burning BC emissions north of 30°N increased from 0.29 to 1.2 Tg BC between 1997, a weak boreal fire year, and 1998, a strong fire year. The end-member years for tropical fire BC emissions from 1997–2005 were 2000 (2.1 Tg BC) and 1997 (7.8 Tg BC). Hence, the recent decade exhibited interannual emissions variability of approximately a factor of four in both tropical and boreal sources.

We estimate Boreal fire emissions changes from 1997 to 1998 increase surface snowpack radiative forcing in the Arctic by about 50% (Flanner et al., 2005) (Figure 1a). These estimates contain many uncertainties and potential Arctic aerosol-related biases including transport and deposition, size distribution, optical properties, aging, and cloud interactions. As part of Objective 1, we will systematically inventory how sensitive Arctic climate response is to BC emission timing (e.g., early vs. late summer boreal fires) and location. Section 4.3 describes our numerical strategies for this.

3.1.2 Snow and Ice Aging and BC Removal

We comprehensively describe dry snow aging in Flanner and Zender (2006). BC heating increases ice crystal size (Figure 1b). This can cause remarkable growth in snow grain size following soot events (cf. Figure 5b), with corresponding decreases in broadband surface reflectance (not shown).

In addition to BC effects, our microphysical model, SNICAR, incorporates the roles of snow temperature, temperature gradient, density, initial size distribution, and irregularity in particle spac-

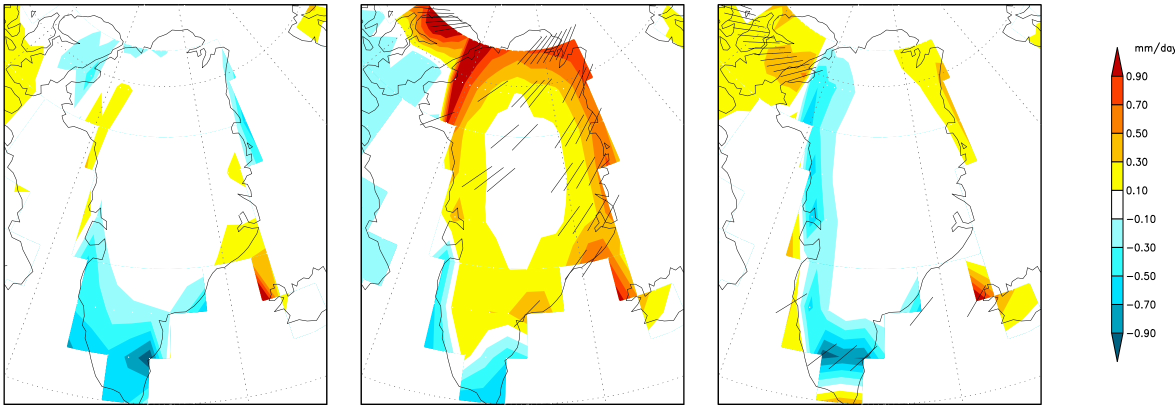

Figure 4: Summertime mean change in Greenland snow melt [mm d^{-1}] due to boreal soot during low (1997, left) and high (1998, middle and right) boreal burn years. Middle panel includes all feedbacks (soot in atmosphere and snowpack), while right panel includes atmospheric soot only. Cross-hatching indicates statistically significant changes ($p < 0.05$) relative to simulations without boreal soot (Flanner et al., 2005).

ing to predict snow albedo evolution. Temperature gradient can have the most profound influence on snow albedo evolution, but is modulated by snow temperature and density. We account for enhanced aging with liquid water in the snowpack using empirical growth rates Brun (1989). Research funded from other sources will also quantify the effects of melt-freeze cycles, sintering (Robock et al., 2006), and wind.

Meltwater flushing is the most important surface BC removal mechanism, since preferential gravitational settling only operates on external mixtures, and is likely extremely slow. Qualitative observations suggest that BC may become more concentrated in surface snow during melt events (Warren and Wiscombe, 1980; Clarke and Noone, 1985). Conway et al. (1996) spread hydrophobic and hydrophilic BC on top of snow, and noticed that hydrophobic BC remains in surface snow longer, maintaining lowered albedo for a longer time. Even greater uncertainty exists for snow processes on sea-ice. Planned IPY field studies by Warren and Grenfell (Section 3.2.1) will help us constrain these scavenging factors (see attached letter of collaboration).

Our simulations suggest boreal soot in snowpack causes seasonal net surface solar radiation forcings of 0.5–0.75 W m^{-2} (Figure 1a) in strong fire years. These forcings induce feedbacks such as larger snow grain size (Figure 5) which together increase seasonal surface absorption by more than 1.5 W m^{-2} (Flanner et al., 2005). Soot-snow feedbacks in strong fire years appear to cause significant increases in meltwater production in Greenland snowpack (Figure 4). Note that neglecting soot-snowpack interactions (and accounting only for atmospheric soot effects) eliminates or reverses the sign of most of the increased snow melt over Greenland. Hence, *significant Arctic change is attributable to aerosol-snowpack feedbacks not represented in most GCMs which only account for atmospheric soot or prescribe surface soot effects*. This makes us eagerly anticipate results in year 3 when SNICAR is embedded in fully interactive sea-ice and glacier models which can fully respond to soot sources.

3.1.3 Satellite-Retrieved Surface Albedo

NASA MODIS, MISR, and AMSR-E retrievals can constrain free model parameters and help us interpret the regional and seasonal behavior of snowpack processes. Figure 5a shows simulated snow spectral reflectance expected in visible MODIS bands for various grain sizes and BC concentrations. Soot concentration is most apparent in visible channels and particle sizes information is most distinguishable in the near infrared (NIR) (Painter et al., 2003), e.g., near MODIS channel 5.

We will use current and near-future NASA reflectance products to characterize observed surface and TOA albedos. MODIS reflectance retrievals (Figure 2) have known biases (e.g., Stroeve et al., 2005) over vegetation-free surfaces such as Greenland. Understanding and reducing the discrepancy between the MODIS-retrieved and ISCCP-inferred snow reflectance and models (Figure 2) is part of Objectives 1 and 2.

Potential contributors to the model-observed surface albedo discrepancy include zenith angle effects, snow grain size and surface impurities such as soot. Retrieved reflectance biases have been associated with large zenith angles and topography (Stroeve and Nolin, 2002; Stroeve et al., 2005). While the annual cycle of zenith angle supports the modeled "happy face" shape in (Figure 2), biases in summer are much more important than winter from energetic considerations. Spring and summer are the periods when soot and snow grain size effects are largest. Accounting for these effects brings the CCSM/SNICAR into good agreement with MODIS and ISCCP surface albedo slopes, although a significant offset still exists. We will explore whether and how much of this discrepancy may be due to snow grain size, to which albedo retrievals over snow surfaces are extremely sensitive (Nolin and Dozier, 2000; Green et al., 2002).

3.1.4 Optics

Aerosol, cloud, and snowpack optical processes will be refined to attempt to improve satellite-model reflectance agreement (Figure 2). Snow and aerosol optical properties link the snowpack microphysical properties (aerosol concentration, particle size distributions) to macroscopic net absorption (Figure 1a), reflectances (Figure 5a), and heating rates that drive the snow melt and temperature change which trigger snow-albedo feedback. These responses are sensitive to optical property assumptions which this project will explore and improve, including

1. BC indices of refraction: Bond and Bergstrom (2005) question the OPAC properties (Hess et al., 1998) (which we use) and recommend other measurements including Chang and Charalampopoulos (1990)
2. BC shape: Treating BC as spheres likely underestimates single scattering albedo relative to more realistic fractal aggregates (Sorensen, 2001; Bond and Bergstrom, 2005)
3. Aerosol mixing: BC and dust in remote regions such as the Arctic are primary deposited via wet scavenging (Clarke et al., 2001, 2004; Zender et al., 2003) and so will often be internally mixed within snow grains. We will treat aged BC as internally mixed coated aerosols (e.g., Bohren and Huffman, 1983; Bond et al., 2006). We will also investigate solutions for dark particles in weakly absorbing media (Markel and Shalaev, 1999) which may be more physically defensible for ice particles.
4. Resonance effects: Optical properties will be computed at high spectral resolution following to resolve resonance effects (Zender and Talamantes, 2006).

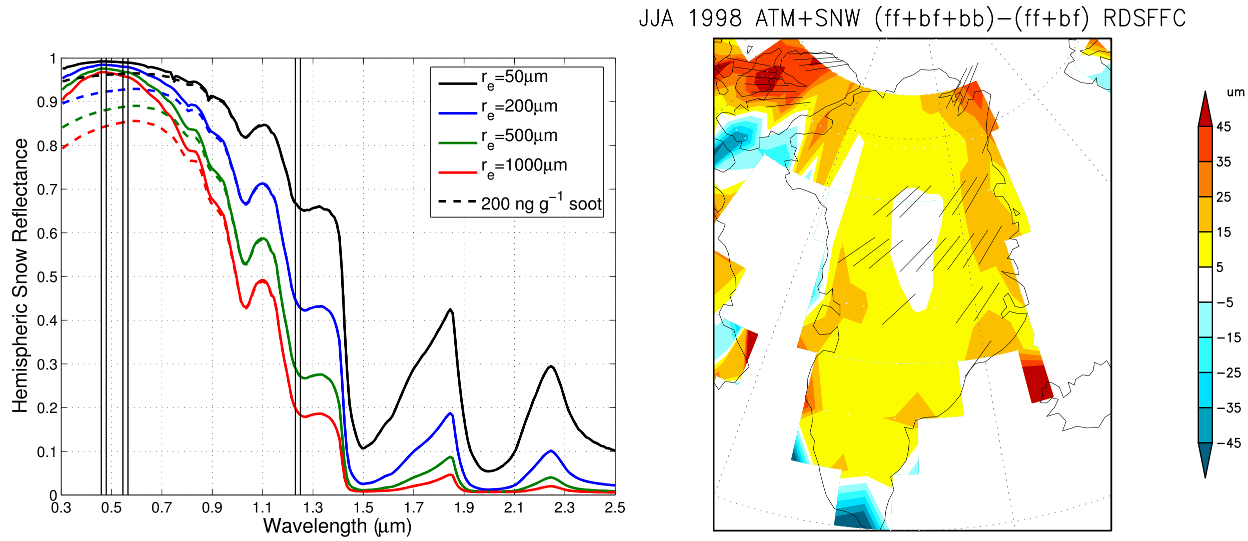

Figure 5: Left Panel: Spectral reflectance of pure snow and snow externally mixed with 200 $\mu g\,kg^{-1}$ BC for different snow size distributions. Vertical lines show positions of MODIS Bands 3, 4, and 5 (left-to-right). Right panel: Change in summertime-mean effective radius r_e [µm] of surface snowpack layer due to 1998 soot. Cross-hatching indicates statistically significant changes ($p < 0.05$) relative to simulations without boreal soot (Flanner et al., 2005).

These optical improvements will, in the net, increase clear sky, cloudy sky, and snowpack absorption relative to our current externally mixed assumption.

3.2 Relative roles of surface and atmospheric BC forcing on Arctic climate sensitivity

Soot concentrations in the surface snowpack strongly absorb visible radiation some of which would otherwise penetrate into the snowpack (Figure 5). Hence surface soot concentrations can cool the lower snowpack much as atmospheric soot cools the surface by reducing insolation. The screening effect of surface soot competes with the temperature-grain-size feedback (Figure 1b). Interestingly, our preliminary simulations reveal conditions of where soot appears to reduce total snow melt. We will numerically assess the relative influences of these competing feedbacks for Arctic climate (Section 4.3). This will require closure experiments based on in situ data from sooty, clear, and cloudy Arctic locations.

3.2.1 In Situ Observations

Arctic atmospheric and snowpack BC measurements span a wide range of concentrations (Clarke and Noone, 1985; Noone and Clarke, 1988; Hansen and Nazarenko, 2004). Snowpack BC concentration is the key diagnostic which integrates aerosol source, transport, deposition, and melt processes. Greenland concentrations are typically 1–4 $\mu g\,kg^{-1}$, and as high as 30 $\mu g\,kg^{-1}$ (Slater et al., 2002). Acquiring and assembling updated and improved (e.g., vertically and size resolved) BC measurements for event evaluation will be an ongoing activity for this project. The most important measurements we need to help reconcile our model discrepancies with observations (e.g., Figure 2) are vertical profiles of aerosol concentration, snow accumulation/melt, snowpack temperature, and spectral or broadband fluxes.

Drs. Steve Warren (U. Washington, see attached letter of support), Tom Grenfell and Tony Clarke (U. Hawaii) proposed an NSF project “Black carbon in Arctic snow and ice, and its effect on surface albedo” to measure BC in snow and ice in tundra regions of Alaska, Canada, and Russia, as well as on the Greenland Ice Sheet and the Arctic Ocean to update and improve the BC survey that Clarke conducted in 1983–1984. They will (continue) to share their measurements with us, including, potentially, BC measurements collected at Dr. Konrad Steffen’s automated meteorological sites in Greenland.

Warren et al. will also measure/estimate scavenging coefficients for removal of atmospheric BC by snow and removal of surface BC during snow melt (Section 3.1.2). These scavenging coefficients will provide important constraints for BC scavenging relevant to Hypothesis 2. In addition to Warren and Clarke’s earlier measurements, Flanner and Zender (2006) evaluated SNICAR against *in situ* and laboratory measurements of snowpack specific surface area, crystal density, albedo, and curvature- and temperature-gradient growth processes. This project will enable us to continue these comparisons as new data become available.

3.2.2 IPY POLARCAT Participation

We will contribute to the IPY “POLar study using Aircraft, Remote sensing, surface measurements and modeling of Climate, chemistry, Aerosols and Transport” (POLARCAT) (see attached letter from IPY program office to POLARCAT PI Stohl). Our contribution is to one of POLARCAT’s main themes—the influence of boreal fire aerosol on Arctic surface properties. Although many observational aspects of POLARCAT are still pending, support for regular aerosol observations at Summit, Greenland appear to be in place. Using modeled/assimilated BC deposition from NCAR collaborator and POLARCAT Steering Committee member P. Rasch, our group will estimate surface reflectance changes at Summit from significant boreal events upwind, and compare them to in situ observations.

3.2.3 ARM IOP at Barrow

Dr. Steve Ghan (PNNL) (personal communication, 2008) is proposing a DOE Atmospheric Radiation Measurement (ARM) Program intensive observing period (IOP) at the North Slope of Alaska (NSA) facility in 2008. The NSA facility at Barrow has been a premier repository of radiometric data in Arctic cloudy and (infrequently) clear skies since about 2001. The IPY IOP would augment these with additional aerosol measurements suitable for assessing effects of Arctic haze. A BC event (upwind fire) during the IOP would be very fortuitous. We plan to join this IOP in Barrow for one week, and use IOP data to calibrate and validate Arctic BC effects.

3.2.4 Greenland Ice Core

Part of Objective 2 is to place current BC forcing of Greenland in a longer term historical perspective. Dr. Eric Saltzman (UC Irvine) measures trace gas and aerosol concentrations in ice cores (e.g., Saltzman et al., 2004) and Co-PIs a pending NSF project "High-Resolution, Biomass-Burning-Specific Tracers in Greenland Ice Cores over the Past 1000 Years". In conjunction with Co-PI Randerson's fire emission database, our project provides a method to quantify the impact of Saltzman's proxy measurements of biomass burning aerosol variability in Greenland over the last 1000 yr. We will convolve ice core records of historic BC deposition to Greenland with present day spatially explicit BC emissions data (Randerson et al., 2005) to study maximum changes in Greenland reflectance and melt due to boreal BC over the past 1000 years.

Microwave brightness temperatures measured by AMSR-E can be used to retrieve several useful cryospheric parameters. Currently, Snow Water Equivalent (SWE) is produced on a 25 km grid over non-ice surfaces. The standard product, archived at NSIDC (by Co-PI Khalsa), uses a static, semi-empirical approach based on Chang et al. (1987) subject to errors due to variable snow crystal size, inadequate wet snow discrimination, and difficulty mapping snow in densely forested areas. A more dynamic SWE retrieval algorithm that incorporates estimates of snow properties is in development. We will compare AMSR-E estimates of mean snowpack grain size with SNICAR predictions (cf. Figure 5b). In particular, we are interested in assessing the influence of extreme aerosol events on the duration of snow cover in seasonally snow covered regions which are most susceptible to snow-albedo feedback (Flanner and Zender, 2005).

Once MISR-inferred spectral snow reflectance and monthly CERES-derived broadband surface reflectance products reach robust operational status, we will also use them to evaluate SNICAR reflectance, and to try to infer r_e (Figures 5a and b, respectively). (We will happily provide our predicted r_e to any retrieval experts attempting to improve MODIS/MISR surface reflectance). In combination with temperature from meteorological analyses, retrieved $\mathcal{R}$ and/or r_e will be used to evaluate SNICAR's snow aging physics (Flanner and Zender, 2006) which predict significant temperature dependence for r_e.

Greenland is an ideal location for evaluation of SNICAR from remote sensing platforms. Much of the ice sheet enjoys year round sub-freezing temperatures which remove the potentially confounding influence of liquid effects. Since soot concentrations rarely exceed 5 $\mu g\,kg^{-1}$ in Greenland, surface snowpack effective radius r_e is the most promising model parameters to retrieve and constrain.

3.3 Assess Arctic BC impacts on sea-ice

Accounting for impurities in sea-ice is important to accurate radiative transfer throughout the atmosphere/ice/ocean system (Grenfell, 1991). Our sea-ice model, CICE (described in Section 4.2) uses a single layer snowpack upper boundary condition and neither the sea-ice nor the snowpack tracks absorbing impurities such as soot as prognostic tracers. A multi-layer snowpack and prognostic aerosol tracer capability will be in CICE in 2006 (W. Lipscomb, personal communication). Graduate student Mark Flanner will merge SNICAR physics (snow aging, radiative transfer, snow-aerosol optics) into this CICE configuration.

The resulting CICE simulations will retain soot deposited directly on bare sea-ice from the atmosphere and from melting snow cover. We will use improved sea-ice radiative transfer physics as available (e.g., Briegleb and Light, personal communication, 2005) to account for aerosols embedded in the complex sea-ice-brine-pond matrix. Sea-ice extent and thickness may then respond to the full lifecycle of Arctic BC. This will be a significant improvement to current models which prescribe BC albedo alterations or remove BC from snow and sea-ice with rather ad hoc mechanisms to prevent excessive concentrations from accumulating in multi-year land and sea-ice (Hansen and Nazarenko, 2004; Jacobson, 2004; Flanner et al., 2005). Residence time estimates for optically active Arctic soot will improve. This may play an important role in studies of Objective 3 (Section 2).

We will incorporate the AMSR-E sea-ice concentration and snow depth over sea-ice products into our investigations. The current AMSR-E retrieval algorithms (Markus and Cavalieri, 1998, 2000) reduce previous ice concentration biases resulting from surface glaze and layering in the snow cover and from thin ice types. Comparisons of sea-ice extent simulations between AMSR-E and CICE during and after strong BC years will help us assess BC impacts on sea-ice.

Lipscomb and Hunke (see attached letter of support) are developing an interactive ice sheet component for the CCSM based on GLIMMER (Payne, 1999). We will provide SNICAR snow-aerosol physics for LANL's GLIMMER. Hence we anticipate the CCSM will have a glacier model component sensitive to realistic snowpack physics and BC interactions by year 3.

3.4 Role of BC forcing on Arctic surface hydrology

AMSR-E estimates surface soil liquid water content for snow free surfaces on a daily 25 km grid (Njoku et al., 2003, 2004). The product seems to underestimate spatial and temporal soil moisture variability (Figure 3a). Figure 3b shows that if BC alters snowpack opacity, it can potentially alter integrated downstream measures of surface hydrology such as river discharge to the Arctic. To tease out the potential links between BC and surface hydrology, which are likely difficult to discern on large spatial scales, we will first simulate hydrologic effects of extreme BC events. Then we will search for similar patterns following strong BC years in available satellite data.

Syed et al. (2005) recently developed a method for estimating total basin discharge (both surface and groundwater) using data from the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al., 2004). This method is currently being implemented globally within Famiglietti's research group, with an important focus on quantifying basin scale variations in surface water and flow to continental margins.

4 Earth System Model Description

Ice-albedo feedback is arguably the most important positive feedback in the polar climate system (e.g., Hartmann, 1994; Holland and Bitz, 2003; Qu and Hall, 2006). Hence an integrated Earth System Model which fully couples aerosols, snow, atmosphere, ocean, and land/sea-ice is required to test our hypotheses (Section 2) against global scale observations. The NCAR CCSM (Collins et al., 2006a) is that model. CCSM polar climate simulations have been continually evaluated against meteorological analyses and satellite observations (e.g., Briegleb and Bromwich, 1998b; Holland and Bitz, 2003; Holland et al., 2006). This project will use CCSM component models with our snow-ice-aerosol physics (Flanner and Zender, 2005, 2006) to ask questions about the integrated impacts of BC aerosol on Arctic climate.

Arctic BC primarily originates from non-frozen land surfaces at lower latitudes (Koch and Hansen, 2005) so it traverses multiple climate "spheres" to the Arctic (biosphere-atmosphere-cryosphere). The project relies on our continuing external collaborations for realistic aerosol distributions and simulation codes (discussed in Section 4). The initial CCSM BC/OC aerosol transport, deposition, and optics we use (and modify) come from long time collaborators Drs. Phil Rasch and Bill Collins (NCAR) (Collins et al., 2001, 2002).

4.1 SNow, ICe, and Aerosol Interactions

The project builds upon, extends, and applies our existing, state-of-the-art, SNow, ICe, and Aerosol Radiative model, SNICAR (Flanner and Zender, 2005, 2006). SNICAR treats snowpack radiative transfer, aging, and aerosol interactions in a unified manner that allows for realistic feedbacks between solar radiation, snowpack temperature gradients, and aerosol concentration. The vertically resolved multi-layer radiative transfer component (Wiscombe and Warren, 1980; Toon et al., 1989) treats snow as a collection of hexagonal prisms based on the equivalent surface area-to-volume approximation (Grenfell and Warren, 1999; Neshyba et al., 2003). A lookup table (computed off-line) contains Mie parameters (single scattering albedo, extinction coefficient, and asymmetry parameter) for any lognormal size distribution of snow. SNICAR accounts for solar zenith angle, direct and diffuse incident radiation, bare surface reflectance (Dai et al., 2003), and vertically-resolved effective radius (r_e), snow depth, density, and concentrations of absorbing impurities (Warren and Wiscombe, 1980).

An off-line version of SNICAR runs at high spectral resolution, 10 nm resolution in the solar spectrum from 0.3–5.0 µm (470 bands). This is useful for simulating narrow-band satellite channels such as MODIS/MISR channels (Figure 5). For climate simulations, SNICAR runs in a host snowpack model, typically the Community Land Model (CLM) (Dai et al., 2003). The CLM uses five vertical snowpack layers (Oleson et al., 2004) and itself runs off-line forced by meteorological analyses or on-line in the Community Atmosphere Model (CAM) (Collins et al., 2006b).

4.2 Sea-Ice and Ice Sheets

Sea-ice is the fulcrum of ice-albedo feedbacks in the Arctic Ocean. Drs. Bill Lipscomb and Elizabeth Hunke of LANL (see attached letter of support) are the principle developers of the Los Alamos sea-ice model (CICE), a primary component of the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM). The CICE model contains an Ice Thickness Distribution (ITD) which maintains a half dozen prognostic categories of ice thickness in each grid cell (Holland et al., 2006). The thinnest ice category is most susceptible to changes in net solar radiation due to snowpack aging and aerosol concentration.

4.3 Numerical Experiment Strategy

Our objectives (Section 2) will be approached in the context of pre-industrial, present day, and next century timescales when appropriate. Natural (i.e., unforced) interannual variability is quite large in the Arctic climate system (e.g., Briegleb and Bromwich, 1998a; Fuhrer et al., 1999). Boreal fire variability is also quite large (e.g., Randerson et al., 2005) and seems to explain most of the variability in Arctic BC deposition (Flanner et al., 2005). Detecting and assessing the relatively small (though important) signal of aerosol-induced Arctic change (Figures 5b and 4) against the noisy background of natural Arctic variability is difficult.

We will continue to employ an ensemble-based approach to increase the signal/noise ratio. The ensemble comprises multiple identical numerical experiments with slightly perturbed initial

Table 1: CCSM/SNICAR Simulations

Scenario	Sources[a]	Interactions[b]	Climate[c]	Optics[d]
Control	All	Sfc.+Atm.	SOM	Coated
Objective 1: Arctic climate sensitivity to timing and location of soot emission				
Fire location	Vary	Sfc.+Atm.	SOM	Coated
Fire seasonality	Vary	Sfc.+Atm.	SOM	Coated
Objective 2: Relative roles of surface and atmospheric BC forcing				
Forcing/Feedback	All	Vary	SOM	Coated
Aging/Scavenging	All	Sfc.+Atm.	SOM	Vary
Objective 3: Arctic BC impacts on sea-ice				
Sea-ice feedbacks	All	Sfc.+Atm.	Vary	Coated
Sea-ice asymmetry	Vary	Sfc.+Atm.	SOM	Coated
Predictions to 2100				
Equilibrium	All	Sfc.+Atm.	SOM	Coated
Transient	All	Sfc.+Atm.	IPCC/SOM	Coated

[a]BC/OC source options include Type (Fossil Fuel/Biofuel and/or Fires), Location (Tropics and/or Boreal), and Regions (North America, Asia), and prescribed burn seasons (e.g., early/late summer).

[b]Feedback options include Surface (post-deposition BC forcing feeds-back to climate), Atmosphere (Atmospheric BC forcing feeds-back), and Both.

[c]Climate options include Analyses (NCEP/NCAR re-analysis meteorology and SSTs), SOM (climatological deep ocean with Slab Ocean Model), IPCC (A1B transient ramp to 720 ppm CO_2).

[d]Optics/aging options include External (soot externally mixed with clouds and snow), Internal (soot internally mixed with clouds and snow), and Coated (aged BC has spherical water coating).

conditions. To obtain the climate responses presented in this proposal we conducted perennial 1997- and 1998-emissions experiments in separate 15 yr. simulations. We used a Student's t-test to quantify statistical significance of Arctic changes between the two ensembles. Significant ($p < 0.05$) changes appear as cross-hatched regions in Figures 5b and 4.

We plan numerous numerical experiments to systematically quantify BC impacts on cryospheric climate sensitivity and surface hydrology (Table 1).

5 Impact and Relevance

Our improved understanding and predictions of snow, sea-ice, and polar climate sensitivity to BC trends will be incorporated via CCSM into the IPCC AR5 report to help society understand, plan for, and, potentially, mitigate cryospheric climate change. At the rate the Arctic is changing, e.g., summer sea-ice retreat Stroeve et al. (2004), accounting for all known significant polar climate amplifiers in AR5 is critical. Our specific advances in our field include

1. Inventory of Arctic forcing efficacies of important BC sources

2. State-of-the-art climatology and evaluation of global snowpack grain size and BC concentration.
3. Methodology to improve prescribed surface boundary conditions (snow reflectance, snow grain size) used in satellite retrievals
4. Improved representation of BC impacts in past, present, and future climate

The project outcomes meets NASA Strategic Goal 3.1 ("Study planet Earth from space to advance scientific understanding and meet societal needs") and IDS Subelement 5 objectives by using **space-based remote sensing** and **global models** to improve understanding and prediction of the **role of black carbon in affecting clouds, precipitation, and the hydrologic cycle**. Our improved understanding and predictions of the cryospheric hydrologic cycle will be incorporated via CCSM into the IPCC AR5 report to help society understand, plan for, and mitigate BC effects on cryospheric climate.

6 Mangagement

6.1 Personnel

Zender will develop, test, and implement BC/OC optical and scavenging property improvements in CAM and SNICAR, lead IPY collaborations, and coordinate design and interpretation of hypothesis testing outlined above. Co-PI Famiglietti and his group will perform and interpret hydrologic evaluations against GRACE and AMSR-E satellite data. Co-PI Randerson will provide and update GFED fire emissions and MODIS reflectance time-series and help perform and interpret Co-PI Khalsa will obtain, screen, regrid, and average AMSR-E products suitable for input to and comparison with model simulations.

UCI graduate student Mark Flanner will merge SNICAR physics into the CICE sea-ice model and, in Year 3, into the CCSM-compatible version of the GLIMMER ice sheet model provided by LANL. Scientific specialist Dr. Chao Luo has specialized in atmospheric dust transport (Luo et al., 2003; Mahowald and Luo, 2003; Luo et al., 2004) and, more recently, cryospheric hydrology based on AMSR-E, ISCCP, and CERES retrievals. Luo will assist with satellite data analysis and model simulations.

Zender will advise an ESS graduate student in Arctic BC processes. We will focus on using satellite products, optical models, and microphysics to improve model-observation agreement in surface albedo and climate sensitivity (Section 3.1). A second student graduate student will focus on larger spatial- and temporal-scale effects of BC on Arctic climate and surface hydrology. This student will pick Famiglietti, Randerson, and/or Zender as primary advisor(s) according to their interests and project needs.

6.2 Schedule and Milestones

Year 1. *Milestones*: 1a. SNICAR interactive with CICE; 1b. Fractal aggregate soot mixtures; 1c. Global snow grain size climatology. *Tasks and Meetings*:

1. Couple SNICAR physics to sea-ice, examine impact on summer melt and extent
2. Update soot optical properties to fractal aggregates

3. Convert/rebin MODIS, AMSR-E SWE ice extent products to model grid
4. Test tropical/boreal/seasonal hypothesis
5. Zender visits Norway/NILU for POLARCAT team meeting
6. Khalsa visits Irvine for IDS team meeting and AMSR-E coordination
7. Flanner visits LANL to coordinate sea-ice simulations
8. Presentations to CCSM PCWG and AGU on Objective 1 and tropical/boreal/seasonal hypothesis

Year 2. *Milestones*: 2a. Sensitivity matrix to BC source/timing; 2b. DOE ARM IOP participation; 2c. IPY POLARCAT participation. *Tasks and Meetings*:

1. Assemble GRACE Arctic water budgets to model grid
2. Produce global snow grain size database for MODIS and AMSR-E retrievals
3. Test sea-ice asymmetry hypothesis, write up results
4. Refine scavenging with Warren et al.'s Greenland BC measurements;
5. Compare SNICAR predictions with AMSR-E inferred $\mathcal{R}$, r_{e}
6. Hunke visits Irvine for sea-ice coordination (separate funding)
7. Zender visits Barrow for DOE ARM NSA IOP
8. Graduate student to LANL to merge SNICAR into GLIMMER
9. Presentations to CCSM PCWG and AGU on Objective 3 and sea-ice asymmetry hypothesis

Year 3. *Milestones*: 3a. SNICAR coupled to LANL glacier-model; 3b. Fully coupled land/sea-ice simulations; 3c. Millennial Greenland BC extrema. *Tasks and Meetings*:

1. POLARCAT Greenland event simulation
2. Hindcast ARM IOP TOA and surface reflectance
3. Re-visit Hypothesis 1 based on outcome of Objective 3
4. If CCSM/GLIMMER ready, estimate soot effect on Greenland ablation
5. Millennial BC impacts on Greenland from ice core data and GFED
6. Presentations to CCSM PCWG and AGU (likely in year 4 also) on Objectives 2 and 1

7 Acronyms and Abbreviations

Table 2: Acronyms and Abbreviations

Abbreviation	Description
ALD	Active Layer Depth (of permafrost)
AMSR-E	Advanced Microwave Scanning Radiometer (satellite instrument)
AOMIP	Arctic Ocean Model Intercomparison Project
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
ARF	Aerosol Radiative Forcing
ARM	Atmospheric Radiation Measurement
ATSR	Along Track Scanning Radiometer and Microwave Sounder
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
BC	Black Carbon (light-absorbing component of carbonaceous aerosol)
BRDF	Bi-directional Reflectance Distribution Function
CAM	Community Atmosphere Model
CCSM	Community Climate System Model
CICE	Los Alamos sea-ice model
CLM	Community Land Model
CRM	Column Radiation Model
EMA	Effective Medium Approximation
ESM	Earth System Model
ESMF	Earth System Modeling Facility
ESS	Earth System Science (Department)
GCM	General Circulation Model or Global Climate Model
GFED	Global Fire Emissions Database
GHG	Greenhouse Gas
GLIDE	General Land Ice Dynamic Elements (core of GLIMMER)
GLIMMER	Ice Sheet Model of Payne et al.
GSFC	Goddard Space Flight Center
ISDAC	Indirect and Semi-Direct Aerosol Campaign
IOP	Intensive Observing Period
IPCC	Intergovernmental Panel on Climate Change
IPY	International Polar Year
ITD	Ice Thickness Distribution
LANL	Los Alamos National Laboratory
MISR	Multi-angle Imaging Spectro-Radiometer (satellite instrument)
MODIS	Moderate Resolution Imaging Spectroradiometer (satellite instrument)

Table 2: (continued)

Abbreviation	Description
NASA	National Aeronautic and Space Administration
NCAR	National Center for Atmospheric Research
NCCS	NASA Center for Computational Sciences
NCO	netCDF Operators
NILU	Norwegian Institute for Air Research
NIR	Near InfraRed
NSA	North Slope of Alaska
NSIDC	National Snow and Ice Data Center
OC	Organic Carbon
OPAC	Optical Properties of Aerosols and Clouds
PI	Principle Investigator
POLARCAT	POLar study using Aircraft, Remote sensing, surface measurements and modeling of Climate, chemistry, Aerosols and Transport (IPY project)
RT	Radiative Transfer
SEM	Scanning Electron Microscopy
SGER	Small Grant for Exploratory Research
SNICAR	SNow, ICe, and Aerosol Radiative model
SNTHERM	Snow Melt model
SOM	Slab Ocean Model
SSA	Specific Surface Area
SWE	Snow Water Equivalent
TG	Temperature Gradient
UCI	University of California, Irvine

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Blue numbers link to proposal section(s) where citation occurs:

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9 Facilities, Equipment, and Other Resources

9.1 Computational Resources

Our IDS project is well-situated to take advantage of UCI's fast computing capabilities for data analysis and relatively short model simulations. PI Zender directs the UCI Earth System Modeling Facility (ESMF), an NSF-supported MRI facility dedicated to coupled global climate, chemistry, and biogeochemistry simulations. The ESMF flagship machines is an 88-CPU Power4+ IBM supercomputer with 192 GB RAM and 16 TB of RAID storage. In Spring 2006, ESMF anticipates acquiring a new Beowulf cluster comprising approximately twenty two-way dual core Opteron nodes (80 CPUs) and about 5 TB of RAID storage.

Since this IDS proposal is squarely fits the ESMF mission, the ESMF will host the primary modeling development and shorter simulations. However, the ESMF is inadequate to perform the bulk of the climate simulations so if funded we will request computing time from the NASA Center for Computational Sciences (NCCS) for the fully coupled CCSM/SNICAR code.

Budget Justification

Salaries and Wages:

One month of summer support is requested for the PI, Charlie Zender, for each year of the project. Prof. Zender will coordinate the overall project, and take responsibility for modeling aerosol, cloud, and snowpack interactions. One month of summer salary for each year is requested for Co-PI Jay Famiglietti and one-half month of summer salary is requested for Co-PI James Randerson. Prof. Famiglietti will perform hydrologic evaluations against GRACE and AMSR satellite data. Prof. Randerson will provide and update GFED fire emissions and MODIS time-series.

Funds are requested to support Dr. Chao Luo, Associate Specialist Step II, at a rate of 0.25 FTE for the first three years of the project. Dr. Luo is the principal scientific programmer associated with UCI's Earth System Modeling facility. He has experience with all the complex models involved in this project (SNICAR, CLM, CAM, CCSM), as well as CERES, ISCCP, and AMSR datasets. Dr. Luo will assist with running the models and analyzing model output.

Salary support is requested for two nonresident PhD graduate students for all three years. One graduate student dissertation will advance understanding of BC, cloud, snowpack interactions through microphysical approaches primarily under the direction of PI Zender. The other graduate dissertation will ellucidate large spatial and temporal scale processes which control BC climate effects.

All salaries and wages were estimated using UCI's academic and staff salary scales. A 2% cost of living increase was applied each year of this proposal as well as a 5% merit increase, where applicable.

Employee Benefits:

Fringe Benefits are actual benefits for named employees based on current financial records. Benefit rates used in this proposal are: Faculty - summer - 12.7% Programmer 31% Student employees - summer - 3% Student employees - academic year - 1.3%. Fees and tuition are requested for two nonresident students. University of California policy requires award payment of fees and tuition for any student with more than 25% support from a grant. Nonresident graduate student fees and tuition are $24,755 for each student in year 1, $27,091 per student in year 2, and $29, 669 per student in year 3. Fees and tuition are excluded from indirect cost assessment.

Equipment:

Equipment funds are requested in the first year for three scientific workstations for model development and data analysis. Workstations will have storage and software to analyze 1 TB of data with GIS and statistical software.

Travel Domestic:

In years 1, 2 and 3 travel funds are requested for the two members of the scientific team to attend the 5-day NCAR CCSM Workshop in Brekenridge. Costs are estimated at $1,500 per person include roundtrip air travel, conference registration, hotel, per diem expenses, and local transportation. Support is also requested in each year for two members of the team to attend the AGU San Francisco meeting for one week. Costs are estimated at $1,500 per person include roundtrip air travel, conference registration, hotel, per diem expenses, and local transportation.

One round-trip at $3000 is requested for the PI to travel to Barrow, Alaska in Year 2 to participate in the DOE ARM IOP proposed for the North Slope of Alaska (NSA) facility. Costs include roundtrip air travel, hotel, per diem expenses, and local transportation. PI will participate in IOP for one week to help characterize arctic haze interactions with clouds.

In year 1, support is requested for Dr. Khalsa to visit Irvine and meet with collaborators for a one-week visit. Costs are estimated at $1,500 per person include roundtrip air travel, conference registration, hotel, per diem expenses, and local ransportation. In year 2, travel support is requested for one person to attend the IGARS conference. Costs are estimated at $1,500 per person include roundtrip air travel, conference registration, hotel, per diem expenses, and local transportation.

Travel International:

One round-trip at $3000 is requested for the PI to travel to Norway in Year 1 to participate in the IPY POLARCAT team meeting activities and to present results. This trip includes roundtrip travel from Irvine to Oslo, one-week hotel and per diem. Travel estimates are based on historical usage.

Other Direct Costs:

Publication Costs: $2,000 in year 1 and $4,000 in years 2 and 3 is requested for publication costs pursuant to this project, which typically include the utilization of expensive color figures. . Charges for journals, photocopying, long distance phone, fax and postage charges pursuant to this project are requested. Included in these expenses are long-distance charges for usage directly related to the project, such as communication with colleagues, journals, and vendors. Photocopying of research materials including publications and results of this sponsored research project are requested as well as mail and shipping for materials related to this project. Costs were estimated according to historical usage.

Indirect Costs:

Facilities and Administrative costs were estimated in accordance with UCI's approved indirect cost rate agreement. The indirect cost rate of 52.5% of MTDC effective 7/1/05 was based upon the nature and location of the work proposed. Graduate student fees and tuition and equipment are excluded from indirect cost assessment. UCI's indirect cost rate agreement was approved by DHHS, the Federal Cognizant Audit Agency for UCI on 12/5/01.

Supplementary Documents

1. ${DATA}/prp/prp_ids/prp_ids_wrk_frc.pdf
1. ${DATA}/prp/prp_ids/prp_ids_ltr_warren.pdf
2. ${DATA}/prp/prp_ids/prp_ids_ltr_lanl.pdf
3. ${DATA}/prp/prp_ids/prp_ids_ltr_polarcat.pdf
4. ${DATA}/prp/prp_ids/prp_ids_cmt_khalsa.pdf
5. ${DATA}/prp/prp_ids/prp_ids_abb.pdf
6. ${DATA}/prp/prp_ids/prp_ids_fcl.pdf