Title:
Monitoring Cryospheric Albedo in a Changing World: Filling the knowledge void on a key climate parameter

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Description:
Earth's vast, remote, and highly reflecting frozen regions respond to, and affect energy and water budgets across local to global scales. They are spatially heterogeneous and rapidly changing in mass, extent, and albedo but inadequately characterized. Global spectroscopic measurements of snow and ice albedo and heterogeneous controls on albedo can fill key gaps in monitoring and modeling our changing climate.

Introduction

Decades of satellite, airborne, and ground observations show clear evidence of increased melting of glaciers and ice sheets, declines in sea ice, and decreasing spring snow cover. The global retreat of our cryosphere is not only the iconic symbol of climate change, but also threatens the health of polar and mountain ecosystems. Reduced snowpacks in boreal and montane regions have led to severe wildfires and unprecedented pest infestations, removing forest cover and exposing a snowy land surface. These changes are rapidly modifying the albedo of Earth's cryosphere, affecting surface energy balance and climate feedbacks from local to global scales.

Key challenges remain for quantifying and understanding the drivers of, and responses to, a shrinking cryosphere. Even a few percent shift in the albedo of these

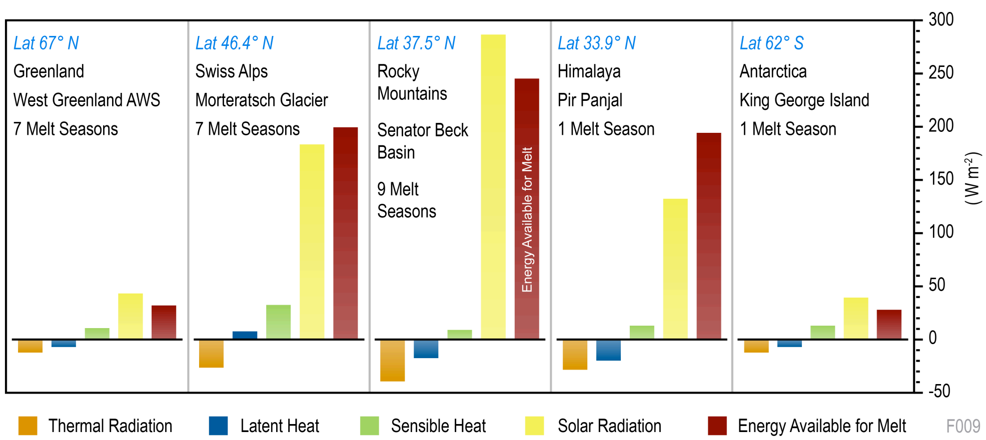

Fig. 1. Observations at instrumented test sites show dominance of absorbed sunlight providing melt energy, independent of latitude.

highly reflecting regions will result in large changes in absorbed solar energy, leading to changing melt patterns and climate feedbacks. Current sensors do not meet the accuracy needs to assess spatial and temporal changes in cryospheric albedo, nor understanding the controls on those changes.

Without these key data, we cannot adequately represent these critical processes in the land surface component of hydrology and climate models, nor understand the relative contribution of greenhouse gas warming to losses of snow and ice. Global spaceborne observations of cryospheric albedo and related forcings combined with model assimilation will significantly improve snow and ice melt predictions, a necessary step in developing adaptive capacity for social-ecological systems.

Changes in timing and magnitude of snow and ice melt are largely controlled by change in the absorption of solar radiation at the surface (Fig. 1), described by albedo. Reduction of snow albedo is controlled mainly by snow grain size (near-infrared wavelengths) and absorption by impurities (visible wavelengths) (Fig. 2). Atmospheric warming due to increased greenhouse gases has its strongest influence on melting through coarsening of snow grain size and resulting decrease in albedo, but also through sensible heating and longwave irradiance. At the same time as warming, there have been regional changes in emissions and deposition to snow and ice of mineral dust and black carbon (BC). The resulting deposition to the cryosphere darkens the surface and lowers albedo. Increases in snowmelt on the glaciers, ice sheets, and sea ice also lead to lower albedo. Albedo-melt feedbacks are well known but not accurately captured in the physical representation of snow processes in models.

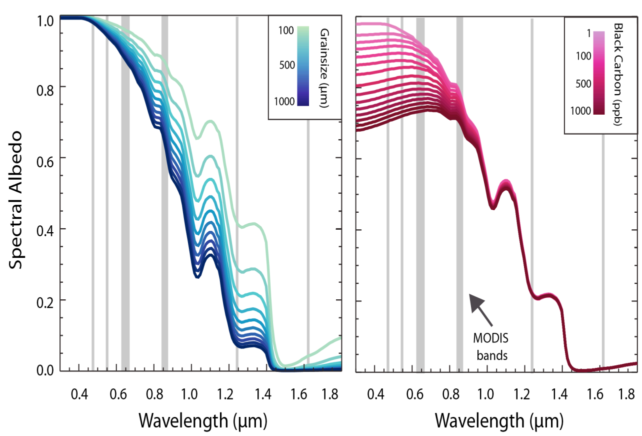

Fig. 2. These spectral albedo curves show the sensitivity of snow albedo to grain size and impurity concentrations.

Landcover change in snowy regions also affects albedo over the vast boreal region and in mountain areas. Expansion of woody shrubs at tree line is decreasing albedo in sensitive ecosystems. Large-scale wildfire is removing dark evergreen forest canopy, revealing the snowy surface in winter and spring, thereby increasing albedo on a regional scale. The mix of these albedo forcings and feedbacks across the global cryosphere is not accurately measured and monitored, leaving land surface hydrology and climate models poorly constrained.

Multispectral optical remote sensing has long mapped the extent of the cryosphere and recent algorithmic improvements have squeezed these spectrally sparse data for indications of snow grain size and radiative forcing by dust and black carbon but with insufficient accuracy. Multispectral satellite remote sensing does not meet the spectral resolution requirements to accurately describe and quantify subtle yet critical changes in cryospheric albedo nor the causes of the change (e.g. dust, soot, grain size/melt, vegetation changes). Modern spaceborne imaging spectroscopy has the technological readiness and demonstrated capacity to acquire such data, with high accuracy, and at low risk of instrumental failure.

What are the key challenges or questions for Earth system science across the spectrum of basic research, applied research, applications and/or operations in the coming decade?

Key Challenge:

Basic research goal: Understand how changes in snow and ice extent and reflectivity (including seasonal snowpacks, glaciers, ice sheets, and sea ice) affect energy and water balance at local, regional, and global scales.

Basic research questions:

1) *How do changes in snow grain size and radiative forcing by black carbon/dust affect albedo, energy balance, and melt rates and what is the magnitude of the radiative feedbacks at local, regional, and global scales?*
2) *How do changes in surface melt patterns affect sea ice albedo, feedbacks, and surface energy balance?*
3) *How do landscape-scale changes in snow-vegetation interactions affect heterogeneity, albedo, and therefore energy and water budgets?*

Applied research goal: Mapping and monitoring changes in the extent and albedo of snow and ice and translating these observations into actionable information for applications support.

Applied research questions:

1) *How can we accurately represent snow and ice albedo processes and their feedbacks in land surface hydrology, sea ice, and climate models?*
2) *How can we accurately represent landscape-scale snow-vegetation heterogeneity in land surface hydrology and climate models?*
3) *What are the water resource management implications of changing melt patterns?*

Why are these challenges/questions timely to address now especially with respect to readiness?

Current and planned cryosphere missions reveal changes in cryosphere *mass* but do not resolve the distribution of energy fluxes that control that melt. That is, those missions let us know how much snow and ice are changing, but not *why*. Moreover, current and planned multispectral missions cannot measure cryospheric albedo to meet accuracy needs. In the polar regions, a spaceborne optical imaging spectrometer can measure reflected solar radiation of snow and ice over the sunlit season to constrain our understanding of the spectrally varying contributors to melting and mass change. In turn, we can quantify albedo-sensitivity to cryospheric warming, and the relative contributions of warming and albedo variations to snow and ice losses, combined with the measurements of mass balance. In snowy regions with forests undergoing disturbance, an imaging spectrometer can quantify and monitor changing albedo and snow extent, which in combination with land surface models can assess surface water and energy budgets for ecosystem recovery.

Climate models have been growing in capacity to fully address energy balance components and assimilate remote sensing products such spectral albedo and related data. By filling voids in observations such as the drivers of snow and ice albedo variation, we can now constrain these models, leading to a more solid physical basis to support projections and assessments of mitigation opportunities. Surface melt versus dynamic ice flux can be better understood to improve our projections of sea level rise. Characterization of sea ice surface energy balance and melt onset will be improved. We will gain fundamental and new understanding of snow-vegetation interactions and their effect on surface-atmosphere interactions. We will better understand changes in water availability from melting mountain snowpacks and glaciers, affecting nearly 1/6th of the world's population.

The technology for the required measurements is now ready based on investments over the past decade by the for the 2007 HyspIRI Decadal Survey mission. The instrument would have full spectral coverage from 380 to 2510 nm with 10 nm sampling. It would have 30-m spatial resolution and a 185 km swath and could be accommodated on a small satellite, launching from a relatively low-cost Pegasus rocket.

Why are space-based observations fundamental to addressing these challenges/questions?-

Global monitoring of cryospheric extent and albedo requires high spectral resolution and spatially extensive, repeat coverage of vast regions of the globe. While airborne observations have demonstrated success, most cryospheric regions are remote and logistically difficult to visit via aircraft with the necessary coverage and number of repeat acquisitions. Space-based observation is the only practical way to provide access to these global fingerprints.

Frequent overpasses in the high latitudes during the sunlit season allow unprecedented observations of the key processes driving recent increases in rates of snow and ice melt. In particular, a near-polar orbiting imaging spectrometer will dramatically improve our knowledge of processes driving polar snow and ice melt. The Airborne Snow Observatory provides regular acquisitions over selected western US mountain basins with an imaging spectrometer and scanning lidar to determine albedo, controls on albedo, and changes in snow water equivalent. Despite its growing domain, simultaneous acquisitions across polar and global mountain regions are not possible from aircraft and therefore requires space-based observation.