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.

  Similarily 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).

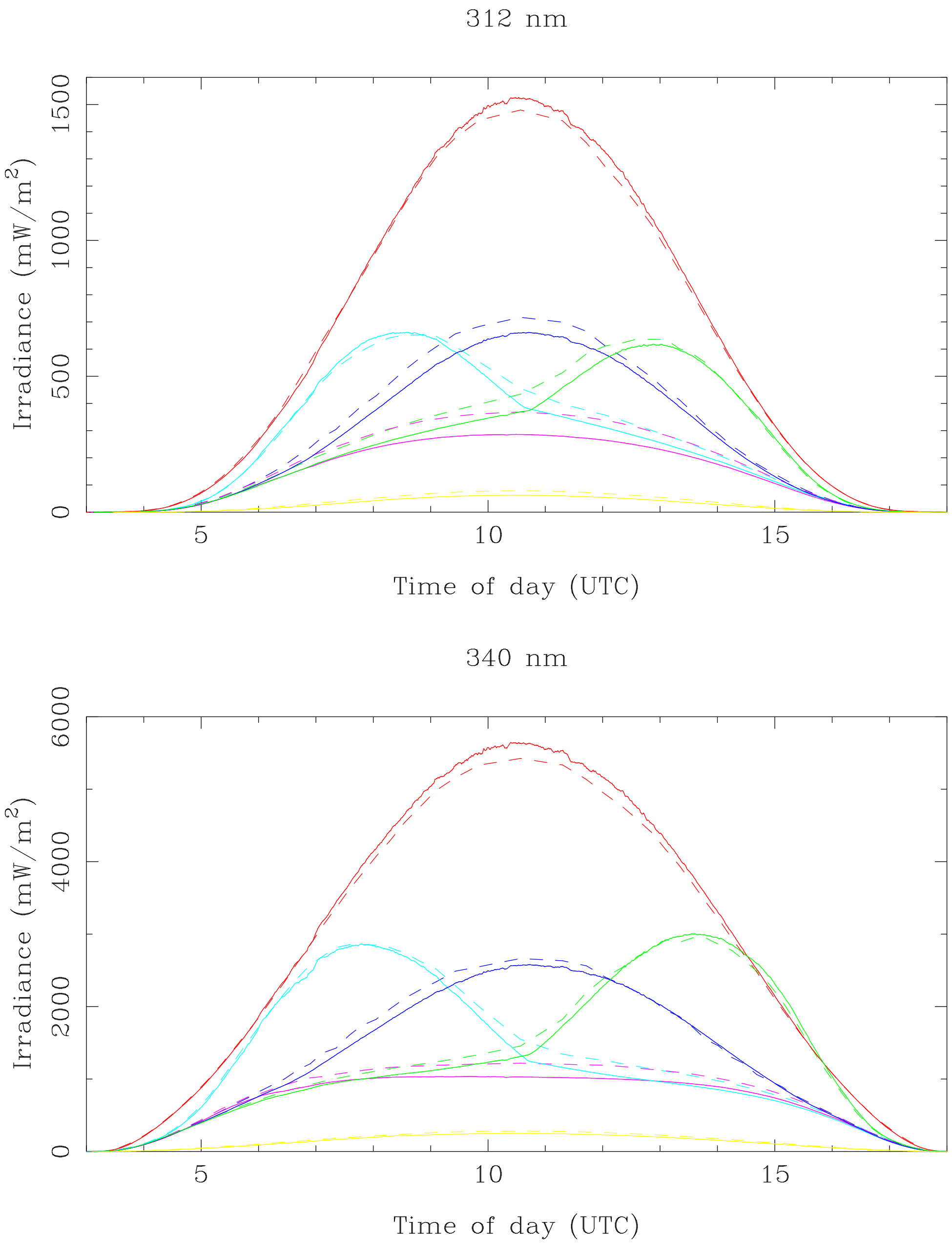

Figure 1: Measured and simulated NILU-CUBE irradiances as a function of time. The measurements were made on 5 Aug, 2000, at Nea Michaniona, Greece, as part of the ADMIRA project (Webb et al., 2002). The downwelling irradiance is shown in red, the upwelling in yellow. The magenta, blue, green and purple 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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