A New Iterative, Geometric-Based, Tilt Correction Method for Radiation Observed by Automatic Weather Stations on Snow-Covered Surfaces: An Application in Greenland

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Abstract. Surface melt and mass loss of Greenland Ice Sheet may play crucial roles in global climate change due to their positive feedbacks and large fresh water storage. With few other regular meteorological observations available in this extreme environment, measurements from Automatic Weather Stations (AWS) are the primary data source to study the surface energy budget, and to serve as ground truth for satellite observations and model simulations. However, there are considerable biases in the radiation measurements by AWS. The largest source is station tilt, caused by surface melt and compaction. In this study, we identify the tilt-induced biases in the climatology of surface radiative flux and albedo, and then correct them based on geometrical principles. Over all the AWS from the Greenland Climate Network (GC-Net), the Kangerlussuaq transect (K-transect) and the Programme for Monitoring of the Greenland Ice Sheet (PROMICE), only ∼15% of clear days have the correct solar noon time, with the largest bias to be 3 hours. Hourly biases in the magnitude of surface insolation can reach up to 200 W m⁻², with daily average biases exceeding 100 W m⁻². The biases are larger in the accumulation zone due to the systematic tilt, although the variability of tilt angles are larger in the ablation zone. Averaged over the whole Greenland Ice Sheet in the melting season, the insolation bias is ∼23 W m⁻², enough to melt 0.51 m snow water equivalent, or to elevate sea-level by 3.1 mm per year. Using measured tilt angles and directions, the corrected data by PROMICE have a ∼20 W m⁻² smaller Root-Mean-Square-Error (RMSE) than the uncorrected data (RMSE against both the Clouds and the Earth’s Radiant Energy System, CERES and the Modern-Era Retrospective Analysis for Research and Applications, MERRA). For stations with no inclinometers, we estimate the tilt angles and their directions by comparing the simulated insolation at a horizontal surface with the observed insolation by these tilted AWS under clear-sky conditions. Our correction reduces the RMSE by ∼30 W m⁻² relative to the uncorrected data, with correlation coefficients over 0.95 for both reference. The corrected diurnal changes of albedo are more smooth, with consistent semi-smiling patterns. The seasonal cycles and annual variabilities of albedo are in a better agreement with previous studies.
1 Introduction

Greenland has experienced a dramatic mass loss and frequent massive melt events in the past 30 years (Nghiem et al., 2012; Tedesco et al., 2013; Velicogna and Wahr, 2013), exerting influences on global climate changes in both energy balance and hydrological cycles (Rignot et al., 2011; Box et al., 2012). Reliable measurements of surface radiative flux are essential (van den Broeke et al., 2004; van Angelen et al., 2012), since the absorbed solar radiation is the largest energy source for surface melt (van den Broeke et al., 2011).

In the highly cloudy arctic area (Vavrus et al., 2008), studies of surface energy budget and mass loss rely on the in-situ Automatic Weather Stations (AWS) measurements of surface radiative flux, since satellites cannot see through thick clouds, and have a large uncertainty at high solar zenith angles and over bright surfaces. The AWS measurements are not only used to determine the surface albedo and energy budget, but also to calibrate and validate satellite observations as well as numeric simulations. Stroeve et al. (2013) evaluated cloud-free albedo retrievals from the MODerate resolution Imaging Spectroradiometer (MODIS) Terra and Aqua combined 16-day albedo product (MCD43) against in-situ measurements by AWS in Greenland. They found a negative trend in albedo during summer from 2000–2012, with a large negative anomaly in July 2012 (0.060 lower than the average of July 2000–2009: 0.627). Wang and Zender (2010) adjusted MODIS MCD43 albedo retrievals over snow covered regions in Greenland to remove the low bias at large solar zenith angles, based on snow optical properties and AWS radiation measurements. The resulting adjustments in absorbed solar radiation are as large as 8.0% and 10.8% for the black-sky and white-sky albedo, respectively. Nevertheless, only AWS observe the all-sky albedo. (van den Broeke et al., 2011) calculated the surface energy balance (SEB) and melt rate in the ablation zone of west Greenland using a SEB model driven by hourly AWS measurements. They found that the seasonal cycle and interannual variability of melt are mainly controlled by absorption of shortwave radiation (SW), except in the lower ablation zone where the turbulent fluxes of sensible and latent heat dominate. The AWS measurements are also used to estimate cloud radiative effects on surface albedo (Kuipers Munneke et al., 2011), and to validate regional model simulations (Pettweis 2007; van As, 2011; Box et al., 2012; Van As et al., 2014).

However, these radiative fluxes measured by unattended stations contain considerable biases (Stroeve et al., 2001; van den Broeke et al., 2004), which may imperil the results of the previous studies. In the assessment of AWS in Antarctica, van den Broeke et al. (2004) summarized the typical problems of SW measurements, including icing and riming of the sensor dome, low sensor sensitivity at large solar zenith angles, and sensor tilt. Other possible problems include the shadowing of the station tower or nearby high structures, and random micro-scale environmental noise (Stroeve et al., 2005). The ice coating of the sensor dome can shield part of the incoming solar radiation, causing an underestimate of net SW. Shadows on the sensor can also lead to an underestimate. On the other hand, riming on the sensor dome can increase the incoming solar radiation due to the enhanced multi-scattering
of the solar radiation, causing an overestimate of net SW. However, icing and riming are not major
problems due to the small thermal mass of the plastic pyranometers (Stroeve et al., 2001). Moreover,
the unlikely high/low values induced by the icing, riming and shadowing can be removed by detect-
ing the sudden change of albedo since the down-looking sensors are generally less sensitive to these
problems. The low sensitivity of pyranometers at large solar zenith angles is intrinsic and can cause
an underestimate in net SW in excess of 5% for solar zenith angles larger than 75° (Stroeve et al.
2001).

Yet, the primary source of the bias in the SW is the instrument leveling (i.e., sensor tilt). Different
snow compaction around the station tower and cable anchors can cause the station towers to drift
over time. The tilted sensors will result in either underestimates or overestimates of radiation mea-
surements, depending on the combination of the tilt angle and tilt direction. The SW is quite sensitive
to these tilt angles. Theoretically, a tilt angle of 1° towards 40°N will induce a ~ 20 W m\(^{-2}\) bias in
net SW (van den Broeke et al., 2004). At South Dome, we found a daily average bias of 57.15 W m\(^{-2}\)
for all-sky conditions and 85.81 W m\(^{-2}\) for clear-sky conditions, with an hourly maximum exceeding
200 W m\(^{-2}\) in surface insolation through melting seasons from 2008 to 2013. Furthermore, the
diurnal phase of radiation will be shifted, suggesting that no sub-daily variabilities can be accurately
obtained without correcting the tilt problem. Both van den Broeke et al. (2004) and Stroeve et al.
(2013) use a 24-hour running average as a workaround. This workaround definitely provides a much
more stable insolation and thus stable albedo. However, it does not necessarily mean the results are
closer to the true values. The PROMICE AWS are equipped with inclinometers, measuring the tilt
angle. The tilt direction is obtained every 1-2 years by re-visiting the station. Insolation observed
by tilted AWS can then be corrected using this information van As (2011). However, in practice,
tilt direction can change dramatically within one month. This sampling frequency may not be suf-
ficient enough to have an accurate tilt correction. Nevertheless, the tilt problem remains at half of
the AWS in Greenland with no inclinometers at all. Our new method depends on no instrumental
requirements. We deduce the tilt angle and direction based on the geometrical relationship between
the observed surface insolation and simulations by a Column Radiation Model (CRM) on clear days,
and then correct data using estimated tilt angle and direction on the neighboring days in a month.

With regards to the bias of longwave radiation, the most important source is the window heating
offset (van den Broeke et al., 2004), which is when the silicon window is warmer than the sensor
housing, caused by an excess of solar radiation absorption. Although this problem cannot be removed
without knowing the window temperature, the overall effect on net longwave radiation is less than
5 W m\(^{-2}\) (van den Broeke et al., 2004), which is quite small relative to the shortwave bias.

Section 2 and 3 describe the datasets we use as well as how we estimate the tilt angles and perform
the correction. In Section 4 we present the tilt angle variabilities throughout stations and explore
the dominating factors for station tilt. In Section 5 we evaluate our corrected insolation against the
Clouds and the Earth’s Radiant Energy System (CERES) and the Modern-Era Retrospective Analysis
for Research and Applications (MERRA) data at all stations, and against data at PROMICE stations, which was corrected by the measured tilt angles. To what degree station tilt affects the diurnal phase and magnitude of SW are also revealed in this section. In Section 6, we show the observed diurnal variability of albedo over Greenland for the first time, and show monthly and annual climatology using the corrected SW. Section 7 discusses the possible limitations of our method, followed by conclusions.

2 Data

AWS used in this study are currently maintained by Greenland Climate Network (GC-Net), the Institute for Marine and Atmospheric Research Utrecht (IMAU) at the Kangerlussuaq transect (K-transect), and the Programme for Monitoring of the Greenland Ice Sheet (PROMICE). The first station from GC-Net was set up in 1995. By 2014, there were a total of 17 long-term AWS from GC-Net, spreading in both ablation and accumulation zones on the ice sheet (Steffen et al., 1996). IMAU began to operate their three AWS at the Kangerlussuaq transect since 2003, with one more station added in 2010 (van den Broeke et al., 2011). Since 2007, twenty-two AWS were set up by PROMICE successively, arranged in pairs with one station in the upper ablation zone near the equilibrium line and the other at a lower elevation well into the ablation zone (van As and Fausto, 2011).

In this study, we corrected the sensor tilt problem in surface SW data observed by AWS from all these three aforementioned datasets during melting seasons (i.e., May–Aug) from 2008 to 2013, when data at most of the stations are available. In addition to the stations with almost all missing data, s05, s06 and s09 from K-transect, and KPC_L from PROMICE are not corrected either, since the diurnal maximum of shortwave upwelling radiation (i.e., radiation reflected by surface) at these stations are at least one hour off from the solar noon. Usually, the reflected radiation is mostly isotropic. As a result, the effect of sensor tilt on the shortwave upwelling radiation is mainly on the magnitude rather than the diurnal phase. An offset of this amount in the diurnal phase of shortwave upwelling radiation could be caused by highly irregular topography, which cannot be corrected by our tilt correction method. All the stations used here are shown on the map with their average tilt angles (see Fig. 1). PROMICE also provides corrected SW by measured tilt angles and directions at their stations, which can be used as a validation for our method.

3 Methodology

Radiation on a tilted surface can be calculated by knowing both the tilt angle and direction of this surface as well as the radiation on a horizontal surface at the same time and place. The radiation measured by a tilted sensor can be treated as the radiation on a tilted surface. By simulating radiation on a horizontal surface on clear days, we can solve for the tilt angle and direction, which can then be used to correct tilt problem on the neighboring days.
3.1 Surface Radiative Flux Simulation

We use CRM, the stand-alone version of the radiation model in Community Atmosphere Model 3 (CAM3) updated from Zender (1999), to simulate surface radiative flux on clear days based on atmospheric profiles and surface conditions. Here we use atmospheric temperature profiles and humidity profiles, and surface conditions (except surface albedo) from the Atmospheric Infrared Sounder (AIRS). Its Infrared and Micro-Wave (IR/MW) sounding instruments retrieve reliable profiles even near the surface (Susskind et al., 2003). The highly heterogeneous surface albedo is the 24-hour running average albedo from AWS, rather than the MODIS surface albedo with a large footprint. Atmospheric constituents with little variability, such as O₃, CO₂ and Aerosol Optical Depth are from a sub-Arctic standard atmosphere.

3.2 Radiation on a tilted surface

Radiation on a tilted surface is comprised of three parts: the direct radiation or beam radiation \(I_{b,t}\), the diffused radiation \(I_{d,t}\) and the reflected radiation from the nearby horizontal surface \(I_{r,t}\). These three parts can be calculated separately, by knowing the tilt angle \(\beta\) and the tilt direction (i.e., rotation angle, \(\alpha_w\)), the time and place, and the radiation on the horizontal surface \(I_h\) (Goswami).
First, the direct radiation is calculated according to the equations below:

\[ I_{b,t} = I_{b,h} \cdot \cos i \]  
\[ I_{b,h} = \frac{I_h}{\cos z + C} \]  
\[ \cos i = \sin z \cdot \cos (a_s - a_w) \cdot \sin \beta + \cos z \cdot \cos \beta \]

\( I_{b,h} \) is the direct part of radiation on the horizontal surface, which can be calculated given the true solar zenith angle \( z \) and the ratio of diffused to direct radiation \( C \). The variable \( i \) is the solar zenith angle observed on the tilted surface. \( \cos i \) follows the geometrical relationship with the true solar zenith \( z \), azimuth \( a_s \), tilt \( \beta \) and rotation angle \( a_w \).

Next, the diffused and reflected radiation are calculated according to these equations:

\[ I_{d,t} = C \cdot I_{b,h} \cdot \frac{(1 + \cos \beta)}{2} \]  
\[ I_{r,t} = \rho \cdot I_h \cdot \frac{(1 - \cos \beta)}{2} \]

Where \( \rho \) is an approximation of surface albedo. A value of 0.8 is used here for snow covered ground as suggested by Goswami et al. (2000).

The relationship between the SW measured by the tilted sensor \( I_t \) and the SW on the horizontal surface simulated by CRM \( I_h \) can be summarized as:

\[ I_t = \frac{I_h}{\cos z + C} \cdot \left[ \cos i + C \cdot \left(1 + \cos \beta\right)/2 + \rho \cdot \left(\cos z + C\right)(1 - \cos \beta)/2 \right] \]

where \( C \) is a constant of 0.2 on clear days. The relatively larger value of \( C \) used here accounts the effects of undetected clouds (Harrison et al., 2008).

### 3.3 Estimate of Tilt Angles and Directions

The SW provided by the three datasets used in this study could include all the AWS problems of icing, riming, shadowing, sensor low sensitivity at high solar zenith angles and sensor tilt. AWS from GC-Net use the LI-COR 200SZ pyranometer, which has a better resistance to rime formation than the standard thermopile pyranometers (Stroeven et al., 2005), due to its small thermal mass. van den Broeke et al. (2004) found the Kipp & Zonen CM3 pyranometer, used by AWS from K-transect and PROMICE, is also less susceptible to riming, since it only has a single dome (rather than double domes), which can be heated up together with the black sensor plate to prevent rime formation.

Furthermore, using only clear days with perfect cosine curves to estimate tilt angles helps remove the effects of icing, riming and shadowing. To limit the sensor low sensitivity effect, only data with a solar zenith angle less than 75° are used to estimate the tilt angles. We assume, therefore, the residual bias is mainly caused by sensor tilt, with an uncertainty in device measurement and random environmental noise. The best pair of tilt angles, \( (\beta, a_w) \), is chosen as the correct phase shift pattern (± 0.5 hours) and the smallest absolute error in magnitude.
3.4 Data Correction

The pair of tilt angles estimated using SW on clear days is used to correct the radiation of that whole month. Usually the variability of tilt angles within a month is negligible, meaning the corrected radiation using tilt angles estimated on one clear day is as good as the one using data from other clear days. However, there are cases in which tilt angles change several degrees in one month. These situations are detected by comparing tilt angle pairs estimated on different clear days, and then are corrected separately if the differences are too large. To correct the tilted insolation of both clear and cloudy days (i.e., calculate radiation on the horizontal surface \(I_h\) from that on the tilted surface \(I_t\)), Eq. 6 shown previously is used with the diffuse ratio (C) calculated by the cloud fraction (cf) from CERES (van As, 2011).

\[
C = 0.2 + 0.8 \times cf
\]  

Since the improvements in the shortwave upwelling radiation are negligible for tilt angles estimated in this study, no correction is performed on it. The radiation with a solar zenith angle larger than 75° is also corrected with physically impossible (i.e., insolation at surface larger than at TOA; or albedo larger than 0.99) and suspicious data (i.e., a sudden change in albedo) removed. Missing data points with both adjoining sides of data available are filled with linear interpolation. This corrected dataset is provided as a supplement.

4 Station Tilt

Of all the stations used here, only KAN_B from PROMICE is anchored into rocks; others are all anchored into glacier ice. Over time, differential snow melt and compaction at different directions can cause station towers to tilt (Steffen et al., 1996; Stroeve et al., 2005), inducing an over-/under-estimate in SW. On clear days, the tilt angle and direction are estimated using Eq. 6 by knowing the measured and simulated insolation (see Fig. 2). The distance from the circle center represents the surface tilt angle (\(\beta\)). The direction represents the station rotation angle (\(\alpha_w\)) with 0° pointing to the South. Different months and years are shown by different markers and colors, separately. The markers are circled in black if the stations were re-visited in those months (no re-visiting record for GC-Net is found). The panels of stations on each sub-figure are arranged in the order of latitude, from North to South. At the GC-Net stations, there seems to be a systematic tilt direction at each station in the accumulation zone. For example, the tower at TUNU-N always tilts to the North, and the one of NASA-E to the West. With regards to the tilt angle, both the maximum (i.e., the maximum distance from the circle center in Fig. 2) and the variability among months are generally larger from North to South, except stations of Jar-1 and Jar-2, which are well into the ablation zone. This phenomenon is also observed at the PROMICE stations with even larger tilt angles, since they are all in the ablation zone. In addition, the largest
and most variable tilt angles are found in July when the snow melt intensity is the strongest during the melting season (i.e., May–Aug). These all suggest a correlation between station tilt and surface melt.

Since AWS do not measure snow melt intensity, surface albedo is used as a representative of surface melt to compare with the tilt angle variability in July (i.e., the absolute value of July minus June; see Fig. 3). It turns out to be a negative correlation between surface albedo and station tilt variability: the higher the albedo (i.e., the less surface melt), the smaller the tilt variability. Although the overall linear correlation coefficient is only 0.51 at the GC-Net and K-transect stations, it is clear in Fig 3 that stations that are in the North and at higher altitudes are affected less by station tilt, whereas stations in the South and at lower altitudes are affected more. If the two exceptional stations, Swiss Camp and Jar-1, are removed, the correlation coefficient rises to 0.91. Since we do not have the re-visit records of these stations, it is unknown whether these exceptions are caused by a better maintenance. At PROMICE stations, the negative correlation coefficient between surface albedo and station tilt variability is even smaller: 0.36. This could be caused by a smaller sample size because only the months without re-visits are included here. Also, although surface melt and snow compaction can lead to station tilt, whether the station towers will tilt, and to what degrees and what direction is highly dependent on random environmental factors. For example, if the areas around all the cable anchors melt at a similar rate, the station tilt may not be as serious as one with melting only in the area around one cable anchor. Nevertheless, the stations in the North are affected less than stations in the South. In addition, within one pair of stations, the one at a higher altitude has a smaller tilt angle variability; vice versa (see Fig. 4). Therefore, at a high altitude, the relatively small station tilt is largely controlled by surface melt. As the tilt angle gets larger at a low altitude, more random factors take effect.

We also found a weak negative correlation between station tilt and wind speed (i.e., the higher the wind speed, the smaller the tilt variability). However, this could be simply caused by the co-occurrence of high albedo and high wind speed at high altitude stations. Moreover, no correlation between the systematic tilt directions of GC-Net stations in the accumulation zone and their dominating wind directions is found. These systematic tilt directions could be a result of the local slopes or station leveling problems at set-up.

5 Validation

Station tilt affects both the phase and magnitude of the diurnal variabilities of surface radiative flux. The phase shift can be easily discerned by comparing the observed solar noon time with the theoretical one under clear-sky conditions. The theoretical solar noon time at one station is known given dates and longitude. We noticed a frequent shift of solar noon in the uncorrected AWS insolation at most stations, represented by the red bars in Fig. 5.
Table 1. RMSE of AWS against the reference datasets under all-sky conditions (unit: W m$^{-2}$).

<table>
<thead>
<tr>
<th>AWS</th>
<th>Reference</th>
<th>Uncorrected</th>
<th>PROMICE Correction</th>
<th>Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROMICE</td>
<td>CERES</td>
<td>148.20</td>
<td>116.22</td>
<td>102.39</td>
</tr>
<tr>
<td></td>
<td>MERRA</td>
<td>186.70</td>
<td>154.42</td>
<td>153.18</td>
</tr>
<tr>
<td>GC-Net</td>
<td>CERES</td>
<td>109.50</td>
<td>78.36</td>
<td>105.78</td>
</tr>
<tr>
<td></td>
<td>MERRA</td>
<td>167.46</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GC-Net denotes stations from both GC-net and K-transect

Over all the stations, only $\sim$15% of clear days have the correct solar noon time. The number of days with a solar noon shift within $\pm$0.5 hours is not even half. Some of the shifts can be as large as 3 hours. On the other hand, over 90% of the corrected data have solar noon shifts within 0.5 hours (represented by the blue bars in Fig. 5).

The improvements in insolation were further examined by comparing these data with PROMICE correction, CERES and MERRA. The AWS from PROMICE are equipped with inclinometers, recording the station tilt angles. The station tilt directions are obtained during re-visits. The tilt-corrected data are provided whenever inclinometers worked, giving a tilt-correction reference at these stations. The CERES insolation is Synoptic Radiative Fluxes and Clouds (SYN) Edition-3A Level-3 data, the spatial and temporal resolution of which are 1 degree and 3 hours, respectively.

The data from MERRA are 1/2- by 2/3-degree hourly flux. AWS observations are compared with the data in the nearest CERES and MERRA grid. Comparisons are only conducted between 6 AM and 6 PM at local solar time, since the extrapolation of data in the early mornings and late nights, when most of the data are removed due to icing and low sensitivity problems, is problematic.

As shown by Fig. 6, our correction improves significantly under clear-sky conditions in comparisons with both CERES and MERRA. At PROMICE stations, our correction using the estimated tilt angles is as accurate as the one using measured tilt angles. The Root-Mean-Square-Errors (RMSE) of our correction (58.50 W m$^{-2}$ for CERES and 59.10 W m$^{-2}$ for MERRA) are both $\sim$30 W m$^{-2}$ smaller than the RMSE of the uncorrected data (93.42 W m$^{-2}$ for CERES and 87.37 W m$^{-2}$ for MERRA). The improvement is even larger than the PROMICE correction (RMSE to be 71.91 W m$^{-2}$ for CERES and 63.26 W m$^{-2}$ for MERRA). Moreover, the correlations of our correction with the reference datasets (i.e., CERES and MERRA) are the strongest. They exceed 0.95 for both CERES and MERRA, in contrast with those for the uncorrected data, which are 0.87 for CERES and 0.90 for MERRA. The improvements remain the same at GC-net and K-transect stations, with $\sim$30 W m$^{-2}$ less RMSE and correlation coefficients over 0.95 (see Fig. 6c and d).

Under all-sky conditions, the improvements in RMSE are also $\sim$30 W m$^{-2}$ for both CERES and MERRA, although the absolute biases are larger (see Table 1). This large bias could be caused by
Table 2. Daily average improvements in insolation.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Condition</th>
<th>Uncorrected (W m(^{-2}))</th>
<th>Corrected (W m(^{-2}))</th>
<th>Absolute Difference (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulation</td>
<td>All-Sky</td>
<td>291.41</td>
<td>386.66</td>
<td>27.80 (9.54%)</td>
</tr>
<tr>
<td></td>
<td>Clear-Sky</td>
<td>329.06</td>
<td>436.04</td>
<td>63.26 (19.22%)</td>
</tr>
<tr>
<td>Ablation</td>
<td>All-Sky</td>
<td>276.29</td>
<td>344.12</td>
<td>20.57 (7.44%)</td>
</tr>
<tr>
<td></td>
<td>Clear-Sky</td>
<td>347.46</td>
<td>438.50</td>
<td>48.63 (14.00%)</td>
</tr>
</tbody>
</table>

Numbers in the parentheses are the percentages of the absolute differences relative to the uncorrected insolation.

the inaccurate estimates of cloud properties by the satellite and reanalysis. We noticed a systematic bias in insolation between CERES and MERRA, which is \( \sim 10 \) W m\(^{-2}\) under clear-sky conditions and over 30 W m\(^{-2}\) on cloudy days. Our improvement is consistently accurate when compared to either CERES or MERRA, because our correction is on the daily time-scale, which is shorter than that of the systematic bias.

Relative to the uncorrected insolation, the largest improvement of our correction occurs at South Dome, with a daily average of 57.15 W m\(^{-2}\) under all-sky conditions and 85.81 W m\(^{-2}\) under clear-sky conditions, as mentioned in the introduction. Although the tilt angles are more variable in the ablation zone, the absolute values are larger in the accumulation zone, caused by the large systemic tilts at the southern stations. Therefore, our method improves the insolation more in the accumulation zone (27.80 W m\(^{-2}\)) than in the ablation zone (20.57 W m\(^{-2}\); see Table 2). The average daily improvement of all stations under all-sky conditions is \( \sim 23 \) W m\(^{-2}\), which is equivalent to a snow melt of 0.51 m throughout the melting season, or a sea-level rise of 3.1 mm per year, using an albedo of 0.7.

6 Application: Snow Albedo Variability

Snow albedo controls the absorbed solar radiation at the surface. The short-term change in albedo can lead to snow-melt and trigger the positive snow albedo feedbacks. Nevertheless, little is known about the sub-daily variabilities of albedo in the Arctic due to a lack of high-temporal-resolution satellite observations and reliable in-situ measurements. Although the polar orbit satellites can pass through parts of Greenland several times a day, only daily average albedo is available due to cloud interference. The low sensitivity of a pyranometer at high solar zenith angles and the sensor tilt can introduce false diurnal fluctuations into AWS observed albedo. In climate models, the diurnal change of snow albedo is typically estimated by solar zenith angle and snow grain size. However, in reality, more factors contribute to this diurnal change, including internal properties (such as particle shape and snow density) and external factors (such as solar azimuth angle and topography) [Flanner and]
With the tilt-corrected radiation, we find a more consistent diurnal change in surface albedo. For example, shown in Fig. 7, curves are more smooth using the corrected data. At stations with large tilt angles, the patterns of diurnal cycles are turned upside down by tilt correction (see Fig. 7c and d).

Sometimes, the pyranometer tilts enough to jeopardize the daily average albedo, which, in turn, impacts the climatological conclusions on the monthly and annual change. For example, at one of the PROMICE stations in the northeast of Greenland, UPE_L, the tilt angle jumped from 7° to 12° from June to July 2010. Without tilt correction, data shows an improbably higher albedo in July than in June (see Fig. 8a), which contradicts the result from a nearby station, UPE_U (see Fig. 8b), as well as the concurrent temperature trend. The high monthly average albedo in the uncorrected data from July 2010 was caused by the abnormally high values in the early mornings and late evenings, due to a shift in downwelling radiation against the upwelling. This misleading effect cannot be removed by either the 24-hour running average or limiting the solar zenith angle to less than 75°. After the tilt effect is countered, the normal climatology is restored.

Sensor tilt can also affect the annual variability of albedo. In 2012, Greenland experienced the largest melt extent in the satellite era since 1979 (Nghiem et al., 2012), which can be observed by an epic low albedo in both uncorrected and corrected data in the accumulation zone (i.e., altitude > 2000 m; see Fig. 9a). In this area, melt only occurs during a limited period of time in summer, and thus the tilt problem is not as serious as in the ablation zone (i.e., altitude < 2000 m). In the ablation zone, the uncorrected data shows the smallest albedo in 2010 instead of in 2012. Moreover, the between-station variability of the uncorrected data is almost 5 times larger than that of the corrected data (shown by the error bars in Fig. 9b), indicating varied tilt effects at different stations. After the tilt correction, the annual trend and the minimum of albedo are in agreement with the results from NASA MOD10A data processed by Jason Box (Box, 2015).

7 Discussion

So far, CRM can provide precise estimates of surface radiative flux only under clear-sky conditions. As a result, our method needs at least one clear day per month to conduct the estimation of the tilt angles. Among all the 768 months used in this study (i.e., 32 stations, 6 years per station and 4 months per year), there are 22 months (2.86%) with no clear days to use. However, most of these months (17 out of 22) have at least half of the AWS measurements missing. For 3 months (out of 22), no qualified AIRS atmospheric profiles can be used on clear days. For only 2 months, it is too cloudy to have any clear days. We, therefore, provide no correction in these months.

The data quality of the corrected SW also relies on the quality of cloud cover data. Higher cloud cover results in a higher diffuse/direct ratio (C), when the SW is less affected by station tilt due to isotropy. With regards to the cloud radiative properties, CERES estimates are reasonably accurate
Moreover, in the Arctic, because the fast-changing convective clouds are rare, the use of the 3-hourly cloud cover is appropriate. Nevertheless, a cloud cover dataset with a higher resolution would further improve the quality of the hourly radiation measurements from AWS.

8 Conclusions

In this study, we correct the SW using tilt angles estimated by comparing CRM simulated insolation with AWS observed insolation under clear-sky conditions, to provide a multi-year consistent SW dataset for analysis of energy budget and surface melt as well as validation of satellite observations and model simulations. The tilt angle variabilities are basically controlled by surface melt, and complexed by random factors. The largest tilt angles occur at the low altitude stations and in July. However, there is no statistically significant correlation between surface melt and station tilt due to the random initial conditions. Station tilt results in considerable bias in insolation. There are only \( \sim 15\% \) days with the correct solar noon time in the uncorrected insolation under clear-sky conditions. The largest bias reaches 3 hours. The daily average RMSE of the uncorrected insolation compared with CERES and MERRA at all stations are almost 100 W m\(^{-2}\) under clear-sky conditions, with a correlation coefficient to be \( \sim 0.85 \). The RMSE are even higher under cloudy skies. Our correction using the estimated tilt angles reduce the RMSE compared with both CERES and MERRA by \( \sim 30\ W\ m^{-2} \), and enhance the correlation coefficients to exceed 0.95, which are even more accurate than PROMICE corrections using the measured tilt angles. Our overall improvement from the uncorrected data under all-sky conditions is \( \sim 23\ W\ m^{-2} \) averaged over all AWS, enough to melt 0.51 m snow water equivalent using an albedo of 0.7. Only with this tilt-corrected SW data can the diurnal cycles of albedo be studied. The derived seasonal and annual variabilities of albedo are more consistent with satellite observations and temperature changes. This corrected SW dataset can be furthered used to better validate satellite observations and model simulations on the energy budget and thus surface melt of Greenland Ice Sheet. This tilt correction method can also be used on AWS in other snow-covering areas, such as Antarctica.

Acknowledgements. NASA funding: K-transect

9 Supplemental Materials
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Numbers in the parentheses are the percentages of the absolute differences relative to the uncorrected insolation.
References


Figure 2. Station tilt angles and tilt directions of a) GC-Net and K-transect; b) PROMICE. There might be multiple tilt angles in one month.
Figure 3. Correlation between surface albedo and tilt angle ($\beta$) variability in July for a) GC-Net and K-transect; b) PROMICE. Numbers on dashed lines are the correlation coefficients. Numbers in the parentheses are the corresponding significant levels based on a two-tailed $t$ test.

Figure 4. Comparison of tilt angle variability between stations at high altitudes and those at low altitudes in July. The boxplot shows the minimum, the lower quartile, the median, the higher quartile and the maximum from bottom to top.
Figure 5. Solar noon shifts of uncorrected and corrected data.
Figure 6. Correlation of shortwave downwelling radiation between a) PROMICE with CERES; b) PROMICE with MERRA; c) GC-Net and K-transect with CERES; d) GC-Net and K-transect with MERRA.

Figure 7. Diurnal variability of albedo with SZA less than 75° in June 2013 at a) KPC_U; b) JAR-1; c) Saddle; d) South Dome.
Figure 8. Monthly average albedo at a) UPE_L and b) UPE_U in May-Aug 2010 with standard deviation.

Figure 9. Annual average albedo in a) accumulation zone; b) ablation zone with standard deviation.