INTERPRETING CHANGES IN ALBEDO AND MASS BALANCE AT WHITE GLACIER, CANADIAN ARCTIC ARCHIPELAGO

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Commission III, WG III/9

KEY WORDS: White Glacier, Albedo, MODIS, Mass Balance, Land Surface Temperature

ABSTRACT:

Alpine glaciers are sensitive to changes in land surface temperature (LST), and measurements of the mass balance are limited, especially for small glaciers. In this study, we investigate the relationship between snow albedo of the melting season (June, July, and August) and annual glacier mass balance of the White Glacier from 2002 to 2018. Since there are many gaps in the albedo data, we use a interpolation method to fill them and then obtain the average value of the melting season. The study results show that surface temperature plays a dominant role in albedo and mass balance changes, and mass balance change and albedo variation show a significant consistency, with an excellent correlation ($R^2 > 0.93$). The acceleration of mass balance shows that the rate of mass reduction slows down, and the albedo change shows that the albedo increases from year to year. The interpolation albedo measurements using MODIS data can provide a useful means to reflect the annual change of glacier mass balance.

1. INTRODUCTION

Melting of glaciers and ice sheets is one of main contributors of the global mean sea level rise (IPCC, 2021). The Canadian Arctic Archipelago (CAA) contains the greatest area of global land ice outside the Antarctica and Greenland ice sheets. According to Randolph Glacier Inventory (RGI) version 6.0 dataset (RGI Consortium 2017), the CAA region has approximately covered 146000 Km^2 glaciated areas, which is covered with a large number of small glaciers. Glacier is an excellent indicator for climate fluctuate. Between 1948 and 2016, the mean temperature increase in Canada is twice than increasing in global average temperature (Zhang et al. 2019). The frontal line of the marine-terminating glacier has a clear retreating trend with increasing temperature in CAA (Cook et al. 2019). The temperature increase accelerates the process of glacier melting. Prolonged glacial melting with the effect of rising temperatures, the mass loss in CAA is accelerated since 2005 (Gardner et al. 2011; Zemp et al. 2019). From Gravity Recovery and Climate Experiment (GRACE) gravimetry, the rate of CAA glaciers mass loss is -60 Gt/yr from 01/2003-05/2013 (Harig and Simons, 2016). However, this method does not work for small glaciers owing to the coarse resolution. Since 1960, there has had actively monitored for glacier mass balance in the CAA based on glaciological method. The glaciological method involves interpolation between in situ measurements of accumulation and ablation at stakes drilled into the glacier surface. In situ measurements of accretion and ablation are interpolated to obtain glacier surface mass balance. These stakes are typically located along the glacier centerline, and interpolation across the glacier basin is undertaken either by assuming that mass balance changes only with elevation or by mapping accumulation and ablation patterns (Østrem and Brugman 1991). Due to the limitations of the monitoring conditions, less than 0.25% of the 250 000 glaciers inventoried in the RGI V.5 are currently monitored with in situ measurements (Davaze et al. 2018). In north CAA, there has five long period glacier mass balance observing net (Thomson et al. 2017), White Glacier is one of them.

There is a significant negative correlation between glacier surface temperature and albedo in the CAA region (Mortimer and Sharp. 2018), and mass loss from White Glacier increases with increasing temperature. The part of the incident shortwave radiation that is reflected is called the albedo and the part that is absorbed is called the net shortwave radiation. Net shortwave radiation is the main source of energy for surface warming. For glaciers, changes in albedo reflect changes in glacier energy uptake. Due to differences in the physical properties of snow and ice, there is a high potential for using optical remote sensing data to monitor regional variation of mass balance.

Generally, there have two albedo aggregation methods to get a single value of satellite measured albedo for entire glacier: melting season minimum and melting season average, which are then correlated to glacier annual mass balance. Using the glacier minimum average albedo from Moderate Resolution Image Spectroradiometer (MODIS) data, a strong linear correlation between glacier mass balance and minimum albedo has been found for glacier, such as: Saint Sorlin Glacier in Western Alps of France (Dumont et al. 2012), French Alps (Davaze et al.2018), New Zealand (Siguey et al. 2016), CAA (Williamson et al. 2020) and the Tibetan Plateau (Zhang et al.2018). The first to investigate the relationship between the average of the minimum values of regional albedo during the melting period and the interannual mass balance is Dumont et al. (2012), they used only the albedo values under clear sky conditions. Minimum glacier-wide albedo is reliable predictor for annual mass balance in New Zealand maritime environment(R^2=0.93) (Siguey et al. 2016). The most comprehensive analysis of entire glacier albedo correlation to mass balance was implemented for 30 alpine glaciers in the French Alps that have annual glacier-wide surface mass balance records, of which 6 also have summer mass balance (Davaze et al.2018). The average melt season albedo correlated better with summer mass balance than did the minimum with glacier annual mass balance, suggesting that the minimum method might not be the optimal solution for glacier mass balance estimation. Cloud shading might affect the true minimum

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albedo value, which could be hidden within a cloud cover gap in the seasonal albedo curve. The average albedo after interpolation can better reflect the changes in glacier mass balance (Williamson et al. 2020)

In this study, we produce an interpolated albedo dataset based on MOD10A1 version 6 snow albedo. The interpolation data are better to depict variation of glacier surface. Then, we get the mean albedo of annual summer, using summer daily albedo. Furthermore, we calculate the correlations between glacier wide average albedo and mass balance estimates during 2002-2018. The results show that White Glacier has a huge amount of material loss, and the rate of loss tends to decrease, accordingly, the albedo shows an increasing trend. The increase in albedo of the glacier has a suppressive effect on the mass wastage.

2. STUDY SITE AND DATA

2.1 White Glacier

White Glacier locates at 79.50º N and 90.84º W, on the Axel Heiberg Island in the CAA (Figure 1), is the focus of numerous glaciological studies since 1960s. White Glacier extends from 1782 m a.s.l. to 85 m a.s.l. and has a 14 km long polythermal valley adjacent to Thompson Glacier. Long-term mass loss has led to a reduction in the area of the White Glacier from 41.07 km^2 (1960) to 38.4 km^2 (2018). The average value of annual precipitation is approximately 100 mm from 2002 to 2018, calculation using ERA5-Land data. Due to the low precipitation of White Glacier, the surface mass balance trend is dominated by summer melt (Thomson and Copland, 2017).

During the term of 2002-2018, the mean mass wastage of White Glacier is -0.37 m $\mathrm{w.e.a^{-1}}$.The narrow outflow channel is the main ablation zone of the glacier. Due to the continuous mass loss, the equilibrium line is in a constant upward movement, the mean equilibrium line altitude (ELA) is 1270 ± 190 m from 2005 to 2015 (Thomson et al. 2016). The current position is more upward compared to the average ELA of 1960-1991, Cogley et al. (1996) reported the average ELA is 970 m.

2.2 MODIS Terra Snow Albedo data (MOD10A1 Version 6)

MODIS sensor aboard on the Terra (2000 to present) is used to observe the spatial and temporal change of the earth, which has 36 spectral bands (0.459-14.385 μm). MOD10A1 is a snow cover daily global dataset with 500 m grid cells, that contains snow cover, snow albedo, fractional snow cover, and quality assessment data (Kelin and Stroeve, 2002). Data are gridded using the MODIS Sinusoidal Tile Grid, and we download for the corresponding grids of White Glacier from National Snow Ice Data Center (https://nsidc.org/data/MOD10A1/versions/6). MOD10A1 snow albedo data is coded as unsigned 8-bit, snow albedo values are recorded as 0-100 (Hall and Riggs, 2016). The accuracy of MOD10A1 Version 6 albedo on the Greenland Ice Sheet was found that there overestimate by up to 0.1 comparing to meteorological station observing bare ice albedo (Ryan et al. 2017).

The quality assessment data based on the input data and solar zenith data, it marked as best, good, ok and others. When the solar zenith angle (SZA) of pixel is in the range of 70º to 85º, the quality assessment value is set to okay to indicate the increased uncertainty stemming from low illumination (Hall and Riggs, 2016). With GEE, we calculated the glacier-wide occurrence rate (<15%) of the data quality flag OK during summer, and find that concentrated in the last ten days of August. Considering that the

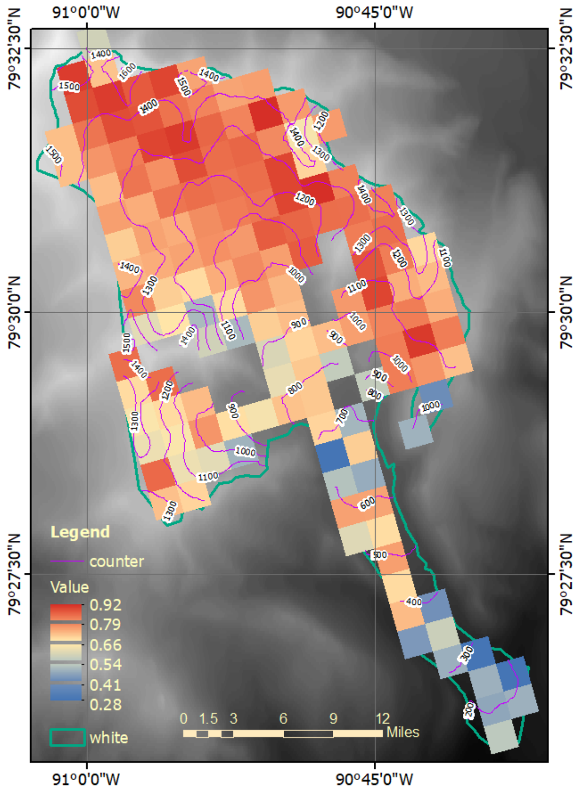

Figure 1. Interpolation average summer albedo data in 2018.The purple line is counter of White Glacier, and bold green line is boundary of this glacier. The hollow in the middle is the location of the rock.

bidirectional reflectance distribution functions for MODIS albedo products of the full inversion and the poorer quality magnitude inversion are similar (Schaaf et al. 2011), we did not use the quality flags related to SZA to filter albedo data.

Large gaps exist in snow albedo data due to cloud obstructions. In order to better understand the variability of the surface, spatial temporal continuous data products are particularly important. Interpolation of existing data is an effective means. Box et al. (2017) proposed a mean to fill gaps in MOD10A1 albedo images, the method includes a smoothing and a gap filling effect on the albedo time series. They use 11 days as a processing period and assign the processing results to the intermediate dates. Tian et al. (2019) enhanced this method by adding a procedure of cubic spline interpolation and their accuracy verification in Greenland Ice Sheet was with RMSE<0.05. We adopt the same method to obtain continuous albedo products.

In order to produce interpolation data, daily albedo data were extracted from the hierarchical data format files and reprojected from the standard MODIS equal-area sinusoidal projection to a Mercator projection, WGS84 datum, using the MODIS reprojection tool version 4.1 (https://lpdaac.usgs.gov/tools/modis_reprojection_tool).

2.3 Glacier Mass Balance

Mass balance describes the mass change of a region, including both the accumulation and loss. For some glaciers, field monitoring of mass balance has been implemented since the 1960s (Østrem and Brugman, 1991). Annual net mass balance observations obtained by glaciological method for White Glacier are conducted each spring (April and May) from 1960 to 2019 and involve the measurement of snow accumulation and melt along stake networks installed along the centerline. Random errors in the glaciological method are related to both in situ measurements and spatial interpolation across the glacier zone, and have been approximately to ± 200 mm w.e.a^{-1} for a single year measurement (Cogley and Adams, 1998). Glacier mass balance data can be download from World Glacier Monitoring Service Fluctuations of Glaciers Database (https://wgms.ch/). In this study, we get glaciological mass balance data from the database.

2.4 MODIS LST (MOD11A1 Version 6)

We use the Daily L3 Global Land Surface Temperature and Emissivity product (MOD11A1) at 1km spatial resolution, the standard deviation of the day-time LST validation errors is less than 0.5K (Wan 2013). MOD11A1 daily LST is computed from Terra MODIS channels 31 (11µm) and 32 (12µm) using the generalized split-window LST algorithm (Wan and Dozier, 1996) under clear sky conditions. The data accuracy of ice and snow surface temperatures can be as low as ±2 ℃ (Hall et al. 2008). The variation in the number of clear sky days within each observation period and from one year to another did not bring significant variability in the remote sensing LST data relative to the true near-surface air temperature in north CAA (Mortimer et al. 2016).

Considering the significant effect of summer snowfall/rainfall on albedo, we investigated the relative changes between the variation of summer snowfall and albedo. After excluding the effect of precipitation, the changes in mass balance and albedo were analyzed.

3. METHODS AND RESULT

In this section, we depict the procedure of mean albedo and result of data processing.

3.1 Mean Snow Albedo Data and LST

The calculation of the average summer snow albedo from 2002 to 2018 involves 1562 images in total. In order to reduce the time-consuming data download work, we use Google Earth Engine (GEE) to do the data computation work. GEE is an online data processing platform with sliced database of various remote sensing data, and MODIS products can be called online through it. When calling data, filter the data by value to avoid input of abnormal values (e.g. 0,100). Using directly average method (Williamson et al.2020) to calculate the average albedo of MOD10A1, during the melt season (June, July, August). The summer data are first averaged, and then a cropping tool is used to obtain the albedo data within White Glacier. The shapefile of the glacier has been uploaded to the cloud, and the file is called directly when cropping. The average images of LST are processed as above. and the value of mean LST are obtained directly by GEE.

3.2 Mean albedo of interpolation data

In consideration of time continuity and the requirements of the algorithm, we use the data from May to September each year to do the interpolation. After processing of interpolation data, we extract the daily June, July, August albedo data. Then, calculate the average albedo in IDL, clip the image in ArcGIS, and obtain the regional mean values.

Considering that White Glacier has a long valley, there is an influence of topography on the satellite observations. Moreover, there is a large number of mass wastage taking place in low elevation valley. Besides, the observed ELA based on mass balance record has risen by an average rate of +9 m a^{-1} over the past 30 years (1995-2015; Thomson and Copland, 2017). To investigate whether the albedo of the melting zone can represent the annual mass balance, we used the 1100 meters contour as the upper boundary of the melting zone to extract the average albedo data.

The MOD10A1, interpolation data during melt seasons albedo values were regressed against glacier mass balance using standard least squares linear regression during the period of 2002-2018.

3.3 Result

In this section, the results of data analysis are presented. First, the average value and long-term trend of each data are obtained. The White Glacier mean interpolation albedo during the melting period, averaged across all 17 years, is 0.62 ± 0.06. The mean value of annual glacier mass balance is -0.37 $\mathrm{m\,w.e.\,a^{-1}}$.

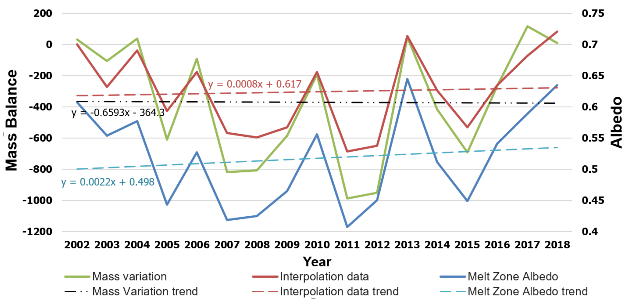

Figure 2. The annual mass balance (left axis; $\mathrm{mm\,w.e.\,a^{-1}}$) and mean albedo (right axis), Melting zone represent the average albedo values of narrow valley. Mass variation is the fluctuate of mass balance in White Glacier.

The mass balance estimates, since 2005, are always lower than 0 except three years (2013, 2017, 2018) (Figure 2). Long-term changes in mass balance show a slight decreasing trend. Interpolated mean albedo data variation has an increasing trend with a variation interval between 0.5 and 0.7 (Figure 2). The melting zone has a more pronounced upward trend compared to the overall regional variation. The average summer albedo and annual mass balance curves have similar variations. Considering the influence of surface temperature on albedo and mass loss in summer, a brief comparison between those curves is made.

The result of regression shows that interpolation data reflects mass balance variation well (Figure 4). In the following section, we only use interpolation albedo data to analysis relationships between melt periodical albedo and annual mass balance.

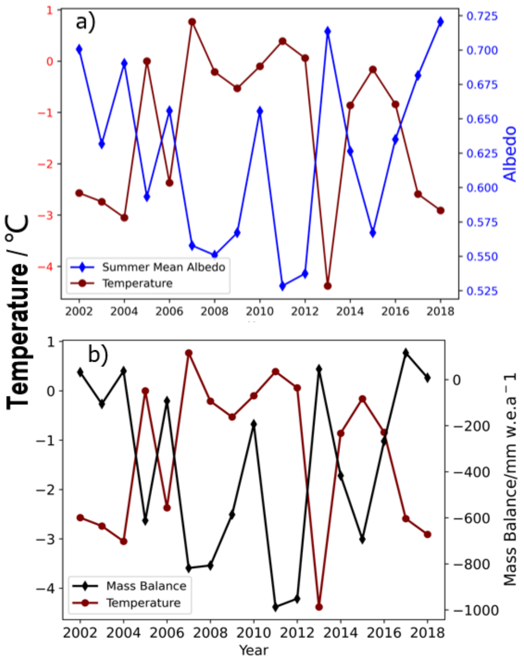

Figure 3. The whole glacier mean temperature (left axis), net annual galacier surface mass balance (right axis of (b)), and the interpolated average albedo (right axis of (a)) for White Glacier for the period 2002 to 2018.

Due to the effect of temperature on both albedo and mass balance, we get the long-term variation curves of those factors (Figure 3). The mass balance was in a state of loss despite the fact that the average summer temperature of the glacier was below 0 Celsius most of the time (Figure.3b). In the years with drastic temperature changes, the albedo and mass balance also showed drastic fluctuations. In years when the average summer temperature decreases, albedo values appear to increase to varying degrees, substance loss is diminished, and even years of substance increase occur. However, the effect of temperature on albedo and mass balance is not as strong as the association between albedo and mass balance.

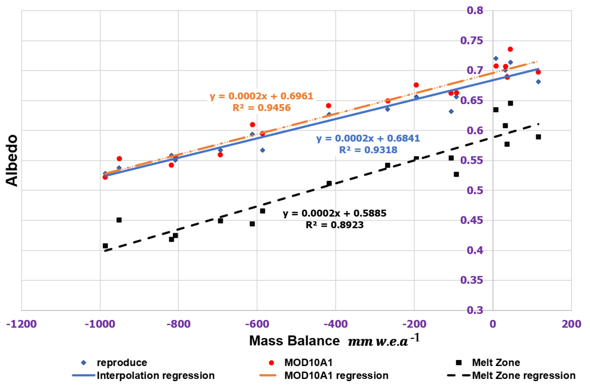

Figure 4. Least squares regression results of several average albedo data against mass balance. The colors of the regression lines correspond to the respective equations. The orange solid circles represent MOD10A1 average albedo of White Glacier. The blue diamond-shaped blocks are data of average interpolation albedo. The black rectangular blocks indicate average albedo data extract from ablation zone of White Glacier.

The regression results for the interpolated albedo and glacier mass balance data are displayed in Figure 4, with a statistically significant correlation between the two variables. The regression results show that the melting zone and the whole region have the same variation factor ‘0.0002’ (y = 0.0002x+b) against mass balance.

For a deeper analysis of the relationship, the inter-annual differences are calculated using the 2002 data as a starting point, and the results for each year are shown in Figure 5. The acceleration of the three data changes can be seen as positive acceleration. The negative acceleration of the material change indicates that the mass loss is weakening. The purple line corresponds to the acceleration of the albedo change in the melting zone, which is particularly increasing compared to the mean albedo of the whole glacier.

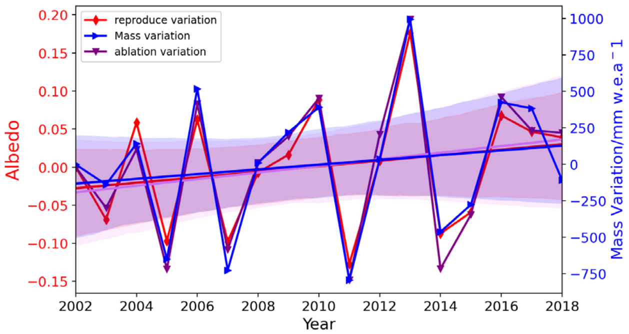

Figure 5. There are difference between glacier mass balance and albedo year-to-year. The red curve is fluctuate of interpolated average albedo, the corresponding straight line is regression line for varation of glacier-wide mean albedo. Using blue curve to depict the variation of interannual mass balance, the blue regression line show tendency of mass loss decrease. The purple line show albedo changing of ablation zone. Light shadow represent a 95% confidence interval, which corresponds with the standard error of the estimate.

In White Glacier, the relationship between albedo and glacier mass balance is clear, although temperature affects the changes in albedo and mass balance to varying degrees. Trends in mass balance can be analyzed using interpolated albedo data without considering the effect of temperature.

4. CONCLUSION

In this study, we confirm that surface temperature can influence the summer albedo and glacier mass balance. For the Canadian Arctic Archipelago region, snowfall in summer was low and did not reflect a statistically significant degree of correlation in its effect on average albedo. The decrease in temperature caused an increase in albedo and a decrease in glacier mass loss, which was more pronounced in years with a sharp drop in temperature. Without considering the effects of other factors, the following relationship between albedo and mass loss in White Glacier exists, where mass loss decreases and the glacier mass balance tends to be positive under a gradual increase in albedo.

ACKNOWLEDGEMENTS

This research was supported by the National Key Research and Development Program of China (2017YFA0603103) and the National Science Foundation of China (41730102).

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