February 10, 2016

Dear Editor,

We thank the anonymous reviewer and Dr. Marie Dumont for their enlightening and constructive comments and suggestions. We have followed all the major recommendations, which improved both the theoretical basis and application of our tilt correction method. After we pointed out the large shift in upwelling radiation at stations of s5, s6 and s9 from the Kangerlussuaq transect project and Station NUK_L from the Programme for Monitoring of the Greenland Ice Sheet, data teams found logger errors at these stations and fixed them. Now upwelling radiation at these stations all peak within 0.5 hr of local solar noon, and are then included in the manuscript. Our findings and conclusions are not affected. Contexts and relating figures are revised accordingly.

A detailed response to each suggestion and comment from reviewers is shown below in blue text. We use *italics* to highlight the added or revised manuscript. There might be other minor revisions in the manuscript to ensure smooth transitions.

Sincerely,
Wenshan Wang
PhD Candidate, University of California, Irvine

Response to comments by the anonymous reviewer

The manuscript describes a novel method to correct for the well-known, albeit often ignored, tilt error in surface radiation measurements. The tilt error may give erroneous surface albedo and surface insolation. The method presented in the manuscript cleverly uses the data together with a radiative transfer model to correct for the tilt error. The error corrected data give a better description of the system studied and is likely to have an impact on our understanding of the energy budget of snow-covered surfaces.

The manuscript is well-written and well-organized. The paper is suitable for publication after consideration of the technical remarks below.

Technical remarks

- Page 6029, line 18: Replace "Multi-scattering" with "Multiple scattering".
  Changed in manuscript.

- Page 6033, line 20: Replace "following algorithm" with "using the algorithm".
  Changed in manuscript.

- Page 6033, Eqs. 4-5: You may consider including a sentence mentioning that Eqs. 4-5 implies that the diffuse radiation is isotropic.
  Dr. Marie Dumont also brought up this issue. We added more explanation to these two equations including the isotropic diffuse radiation assumption:

  The diffuse radiation on a tilted surface ($I_{d,t}$) can be calculated by multiplying diffuse radiation on a horizontal surface ($C \cdot I_{b,h}$) by the view factor between the sky and the tilted surface, as below (assuming isotropic diffuse radiation):

  $$I_{d,t} = C \cdot I_{b,h} \cdot (1 + \cos\beta)/2 \tag{4}$$

  Part of the upwelling radiation from a nearby horizontal surface can be intercepted by the tilted surface. This reflected radiation on the tilted surface ($I_{r,t}$) can be obtained by multiplying upwelling radiation from the horizontal surface ($\rho \cdot I_h$) by the view factor between the horizontal surface and the tilted surface (assuming isotropic reflected radiation):

  $$I_{r,t} = \rho \cdot I_h \cdot (1 - \cos\beta)/2 \tag{5}$$

- Page 6034, line 7: Replace "accounts" with "includes".
  Changed in manuscript.

- Page 6034, line 15: Remove "is also".
  Changed in manuscript.

- Page 6035, line 6: Replace "which tilt" with "which the tilt".
  Changed in manuscript.

- Page 6041, line 2: Replace "RIGB" with "The RIGB".
  Changed in manuscript.

- Page 6054, Fig. 5: In the caption and the text it is said the Fig. 5 presents the albedo. However, the left y-axis label states that this is the "Albedo anomaly". However, this term is not defined

in the manuscript. Please either define this variable and adjust caption and text accordingly or plot the albedo. Similarly for the y-axis where the label reads "cos(sza) anomaly" and this quantity is not defined anywhere.
We modified the caption of Fig. 5, as follows:
Figure 5. Diurnal variability of albedo at SZA less than 75º at (a) KPC_U; (b) JAR-1; (c) Saddle; (d) South Dome. The anomaly used here is the monthly average of anomalies against daily averages. $\cos(SZA)$ *represents the cosine of solar zenith angle. The station altitude and tilt angle-direction as well as data time period are labeled on the top of each panel.*

- Page 6056, Fig. 7: The left and right y-axis are labelled albedos. However, the y-axis range is symmetric around zero implying that some offset has been subtracted. Please clarify this and plot the albedo or other relevant quantity. Change text accordingly.
  We modified the caption of Fig. 7, as follows:
  Figure 7. Annual average albedo using unadjusted data (on the left Y axis) and RIGB-adjusted data (on the right Y axis) in (a) accumulation zone; (b) ablation zone with standard deviation as error bars. The values are anomalies against the corresponding station averages.

- Page 6057, Fig. 8: Please make figure larger. It is very hard to read.
  Modified in manuscript.

Response to comments by Dr. Marie Dumont

This paper presents a really interesting new methodology to correct automated short- wave measurements from stations tilt. This is an important issue for radiation budget and surface energy balance over snow covered areas and the solution proposed by the authors "only" required simulated broadband shortwave irradiance and cloud fraction. The results show improved SW and albedo compared to two reference datasets. The authors also provide an interesting investigation of station tilt variability versus melt intensity. This study fits well with The Cryosphere scope but I think that several comments should be addressed before it can be published. This is detailed in the following.

Main Comments

1. My first main comment in on the equations used in the methodology and discussed in the section 3.2 and 3.4. From equation (2), it seems to me that Ib,h is the direct incident radiation in the direction of the solar beam and C=Id,h/Ib,h. However, no definition of C is given, Id,h is defined as the "direct part of SW radiation on the horizontal surface" and the above definition of C is, if I understand correctly, not compatible with equation (7) which requires that C=diffuse/total. These questions must be clarified in a future version of the paper. In addition, though I agree with equations 4 and 5, I think that they must be further explained and justified.

   We thank the reviewer for finding this mistake. The definition of C, the diffuse ratio, should be C = $I_{d,h}/I_{b,h}$, which is diffuse/direct radiation. Therefore, Equation (7) will be revised to:

   $$\mathrm{C} = \frac{0.25 + \mathrm{CF}}{1 - \mathrm{CF}}$$
   $$\text{When } \mathrm{CF} \to 1, \mathrm{C} \to \infty$$

   The whole dataset has been re-processed using the same definition of C. The main findings and conclusions are not affected. The average tilt angle and direction are changed by 0.85° and 15°, respectively, resulting in an average change of 7 W m^{-2} in adjusted insolation. The new results are shown in the revised manuscript.

   We further explained Eq. 4 and 5 in the manuscript as below:

   The diffuse radiation on a tilted surface ($I_{d,t}$) can be calculated by multiplying diffuse radiation on a horizontal surface ($C \cdot I_{b,h}$) by the view factor between the sky and the tilted surface, as below (assuming isotropic diffuse radiation):

   $$I_{d,t} = C \cdot I_{b,h} \cdot (1 + \cos\beta)/2 \quad (4)$$

   Part of the upwelling radiation from a nearby horizontal surface can be intercepted by the tilted surface. This reflected radiation on the tilted surface ($I_{r,t}$) can be obtained by multiplying upwelling radiation from the horizontal surface ($\rho \cdot I_h$) by the view factor between the horizontal surface and the tilted surface (assuming isotropic reflected radiation):

   $$I_{r,t} = \rho \cdot I_h \cdot (1 - \cos\beta)/2 \quad (5)$$

2. The imperfect cosine response of the sensor is another of the major sources of error in radiation measurements especially when the solar zenith angle is high as noticed by the authors in the

introduction. I think that the discussion should include a more quantitative assessment of the comparative errors induced by tilt and imperfect cosine response based on former studies on the angular response of optical sensor.

Yes, we agree that cosine error is another major error source for radiation measurements. We didn't include a comprehensive quantitative assessment of cosine error, because it largely depends on instrument types and manufacturers. As for the pyranometers used at the Automatic Weather Stations in Greenland, errors induced by sensor tilt in insolation are larger in magnitude, and much more variable in time and place than cosine errors. Now we discussed more about cosine error in Section 1 Introduction, as follows:

The cosine response error at large solar zenith angles is intrinsic, and variable with instrument types and manufacturers, some of which we characterize in the following. Using an intermediate resolution spectrophotometer, Grenfell et al. (1994) found the departures of measurements from an ideal cosine law were less than 15% at solar zenith angles less then 72º. Using a Brewer spectroradiometer in UV band, Bais et al. (1998) reported a cosine error range from 2% to 7%. One of the AWS projects in Greenland, Greenland Climate Network, employs LI-COR 200SZ pyranometers. Stroeve et al. (2001) observed deviations of this pyranometer from highly accurate instruments in excess of 5% at solar zenith angles larger than 75º. van den Broeke et al. (2004) obtained negative net shortwave radiation at high solar zenith angles using Kipp & Zonen CM3 pyronometers, equipped by the two Greenland AWS projects, K-transect project and the Programme for Monitoring of the Greenland Ice Sheet networks. According to the manufacture report, the typical percentage deviation of Kipp & Zonen CM3 from ideal cosine behavior is $\sim 2\%$ at solar zenith angle of 80º, with a maximum of $\sim 8\%$, which is on the same magnitude of that of LI-COR 200SZ (Kipp & Zonen, 2004). The newer version of LI-COR pyranometer, LI-200R, claims a typical cosine error of less than 5% up to solar zenith angle of 82º (Biggs, 2015). None of the cosine errors reported in the above proceedings exceed the mean tilt-induced biases as we document below.

3. The correction provided in this study is for broadband values. Some of the equations used in the study (e.g. equations 2, 4,5, . . .) are theoretically valid only when I, C, and are written as functions of wavelength. Though I completely agree that a spectral correction of the measured SW in beyond the scope of this study, I think that the paper should include a discussion on the impact of using broadband values only and on spectral corrections. This is also related to my main comment 2/ above.

Since the radiation measurements by the Automatic Weather Stations (AWS) are in broadband, we chose a wavelength-independent diffuse ratio (C) estimated from broadband radiation measurements using linear regression. Thus, Eq. 2, 4 and 5 are the forms of I integrated over broadband wavelengths. We now included a discussion of the dependence of C on wavelength and how our method can be applied on spectral correction in Section 6.3 Uncertainty in the Tilt-Corrected Insolation in the manuscript:

The AWS used in these three projects over Greenland Ice Sheet measure only broadband radiation. Therefore, we use a wavelength-integrated relationship between diffuse ratio (C) and cloud fraction (CF), derived from broadband radiation measurements using linear regression. Regression models using higher orders or more predictors, such as relative humidity, do not perform significantly better (Paulescu and Blaga, 2016). Also, there is no significant difference in the calculation of radiation on tilted surface by using diffuse radiation estimated from a diffuse fraction correlation or retrieved from observations (Reindl et al., 1990). Although tilt-induced errors are independent of wavelength for direct radiation, they vary with wavelength for *diffuse radiation (Bogren et al., 2015). The diffuse/direct ratio (C) also increases with shorter wavelengths (Hudson et al., 2006; Bogren et al., 2015). The equations in Section 3 could be instead written as function of wavelength with diffuse ratio, $C(\lambda)$, and radiation fluxes, $I(\lambda)$. Therefore, if narrow-band measurements of shortwave radiation and the corresponding diffuse ratios are available, RIGB can be applied to correct spectral tilt-induced errors.*

Specific Comments

1. Page 6031 lines 24-26: Does that mean that the shift of the diurnal maximum of upwelling radiation is an additional criteria to filter the data? Does that imply that all stations over significant surface roughness (sastrugi...) are discarded from the analysis?

   It turned out the large shifts in shortwave upwelling radiation are all caused by data logger problem. After we pointed out, the data teams fixed this problem. Now no shifts larger than 1 hour are found. Therefore no stations are discarded due to surface roughness. Page 6031 Line 24-27 and Page 6032 Line 1-4 are removed. The contexts are revised as:

   Stations with more than two years of missing data are excluded from consideration, including Crawford Point1, GITS, NASA-U and Petermann Gl. from GC-Net, s6 from K-transect, and MIT, QAS_A and TAS_A from PROMICE. The remaining number of stations is 35, of which 13 stations are from GC-Net, 3 from K-transect and 19 from PROMICE (Fig.1).

2. Page 6031 line 27: the reflected radiation is not isotropic. Snow surfaces are not lambertian (e.g. Painter and Dozier 2004). This sentence should in my mind be reformulated, and a discussion should be included on the effect of snow bidirectional reflectance on measured upwelling shortwave.

   We removed Page 6031 Line 27 according to the modification for the last question. In the absence of data for snow grain size, surface roughness etc. that contribute to snow bidirectional reflectance, we use equations with assumption of isotropic reflected radiation following the previous studies on station tilt (*Grenfell et al.*, 1994; *Goswami et al.*, 2000; *Bogren et al.*, 2015). Although snow surfaces are not perfect Lambertian surfaces, we think it's reasonable to assume so in this manuscript. On surfaces with randomly oriented roughness, such as in Greenland, forward scattering of snow are weaker than on flatter surfaces (*Warren et al.*, 1998). Moreover, the angular scattering is mostly effective at large viewing zenith angles (*Hudson et al.*, 2006). Since the pyranometers that we retrieved data from have a field of view of almost 180°, the measurement is the sum of radiation from all angles above sensor panel (up-looking sensor). Further discussion on the uncertainty induced by assuming Lambertian snow surfaces will truly be beneficial if snow surface property data are available at these Automatic Weather Stations we used.

3. Page 6033 lines 3-4: Maybe the authors should include values for Ozone, AOD, water vapour, etc . . .

   Sure. We included a table showing the constants we used for Ozone, CO_2 and AOD (see table below). Water vapor data are from the real-time Atmospheric Infrared Sounder (AIRS), as we mentioned in the middle part of Section 3.1.

4. Section 3.2 Scheme describing all the angle and radiations would probably help the reader.

   It's a good idea. We included one table explaining all these variables in Appendix.

Table 1: CRM Parameters.

Parameter	Unit	Value
Number of vertical levels	layer	100
Ozone column mass path	DU	348.64
Aerosol visible extinction optical depth in North		0.12
Aerosol visible extinction optical depth in South		0.14
Solar constant	W/m^2	1367.0

Table 2: Nomenclature.

I_h	Shortwave radiation on a horizontal surface, W m^{-2}
I_t	Shortwave radiation on a tilted surface, W m^{-2}
$I_{b,h/t}$	Beam radiation on a horizontal/tilted surface, W m^{-2}
$I_{d,h/t}$	Diffuse radiation on a horizontal/tilted surface, W m^{-2}
$I_{r,t}$	Reflected radiation from a nearby horizontal surface on a tilted surface, W m^{-2}
β	Tilt angle, radians
a_w	Tilt direction, radians
z	Solar zenith angle observed from a horizontal surface, radians
i	Solar zenith angle observed from a tilted surface, radians
a_s	Solar azimuth angle, radians
C	Diffuse ratio
ρ	Surface albedo approximation
CF	Cloud fraction

5. Page 6034 line 9: "only the term of diffuse radiation is used". This should be either detailed, or removed considering the contradictory information given page 6035 lines 15-16.

   We removed this sentence to stay consistent with Page 6035 Line 15-16.

6. Page 6034 line 20: The value of 75° must be further justified.

   The threshold of 75° is only used to estimate tilt angle and direction. Data at all solar zenith angles are adjusted using the estimated tilt information. As we mentioned in a previous question, cosine errors are less than 5% at solar zenith angles smaller than 75°, according to both field work (*Stroeve et al.*, 2001) and lab experiments (*Kipp & Zonen*, 2004; *Biggs*, 2015). In fact, it is the radiation data around local solar noon that control the final solutions of the equations, since the numerical pathway we used to solve for tilt angles is most sensitive to the large insolation at noon. The results will not change if we choose a slightly smaller or larger value. We further explained the reasons in the manuscript:

   Although the numerical solutions of tilt angle-direction are most sensitive to insolation at solar noon, in order to further limit effect of cosine response error, we only use data at solar zenith angles smaller than 75°, when the cosine response error is typically less than 5% (Kipp & Zonen, 2004; Biggs, 2015; Stroeve et al., 2001).

7. Section 3.4. Line 4: Could you quantify "negligible" ? In my opinion, it is quite difficult to

understand from this section which tilt angles values are used to adjust the radiation: monthly mean over clear days ? daily values ?

By "negligible", we mean in most of the months, the standard deviation of the discrepancies between RIGB-adjusted and CRM-simulated insolation on all clear days in one month is less than $5\,\mathrm{W\ m^{-2}}$. We actually didn't neglect anything here. We first estimate the best pair of tilt angle-direction from all the clear days in this month. If the aforementioned standard deviation is less than $5\,\mathrm{W\ m^{-2}}$, we then use this one pair of tilt angle-direction to adjust insolation on all the days in that whole month. If this standard deviation is larger than $5\,\mathrm{W\ m^{-2}}$, we divide this month into shorter time periods until the standard deviation in each period is less than $5\,\mathrm{W\ m^{-2}}$. We then use these different pairs of tilt angle-directions in their corresponding time periods in this month. The manuscript is rephrased as below:

The best tilt angle-direction pair estimated using insolation on all the clear days in one month is used to adjust radiation of that whole month. However, there are cases in which tilt angle changes several degrees in a month. If the standard deviation of RIGB improvement on different clear days using this one pair of tilt angle-direction is larger than 5 W m^{-2}*, this month will be divided into shorter time periods and processed separately.*

8. Page 6035 lines 16-20: I don't understand this sentence.

   Only insolation at solar zenith angles smaller than 75° is used to estimate tilt. However, all the data are adjusted using the estimated tilt angles. We added this transition in the manuscript:

   Although only insolation at solar zenith angles smaller than 75° is used to estimate station tilt, SW data at all solar zenith angles are also adjusted, 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) excluded.

9. Page 6036 lines 7-15: This should be described in the "Data" section.

   We added description of CERES and MERRA in Section 2 Data, as follows:

   We also use insolation from the Clouds and the Earths Radiant Energy System (CERES) (CERES Science Team) and the Modern-Era Retrospective Analysis for Research and Applications (MERRA) (Rienecker et al., 2011) as references to evaluate RIBG improvements. They are now aboard three satelites, including Terra, Aqua and the Suomi National Polar-orbiting Partnership (S-NPP) observatory. CERES measures both solar-reflected and Earth-emitted radiation from TOA, and derives solar radiative fluxes at Earth surface. The insolation we use is Synoptic Radiative Fluxes and Clouds (SYN) Edition-3A Level-3 data, the spatial and temporal resolution of which are 1 °and 3 h, respectively. MERRA is the new generation of reanalysis, which uses the Data Assimilation System component of the Goddard Earth Observing System (Cullather and Bosilovich, 2012). It provides near-real-time hourly climate analysis with 1/2° in latitude and 2/3° in longitude, from 1979 to present.

10. Page 6036 line 14: What are the elevation and distance maximum difference between stations and grid points ? How would that impact the comparison?

    The maximum elevation and distance difference is 600 m and 25 km, respectively. The discrepancies between station data and grid data are not only from the geophysical distance, but also from the different sensor foot prints. That's why we don't intend to achieve an absolute agreement between station and grid data, but instead, focus on the relative improvement of RIGB adjustment over the unadjusted data.

11. Figure 3: Is this for all-sky values or only for clear-sky ? This should be included in the legend.

    This is for clear sky. We added this information in the caption:

    Figure 3. Correlation of insolation ($W\,m^{-2}$) on clear days 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.

12. Figure 3: It could worth including regression coefficients. It looks like the data are positively biased at least for high SW values. Maybe the authors could include a discussion on this result.

    Yes, insolation measured at AWS are positively biased at high values, compared to satellite data (CERES) and reanalysis (MERRA). This high bias exists in both the unadjusted and RIGB-adjusted data. This systematic bias is improbably caused by station tilt, since tilt errors are much more variable in time and place. Therefore, tilt correction will not improve the regression coefficients. As mentioned in a previous question, there are many factors other than measurement errors that can contribute to the discrepancies between ground measurements and satellite retrievals, such as geophysical distance, sensor footprints, sensor sensitivities etc. It could be a whole new topic to discuss and attribute these discrepancies. We'd like to stay focus on the relative difference between RIGB adjustment and unadjusted data.

13. Page 6037 lines 6-8: I don't understand the sentence.

    We intended to explain why RIGB adjustment shows better consistency with two datasets which contain a systematic difference between them. We rephrased the sentence as below:

    In despite of this systematic difference between the two reference datasets, RIGB adjustment shows better consistencies with both. A possible reason is that our adjustment is on the daily time-scale, which is shorter than that of this systematic difference.

14. Page 6037 line 18: South Dome also has a large value of tilt angle.

    Yes, that is why the improvement is large at this station. We use insolation instead of tilt angle to show improvements because the effect of tilt angle is modulated by the relative position of tilt direction and the sun. The same tilt angle could cause large difference in insolation when stations tilt to different directions at different times of year.

15. Page 6038 line 7: I am not sure cloud interference is the main reason for the daily albedo product.

    We obtained this information from studies on remote sensing of surface albedo. For example, the web-page (*MODIS Science Group*) and theoretical basis of MODIS land surface albedo (*Moody et al.*, 2005) specifically mention that land surface obscured by cloud coverage is the main reason to keep passive sensors such as MODIS from producing high temporal resolution data. Since cloud interference is not the sole reason, we modified the manuscript as follows:

    ...only daily average albedo is available mainly due to cloud interference.

16. Page 6038 lines 14-17: Figure 5 gives really interesting examples of the efficiency of the adjustments but it's only a few examples. How does the algorithm performed over the whole data set with respect to the albedo diurnal cycle?

    Albedo diurnal cycle could be highly different from station to station, depending on the local factors such as cloud cover, snow metamorphism and surface roughness (*Wang and Zender*, 2011). Here we employ the albedo diurnal range (maximum minus mininum) to help quantify how much RIGB changed the albedo diurnal variability. We added the results in the manuscript as follows:

The average diurnal range (maximum minus mininum) of all stations declines from 0.18 to 0.12 with a 3-times smaller standard deviation.

17. Table 2 and Figures 6,7: The correction on the SW values is higher for the accumulation than for the ablation zone but the impact on the albedo values is higher in the ablation zone. It could be interesting to add a really short comment on that.

    The average tilt angles are larger in the accumulation zone mainly due to severe tilts at the southern stations of DYE-2, Saddle and South Dome. The reasons for such a large tilt to one direction at this high altitude are not confirmed yet. It could be caused by local slopes or glacier movement. However, in the ablation zone, tilts are much more variable, resulting in more inconsistency among stations. We explained in the last paragraph of Section 4 and the first paragraph of Section 6.1 in the original manuscript.

18. Page 6040 line 25: Is there any effect of glacier dynamic on station tilt and rotation ?

    Yes, this is a good point. We modified the manuscript as follows:

    Page 6027 Line 7-8:
    Station tilt, due to irregular surface melt and/or compaction and glacier dynamics (Andreas Peter Ahlstrøm, 2015: personal communication) causes considerable biases in the AWS shortwave radiation measurements.

    Page 6029 Line 27-29:
    Different snow melt and compaction as well as glacier movement around the station towers and/or cable anchors can cause the station to drift over time.

    Page 6040 Line 26-28:
    These systematic tilt directions could be a result of the local slopes or glacier dynamics (Konrad Steffen, 2015: personal communication).

19. Page 6042 line 8: 10 W.m-2 is the same order of magnitude of the adjustment effect (16 or 19 Wm-2 according to results shown in Table 2). A comment of this should be included in the paper.

    The cloud effect on station tilt correction depends on cloud fraction and uncertainty, tilt angle and tilt direction. The CERES cloud fraction uncertainty is estimated as 0.15 by *Minnis et al.* (2008). Assuming the worst situation when tilt angles are 30º or 210º, and cloud cover is close to 0, the maximum uncertainty in insolation adjustment caused by cloud uncertainty is 7.5 W m^{-2} at a tilt angle of 10º. However, in 90% of the station-months, tilt angles are less than 10º, and the average cloud fraction in the Arctic during summertime is 0.81 (*Vavrus et al.*, 2008). Therefore, the insolation adjustment uncertainty caused by cloud fraction uncertainty is well below this maximum value. We intended to express that this adjustment uncertainty is one magnitude smaller than the adjustment itself by using "well under 10 W m^{-2}" which, as the reviewer pointed out, is the magnitude of the adjustment. We now modified Line 2-9 on Page 6042 to make it clearer:

    The adjustment becomes smaller when stations tilt less, or cloud fraction is close to 1. In the worst situation when stations tilt to 30º or 210º and the cloud fraction is close to 0, the uncertainty in insolation adjustment caused by cloud uncertainty is up to 7.5 W m^{-2} at a tilt angle of 10º. In 90% of the station-months we used, tilt angles are less than 10º, 95% less than

15°. The average cloud fraction in the Arctic during summertime is 0.81 (Vavrus et al., 2008). Therefore, the uncertainty in insolation adjustment caused by the uncertainty in cloud fraction should be well below 10 W m^{-2}, the magnitude of the adjustment itself.

20. Page 6042 line 26: "agree better with satellite observations" this has not be demonstrated in the paper . . ..

    In Section 5, we compared our tilt-corrected long-term trends of albedo with the results from *Box* (2015) using MOD10A data, which is satellite observation.

Minor Comments

1. Page 6027 lines 13-14: "insolation on fewer than 40% of clear days . . ." Is this related to corrected on to uncorrected data ?

   No, this only concerns the unadjusted data. The theoretical solar noon is calculated given time and location.

2. Page 6027 line 15: "biases" with respect to?

   Biases with respect to model simulation on clear days. Manuscript is changed to:

   Hourly absolute biases in the magnitude of surface insolation can reach up to 200 W m^{-2}, with respect to the well-understood clear-day insolation.

3. Page 6027 lines 20-21: I think it could worth giving the RMSE and correlation coefficient values after and before the correction so that the reader gets an idea of the relative efficiency of the correction.

   It is a good idea. We added the percentage here to save space:

   Our adjustment reduces the Root-Mean-Square-Error (RMSE) against references from both satellite observation and reanalysis by ∼ 20 W m^{-2} (30%) and raises the correlation coefficients with them to above 0.95.

4. Page 6030 line 2: "quite sensitive" maybe highly and significantly is more appropriate.

   Sure. We changed it to "highly".

5. Page 6032 lines 12-13: is not corrected for ?

   Revised manuscript:

   However, this PROMICE product has not been corrected for the inclinometer orientation shift yet.

6. Page 6033 line 1: "running average albedo" this one is not corrected for tilt ? Though I am convinced it wont make much a difference on the correction, it would worth mentioning it. We realized now that we actually didn't use the simulated upwelling radiation. We used the simulated downwelling radiation to estimate tilt angles, and found the adjustment on upwelling radiation is negligible using these estimated tilt angles. Therefore, input albedo is not a relevant parameter here. We removed this sentence as a result.

7. Page 6035 line 25: It would worth including a reference for solar noon time calculation.

   Sure. See below:

   The solar noon time at one station is known from its longitude and the date (Goswami et al., 2000; Reda and Andreas, 2004).

8. Figure 2: What does "precision of solar noon" mean?

   We changed the caption of Figure 2 as follows:

   Figure 2. Shifts of maximum insolation time to solar noon in unadjusted data and RIGB adjustment. The bins of solar noon time are non-linear with a minimum of 0.5 hr.

9. Page 6036 lines 2-3: I guess this is related to unadjusted radiations ?

   Yes, this is the unadjusted data compared with the theoretical values.

10. Page 6036 line 4: "The maximum shift is 0.5h": this is included in the constraints of your optimization.

    Yes, 0.5 h shift is the constraint. We didn't choose a smaller shift because the observation is hourly data. Although we can interpolate it to a higher precision, there are uncertainties in both observations and simulations. This down-scaling may not provide more accurate results.

11. Page 6037 line 11: Is it possible to quantify "small" ?

    Not for now. If the stations are equipped with compasses in the future, we will be able to tell the actual rotation.

12. Page 6037 line 13: Is it possible to add the value of RMSE over one month ?

    Sure, we added both Root-Mean-Square-Difference (RMSD) between estimated and measured tilt angles, and RMSD between adjusted insolation using estimated and measured tilt angle-directions, since the effects of tilt angles on insolation vary with tilt directions. The manuscript is modified as follows:

    The maximum absolute differences in the tilt angle and direction are 2.24^{o} and 33.35^{o}, with a Root-Mean-Square-Difference (RMSD) of 1.09^{o} and 14.19^{o}, respectively. The resulting RMSD in insolation adjustment is 6 W m^{-2}.

13. Page 6037 line 26: I guess 0.7 is used instead of 0.8 because of melting snow. It can be interesting to add the information in the paper.

    Sure. This calculation of snow water equivalent from radiative forcing is an approximation, designed for readers who are more familiar with mass balance. We modified the manuscript as suggested:

    ...using an albedo of 0.7 for melting snow.

14. Page 6038 line 10: 'estimated by' → simulated as a function of ?

    We rephrased the manuscript as follows:

    In climate models, the diurnal change of snow albedo is typically simulated as a funciont of solar zenith angle and snow grain size (van den Broeke et al., 2004; Flanner and Zender, 2006).

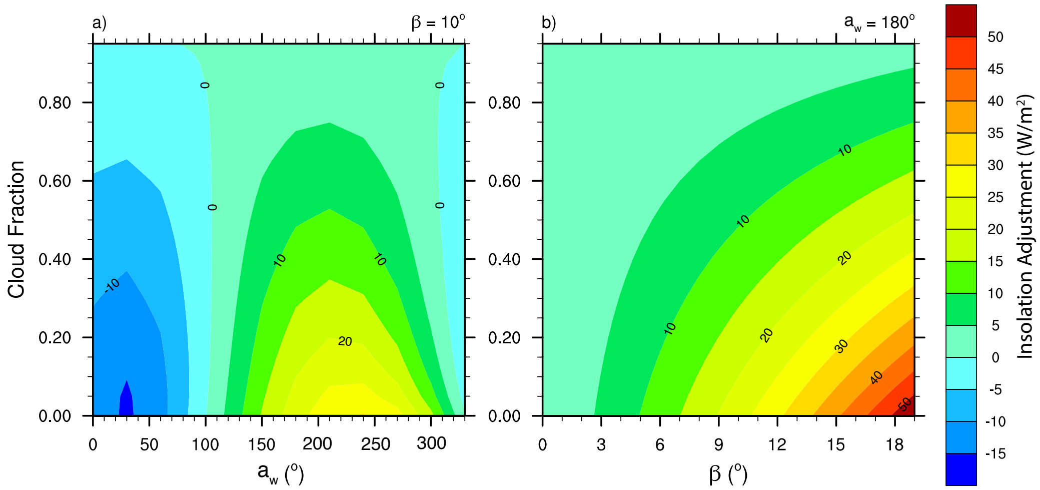
15. Page 6039 line 20: "Except for station south dome": is there any explanation for that?

    We excluded the effect of snow melt, snow compaction and wind. It could be caused by local slope or glacier dynamics. Further examination is needed.

16. Page 6040 lines 19-20: What does "environmental factors take effect" means. Figure 10 A): Could be clearer that change x-axis labels from 0 to 360 ?

By environmental factors, we mean the initial triggers and the following processes that control the onset and acceleration of melt at a certain direction. Stations in the ablation zone are more susceptible to tilt. However, whether stations will tilt, and to what degree and direction also depend on these environmental factors. Therefore, we conclude that station tilt is largely controlled by surface melt/compaction, yet affected by environmental factors.

The x-axis lable of Figure 10 a) has been changed to the range of 0-360°, see below:



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