Title:

Understanding the controls on cryospheric albedo, energy balance, and melting in a changing world

Themes:

(I) Global hydrological cycles and water resources(IV) Climate variability and change, seasonal to centennial

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Section 1. Climate change has a disproportionate impact on Earth's cryosphere due to the widespread existence of snow and ice near its melting point. Decades of satellite, airborne, and ground observations clearly show increased melting of glaciers and ice sheets, declines in sea ice, and decreasing spring snow cover. This increased melting of cryosphere cover makes Earth more absorptive of sunlight (snow-albedo feedback) and moves enormous volumes of stored water from frozen state to liquid, raising sea level and changing water availability to large populations. However, the distribution and quantification of forcings controlling this accelerated melting are poorly known.

Atmospheric warming from radiative forcing by anthropogenic increases in greenhouse gases (GHG) (~3 W m⁻²) is contributing to this acceleration. However, the proportion of this contribution is uncertain because of the large uncertainties in the controls on the dominant contributor to annual melt - absorbed sunlight - itself modulated by albedo (Fig. 1). Despite this crucial role of albedo and solar radiation in snow and ice melt, sparse global measurements have kept us from understanding the global distribution of controls on albedo, grain size (GS), and radiative forcing by dust/black carbon (BC) (Fig. 2), and from accurately modeling melt processes worldwide (Fig. 3). In some regions where robust radiation and EB measurements are available, we know that melt rates of seasonal snow and supraglacial snow are dominated by radiative forcing by impurities (1-4). Such an understanding is crucial to determining cryosphere melt in the present, projecting its future behavior, and understanding the already powerful changes observed that are not attributable to anthropogenic warming (5). This critical need leads to the overarching goal:

QESO: Determine the controls on absorbed solar radiation in snow and ice by grain size variation and radiative forcing by dust and black carbon to within daily mean of 3 W m⁻².

Current general circulation models (GCM) and regional climate models (RCM) that include snow/ice radiative transfer modeling suffer from poor knowledge of the global distribution of grain growth rates and deposition of dust and BC. With well-constrained GCMs/RCMs, we will begin to answer fundamental questions related to past, current and coming changes in the global water cycle and global climate:

- 1. What is the contribution of regional warming (including its influence on snow grain size growth) and radiative forcing by dust and black carbon to present day snow and ice melt?
- **2.** How will climate-driven and population-driven increases in desertification and forest fires lead to accelerated snow and ice melt and perturbation of the global water cycle and regional water supplies?
- **3.** How will perturbations of snow and ice albedo impact mountain and ice sheet glacier mass balance?
- **4.** For how long would reduction of radiative forcing by dust and BC mitigate against increased melt and sea level rise from climate warming?

Importance of this Science Target to Themes

By addressing the albedo controls on snow heating and melting across the global cryosphere, we will markedly advance two of the five 2017 Decadal Survey Themes: (I) Global hydrological cycles and water resources, and (IV) Climate variability and change, seasonal to centennial. Understanding the controls on snow and ice melt is fundamental to understanding the impacts of the anthropogenic experiment that has been playing out across the Anthropocene.

The IPCC 5th Assessment Report indicates that uncertainties in aerosols continue to contribute the largest uncertainty to the total global RF estimate, part of which comes from the perturbation of cryosphere albedo and only incomplete assessment of BC relative to mineral dust (6). BC impacts on cryosphere albedo are estimated by the IPCC report to be the third largest emitted radiative forcing but with the largest uncertainties. However, in the Cryosphere chapter, it is acknowledged that our understanding of snow albedo changes is extremely limited (7). The World Bank suggests that mitigation of black carbon from snow and ice could reduce warming in the Arctic and Himalaya by more than 1 °C and 25% reduction in seasonal snow cover loss by 2050, but with marked uncertainty due to poor measurements and inadequate treatment of coincident dust (8).

The NRC report on Himalayan Glaciers (9) called explicitly for "improved monitoring of the amount of black carbon on glaciers and how much it affects the albedo". Even back in 1989, the NRC recommended that the imaging spectrometer HIRIS (deselected from EOS) was needed to provide albedo to within 2% and the ability to resolve radiative forcing by impurities and changes in GS (10).

Advancing the Hydrological Sciences and Climate Change/Variability Themes

Understanding controls on snow heating and snowmelt rates with quantitative energy balance modeling, constrained by these measurements, will bring GCMs and RCMs to the ability to address physical processes explicitly. In turn, we will markedly advance the *Global Hydrological Cycles and Water Resources* theme by understanding controls on snowmelt runoff, controls on regional heating through snow-albedo feedback and impacts on monsoonal strength due to seasonal perturbation of heating. Likewise, we will markedly advance the *Climate Variability and Change* theme by understanding melt of the climatic impactful snow cover across prairies, tundra, taiga, and sea ice, as well as modulation of the energy and mass balance of ice sheets, mountain glaciers, and by their fluxes controls on sea level rise.

Section 2. To achieve the science target, the controls on variation in snow and ice albedo by GS variation and radiative forcing by impurities must be measured spectroscopically with the accuracy and precision for which we understand the distribution of present GHG warming (~3 W m⁻²). With these quantitative retrievals, mesoscale to global scale climate models and snowmelt models can be constrained with physically correct GS variation and present-day radiative forcings by dust and BC (Fig. 4). In turn, the relative contributions to cryosphere loss and changes in snowmelt runoff of changes in climate and aerosol loading can be forecast with much lower uncertainties (Fig. 3), in turn reducing uncertainties in the climate sensitivity control on the powerful snow-albedo feedback.

Current GCMs and RCMs that include snow and ice radiative transfer modeling suffer in particular from poor knowledge of the global distribution of grain growth rates and deposition of dust and BC (11-16). With these spectrally derived forcings, we can determine the time series of daily and cumulative radiative forcings from GS variation and radiative forcing by dust and BC (Fig. 5). We will also constrain the National Center for Atmospheric Research Coupled Earth System Model (CESM) for global cryosphere and the Weather Research and Forecasting (WRF) model for the mountain cryosphere to understand the albedo forcing contributions to melting of snow and ice relative to other components of the energy balance and to markedly decrease melt uncertainties (Fig. 3).

The CESM and WRF models have advanced capacity to simulate physical processes governing changes in snow albedo by simulating radiative transfer with the Snow, Ice, and Aerosol Radiation (SNICAR) model (13, 17). The SNICAR model has been shown to accurately model snow reflectance (18) and the radiative influence of dust and BC in snow (19-21), but only when the physical state of the snow is well constrained (22, 23). However, GS growth rates are poorly known around the global cryosphere (16). Impurity depositions are likewise poorly known, coming largely from coarse and insufficiently validated GCM simulations (14, 24).

We will incorporate a high-spectral-resolution version of SNICAR into CESM and WRF to simulate global spectral albedos of snow and ice that are directly comparable to the measurements. These comparisons give immediate understanding of the magnitude of the uncertainty error in our current estimates of spectral albedo, net solar radiation, and its contribution to melt. GS and impurity radiative forcing measurements then constrain SNICAR in each model (GCM/RCM) in the respective modeling domains (global and mountain regions). GS is used as a direct insertion to the model. The impurity radiative forcing is a constraint that forces us to adjust model aerosol deposition fields, impurity optical properties, and meltwater retention efficiencies.

Current and planned cryosphere missions, such as ICESat-2, IceBridge, GRACE, NISAR, and others, focus on **how much** snow and ice are changing, but not **why**. The direct measurement of controls on snow albedo described here will address **why** snow and ice are changing by capturing the rapid changes in GS and radiative forcing by impurities, and in turn constraining our understanding of the contributors to melting and ensure that models properly represent processes for global climate and water availability projections. Changes in snowfall themselves are addressed in the RFI#2 response on snow water equivalent measurements (25).

Section 3. In order to address the QESO, we must retrieve changes in GS and radiative forcing by impurities with equivalent changes in solar energy available for snowmelt within ± 3.0 W m⁻² daily mean.

Capability and performance requirements:

Fig. 5 shows proposed spectra (top) and cumulative radiative forcings from impurities and GS change (bottom) that will be available for every pixel from these measurements. Spectral sampling of \leq 20 nm, response function width \leq 20 nm, and \leq 5% spectral calibration uncertainty are required to discriminate changes in radiative forcing and GS to within the required instantaneous 7.5 W m⁻² or daily mean 3 W m⁻² (Fig. 6).

The QESO requires observation of radiometrically unsaturated, spectral radiance reflected from snow and ice surfaces in the wavelength range 400 to 2350 nm. These acquisitions must span gradients in snow and ice heating and melting (Fig. D-6). The instrument functional requirement for spectral range (400–2350 nm) supports the observable measurement requirements by spanning the range of wavelengths covering the absorption features shown in Fig. 5, the atmospheric features used in the atmospheric correction (26), and facilitating the spectral mixture analysis to screen out mixed pixels (27). These acquisitions must span gradients in snow and ice heating and melting (Fig. D-6). These gradients are spanned within swath width that must be greater than 25 km to accommodate mountain massifs (28).

The instrument functional requirement for radiometric range (1.5× Lambertian reflectance) avoids saturation of measured radiance from snow. Radiometric calibration of \leq 10% uncertainty enables radiative transfer model-based atmospheric correction. The spatial sampling requirement (<50 m) supports the observable measurement requirements because it addresses spatial structure changes at ~40-m-length scales (29), ensures sampling homogeneous snow pixels, and minimizing spectral mixtures that occur at coarser spatial scales in rough mountain terrain. The FOV requirement also allows aggregation of areas inward of ice sheet perimeters where spatial gradients are less steep.

Fig. 7 shows definitive regions of the cryosphere with the parameter space of direct albedo reduction (impurities from clean to dirty) and grain growth

(atmospheric temperature from colder to warmer). These regions must have approximately weekly acquisitions during accumulation and ablation seasons to address changes in heating and melting (30). The requirement for illumination geometry, <70° local SZA, is driven by numerical stability of radiative transfer modeling of snow reflectance and the need to allow for atmospheric/topographic conversion of spectrometer radiances to directional reflectance. The key requirements to achieve the science target are summarized in Table 1.

Section 4. These measurements can be achieved affordably in the decadal timeframe, due to previous investments in response to global terrestrial/coastal coverage missions outlined in the 2007 NRC Decadal Survey (31) and NRC *Landsat and Beyond* report (32) and other initiatives. These measurements build on a legacy of airborne instruments such as AIS (33), AVIRIS (34), and AVIRIS-NG (35), and space-based instruments such as NIMS (36), VIMS (37), Deep Impact (38), CRISM (39), EO-1 Hyperion (40, 41), M3 (42) and MISE, the imaging spectrometer now being developed for NASA's Europa mission.

NASA-guided engineering studies in 2014 and 2015 show that a Landsat-class VSWIR (380 to 2510 nm @ \leq 10 nm sampling) (Fig. 8) imaging spectrometer instrument with a 185 km swath, 30 m spatial sampling and 16 day revisit with high signal-to-noise ratio and the required spectroscopic uniformity can be implemented affordably for a three year mission with mass (98 kg), power (112 W), and volume compatible with a Pegasus class launch or ride share (Fig. 9).

The key for this measurement is an optically fast spectrometer providing high SNR and a design that can accommodate the full spectral and spatial ranges (43). A scalable prototype F/1.8 full VSWIR spectrometer (44) has been developed, aligned, and is being qualified (Fig. 10). Data rate and volume challenges have been addressed by development and testing of a lossless compression algorithm for spectral measurements (45-47). This algorithm is now a CCSDS standard (48). With compression and the current Ka band downlink offered by KSAT and others, all terrestrial/coastal measurements can be downlinked (Fig. 11).

Efficient and accurate software for snow albedo properties is used in an operational framework of the NASA Airborne Snow Observatory (30), based on two decades of algorithm development and validation on data from AVIRIS (27, 49-59). These products presently meet the data requirements discussed above but the spatial and temporal measurements needed for the global cryosphere are logistically impossible from aircraft.

Measuring from space is the only practical way to provide this global view of the cryosphere. For example, in summer 2015, NASA's airborne AVIRIS-NG acquired data in northwest Greenland in support of ICESat-2 preparation, taking three weeks to acquire approximately 19,000 km² or only about 5% of the area of the Greenland Summit (Fig. 7), and at various times of the day with varying cloud conditions. The revisit coverage of multiple climate zones and multiple elevation gradients provides the data needed to regionally characterize snow GS and radiative forcing impurities, and in turn their control on snow heating and melting.

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Figures



Fig. 1 Quality observations to determine snow/ice albedo changes at instrumented test sites show that the complexities of melt energy are dominated at all latitudes by absorbed sunlight.



Fig. 2 These spectra show the sensitivity of albedo that requires spectroscopy for improved understanding. MODIS bands can provide qualitative retrievals, but not the accurate atmospheric correction and retrievals acquired by the spectrometer.



Fig. 3 CESM modeling uncertainties in impurities and grain growth result in large uncertainties in melt rates (top). SIRFA will reduce uncertainties in MODIS retrievals of (1) radiative forcing and (2) grain size leading to (3) order of magnitude reduction in modeling melt uncertainty, allowing better understanding of process importance.



Fig. 4 Determine snow/ice albedo changes is motivated by (a) the scientific and societal benefits of increased understanding of the processes driving snow and ice melt and (b) the value of satellite observations to investigate this issue and inform current models. The data are from NASA's AVIRIS-NG data collected over NW Greenland in summer 2015.



Ablation Season

Fig. 5 Time series of measured spectral evolution over entire melt season (top), and radiative forcing calculated from that data (bottom).



Fig. 6 Radiative forcing requirement of 7.5 W m⁻² defines the spectral resolution of 20 nm (red arrow) in the visible range (400-900 nm) bands, which derives from the change in wavelength divergence between clean snow and the impure snow reflectance.



Fig. 7 Regions of interest in which we have suggested but incomplete understanding of the permutations of cold to warm snowpacks and clean to dirty snowpacks



Fig. 8 (left) Full spectrum measurement from 380 to 2510 nm for science and application objectives and providing continuity with Landsat and Sentinal-2 bands. (right) Signal-to-noise ratio for 30 m sampling with F/1.8 VSWIR Dyson imaging spectrometer for a range of reference radiances. The measurement will not saturate at full Lambert radiance.



Fig. 9 (left) Opto-mechanical configuration with one telescope feeding two field split wide swath F/1.8 VSWIR Dyson spectrometer providing 185 km swath and 30 m sampling. (center) Imaging spectrometer with spacecraft configured for launch in a Pegasus shroud for an orbit of 429 km altitude, 97.14 inclination to provide 16 day revisit for three years. (right) Orbital altitude and repeat options showing an altitude of 429 km with a fueled spacecraft supports the three year mission with the affordable Pegasus launch. Higher orbits are viable with a larger launch vehicle.



Fig. 10 Design of a wide swath F/1.8 VSWIR Dyson covering the spectral range from 380 to 2510. (right) Dyson imaging spectrometer in qualification that uses a full spectral range HgCdTe detector array.



Fig. 11 (left) Global illuminated surface coverage every 16 days. (right) On-board data storage usage for illuminated terrestrial/coastal regions with downlink using Ka Band (<900 mb/s) to KSAT Svalbard and Troll stations. Oceans and ice sheets can be spatially averaged for downlink.

Table 1 Science Traceability Matrix (STM) shows the flow from Science Themes through Objective to Physical Parameters and the Observable and requirements.

Science Targets	QESO	Scientific Measurement Requirements		Instrument Requirements		Mission Requirements
		Physical Parameters	Observable and its Requirements	Parameter	Requirement	Requirement Performance
Understand the controls on melting of Earth's snow and ice in high latitude and high elevations THEMES: (I) <i>Global</i> <i>hydrological</i> <i>cycles and</i> <i>water</i> <i>resources</i> (IV) <i>Climate</i> <i>variability</i> <i>and change,</i> <i>seasonal to</i> <i>centennial</i>	Determine the controls on absorbed solar radiation in snow and ice by grain size variation and radiative forcing by dust and black carbon to within daily mean of 3 W m ⁻²	Snow and ice spectral albedo in 400– 2350 nm spectral range with 30-nm spectral resolution by 0.03 Spectrally-integrated snow albedo in the range 0.3– 0.9 unitless, by 0.015 Snow grain radius: 50–2000 μ m, by 20 μ m Solar at-surface radiative forcing by dust/BC/organics by < 7.5 W m ⁻² (instantaneous, from which daily mean is determined) In representative areas from polar ice sheets, tundra/taiga snow, Midlatitude glaciers and snow, equatorial glaciers	Visible/shortwave infrared radiance spectra, 400–2350 nm • 20-nm sampling at 400–900 nm for radiative forcing due to dust and BC • 30-nm sampling at 980–1070 nm for snow grain size • 20-nm sampling at 740–780 nm for oxygen A-band atmospheric correction • 20-nm sampling at 860–1020 nm and 1050–1250 nm for water vapor corrections	Spectral range Spectral sampling SNR Radiometric range Spatial sampling Swath	400–2350 nm (radiative forcing; clouds; mixed rock/snow pixels) ≤ 20 nm sampling >32 (Visible) >158 (NIR) (specific bands available) 1.5 × Lambertian (snow HDRF never exceeds 1.5L) ≤50 m (scale of dust, carbon content spatial variability) >25 km (size of mountain glacier rocions)	I. Coverage: >90% probability of approximately weekly acquisitions during accumulation (heating) and ablation (melting) seasons. Pointing capability required. II. Lighting: Imaging only when solar zenith angle <70 deg III. Duration: Stable for > 5 years