A brief summary of snow albedo

Samip Karki

Introduction

Snow is an important aspect of the climate. Many different metrics show that the amount of snow and ice on Earth has been decreasing significantly in the past fifty years due to natural and human processes. For example, the extent of Northern Hemisphere June snow cover has decreased 11.7% per decade over the 1967 to 2012 period (*IPCC* 2013). One important role snow plays in climate is as a reflector of solar radiation. Snow has a very high albedo, which is the percentage of incoming light which gets reflected by a surface. In contrast, ice, melt water, and soil have lower albedos and absorb more light than they reflect. Because snow reflects most incoming light, it acts like a shield to resist surface warming due to sunlight being absorbed by the Earth. However, snow's albedo is not constant and can get reduced by many different factors. The two main factors which influence the reduction of snow albedo are snow grain size and impurity content. Although scientists understand how these two factors reduce snow albedo, predicting how they will affect albedo in the future remains difficult.

Snow Grain Size

Snow grain size is one of the most important factors which influence snow albedo. Increased grain size will decrease albedo particularly in the near infrared to infrared spectrum of light [*Tedesco et al.* 2015]. As grain size grows, scattering within the snowpack will decrease and the amount of time which light spends inside the snow grains lengthens increasing the probability of absorption [*Adolph et al.* 2017]. Evidence shows that snow grain size is a primary factor of snow albedo reduction. *Adolph et al*. [2017] found that snow in New England with large grains had about 25-35% lower near-infrared albedo

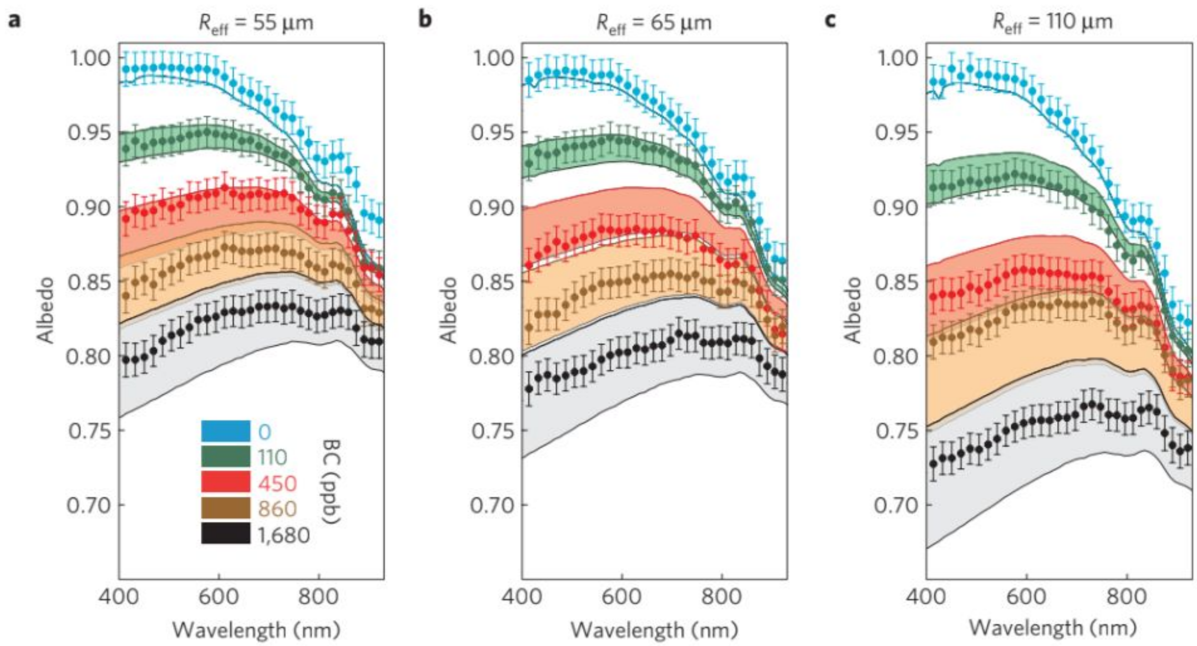

Figure 1. Taken from *Hadley and Kirchstetter* [2012]. Snow albedo of laboratory snow at different wavelengths is shown with effective grain radius of **a)** 55um, **b)** 65um, and **c)** 110 um. Different colors represent various amounts of black carbon (BC) concentration. The colored bands represent SNICAR modeled data while the colored dots represent experimental data. Main takeaways from this figure are that albedo in the near infrared spectrum (+700 nm) decrease mainly due to increased effective radius (grain size) and albedo in the visible spectrum (400-700 nm) decrease mainly due to increased BC concentration.

than small-grained snow. *Aoki et al.* [2007] and *Kay et al.* [2003] found similar results in Sapporo, Japan and Mt. Rainier Washington respectively. Additionally, various models are consistent in reporting the relationship between grain size and albedo [*Hadley et al.* 2012 (Figure 1.); *Aoki et al.* 2007; *Adolph et al.* 2017; *Kaempfer et al.* 2007 and *Kay et al.* 2003]. The consistency of the models and empirical data shows that scientists understand the general relationship between grain size and albedo.

Although the relationship between snow albedo and grain size is clear, grain size evolution is still difficult to predict because there are multiple parameters which affect the rate of grain size growth. Snow grain size growth is caused by the breakdown and reassembly of smaller snow grains into larger grains.

According to a model by *Flanner and Zender* [2006], four variables that increase the rate of snow grain growth are greater initial variability of grain size, greater temperature, greater temperature gradient, and lower snow density. However, these relationships were found in a laboratory setting where all other factors are held constant. Actual on site snow grain size is harder to predict for a few reasons. One reason is because of a grain size feedback process. When temperatures become closer to melting, snow grain size increases which lowers the albedo of the snow leading to further surface warming and grain size increase [*Hadley and Kirchstetter* 2012]. Because of feedback processes like this, it is hard to predict snow albedo especially during spring months where snow starts to melt. Another reason why snow grain size is hard to predict is because of the variability of snow fall. Snow grain size tends to be smaller at the top because fresh snow has a smaller grain size, so when snow falls, the albedo of the snow pack will be higher due to the fresh snow on the surface of the pack [*Aoki et al.* 2007]. Because snowfall varies from year to year and because the rate of the grain size feedback process is not yet quantified, these can be sources of uncertainty when predicting snow albedo.

Impurity Content

Another primary factor which influences snow albedo is snow impurity content. Because of snow's generally very high albedo, a few impurity particles within a snow pack can decrease the overall albedo by a significant amount. Unlike snow grain size which mostly affects the infrared spectrum of light, impurities in the snow reduce albedo in the visible spectrum [*Tedesco et al.* 2015]. The impurity which scientists are most interested in is black carbon (BC), found in microscopic particles of soot produced by burning fossil fuels and biomass. Small amounts of BC on the order of 10-100 parts per billion by mass can reduce albedo by 1-5%. However, some areas of the world have significantly higher impurity content. For example, *Aoki et al.* [2007] found typical winter BC concentration to be about 3000 parts per billion in Sapporo, Japan. To put this into perspective, *Hadley and Kirchstetter* [2012] found in their laboratory experiment that only 1680 parts per billion by mass of black carbon can reduce visible albedo by 20-30% (Figure 1.). So, in some places, the impurity content of the snow can considerably reduce snow albedo.

Just like snow grain size, snow impurity has many secondary factors which makes predicting its contribution to albedo difficult. Many scientists studying snow albedo will simplify snow impurities by assuming there are only black carbon impurities in the snow. However, because other snow impurities, such as soil dust or organic carbon, have different absorption spectra than black carbon, it is important to distinguish between black carbon and non-black carbon impurities (*Grenfell et al.* 2011). For example, *Doherty et al.* [2014] found that most of the snow impurity in the U.S. Great Plains was due to soil while snow impurity in Pacific Northwest mainly due to black carbon. This shows that snow impurity can vary greatly based on geographical considerations such as presence of large cities or farms. Additionally, impurities can be deposited into snow from snow storms. *Adolph et al.* [2007] found that snow in New England had higher impurities based on the trajectories of the storms. Storms which passed through large cities tend to deposit greater amounts of impurities on the snow possibly because the storms pick up impurities from the less clean air of cities. Another factor which makes predicting albedo difficult is a feedback process due to impurities [Tedesco et al. 2015]. As snow melts, the impurities in the melted layer of snow consolidate with the snow layer beneath it, effectively making a higher concentration of impurities in the top layer which lowers the albedo of the snow pack and leads to further melting. To support this idea, *Aoki et al.* [2007] found that during the melting season in Sapporo, Japan, impurity concentrations in the top layer of the snow rose considerably, sometimes up to 100,000 parts per billion by mass. All of these considerations make impurities content of snow a difficult parameter to predict.

Conclusion

Moving forward, scientists should continue studying albedo of snow from different places around the world and isolate the albedo reduction caused by grain size or impurity content. Snow in different places differ in how much grain size or impurity content influence albedo. For example, *Adolph et al.* [2017] discovered that the variability of snow albedo in New England was dominated by grains size but impurity content was negligible. In contrast, *Aoki et al.* [2007] found that both snow impurities and grain growth were significant in the reduction of albedo in Sapporo, Japan. Scientists should also look for other parameters which may influence albedo and include these into their models. For example, recent studies have shown that the close packing of snow grains [*He et al.* 2017] and the macroscopic roughness of snow [*Larue et al.* 2020] also noticeably reduce snow albedo. Other ways which scientists have been making meaningful progress advancing snow albedo science are by developing a ray tracing model which tracks a ray of light's trajectory through a simulated snow pack [*Kaempfer et al.* 2007] and by making a more sophisticated analytical model to predict snow albedo [*Kokhanovsky et al*. 2018] Better understanding snow albedo is an important aspect of understanding how global climate will change in the future.

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