IASC/ICARP III Workshop on "*Quantifying Albedo Feedbacks and Their Role in the Mass Balance of the Arctic Terrestrial Cryosphere*"

University of Bristol, UK 21-23 September 2014

Organisers: Martin Sharp (U.Alberta) and Martyn Tranter (U. Bristol)

Participants (*= ECR; ** = Invited Speaker)

Thomas Goelles* (Austria)
Stef Lhermitte (Belgium)
Martin Sharp (Canada)
Chad Thackeray* (Canada)
Libo Wang (Canada)
Marek Stibal* **(Czech Republic; Denmark)
Carl-Egede Boggild (Greenland/Denmark)**
Jason Box (Denmark/USA)**
Pia Englyst* (Denmark)
Kati Anttila (Finland)
Aku Riihela* (Finland)
Ghislain Picard(France)**
Stefanie Lutz* (Germany; UK)
Charles Fierz (IACS; Switzerland)
Kathrin Naegeli* (Switzerland)
Alex Anesio (UK)
Liane Benning (UK)
Arwynn Edwards (UK)
Andrew Hodson (UK)
Tris Irvine-Fynn (UK)
Dan Lunt (UK)**
Ed Pope* (UK)
Martyn Tranter (UK)
Eugenie Euskirchen (USA (Alaska))**

In addition to these registered participants we had significant participation of Bristol-based scientists, from the Bristol Glaciology Centre and the Biology Department.

Background

The workshop was planned as a contribution to the *Third International Conference on Arctic Research Planning (ICARP III),* to be held during Arctic Science Summit Week (ASSW) in Toyama, Japan in April 2015.

ICARP III is intended to provide a framework

- to identify Arctic science priorities for the next decade;

- to coordinate various Arctic research agendas;

- to inform policy makers, people who live in or near the Arctic and the global community, and

- to build constructive relationships between producers and users of knowledge.

IASC provided funding to support a number of workshops to help develop products that address one or more of these objectives. The goals of this workshop were to articulate scientific priorities and a research agenda related to the topic "*Quantifying Albedo Feedbacks and their Role in the Mass Balance of the Arctic Terrestrial Cryosphere*" and to formulate these in a way that would allow them to be presented at the Toyama Symposium and incorporated into the ICARP III products, which will include a "consensus statement identifying the most important Arctic research needs for the next decade".

Workshop Agenda

The workshop was designed to be primarily a brainstorming session, but we started it with five plenary presentations to provide an initial basis for discussion. These were each 45 minutes long, followed by 30 minutes (or more) of discussion. An additional presentation was added on Day 2.

This left a full day for breakout groups and whole group discussion.

The workshop started at 7.30 pm on the evening of September 21st with the first Plenary talk and ensuing discussion. It reconvened at 9am on September 22 and ran until 6pm that evening. On September 23, it started at 9 am and finished in the early pm to allow people to travel home that day. The meeting venue was the School of Geographical Sciences, University of Bristol. The group ate breakfast and dinner together each day.

Plenary Presentations

1. Dan Lunt (Bristol): Cryospheric Albedo in Climate Models.

2. Ghislain Picard (Grenoble): Process and Modelling challenges in representing snow grain size - albedo feedbacks in state of the art snow evolution models.
3. Jason Box (GEUS, Copenhagen): Albedo Feedbacks on the Greenland Ice Sheet and Arctic glaciers.
4. Eugenie Euskirchen (U. Alaska, Fairbanks): Albedo and Permafrost Feedbacks to Climate in High Latitude Terrestrial Ecosystems.
5. Marek Stibal (GEUS, Copenhagen): The Role of Biological Processes in Albedo Feedbacks Affecting the Terrestrial Cryosphere.
6. Carl Egede Bøggild (Danish Technical University, Copenhagen). Conceptual models and quantification of the “impurity”-albedo relation based on in situ observations.

Dan Lunt provided a brief introduction to the history of climate modeling, and an assessment of the ability of these models to replicate observations of several different climate parameters (air temperature, sea ice distribution, seasonal snow cover). He then outlined how the albedo of snow, land ice and sea ice was represented in a range of simple and more complex climate models, and presented the single scattering albedo values typically used for various forms of impurity that are found in snow and ice. He described how models such as SNICAR represent the effects of snow aging on albedo through evolution of an effective ice grain size that is driven by wet/dry snow metamorphism, refreezing of liquid water and addition of fresh snow. Snow darkening in models occurs because of snow aging as well as by darkening by deposition of dust and black carbon. He showed examples of how different GCMs represent albedo over Greenland, and of how albedo changes over glacial/interglacial cycles may be linked to time varying rates of dust deposition. CESM was identified as one of the more advanced climate models in terms of how it represents cryospheric albedo feedbacks, but Dan stressed that although representations of albedo significantly affect climate model results, there are considerable uncertainties about how they should be represented in climate models.

Ghislain Picard talked about the representation of processes affecting the albedo of snow in state-of-the-art snowpack evolution models. He emphasized the magnitudes of variations that typically occur in snow albedo, incident energy, air temperature variations and Greenland ice sheet mass balance on climatically-significant timescales. He presented 3 case studies that illustrate how well models agree with observations and what they indicate about where models need improvement. These include (i) grain-size effects on the brightness temperature of snow, and the fact that summer precipitation may inhibit the growth of snow grains that would be expected from consideration of temperature forcing alone. He also how explained how longwave emission from a snow surface will cool the surface relative to snow at depth so that surface grains may grow more slowly than those that are buried, with the result that the surface albedo does not decrease over time in response to grain growth driven by radiation forcing. The implication is that climatically induced changes in precipitation can modulate the albedo response of snow-covered surfaces to climate warming; (ii) Accumulation Area albedo in Greenland has increased with rising air temperature, even though the albedo over the ice sheet as a whole has decreased. For the ice sheet as a whole, albedo has decreased in spring, before the onset of melt. This seems to be linked to a change in snow impurity content starting in 2009, probably linked to increased dust advection from North America that is linked to a concurrent reduction in spring snow cover extent there; (iii) The presence of hoar crystals on a snow or ice surface can affect its albedo. Their formation and disappearance are linked to wind strength and direction, and the cycle of growth and decay lasts days to weeks. Hoar crystals can form by condensation or by sublimation (frost-flower like crystals). Their presence directly affects the albedo, but it can also affect the probability that precipitation will settle on the surface, affecting both albedo and surface mass balance. The implication is that hoar effects on albedo vary on relatively long timescales as atmospheric conditions governing their formation and destruction change, but also on short time scales as a result of within snowpack processes affecting surface grain size, radiation penetration depth, and the vertical temperature gradient in the snowpack. The complexity of the feedbacks involved is such that they can only be understood if fully quantified.

Based on these case studies, Ghislain reviewed the state of the art in snowpack evolution models, highlighting areas where they were deficient and in need of improvement (focusing on issues of snow metamorphism, snow settling and snowpack building, the depth-concentration profile of impurities in the snowpack and how it might change with time, and issues associated with radiative transfer modeling. He also provided an assessment of the magnitude of the challenges to be overcome in addressing each of these issues. The importance of the very top layer of the snowpack (and its spatial variability) in many key processes was highlighted, as were the limitations of point-based simulations that do now allow lateral transfers of mass to affect snowpack evolution. Another key requirement is knowledge of the vertical concentration profile of light-absorbing impurities in a snowpack and its dynamics, and the absorption spectra of the impurities. Knowledge is also needed of how these parameters might be affected by biological and chemical processes. Ghislain concluded that many improvements are required to state-of-the-art snow models if they are to do a better job of simulating albedo dynamics.

Jason Box talked mainly about ice-albedo feedbacks on the Greenland Ice Sheet, explaining the fundamental processes by which they reinforce the effects of climate warming/cooling on ice sheet mass balance. These involve changes in snow metamorphism, snowfall and snow cover and when, broader, hemispheric scale feedbacks are considered, the incidence of fire, dust deposition and rainfall. He highlighted major albedo reductions (and increases in net shortwave radiation) over Greenland between 2000 and 2012 (up to -21% in places), and linked them to a persistent anticyclonic atmospheric circulation anomaly in summer over Greenland during that period. Albedo minima typically occurred in 20120, 2012 and 2014. The bulk albedo feedback from 2000-2011 was as high as 36 W m^{-2}. The sign of the feedback was typically negative around the ice sheet margins and positive in the ice sheet interior, especially in the north. The feedback was largest near the ice sheet margin in western and northern Greenland – a pattern well replicated by the HIRHAM-5 climate regional model.

Jason presented evidence of transport to Greenland of particulate debris from tundra fires in northern North America, and showed depth-concentration profiles of black carbon and other light absorbing impurities in Greenland snow. He also showed how microbial colonisation of snow and ice surfaces could lower their albedo, as could the accumulation of particulates along surface meltwater drainage pathways. In conclusion, he argued that changes in snowfall, rainfall, snow cover, deposition of dust or biomass burning products, microbial colonization, and snow metamorphism could all contribute to feedbacks involving the albedo and temperature of the ice surface.

Carl Bøggild pointed out that melting of dust-rich ice around the margins of the Greenland Ice Sheet accounts for the existence of a distinctive low-albedo "dark zone". He also presented a model for the development of cryoconite-covered surfaces from such ice, arguing that albedo initially decreases as ice is exposed and dust melts out, but then increases again if dust is concentrated in the bottom of cryoconite holes that grow deeper over time. Once such a cryoconite-hole covered surface develops it takes a major melt event to empty the cryoconite holes. He also showed how the development of rough surface topography can produce substantial local heterogeneity in albedo – with the biggest variability occurring in the 400-900 nm part of the wavelength spectrum. For one location, he showed that the amount of dry mass per m^2 found in cryoconite holes increased with increasing distance from the ice sheet margin – largely as a result of the formation of deep cryoconite holes. However, the relationship between albedo and dry mass abundance is not linear because of the tendency for dust at some locations to accumulate in the base of deep cryoconite holes when it is abundant. At a local scale, there is large spatial variability in albedo, related to dust abundance and its pattern of distribution. The local variability in ice albedo is significant and can produce spatial variations in melt rates of similar magnitude to the temporal variations associated with a five degree Celsius change in air temperature (as calculated using a degree day approach).

Marek Stibal recognized two ways in which microbes can influence the albedo of snow and ice surfaces: (i) they can aggregate surface debris into cryoconite granules by bioflocculation and filamentous binding (which is aided by extra-cellular polymeric substances that they produce), and (ii) they can produce light-absorbing substances. However, whether aggregation increases or decreases the albedo is a matter of debate. By concentrating debris in a small fraction of the ice surface, it may increase the albedo. However, aggregation binds particles together and may increase their residence time on the surface, increasing the albedo. Which process dominates under what conditions has yet to be determined. Dark colored humic material is formed during the degradation of organic matter and is a detectable component of cryoconite. The aggregate cryoconite material is less reflective of light than pure mineral particles. Photosynthetic microbes, especially ice algae, produce protective pigments that can contribute to surface darkening. It is hypothesized then that surface melting stimulates microbial growth and that this has the effect of lowering albedo and further increasing melt. In situ measurements suggest a tendency for albedo to decline as the number of algal cells/mL of surface ice increases, although mineral material needs to be removed from the cryoconite to be sure that this is a reflection of organic matter properties.

Eugenie Euskirchen talked about albedo and permafrost feedbacks to climate. She noted that permafrost has been warming in Alaska for over 50 years, especially in the continuous permafrost zone. Ultimately this is expected to significantly reduce the permafrozen area. At the landscape scale, permafrost distribution is linked to landform characteristics, and the distribution of sediment and vegetation types. Two key feedbacks affecting permafrost stability involve the role of surface water in degrading permafrost and of vegetation and soil organic matter in protecting it by insulation. A complex array of biogeophysical feedbacks between snow cover, vegetation type and distribution, and total lake area controls surface albedo in permafrost landscapes. Changes in permafrost distribution are associated with an array of potential biogeochemical feedbacks involving the production or consumption of methane and carbon dioxide affects rates of release of greenhouse gases to the atmosphere, with potential implications for air temperature. Changes in fire regime, forest age structure, shrubification, and Reindeer grazing can all contribute to vegetation and albedo change. The key albedo-related issues associated with changes in fire regime are the effects on stand composition, the formation of taliks, the growing occurrence of tundra fires and the way in which soil type influences permafrost thaw and active layer depth. It seems likely that shrubification will reduce the summer albedo of tundra. In winter, shrub growth may influence the albedo through its effect on the extent and pattern of snow accumulation. Shrubs may also shade the ground, reducing active layer depth. Clearly the processes involved are complex, and there is no simple relation between albedo change and permafrost thaw, but ground warming generally changes the albedo and the heat flux to the atmosphere. In the vegetated landscapes where permafrost occurs, both biogeochemical and biophysical feedbacks play a role in mediating the relationship between albedo and climate.

Issues Arising from Breakout Groups and Open Discussion

(i) Albedo measurements

- What is the accuracy of typical albedo measurements? Is it high enough to detect significant changes? It has been argued that 0.01 accuracy is required – but can this be achieved with satellite measurements?
- The scale of an albedo measurement is linked to the accuracy and resolution attainable. How does this affect our estimates of climate/albedo sensitivity?
- Satellite albedo measurements are biased to clear sky conditions? What is the significance of this for our understanding of albedo-temperature feedbacks?
- How do we ground-truth satellite albedo measurements given the differences in measurement scales

(ii) Temporal Evolution of Albedo

- Does rain play a role in starting the melt season? Are there implications for how snow albedo evolves if this happens?
- How effective is rain in removing particulates from glacier ice surfaces?
- Which stage is most important for microbial impacts on albedo – the bloom or the death stage?

- Can we characterize albedo evolution on snow/ice surfaces that are sublimating rather than melting?
- What controls the albedo of glacier ice – can we understand that as well as we understand what controls snow albedo?
- What are the major challenges in predicting future albedo changes for different cryospheric surface types?

(iii) Impacts of Mineral Impurities and Black Carbon on Snow/Ice Albedo

- Do particulates and/or organisms within near-surface ice affect ice albedo? If so, to what depth do they do this?
- Why is there such a strong albedo-temperature feedback in the lower ablation zone on Greenland? Is it due to the release of legacy dust?
- What determines the transition between when a surface debris cover enhances melt and when it insulates the underlying ice? At what point does surface albedo cease to be a direct influence on ice ablation rates?
- How do we define Black Carbon (optically or on the basis of aromaticity)? Does it matter?
- How do we separate Black Carbon from mineral dust?
- How do we separate younger functional groups of carbon (like EPS) and determine which organisms are producing them?
- Is the albedo impact of extreme impurity deposition events greater than that of more distributed deposition?
- What are the deposition rates of dust and black carbon on Arctic land ice? How have they varied historically?

(iv) **Biological Impacts on Cryospheric Albedo**

- Is microbial colonization of glacier surfaces a recent phenomenon (perhaps linked to increasing rates of atmospheric deposition)?
- What determines which surfaces microbes will colonise? Is there a biological succession on ice?
- Are algal blooms on glacier surfaces unique to Greenland or do they occur everywhere?
- How much melt is needed to initiate an algal bloom on a glacier? Does topography influence where and when blooms occur?
- Are there seasonal refugia for ice algae? If so, where are they?
- Need to develop an understanding of the biogeography of the microbial consortia that exist on glacier /ice sheet surfaces
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- Do heterotrophic microbes have an influence on snow/ice albedo, or is it only phototrophic microbes that do so?
- What energy/nutrient sources do ice algae exploit? Are dust and black carbon important? If black carbon is important, does it matter whether it is old or recently produced? Is Fe an important nutrient source?
- How do microbial cells attach to mineral particles? Are they extracting nutrients or energy from them?

- Do microbial populations have growth thresholds?
- Can we measure microbial biomass/abundance on snow/ice surfaces and its spectral properties?
- Why don't we see cryoconite in maritime glacial environments?
- How does vegetation type determine the relationship between biomass and albedo in permafrost regions?

- **Need to use IPCC type language when describing the level of our understanding in this field**

Possible Themes for ICARP III

- What is the recent history of albedo changes on the Arctic landmass?
- What is the sensitivity of albedo to air and land surface temperature changes on different surface types? Does it depend upon the radiation regime (long-wave/short-wave balance)?
- What is the availability of ground-based albedo measurements in the Arctic? In what ways does it need to be improved?
- How do we best calibrate/validate satellite albedo measurements?
- How do we need to characterize snow packs in order to achieve more accurate modeling of how snow pack properties affect surface albedo?
- What would we need to do to develop models for the seasonal evolution of glacier ice and lake ice albedo that are comparable in performance to existing model of snow albedo?
- What are the roles of dust and black carbon in modifying the albedo of snow and glacier/lake ice?
- How do biological processes affect the albedos of snow, firn, glacier ice, lake ice and frozen ground/permafrost?
- How do organic and inorganic particulates, and living organisms affect the spectral albedo of snow and ice? Are there connections between particulate deposition rates and the magnitude of biological impacts on snow/ice albedo?
- How can we better represent albedo-related feedbacks involving different elements of the terrestrial cryosphere in climate models?