Comments and responses

Additional changes

In addition to the changes made to address the comments of the referees, the following changes have been made.

- Updated references in section 2.1.
- Figs. 1-3 and Tables 1 and 2 have been updated. The text discussing the Figures and Tables have been updated correspondingly.
- In the "Discussion" section the following text has been moved from paragraph 2 to 3:

  > It is not suggested that every measurement from a sensor which may have been tilted is subject to the maximum potential error; nor is it even suggested that existing measurements are too greatly influenced by this error to be useful. We do recommend greater care be placed into the levelling of measurements and feel hand leveled observations (e.g. on a hand held extension) are prone to larger errors than operators may expect.

- Numerous minor changes have been made to improve the presentation.

Response to comments from Referee # 1

We thank the referee for the reading of and comments to our manuscript. The referee's comments are repeated below in italic font. Our responses to the comments are shown in roman font.

Comments and responses

- *Currently, one can measured solar radiation with two methods. The first, one can measure total solar radiation with a pyranometer. The second, one can also measure direct solar radiation with a pyrheliometer and measure diffuse solar radiation with a shaded pyranometer. Total solar radiation can be calculated as a sum of these two measurements. The authors did not mentioned which method they targeted. For the first one, only total solar radiation is measured and its error depends on the received energy by detector of pyranometer. For the second one, the error of observed direct solar radiation is determined by whether the pyrheliometer tracks the sun exactly. For a 5 degree error, the pyrheliometer can totally miss the sun and error of the observed direct solar radiation can be huge. The model simulations did not address none of the above mentioned factors.*

  The above mentioned instrument types measure the direct and diffuse radiation. These are the quantities that we have investigated for instrument tilt errors. However, to keep the discussion general we have not addressed specific instruments. We realize that this may be of interest and in the revised manuscript we have included a short description of the type of instruments used for albedo measurements.

- *To quantify the tilt errors, the authors should set up instruments with a reference measurements. The errors can be studied by comparing the observations.*

  As stated in the title of the manuscript, this is a model study. We of course agree that the tilt errors can be studied by comparing observations and greatly value the contribution of observations. However, all measurements may be subject to some degree of error, so pure theoretical modeling studies allow one specific source of error to be closely examined using model simulations; as done in our manuscript.

  Both observational and model investigations are needed and complement each other and we agree that a detailed controlled study - such as intercomparison studies with different instruments are done - would be valuable but is beyond the scope of our intended evaluation.

  Please also see our response to the first comment by D. van As.

- *To quantify the measurement errors, the authors should know more about the instruments and measurements, and updated references in the field.*

  We would like to emphasize that the two first authors have participated in several field campaigns where albedo measurements were made over snow covered surfaces. As such we are familiar with these type of instruments and measurements and the problems associated with them. Indeed, it was while experiencing the problems with these type of albedo measurements that the idea for the present study originated.

The referee does not indicate which references are missing. However, to address the comment we include in the revised manuscript a table of relevant publications.

Response to comments from C. S. Zender (Referee)

We thank the C. S. Zender for the reading of and comments to our manuscript. The comments of C. S. Zender are repeated below in italic font. Our responses to the comments are shown in roman font.

General comments and responses

- *However, the manuscript unintentionally exaggerates the role of tilt-bias by considering only clear sky (not cloudy sky) conditions.*

  The manuscript has been updated to also discuss cloud sky conditions. However, we do consider this analysis to demonstrate the significance this error may have, particularly when one considers the importance of clear sky observations for the validation of satellite retirievals.

Specific comments and responses

- *The manuscript quotes Stroeve et al. (2006) that leveling errors dominate snow albedo measurement errors. On this basis the manuscript restricts itself to a theoretical quantification of that error, especially at the large zenith angles appropriate to polar environments. However, the Stroeve et al. claim is unverified until/unless someone examines actual AWS albedo measurements and show that removing the tilt-induced bias consistently eliminates at least half the error (e.g., versus a known good calibrated measurement like BSRN or some other metric). Has this been done? This manuscript would be more interesting if it showed readers how much better a tilt-adjusted albedo looks than a raw albedo from actual measurements. The inclusion of measurements would also add balance to this model study.*

  Measurements are the acid test of any theory. Our investigation is purely theoretical as indicated in the title. However, our model has been validated against measurements numerous times, albeit not for the specific conditions studied here. Paragraphs describing the model validation have been added to the revised manuscript. Please also see our response to the second comment by D. van As.

  We are not aware that anyone has examined "actual AWS albedo measurements" against "known good calibrated measurement like BSRN " and showed "that removing the tilt-induced bias consistently eliminates at least half the error". However, the recent paper by Wang et al. (2015) clearly shows that tilt-correction reduces errors. We were unaware of this paper while submitting our manuscript. The Wang et al. (2015) manuscript is discussed in our revised manuscript.

- *p. 4364: The manuscript mentions some effects of cloud cover, but the authors chose not to include more results because the values are entirely dependent on the definition of many separate parameters controlling the properties of the cloud cover. I disagree with this decision and think the manuscript would be more interesting if it presented* *results for homogeneous cloud cover. The manuscript is a sensitivity study that already makes numerous assumptions (flat snow, Lambertian albedo, no aerosols). Snow-covered surfaces in the arctic are often cloud-covered, and ignoring that aspect inflates the AWS tilt-errors relative to their all-sky values. It takes instrument teams months of planning, days of installation, and sometimes years of maintenance to collect their measurements. They (an TC readers) deserve a model-sensitivity study that attempts to replicate the field conditions to greatest extent possible. I suggest you expand the study to include tilt-sensitivity to some arguably representative plane-parallel 100% cloudy conditions. Apparently you have already done the calculations, so it would be a matter of incorporating them into the manuscript. Then you will have more carefully bounded the tilt problem for your readers.*

The tilt-error under cloudy conditions have been addressed in the revised manuscript. The "Discussion" and "Conclusions" sections have been re-arranged and partly re-written to include the cloudy results. Furthermore, results for cloudy situations have been added to Figs. 1 and 2.

- *p. 4366: Sensors for monitoring orientation (like inclinometers) are helpful though not required to ascertain (and thus adjust for) tilt. Our manuscript currently in review in The Cryosphere demonstrates how to estimate tilt angles from tilt-biased broad-band radiometer measurements (with adequate temporal resolution) in clear-sky conditions. The method is called RIGB (Retrospective, Iterative, Geometry-Based). It is retrospective because it works with (sub-daily clear-sky) timeseries measurements already taken, and its tilt-adjusted values have lower biases than measurements from AWS without and with (!) inclinometers (that can have their own problems). Please include in the Discussion non-invasive methods such as RIGB which can adjust for tilt without (and with!) the added expense and complication of additional instrumentation.*

  A discussion of the tilt-correction method by Wang et al. (2015) has been included in the revised manuscript.

Response to interactive comment by D. van As

We thank D. van As for the reading of and comments to our manuscript. The comments of D. van As are repeated below in italic font. Our responses to the comments are shown in roman font.

- *First suggestion would be to validate your model study where possible. Quite a few measurements or radiation and tilt have been taken over high-latitude snow and ice. A selection of these must be of use to validate various aspects of your results. I realize that you prefer to isolate the issue that is tilt, which is not something that you can do when using measurements. Yet your model does come with its own set of uncertainties, and it is important to have them addressed properly - and the most convincing method is by validation against measurements. You can argue that tilt dominates any other signal in the model, more that those related to e.g. atmospheric assumptions; but likewise you could then argue that tilt errors will dominate in measurements, especially for relatively low zenith angles.*

  Validation of radiative transfer models is not simple. Closure experiments where all input to the radiative transfer model and the radiation quantity of interest have been measured, have rarely been performed even for "simple" atmospheric and surface condtions. The radiation model used in this study has been validated against both other models and measurements. These validations are summarized in Mayer and Kylling (2005). For tilted surfaces the model has been successfully compared against extremely tilted surface as shown in Fig. 13 (Mayer and Kylling, 2005) and reproduced here in Fig. 1.

  Similarly the model has been compared for large solar zenith angles (up to 94°) to, for example, ballon measurements, by Kylling et al. (2003). The model has not been validated against a measurement study dedicated to small tilt angles for large albedos and large solar zenith angles. However, in the above cited studies the model has been successfully compared against measurements made at large solar zenith angles and extreme tilt angles.

  A dedicated validation study for various tilt angles under a high sun is certainly warranted but beyond the scope of this investigation. To design and perform such a study is by no means simple. Kreuter et al. (2014) compared several UV and visible spectrometer measurements in the Arctic with a detailed 3-D version of the radiative transfer model used in the present study. A detector tilt of about 1° was one of the plausible explanations for the differences between measurements and simulations observed at one of the measurement stations.

  To address the comment we have added the following paragraph to section 2.1 of the manuscript:

  > The libradtran radiative transfer model has been compared and validated against both other models and measurements. A summary of these are given in Mayer and Kylling (2005).

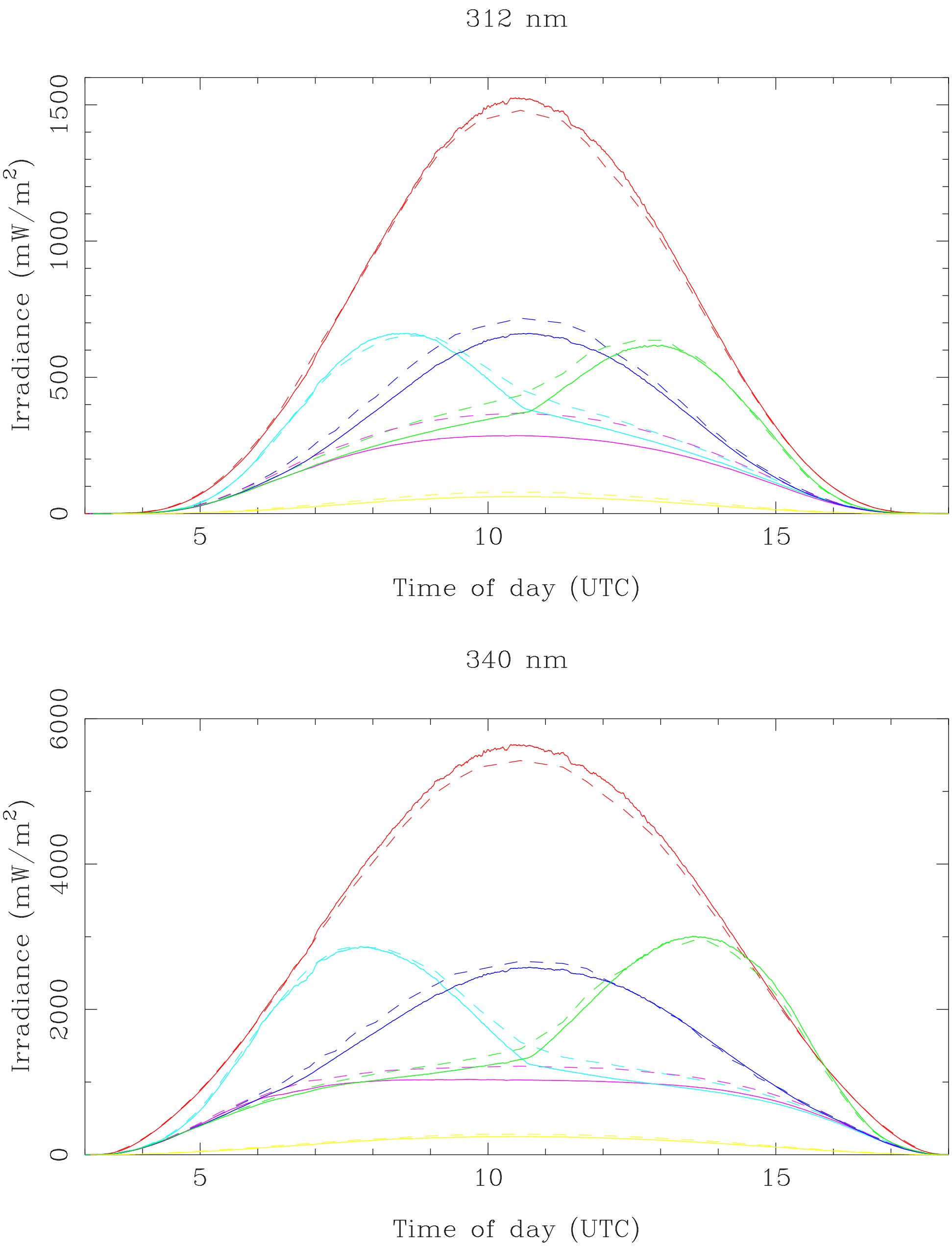

Figure 1: Measured and simulated NILU-CUBE irradiances as a function of time. The measurements were made on 5 Aug, 2000, at Nea Michaniona, Greece, as part of the ADMIRA project (Webb et al., 2002). The downwelling irradiance is shown in red, the upwelling in yellow. The magenta, blue, green and purple colored lines represent the vertical east, south, west and north irradiances respectively. Reproduced from Mayer and Kylling (2005).

To the end of section 2.2 we have added:

The angres tool combined with output from uvspec has been succesfully

> compared against measurements for levelled and extremely tilted (90°) sensors by Mayer and Kylling (2005, Fig. 13).

Finally we have added the following text section to the discussion section 4.

> This was exemplified by the study of Kreuter et al. (2014) who compared several UV and visible spectrometer measurements at a coastal site in the Arctic with a detailed 3-D version of the radiative transfer model used in the present study. Besides changes in drift ice, aerosol and distant high clouds, a detector tilt of about 1° was one of the plausible explanations for the differences between measurements and simulations.

and the following to the Conclusions:

> The measurements made by the AWS stations are extremely important to follow the changing climate. As such increased understanding of the importance and quantification of the tilt error is warranted. Thus, a dedicated validation study for various tilt angles under a high sun and high albedo is warranted. Such a study should also include the testing and validation of tilt-correction methods.

- *Secondly, I've been working on tilt corrections for weather station measurements, e.g. in Van As D (2011) Warming, glacier melt and surface energy budget from weather station observations in the Melville Bay region of northwest Greenland. J. Glac., 57 (202), 208-220. We also provide our data with a tilt-corrected value. Yet I am sure that there is still much to gain in such corrections. It would be very valuable to anyone measuring shortwave radiation (and sensor tilt), and thus for the impact of your paper, if you could provide an alternate method for tilt correction, to not only point out, but also remedy tilt issues.*

Tilt correction methods applicable to all situations are not easily developed. In the revised manuscript we have added a discussion of various tilt correction methods and their strengths and weakness. We also suggest a way for further refinement of an existing method. The following paragraphs have been added to the manuscript in the Discussion section.

> Any tilt correction method will depend on the information available about tilt and rotation of the instrument. Furthermore, the tilt correction will depend on the state of the atmosphere. The need and importance of tilt correction depends on the use of the data. Satellite validation requires cloud free data for which the tilt error is one of the major uncertainties and reaches a maximum. For studies including all weather data the cloudy data will be less affected by tilt errors.
>
> In the case where no information is available about tilt or orientation and the state of the atmosphere, 24 hrs running averages have been used by several authors, including van den Broeke et al. (2004) and Stroeve et al. (2013). While this approach may intuitively be appealing it will miss

any daily variation in the surface albedo and, as shown above, may, for example, give errors around ±5% for sensor tilts of 3° for Summit, Greenland over a two month period around solstice. These shortcomings are largest for a cloudless sky and 24 hrs running averages may be justified under stable cloud conditions. If tilt and rotation information is available, this may be used to correct the downwelling shortwave radiation. Using inclinometer and compass information Van As (2011-04-01T00:00:00) tilt-corrected the direct component of the downwelling shortwave radiation. Wang et al. (2015) recently presented a retrospective iterative geometry-based tilt correction method. For cloudless sky measurements the tilt and rotation angles are estimated by finding the modelled insolation for various tilt and rotation angles that best agrees with the measured insolation. The estimated tilt and rotation angles may subsequently be used to correct both cloudless and cloudy measurement data. Wang et al. (2015) show that this tilt correction method gives lower biases both for unadjusted measurements and also for measurements tilt-adjusted using inclinometer information. This method requires no extra measurements of tilt and orientation to be made. It may thus be used for all past radiation measurements where such information is not available. Another tilt-correction method was presented by Weiser et al. (2015). It, however, requires data from a nearby levelled sensor, and as such is not applicable applicable for most long-term installations such as AWS stations.

The simulations presented here demonstrate that the impact of the tilt error is largest for cloudless skies. It is also these measurement conditions that are used for satellite validation. The impact of the tilt error decreases in the presence of increasingly optically thicker clouds. This is caused by changes in the ratio of diffuse versus global radiation. Tilt correction methods that rely on knowledge about this ratio may benefit from the estimates of this ratio.

AWS stations provide long term records of essential climate variables. As such, methods to correct past, present and future data where limited ancillary information is available, is of great value. The method presented by Wang et al. (2015) may be used for this purpose. It does require assumptions about the cloud fraction. An alternative way for estimating the cloud fraction may be to 1) identify truly cloudless data to obtain tilt information using the RIGB method; 2) Calculate albedo for the cloudless days; 3) For cloudy days use a method similar to Stamnes et al. (1991) to obtain estimate of cloud optical depth (and hence indirectly cloud fraction) Here the albedo from 2) is used; 4) Perform tilt correction for cloudy days based on tilt information from 1) and cloud fraction from 3). For future instrument deployments it may be worthwhile also considering increasing the time resolution of reported data, if feasible, to provide more data to the RIGB and other tilt-correction methods.

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