Dear Editor

The paper has been fully rewritten and the title changed accordingly to Referee 2. Figures have been updated in order to answer to the well-posed questions of the reviewers. The general structure of the paper has been changed and additional paragraphs introduced. All typos have been corrected.

We thank all reviewers for the helpful comments and suggestions on how to improve the manuscript. In the course of revision of the manuscript several changes were made. Therefore, some of the suggestions have been included and others were obsolete due to the changes in the manuscript. Please see our answers to the points below:

Answer to the General Comments of Reviewer # 1, R. Hellstrom:

Although I feel this contribution is very useful for correcting instrument orientation anomalies in ground-based measurements of albedo and global radiation, I advise minor grammatical and technical revisions throughout the manuscript prior to publication. In addition, I urge the authors to include a few examples of applications for polar and alpine studies that would benefit from the albedo measurement correction. Suggested edits below:

pages throughout [consider changing "directions" to azimuths, the more commonly accepted terminology]

We decided to leave "directions" or "aspects", as they refer to slope- or a sensor-tilts

p. 2710 line 17, rephrase sentence: Once the under lying snow/ice is isothermal, the energy balance of a glacier surface defines the amount of …

Rephrased.

line 23, "physical conditions" is very broad => environmental or meteorological

Due to changes in the manuscript this part is now changed.

line 23, "snow cover" is too specific => glacial surface or glacial morphology

Due to changes in the manuscript this part is now changed.

p. 2711 line 3, be several 100% is odd and difficult to read, try Many publications . . .can (more than double) when . . .

Due to changes in the manuscript this part is now changed.

line 5, define what you mean by diurnal albedo, as diurnal commonly refers to daylight and nocturnal conditions.

With 'diurnal' we mean the diurnal cycle of albedo during one day.

line 15, underestimation of "global radiation", define this clearly as the sum of incoming direct and diffuse shortwave (solar) radiation.

Due to changes in the manuscript this part is now changed.

line 19, small "opening angle", this is not a common term used in optics, better to use "field of view", such as narrow field of view replace throughout

Thank you, changed.

line 22, add sentence stating it is nearly impossible to maintain a constant sensor orientation (tilt) on snow and ice surfaces because of metamorphism and hence changes in micro topography.

Due to changes in the manuscript this part is now changed. The sentence was added in next section.

p. 2712 line 19, on "a" preceding overcast day. change clouded to overcast (a more common term)

Thank you, changed.

line 27, albedo measurement is fitted to contrast, (eliminate "developed and" since your intent is to focus on measured data)

Due to changes in the manuscript this part is now changed.

p. 2713 line 10 and throughout your manuscript you must always define the units of variables as they are defined for equations. Fup, reflected and Fdown, global radiation (W m-2 or W/m2)), This helps the reader and author recreate the experiment or derivation of equations.

We added am appendix with all used symbols and their units added.

line 22, both the "slope" and the sensor, (replace slope by glacier surface to be more explicit)
Due to changes in this part of the manuscript this part is now changed.

p. 2714 line 6, within two opposite . . . (replace opposite with opposing)

Thank you, changed.

line 17, again, replace all occurrences of “opening angle” with “field of view”

Thank you, changed.

line 23, A solar panel alone does not serve as the power source, so add A solar panel "and battery" serve as a power supply..

Thank you, changed.

line 25, use of an inclinometer should be highlighted earlier in this section since it is a critical measurement in your approach

Due to changes in the manuscript this part is now changed. Mentioned earlier.

p. 2715 line 3, awkward sentence starting with Due to . . .eliminate this and state, (The orientation of the AWS on the glacier changes continuously and is therefore estimated with an uncertainty . . .) since the sensor is fixed to the AWS support hardware.

Due to changes in the manuscript this part is now changed.

line 6, cannot have just a sentence sitting alone like this, please add your reasoning for choosing one, ten, and sixty minute averages to expand.

Due to changes in the manuscript this part is now changed.

line 8, this sentence is difficult to read, use active voice instead of “is used” . . .rewrite as, We used data from Suntracker, which is .. Network (BSRN) to determine the optical properties of the . . . radiation.

Due to changes in the manuscript this part is now changed.

Line 12, opening angle => field of view

Changed.

line 14, eliminate the word employed, not needed

Changed.

p. 2716 all equations should have units [W m-2] either in the previous definition of variables on simply after your equations

We added am appendix with all used symbols and their units added.

line 22, parameters e and V are non-dimensional, right, since S is [W m-2]

Yes, epsilon and V are dimensionless, see appendix.

*p. 2717 equation 7, cos thetatilt = Fdownbold * n, you need to clearly define Fdownbold as a vector direction, not Fdown magnitude [W m-2], otherwise your equation does not make sense as non-dimensiona. Maybe state that the bold version of variables is the direction component only, not the magnitude. This is just to be clear for some readers of your paper. You may consider a table to clarify your parameters, variables and units/vectors . . .an Appendix of Parameters and Variables at the end?*

Thank you, we clarified this in the text, bold symbols are defined as vectors, the Appendix with all used symbols and their units was added.

p. 2719 Maybe after equation 17, add a sentence stating that the previous derivation assumes a constant azimuth angle of theta tilt (south).

Added.

p. 2720 line 4, . . .the incoming irradiance "hitting", change to orthogonal or perpendicular to the up-facing . . .

Changed.

equation 19, because Fup/Fdown appears to only multiply Pdiff, you need to add ( ) to indicate it multiplies both terms.

Added.

p. 2723 equation 24, units W m-2, and the < > brackets indicate the average of daylight reflected solar radiation equation at bottom needs parentheses around the numerator and denominator to clarify

( ) added, Appendix with all used symbols and their units added.

p. 2724 line 6, remove "as well as" replace by and

Changed.

line 10, The shortwave "radiative balance" . . . is more specifically called the net shortwave radiation, SW [W m-2] Also, I suggest the symbol change to SWnet rather than SW.

Thank you, we changed this.

p. 2725 line 9, the lower (down-facing) pyrometer is 180 degrees in the opposite direction of the up-facing, so the direction is 90 degrees or easterly

Sentence removed.

line 13, this should not be a new paragraph, since there is only one sentence above, combine

Combined.

p. 2726 line 24, smaller than in winter months due to a (lower) zenith angle in summer, rather than "different."

Changed.

p. 2727 This discussion is too brief, should add a couple examples of where your approach could help increase accuracy of albedo measurements. Reference studies of albedo in high latitudes over snow and ice, or instances where high zenith angles occur.

We rewrote the discussion section.

line 25, change "flat" to greatest

Due to changes in the manuscript this part is now changed.

p. 2728 line 12, "cut-offs" is not specific enough, try "extreme climates and time constraints"

Due to changes in the manuscript this part is now changed.

line 19, this sentence would read better if your remove ", which"

Due to changes in the manuscript this part is now changed.

p. 2729 line 10, replace the word "flat" with high or "close to the horizon"

Due to changes in the manuscript this part is now changed.

line 20, same thing You need to make it clear that your approach to correcting albedo, equation 20, requires that AWS units incorporate 2-axis inclinometers to obtain tilt and azimuth of the pyronometer

Due to changes in the manuscript this part is now changed.

Figure 2. angle sigma should be sigmat for the tilt angle and vector Fdown from the solar

beam appears almost parallel to the tilted surface . . .you might consider decreasing thetaS so the solar beam zenith is different than the tilted surface

Changed into sigma_t, we decided not to change theta_s, because a similar figure shown in 2D to clarify solar beam reaching a different tilted surface.

Figure 10. It is confusing when you use SW to represent what you call the radiative balance (net solar radiation is better), you might consider representing the net radiation as SWnetmeas and SWnetcorr.

We decided to change this Figure, due to the consistency with the manuscript.

Answer to the General Comments of the Short Comment of G. Picard:

The paper proposes a method to correct broadband albedo measurements from errors caused by the unknown slope of the under lying surface and the imperfect levelling of the sensor. This problem is common and not often addresses in the literature. This makes the goal of this paper important. Unfortunately the paper and more specifically the introduction and first subsections of the method are not well written, not rigorous enough and as a consequence subject to mis-interpretation. Many statements lack proper references, are vague or are only valid for a very specific context (e.g. alpine conditions) without this context being explicit. This is incompatible with the international audience of The Cryosphere. The

discussion is short and provides too basic information. At last, the terms referring to optical variables do not follow scientific standards or are not precise enough (in the introduction, this improves in the other sections). Various terms seem to be used for the same meaning (e.g. radiance / irradiance, global / total, directly, . . .) which is confusing.
The description of the direct model and the fitting approach is exhaustive and well done. The assumptions are also clearly stated. However, the assumption that the (true) albedo of snow surface is constant over the day is overoptimistic. It is well known that snow albedo depends on the solar zenith angle and many studies present this result through analytical derivation, experimental results or numerical computations.
The correction proposed by the authors relies on the measured albedo variation as a function of the SZA during the day and is designed to minimize the albedo variations during each day. By doing so, it remove not only the geometrical artifacts (which is good) but also the variations of physical origin (which is bad). It over-corrects the albedo and it is difficult to know if the corrected one is better than the un-corrected one. To solve this major issue, it is suggested to either include theoretical/analytical calculation of snow albedo into the direct model presented in the paper or, at least, show a few computations (or find some data) to evaluate the relative effects of the slope versus “normal” sza dependence and demonstrate the physical variations are second order compared to geometrical artifacts.
As a conclusion, the method presented in this paper may be interesting once the albedo dependence to SZA is taken into account and the text is improved. The following detailed comments should help for a first correction. At last English should be revised.

Detailed comments:
** P2710 L17 “The energy balance of a glacier surface defines the amount of energy available for the ablation processes, once the underlying snow/ice is isothermal”.*
Please clarify isothermal. Do you mean “reach freezing point” ?

We refer here to the freezing point as we are on a glacier, isothermal means a constant temperature.

** P2710 L20 What is an “isolated area of a glacier” ?*
‘isolated’ changed into ‘remote’

** P2710 L25 “ideally southwards”. Specify in which hemisphere*

Due to changes in the manuscript this part is now changed.

** P2710 L25 it is not clear what “changing conditions” refers to: weather, snow or instrument ?*

Due to changes in the manuscript this part is now changed.

** P2711 L1 “In the method described in this paper”. Give first the objective of the paper. It is not clear at this point that the paper is about a method (introduction must be independent of the abstract).*

Due to changes in the manuscript this part is now changed. References were added and we explained it in more detail.

** P2711 L1 “cosine law” is not clear for most readers, especially when it is used to refer to the error with respect to the ideal cosine law. Give a reference or details and check throughout the paper the use of this term.*

Due to changes in the manuscript this part is now changed. References added and explained in more details.

** P2711 L3 “Many publications”. Give references of several of them.*

Due to changes in the manuscript this part is now changed. More references added.

** P2711 L9 “caused by the specular components of daily albedo”. What is “daily” albedo ? Is it the averaged ? Explain also “specular components” (especially the plural).*

Explained, rephrased and referenced. (specular reflections)

** P2711 L14. Remove the parenthesis*

Corrected.

** P2711 L14 “global radiation”. The term global is not clear. Correct throughout the text.*

Due to changes in the manuscript this part is now changed. It is now explained better in the text.

** P2711 L19. References needed.*

References added.

** P2711 L23 “described problems of albedo” is vague*

Due to changes in the manuscript this part is now changed.

** P2712 L7 “These results are essential because albedo of a forest is expected to be almost constant, in contrast to snow albedo which changes over time.”. It is not clear why the result is essential.*

Due to changes in the manuscript this part is now changed. Also explained better with more details in the text.

** P2712 L12 “Extinction coefficient” seems to be misused here. Do you mean optical depth ?*

Rephrased and References added.

** P2712 L19 “on preceding clouded day” → cloudy. Check everywhere.*

Thank you, changed.

** P2712 L20. Not sure the reference Weiser, 2012 is perennial and useful for many readers (not in English and no doi). Understanding the text should not depend on it.*

Due to changes in the manuscript this part is now changed.

** P2712 L20-21. The sentence is difficult to understand. The value +0.15 depends on the solar zenith angle (+other parameters). Precise the conditions (latitude/period of the year or sza).*

Due to changes in the manuscript this part is now changed.

** P2713 L5. Equations must be ordered (first is (1), second is (2), . . .)*

Equations ordered.

** P2713 L14. References needed.*

Due to changes in the manuscript this part is now changed.

** P2713 L15. What is "Realistic physical range" ?*

Due to changes in the manuscript this part is now changed. Ranges listed in results and explained in details what is expected.

** P2713 L18. "the tilts of the sensors increase over time". This statements is not always true. Give references, examples or remove it.*

Due to changes in the manuscript this part is now changed. Explanations and references added.

** P2713 L20. "Reasonable" is subjective, remove. Define "diurnal mean albedo"*

Due to changes in the manuscript this part is now changed. Definition added.

** P2713 L21. "The method described in the present paper shows how to correct the true albedo with unknown tilts and directions of both the slope and the sensor." → the present paper proposes a method to correct measurements of albedo . . .*

Due to changes in the manuscript this part is now changed.

** P2713 L23. "the direct incoming radiation being reflected diusely". Do you mean the reflected radiation ?*

Due to changes in the manuscript this part is now changed. Explained in Discussions and demonstrated in Figure 4.

** P2713 L24. "the slope of the observed apparent diurnal variation of albedo". Which slope ?*

Due to changes in the manuscript this part is now changed.

** P2714 L17. "For an opening angle of 160 the cosine error" is not clear.*

Due to changes in the manuscript this part is now changed.

** P2715 L1. “0.5 %”. Do you mean 0.5 degrees or 0.5% of something that must be specified in the text?*

The error details are taken from the data sheet.

** P2715 L5. “5%”. Where this value comes from ?*

The error details are taken from the data sheet.

** P2715 L10. References needed for BSRN and Suntracker.*

References added.

** P2715 L18. Remove “described”. It is not yet described.*

Due to changes in the manuscript this part is now changed.

** P2715 L20. The assumption of constant broadband albedo seems not reasonable because snow and probably concrete albedo has a strong dependence to SZA and spectrum of the incident radiance.*

Due to changes in the manuscript this part is now changed.

** P2717 L5. “As most glaciological measurements “ unnecessarily subjective. Rephrase.*

Rephrased.

** P2719 L13. “On a real measuring site,” → in practice*

Rephrased.

** P2720 L18. Epsilon is not an extinction coefficient. It includes the path length (which is not constant) and should be renamed to avoid confusion.*

References were added to epsilon.

** P2720 L1. Assumption 3 is very strong! Discussion and evaluation of this effect should be done especially regarding the statement P2716 L18.*

Due to changes in the manuscript this part is now changed.

** P2720 L3. Reference is needed for the assumption 4*

Due to changes in the manuscript this part is now changed.

** P2721 L12. Give details on the time resolution and the hours (or sza) used for the fitting.*

Due to changes in the manuscript this part is now changed.

** P2721 L11 and L19. Is V a atmospheric parameter ? Or is it mainly related to the sensor ?*

Due to changes in the manuscript this part is now changed. Meaning of V explained. V is the ratio between spectral range of pyranometer and TOA irradiance

** P2721 L15. "Radiation model" is not clear. Which equation is it referring to ?*

Explained earlier in the text. Refers to the solar position algorithm (SPA).

** P2723 L23. I don't understand the sentence with "... where... where..."*

Due to changes in the manuscript this part is now changed. Meaning of V explained.

** Section 2.3.3 is obscure. E.g. P2723 L5 "factor C should be as constant as possible" and the following sentence: "the constant C" and again at the end of the section "C is as constant as possible".*

Rephrased.

** P2724 L2. I don't understand "flat" zenith angle.*

Due to changes in the manuscript this part is now changed. 'Flat' should be 'high'.

** P2724 L6. What is "SD" ?*

SD = standard deviation, it is now explained in the text.

** P2724 L11. Remove the middle equation*

Removed.

** P2724 L14. I don't understand*

Alpha means albedo in general, measured, modeled, corrected and true albedo.

** P2724 L20. Where are the results/data ?*

References to Tables with results added.

** P2724 L21. Not sure to understand “weighted”.*

Due to changes in the manuscript this part is now changed. ‘Weighted’ means ‘determined’, but sentence rephrased anyway.

** P2724 L21. How the range is obtained ? Can it be shown in a figure ? Why is it so large ?*

Explained, referenced and discussed.

** P2724 L22. This is not shown by the results and should be moved to the discussion (with references).*

Due to changes in the manuscript this part is now changed.

** P2724 L22. Same question. Why such a ranges ?*

Explained, referenced and discussed.

** P2725 L24. I don’t understand.*

Rephrased and paragraph added for explanation.

** P2725 L25. Remove “Reasonable” and give uncertainty range or other scientific arguments. As far as I see, the corrected albedo is not more constant than the uncorrected one (please give standard deviation or any statistical metric that can help to give objective arguments). It means the correction is not efficient, can you comment on this ?*

Due to changes in the manuscript this part is now changed. Detailed explanations given are in the discussion section.

**P2726 L13: “acceptable zenith angles” is subjective. Again L14*

Due to changes in the manuscript this part is now changed.

**P2726 L22: observed albedo ?*

Rephrased and explained in more details.

** P2727 L2: “directly” is not clear and not used before, which is disturbing.*

Due to changes in the manuscript this part is now changed.

** P2727 L3: remove "(true)". True albedo is the goal. Estimated or corrected albedo is ok.*

Due to changes in the manuscript this part is now changed. We decided to still use 'true' albedo, because the true albedo is the unknown albedo we want to find.

**P2727 L25: "flat" is not adequate + I don't understand the end of the sentence.*

Due to changes in the manuscript this part is now changed.

**P2728 L3: which "direction" ?*

Due to changes in the manuscript this part is now changed.

**2729 L10: "flat"*

Due to changes in the manuscript this part is now changed.

**2729 L10: "differences" between what ?*

Due to changes in the manuscript this part is now changed.

**2729 L20: "flat"*

Due to changes in the manuscript this part is now changed.

Figures 3 and 5. Instead of using UTC for a specific day and latitude, why not to compute as a function of SZA ? Otherwise, add the relevant information of latitude and day in every figure and in the text.

We decided to leave UTC and not add a specific day, as these Figures show the diurnal variation of albedo when either the slope or both, the slope and the sensor is tilted, no matter which surface in any area is observed.

Figure 4. Can be removed because it is not useful unless angle notations are added.

We decided not to remove it for better understanding.

Figure 5. The colors of the curves should be taken from a circular continuous color scale. South and north facing could be shown with a stronger face (instead of showing the 315 degrees curve with dash).

Colors are continuous now, we left the output values, as there are shown four different Figures with different tilts and directions.

Figure 6. Title should include "... and compute the net SW radiation"

Changed into: net shortwave radiation balance.

Figure 7. the albedo labelling on the right y-axis needs to be extended down to 0.

Irrelevant, because only SZA<50° was considered.

Solve the overlap of the date and label on the x-axis...

Solved

The cyan color should be avoided.

We decided to leave the color.

Most figures: Units should be written without slash, use scientific notation.

Symbols and units explained in the Appendix with scientific notations.

Answer to the General Comments of Reviewer # 2:

General comments

This paper presents a method to correct snow and ice broadband albedo measurements affected by tilts of the surface and pyranometer, when the latter are unknown. For this, the tilt of the pyranometer is first estimated using a reference measurement from a nearby leveled sensor. The tilt of the surface is then fitted in a simple radiative transfer model to match the measured diurnal cycle of albedo, assuming that the true albedo is constant over a day of measurement. Once both tilts are determined, the true albedo of the surface can be computed from the measured one. The question of albedo measurements errors due to tilts is critical because i) these errors can significantly impact the estimated surface energy budget of snow and ice surfaces and ii) such albedo measurements are used in a wide range of applications by users not necessarily aware of the complexity of performing accurate albedo measurements. Hence proposing a method to correct albedo measurements is of great interest and the ideas developed in the present paper are interesting. Unfortunately, the method proposed relies on questionable assumptions. In particular, it neglects the dependence of snow albedo on solar zenith angle, which represents a significant shortcoming. In addition, the overall manuscript is poorly written, the introduction and discussion being particularly hard to follow for the reader. The structure generally lacks of organization and clarity which makes very difficult for the reader to understand the ins and outs of the method. The multiplication of inappropriate or approximate terms along with too abundant equations exacerbates this feeling. As is, the manuscript does not meet the standards *required for publication in The Cryosphere, and should not be accepted unless substantial parts are entirely rewritten and major corrections are made.*

Specific comments
1) The manuscript is overall poorly structured, with many repetitions, misplaced information and inappropriate content. Several paragraphs are made of a single sentence which perturbs the flow of reading. The abstract could be substantially improved, for instance by adding a context sentence and illustrating the main results with numerical values.
The introduction fails to introduce the context, issues and approach of the study. These ideas are indeed presented in a very fuzzy way, without an obvious consistent organization. Hence it is difficult for the reader to understand what the authors really aim at doing before the Methods section. The last paragraph is more clear but a description of the paper organization would be very helpful at this point. I would recommend the authors to rewrite completely the introduction, following generic steps such as: i) Context: surface energy balance of snow surfaces critically depends on snow albedo ii) Problematic: accurate albedo measurements are difficult to perform because of tilt errors iii) Objective: developing a method to correct albedo measurements since current methods are not satisfying iv) Approach: simple geometric considerations and use of a leveled pyranometer to estimate successively pyranometer and slope tilts, from which the true albedo can be retrieved.
The Methods section is more clear but several paragraphs are unnecessary or should be moved to the introduction. Many equations are displayed while some of them could/should be skipped. There is some redundancy between the model description and the algorithm description that come in two distinct sections. See more details in Technical corrections.
The Results section is too abrupt. For each experiment described, the context should be reminded to the reader for more clarity.
The discussion is currently a succession of independent sentences that form individual paragraphs. It contains information that should be placed in the introduction or Methods and does not discuss much about the results.
As for the conclusion, it does not provide any perspectives for future work or consequences of this research, while this is the main interest of proposing a method tocorrect albedo measurements.

The abstract and introduction has been rewritten and a description of the paper organisation was added. The methods improved and more details added. More results and errors were added. The discussion has been rewritten, also the conclusions.

2) A major flaw of the study is the assumption that the albedo of a snow surface is constant throughout the day. In fact, snow albedo varies with the solar zenith angle (SZA), which generates a diurnal cycle (e.g. Wang et al. 2011). This effect might be negligible compared to tilts errors when the latter are very large (e.g. 25 ◦ in the text) but probably becomes significant for small tilt errors and at high SZA. As a consequence, using a concrete surface to validate a method dedicated to snow surfaces is not ideal because snow and concrete do not reflect light the same way. I'd recommend to use a

parameterization of albedo that accounts for this dependence. Carroll and Fitch (1981), Gardner and Sharp (2010) and Kuipers Munneke (2011), among others, propose that kind of parameterizations. At least, the limits of the constant albedo assumption should be discussed in more details, and the method adapted in consequence.
The assumptions have been improved, referenced and explained in details in the rewritten discussions. The appendence of the albedo of SZA has been eliminated, as we only used SZA ranges <50°. The validation of albedo of concrete is not explained to show the reflectivity of the surface, it proves that albedo of any surface has to be corrected on clear-sky days when either the sensor or the surface or both are tilted.

3) The manuscript makes reference to only 17 studies (10 in the introduction). This is clearly not enough for a topic that has already been largely investigated. This number should be at least doubled to strengthen the argumentation and method. Some suggestions are made in the Technical corrections. Currently, the few studies used as references are poorly used. In the introduction they mostly appear as a concatenation of previous works without any clear progression from one to another. Furthermore, the description of these studies is often unclear (e.g. Dirmhirm and Eaton (1975)).
Much more references are added and used, since the abstract, the introduction, the discussion and the conclusions have been rewritten and the methods changed into a more scientific section.

4) The use of inappropriate or unusual terms in the text (e.g. "global radiation" or "flat zenith angle") sometimes makes it complicated to understand their meaning. The unnecessary multiplication of inter mediate symbols in the formula also participates to an apparent complexity of the method while it is actually not complicated. Efforts should be made to make the reading easier.

All terms have been explained now and unnecessary terms have been removed. An Appendix with all used symbols, their explanations and units has been added. The workflow is more comprehensible now.

Technical comments
NB: Italic indicates suggested vocabulary changes
Title: It is too fuzzy. What kind of albedo is corrected? Broadband, spectral? On which surface? Any, concrete, snow, glaciers? What does geometry refer to? Also, the correction is not "due to" unknown geometry, it is a necessary consequence of it. Suggestion: "Correction of [broadband] snow albedo measurements affected by unknown slope and sensor tilts"

Title changed.

Abstract: l.1: This first sentence is vague. "can be relatively high" should be more quantitative. The tilt errors (slope and sensor) should be mentioned as soon as possible.

Due to changes in the manuscript this part is now changed.

l.2: Clearly state that the present paper proposes a general method of correction. Then describe the method.

Due to changes in the manuscript this part is now changed.

l.6: is needed – is used

Due to changes in the manuscript this part is now changed.

l.10: can be corrected – are corrected

Due to changes in the manuscript this part is now changed.

Introduction: p.2710 l.1: remove "reflected solar radiation and hence" because reflected solar radiation is determined by (not "depends on") albedo. Add reference.

Due to changes in the manuscript this part is now changed.

l.2: the surface energy balance of a glacier defines...

Changed.

l.20: before saying that tilts are difficult to estimate, state that tilts alter albedo measurements

Agreed. Due to changes in the manuscript this part is now changed.

l.23: what are "physical conditions"?

Description added. Due to changes in the manuscript this part is now changed.

p.2711 l.1: what is "the cosine law"?

Description added. Due to changes in the manuscript this part is now changed.

l.2: "other measurement errors and uncertainties" is unclear

Description added. Due to changes in the manuscript this part is now changed.

l.3: you mention "Many publications" but don't provide a single one with such numerical values

References were added.

l.9: "specular components of daily albedo" is unclear

Explained, rephrased and referenced.

l.19: add reference

References were added.

l.23: detail the kind of "problems" mentioned in that paper?

Due to changes in the manuscript this part is now changed.

p.2712 l.7: specify why snow albedo changes with time? Maybe mention SZA effect, metamorphism, preferential orientation of surface roughness... (e.g. Pirazzini et al., 2004)

Due to changes in the manuscript this part is now changed.

l.9: it is not clear why they consider "the extinction through the atmosphere". More generally the work of Allen et al. (2006) is difficult to understand

Explained and rephrased.

l.12: "in the following" is awkward. Prefer "contrary to" in the next sentence.

Due to changes in the manuscript this part is now changed.

l.19: clouded – cloudy (also elsewhere in the text)

Thank you, changed.

l.20: it is not clear what Weiser (2012) has done with regards to Mannstein (1985)

Due to changes in the manuscript this part is now changed.

Methods p.2713 l.4: title of subsection does not sound like a method. Most of this subsection should be merged with the introduction

Title of subsection left, because the explanation of albedo over snow and ice surfaces is essential for the described method. Contents rewritten.

l.5: avoid to make a reference to an equation that appears later in the text

Removed.

l.5: "in turn" is inappropriate, there is no causal relation between both assertions.

Removed.

l.8: global – incident

Changed.

l.13: add reference

Rephrased and references added.

l.15-17: add reference

Rephrased and references added.

l.18: explain why tilts increase over time

Explained

p.2714 l.1-4: too general. The reader has no idea how the method concretely works

Due to changes in the manuscript this part is now changed.

l.9-12: consider removing this paragraph and adding a reference after "pyranometer" instead

Paragraph left because accurate measurements are essential in this manuscript, also the sensitivity of the used sensors. Reference added.

l.17: cosine error should be defined or a reference should be added (e.g. Grenfell et al., 1994)

Due to changes in the manuscript this part is now changed.

l.20: maybe add GPS coordinates and Table 1 here

Due to changes in the manuscript this part is now changed.

l.26-28: is the full description of the inclinometer necessary for the understanding of the method?

Description left because accurate measurements are essential in this manuscript, also the sensitivity of the used sensors.

p.2715 l.8: at this stage, it is not clear what the optical properties of the atmosphere are and why they are needed?

Due to changes in the manuscript this part is now changed, and explained in detail.

l.18: the method has not yet been described, so the reader does not understand why measurements on concrete are presented.

Due to changes in the manuscript this part is now changed.

l.20-21: how does this reference serve the manuscript?

This reference defines the albedo values of concrete, which is important for the described method because the experimental measurement proves that albedo on clear sky days has to be corrected when either the slope, or the sensor or both are tilted.

l.22: for sake of clarity, it might be useful to have an overview of the method with the main steps before to start the detailed description of each step. This might correspond to subsection 2.3.

Overview added at the end of the Introduction.

p.2716 l.3: check the consistency of the terms (irradiance is in Wm-2). The various terms "irradiance", "solar radiation", "radiant flux" are quite confusing. Do they all actually correspond to distinct quantities?

All terms explained, we also added am appendix with all used symbols and their units added.

l.15: This formula is probably valid only for clear atmospheres without multiple scattering. If this is the case, specify here (and maybe in the abstract and/or introduction) that the method is valid only for clear skies.

It is explained earlier that the whole method of correction is valid for clear sky days and why it is not used on cloudy days.

l.22: please clarify the difference between Sterr and I. Also it seems that Sterr is the measured solar radiation, not the full solar radiation as suggested by the definition l.10.

All terms explained, we also added am appendix with all used symbols and their units added.

p.2718 l.2: is it necessary to describe the idealized case with only direct radiation if later on the diffuse part is accounted for in the method? I'd recommend to introduce the diffuse part from scratch.

Due to changes in this part of the manuscript this part is now changed. The diffuse part is described in details.

p.2719 l.9: "derived" is awkward because Eq. (13) does not contain Fdir and Fdiff as expected. Just keep the end of the sentence that introduces the albedo formula.

Thank you, Eq. (13) changed to Eq. (14). Sentence left for a better understanding.

p.2720 Eq. (18): remove the last term and reverse the 2nd and 3rd terms for clarity. But again, why to introduce this equation when the more realistic/general Eq. (19) comes just afterwards?

Removed.

l.4: specify here that υ p is derived as in Eq.(7) because "inclination angle" is not clear. Eqs. (19) and (20). Use αmeas instead of the ratio.

Rephrased and changed.

l.16: assumptions can be made, but they should as much as possible be supported by relevant references and/or discussed in the discussion if questionable.

Due to changes in this part of the manuscript this part is now changed.

l.19: two objects with different dimensions are compared: spectral range (wavelength in microns for instance) and irradiance (Wm-2)

Due to changes in this part of the manuscript this part is now changed.

p.2721 l.2: the assumption about constant albedo cannot be used without a reference to support it, especially because it is a major shortcoming.

Due to changes in this part of the manuscript this part is now changed.

l.3: add reference

Due to changes in this part of the manuscript this part is now changed.

p.2722 l.3: Reference to Eq. (13) is not straightforward.

Thank you, Eq. (13) changed into Eq. (15).

l.8: Eq. (22) should appear on p.2720 when υp is first introduced

Thank you, removed.

l.22: use a proportionality sign rather than "="

Left, because it is equal, not proportional.

p.2723 l.9: Eq. (25) should appear on p.2720 when υ t is first introduced

Thank you, removed.

l.11: the optimization method is not clear because l.11 suggests that C is optimized while σ t and γ t actually are.

Phrase added at the end of Step C for a better understanding.

Eq. (26) meaning is not clear

Phrase added at the end of Step C for a better understanding.

l.18: it seems that the true albedo could be derived simply from Eq. (23) now that υ t is known, so that Eq. (20) appears useless. This equation should anyway not be rewritten here.

Phrase added.

p.2720 l.1: what is the "opening angle" of a pyranometer? Is it a field of view, an apparent SZA?

Due to changes in the manuscript this part is now changed.

l.2: "flat" zenith angle – high SZA

Due to changes in the manuscript this part is now changed.

l.3-6: this sentence is probably not necessary

Sentence removed.

l.7-14: this subsection seems useless. It could serve as a start for a discussion but should be removed from the methods

The correction of albedo values is essential for the radiative balance, see also Introduction, Results and Discussion.

Results: p.2724 l.21: Do these values compare well with known measurements or previous studies?

Explanation and references added.

l.21: "which occurs" - as a result of

Due to changes in the manuscript this part is now changed.

p.2725 l.4-5: Keep only (Step B) in parenthesis

Due to changes in the manuscript this part is now changed.

l. 4-6: Are you applying the method to a specific case study? Then mention it because it is not straightforward for the reader.

Due to changes in the manuscript this part is now changed.

l.7subsequently (to what?). σ p is very large, is it realistic for in situ measurements?

Explained later in the text.

l.8-10:consider removing this sentence

Removed.

l.11: keep this sentence with previous paragraph

Thank you, changed.

p.2726 l.1-3: this should be mentioned when detailing the model assumptions

Due to changes in the manuscript this part is now changed.

l.9-10: this sounds more like a conclusion of this subsection rather than an introduction

Sentence removed.

l.20: where the actual tilts measured at some point to validate the retrieval?

Due to changes in the manuscript this part is now changed. Not relevant.

Discussion: p.2727 l.18-19: the method was described for clear-sky days. How can it be applied to mostly cloudy days? Why 2-3hrs? How does the method deteriorate with less time to perform the fit?

Due to changes in the manuscript this part is now changed.

l.24-26: I don't understand the point of this sentence.

Due to changes in the manuscript this part is now changed.

P2728: l.10-16: this is certainly one of the most understandable paragraph in the paper and the whole discussion should be built on that kind of statement.

Due to changes in the manuscript this part is now changed.

l.17-20: after a whole study on the impact of tilts this sounds like a common place. This should be moved in the introduction or just removed

Due to changes in the manuscript this part is now changed.

Conclusions: p.2728 l.24: This sentence is awkward. Just say that a method was *developed to retrieve the tilts and directions of sensors and slopes in the case these parameters can hardly be measured in situ. This could be moved to the introduction.*

Due to changes in the manuscript this part is now changed.

l.26: to compensate - to overcome

Due to changes in the manuscript this part is now changed.

p.2729 l.3-7: the description of the method is not understandable at all.

Due to changes in the manuscript this part is now changed.

l.11: "prove" – validate

Changed.

l.12: again the validation of a model dedicated to snow measurements using a concrete surface is very questionable

Due to changes in the manuscript this part is now changed.

Tables: 2: Remove "results" from the caption. "Corrected" - retrieved 3: same as 2
Results, because the Tables represent the results.

Figures: 2: the solar azimuth is not clear. Maybe add dots starting from the incident beam to show the correspondence.

Sigma changed into sigma_t.

5: increase labels size

Left, because label does not overwrite data.

7: increase labels size and figure size.

Left, because label does not overwrite data.

8: Add ylabel

Added.

Answer to the General Comments of Reviewer # 3:

The authors present a method to correct errors that are introduced to glacier surface albedo measurements by sensor tilt relative to the surface. The method is based on a comparison of the measured radiation data at the study site with measurements made at a nearby, not-tilted sensor installation.
I compliment the first author on the development of a method that is well worth to form the master thesis cited in the references section. Such a master thesis is mainly meant to show and demonstrate methodical knowledge. However, and unfortunately, this is not enough for the content of a scientific paper. The study in its current stage and as it is presented in the given manuscript does not at all meet the high quality criteria demanded by a high-ranked journal like The Cryosphere.
The manuscript is poorly written. It that lacks any red thread over most parts except for the method description. The introduction is missing a clear and comprehensive over view and explanation of the theoretical background of snow albedo physics. Topicspecific terms (e.g. "cosine measurement error", "cosine law" or "cosine error") that are not straightforward to understand for readers without background in solar geometry are never explained. Measurement principles of sensor are, in contrary, explained in too lengthy detail. The methods section in total is also much too lengthy and given with far too little illustration so that the reader easily gets lost on the way from Eq. 1 to Eq. 27. The results section is exclusively limited to examples and needs to be much more comprehensive. The discussion section is simply a stringing together of single notes without any identifiable ideas behind.
Apart from these more editorial concerns I have a couple of very serious, methodrelated issues that prevent me from supporting any further consideration of this manuscript. I therefore refrain from giving detailed comments and only list my major concerns in the following:

1) The presented method is only applicable for days with at least 2-3 hours of sunshine, it needs to be calibrated separately for each day (but this cannot be done in a fully automated way) and a reference measurement that needs to meet very high quality criteria needs to be available in the vicinity. I assume that the method is meant to be applied in glaciology. However, given the above mentioned serious drawbacks regarding its straightforward applicability I cannot see any benefit at all with respect to potential future applications of this method. Especially as there are simple, small and rather inexpensive sensors that can be mounted to automatic weather stations to continuously measure the instrument's tilt adequately (and without cloud-cover related restrictions or the need of high quality reference measurements that are rather unfeasible in the framework of a glaciological field measurement setup).

The fact that this method is also applicable for days with 2-3h of sunshine improves and expands it, because completely clear-sky days are rare.

For accurate corrections tilts and directions have to be calibrated for each day, which can be improved and it is explained in the Discussions.

We expanded the method for cases where no reference measurement is available with the usage of a high resolution radiation model. This model is explained in details and the results are compared with the results from the reference measurements. With the introduction of this radiation model the dependency of horizontally leveled reverence measurements is eliminated.

It is explained in details why automatic tilt sensors are difficult to use for the accuracy of this method.

2) The consideration of diffuse radiation that is known to have the potential to strongly influence snow surface albedo is rather insufficient and maybe even misleading. The method compares albedo measurements at two sites without taking into account (or at least discussing) influences of differing sky view factors or cloud conditions. The method does also not account for different spectra of light (induced by these varying cloud conditions) that are reflected differently at the snow surface and thus lead to different surface albedos. Finally, and most important, the differentiation between direct and diffuse radiation in Eq. 15 and 16 is a very rough assumption rather than any profound physically based theory. The basis for these two equations is formed by Eq. 5. This equation describes the reduction (not the "weakening") of direct solar radiation due to absorption and scattering on the way through the atmosphere. Diffuse radiation originates from these scattering processes so how can it be calculated like given in Eq. 16? This does not make sense at all. Or even further, if this is not complete nonsense it needs to be by far better motivated, explained and referenced. Apart from that, the partitioning between rho(dir) and rho(diff) seems to be based on assumptions only. If this is really the case, it is not a valid approach for an in general so accurate and complex correction method.

It is explained why albedo does not have to be corrected on diffuse days. Furthermore the diffuse part of the incoming is considered and explained in details why it can be assumed with p_diff~10%. Data from different Suntrackers and a radiation model are considered over a long time period to come to this assumption.

The reflection of snow surface is assumed isotropic, considering additional added references and explained in more detail.

3) The most crucial step of the presented method is the calibration of the two parameters epsilon and V. However, the description of the calibration process is completely insufficient and limited to a single statement regarding which method of fitting is used. No calibration results are visualised or explained in detail. No error assessments or sensitivity studies are carried out at all. This is not acceptable as the main parameters *that form the heart of the method need to be given with appropriate uncertainty ranges in order to be able to judge about the reliability and final accuracy of your albedo correction. Also a visualization of the C values (Eq. 24) is completely missing and the reader is not able to judge whether or to which extent the criterion of similar C values across the diurnal cycle is really met or not.*

Epsilon and V are based on references. These parameters are explained in more details now, more references are added and the ranges of their results are discussed.

The workflow of the method and the used equations are explained in more details for a better understanding.

All results are visualized in the Tables and Figures, which have been expanded.

Sensitivities and uncertainties of the used sensors are explained in the method section. Standard deviations are listed with the results and an additional table was added, where the mean bias error (MBE) and the mean absolute error (MAE) of corrected albedo values are shown.

C is an auxiliary factor to find accurate tilts and directions of the slope. C is introduced and omitted later. Some major changes were made for a better understanding why C is needed for a calibration with the method of least squares.

4) In total, calculations have been done for four days only. The question that needs to be asked is if the introduction and demonstration of a newly designed method for the example of only four days is sufficient to prove reliability, stability and transferability of this method. I doubt that. Issues of varying solar zenith angles over the year are not taken into account. Nothing can be derived about systematic temporal cycles or pattern of the method's parameters. No statements can be given about the performance of the model under varying cloud cover conditions (which is crucial when dealing with the accuracy of albedo measurements). At the current stage, your study does not at all prove to be transferable, not in time nor in space.

The calculations were done for a time period of almost two years, for every clear-sky day and days with at least 2 hours of clear sky. Also Figure 9 shows all corrected and not corrected albedo values and their over- and underestimations in two scatterplots for the two observed glaciers.

It is explained in details and referenced, why albedo doesn't have to be corrected on cloudy days.

Taken together there is no other possibility than to reject this study (and thus the related manuscript) in its current stage. However, it would be great to see the authors investing more work in this topic. The above mentioned issues needs to be accounted *for and, most important, the dependency on any unfeasible reference measurements and the manual determination of data cut-offs definitely need to be eliminated. If these goals could be accomplished I would strongly encourage a resubmission of a (better written and better structured) manuscript as in this case the method could really be of importance for postprocessing of glaciological fieldwork.*

Answer to the General Comments of Reviewer # 4:

Weiser and colleagues present a methodology to correct tilted albedo measurements over a non-flat snow/ice surface using nearby leveled shortwave incoming radiation. The method is based on the assumption of constant diurnal atmospheric conditions, constant diurnal albedo values and constant sensor tilts and surface slopes. They apply the methodology for some days by comparing the modeled albedo with the observed albedo, but never validate the retrieved tilt, slope angles.

2 Assessment

Although Weiser and colleagues present a study on a interesting topic for the TC community, the manuscript has too many issues in its current status (see major and specific comments) to warrant publication in TC. Therefore, I would recommend a resubmission where the authors can tackle the issues mentioned in this review and in the review reports of my colleagues which all raise valuable concerns.

3 Major comments:

- *The manuscript is poorly written. The English needs a thorough revision and the structure of the paper is poor. For example, both the introduction and discussion lack a comprehensive overview and seem a collection of loose ideas without a clear rationale. Both sections also fail to put the methodology in a context in terms of applicability. Also the references lack a clear overview of the state of the art in the domain. The methodology section on the other hand is extremely technical and often difficult to follow.*
- *The results are based on some illustrations and examples, but fail to provide any idea on the accuracy of the method, applicability, etc.*
- *Although the methodology is interesting, it is based on some assumptions which are difficult to defend. Firstly, the methodology assumes a constant diurnal albedo and therefore does not account for diurnal variations in albedo, which can range above 0.1 depending on the solar zenith angle. Secondly, it does not account for any other physical condition that can have an effect on diurnal albedo (e.g. surface roughness; Lhermitte et. al.). Thirdly, the method fails to provide any correction of cloudy conditions and therefore still limits its use to calculate daily albedo values, etc.). Fourthly, the method assumes that the sensors only 'sees' the sky (upward sensor) or snow/ice (downward sensor), whereas this is often not the case for tilted surfaces: e.g. differences in skyview factors or a downward facing sensor which receives radiation from nearby mountains etc.*
- *Although the method is very interesting, it is, given its dependence on a 'third' leveled sensor nearby, very difficult to apply in real polar conditions, where the installation of an*

unattended leveled AWS is practically almost impossible. I think this drawback of the method should be clearly discussed.

4 Specific comments:

p2710 L20: automatic tilt meters can be installed to make such measurements in realtime (e.g. PROMICE data set)

An explanation on why it is difficult to use automatic tilt meters for the accuracy of the described method is added and described in details.

p2710 L22: "changing physical conditions" What is meant by that? Does this include changes in diurnal albedo (e.g. Gardner and Sharp, doi:10.1029/2009JF001444.) and/or changes in roughness and homogeneity of snow cover in the surrounding of the measurement site (e.g. Lhermitte et. al., www.the-cryosphere.net/8/1069/2014/)

Due to changes in the manuscript this part is now changed. Explained in details.

p2710 L25: 'ideally southwards': ideally a sensor is not tilted at all. On the other hand, the only reason to prefer a direction, has to do with the shadowing effect. Because all other tilt effects could theoretically be corrected for if the tilt is known. In this context, 'southwards' is only true for the northern hemisphere.

Due to changes in the manuscript this part is now changed.

p2711 L1: the cosine law does not introduce the errors. The assumption of a flat surface/sensor when it is not flat, introduces the error and this error could be corrected using the cosine law.

Due to changes in the manuscript this part is now changed.

p2711 L3: Many publications: true, but the introduction and discussion should benefit strongly of a more comprehensive overview of these publications. Some examples of publications worth including are: MacWhorter, M. (1991). Error in measurements of incoming shortwave radiation made from ships and buoys. Journal of Atmospheric and Oceanic Technology. Van den Broeke, M., van As, D., Reijmer, C., van de Wal, R. (2004). Assessing and improving the quality of unattended radiation observations in Antarctica. Journal of Atmospheric and Oceanic Technology, 21(9), 1417–1431.

Thank you, many references added.

p2711 L28: 'measured tilts and directions': the words tilt, surface, angle, directions are often used confusingly. A sensor can have a tilt, which has a zenith angle and azimuth angle in a cer tain direction, whereas a surface can have a cer tain slope with *corresponding slope angle and azimuth angle. In my opinion, a glacier/snow surface is not tilted.*

Glaciers that represent the slope in the described model are not horizontally flat, they are tilted with an aspect or in a certain direction. Sensors (pyranometers) are inclined with an aspect or in a certain direction.

p2713 L13: what about variations due to variations on solar zenith angle, cloudiness, etc. (Gardner and Sharp)
Due to changes in the manuscript this part is now changed. SZA dependency of albedo was eliminated and cloudiness was explained in details.

p2713 L19: Not all AWS's are drilled into the ice. Some setups use tri- or four-pods standing on the ice.
The AWS used for this method were drilled into the glacier, but even AWS that use 3- or 4-pods are tilted.

p2713 L20 "estimate reasonable diurnal mean albedo values". This is certainly true, but how is the proposed method going to change this without a valuable method that accounts for cloudy albedo values
Due to changes in the manuscript this part is now changed.

p2713 L24: What is the slope of albedo variation?
The Method section 2.1 should clearly indicate how many times was measured etc.
Due to changes in the manuscript this part is now changed.

p2715 L4: changes continuously? What is meant by continuously (ever y day, five minutes) and how much does it change? Moreover, if a data logger is connected to the inclinometer the sensor tilt can be logged over time.
Due to changes in the manuscript this part is now changed.

eq. 2 is irrelevant for the rest of the story
It is relevant and explained why.

Fig.2: Seems rather irrelevant
Relevant for a better understanding of a complex method

p2716 L16: 'are used from here on': Why aren't uniform symbols used from the start. It would certainly increase the readability of the manuscript. Moreover, I would recommend to use clear subscripts. The subscript tilt for example can create confusion as both the pyranometer and surface can show a 'tilt' in the definitions that are given.

An appendix with all used symbols, their meaning and their units was added.

Eq. 9: this is not necessarily true as the downward facing pyranometer, might also be receiving radiation from other terrain parts within its field of view. For heavily tilted pyranometers, for example, the downward facing pyranometer might 'see' parts of the horizon or nearby mountains etc.
Explanation added that downfacing sensor only sees the glacier surface.

p2718 L11: and how is the downward facing pyranometer leveled?
Due to the fact that both pyranometers use the same housing (see also: Section Albedo measurements), they have the same tilts.

p2718 L12: This also assumes that the surface is completely flat and homogeneous (e.g. Lhermitte et. al)
Explanation added.

p2718 L18: part: I assume this means fractions between 0 and 1? Part is very unclear and does not necessarily imply that the values are between 0 and 1.

On clear sky days the total incoming radiation consists of a direct beam (part) and a diffuse part (blue sky).

Eq. 16: I don't understand the logic for Eq. 16 and I think it should be proven in this case. Normally the diffuse radiation is dependent on the sky view factor, the solar zenith angle (i.e. longer atmospheric path -> more scattering, etc)
Explanation and assumption of the diffuse part of the radiation, including references, added.

p2719 L17: 'Irrelevant': this is not true, depending on the tilt angle, the sky-view factor (or perhaps better ground-view factor) will change, i.e. the pyranometer will see more of the surrounding mountains, horizon, etc.
Explained earlier.

Eq. 18: The derivation of Eq. 18 is very confusing as in Eq. 10 it is still defined based on solar zenith angle. Moreover, eq. 18 is only true for 100
Eq. 18 'rephrased'

Eq. 19: Where does the cos Θ s come from
Explained in the text.

p2721 Assumption 3 is really problematic as the solar zenith angle, changing surface properties (Gardner and Sharp) as the surface properties (Lhermitte et. al.) will have an effect on the diurnal albedo which certainly cannot be neglected (i.e. variations of 0.1 on an albedo of 0.7 due to SZA alone)
Due to changes in the manuscript this part is now changed.

p2721: Why a constant diffuse fraction is assumed if the diffuse fraction could be expressed as a function of the solar zenith angle?

Due to changes in the manuscript this part is now changed.

The workflow is often very unclear. E.g. p27222 L1 'for one specific day': so the sensor tilt is only determined once and assume it constant afterwards? Moreover, it is always guessing what has been performed exactly on what data. This should be clearly clarified.

The workflow is described in details for one example day. This was made for every clear-sky day and days with at least 2 hours of clear sky in a time period of almost two years.

p2722 L12: it is very unclear which equations to minimize.
Explained in details which equations are used.

p2723 L15: As constant as possible. First, it is physically wrong to assume a constant albedo (see previous comments). Second, what is 'constant as possible'? What is the range that is allowed? Is this based on some minimization?
Rephrased and information added. C is a constant value for the day in progress.

p2723 last line: equation does not have a number
Removed.

Eq. 27: how can you estimate errors in balance if the method does not allow to account for cloudiness?
Explained in details with references earlier in the text an in the Discussions.

p2725 L4-10: This should be in the method section. All these setups are now never explained in the method section and appear in the result section, where they don't belong

Due to changes in the manuscript this part is now changed.

p2726 L4: So there is no diurnal variation in pdiff?
The diffuse part of the incoming radiation has no diurnal variation, see also Methods and Discussions.

p2726 L16-20: Ok, but how certain are we that corrected one is effectively the correct one, when there is no correct measurement to compare it with?
Due to changes in the manuscript this part is now changed.

p2726 L21-22: this is kicking in an open door as it is already the motivation of the article
Due to changes in the manuscript this part is now changed.

p2727 L12 'Over the year 2011' how is this assessed when the method has no way to account for cloudy observations?
Explained earlier, in an appendix I send you two figures that show typically diffuse/cloudy days and should clarify why albedo does not have to be corrected.

P2728 L1-3: True, but also for small angles (and even for all non-flat surfaces) the sensor can also 'see' neighboring mountains, etc. . .
Explained earlier.

p2728 L12: without reference measurement the method can indeed not be used and this completely limits the use of the method as getting such a reference measurement is practically impossible (e.g. no flat nearby terrain on large ice caps etc.)
Due to changes in the manuscript this part is now changed.

p2728L17: adjusted parallel. This is practically impossible and I challenge the authors to perfor m such a setup. Installing a flat unattended sensor is already 'impossible'
Due to changes in the manuscript this part is now changed.

p2728L21: 'High' or low etc.
Due to changes in the manuscript this part is now changed.

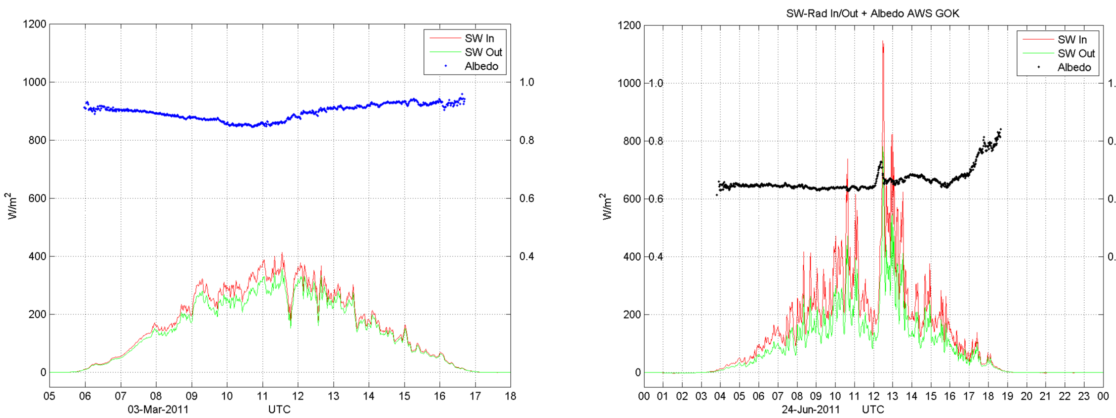
p2728l9: Winter months: Sep and June are not a winter months. Moreover, this is hemisphere dependent. I also challenge the authors to apply this method in polar areas as it practically impossible to do a flat unattended reference measurement over ice caps etc.
Due to changes in the manuscript this part is now changed.

Fig.9 is SWout, not albedo

Albedo is defined in Eq. (1) → reflected radiation/incoming radiation → the measured and corrected values are presented in a scatter plot, the result is the measured and corrected albedo.

Appendix:

Measured albedo values for two different cloudy/diffuse day:



Additional changes of the manuscript:

Abstract, Introduction, Discussion and Conclusions rewritten.

High resolution radiation model introduced to improve and expand the described method.

Solar zenith angle limited to 50°, where no albedo dependence occurs.

Appendix with all used symbols and their units was added.

Manuscript prepared for The Cryosphere Discuss.
with version 2014/07/29 7.12 Copernicus papers of the LaTeX class copernicus.cls.
Date: 2 November 2015

Correction of broadband snow albedo measurements ~~due to~~ affected by unknown ~~geometry~~slope and sensor tilts

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Abstract

~~The diurnal albedo variation of glaciers on clear sky days can be relatively high due to geometric~~ Geometric effects induced by the underlying terrain slope or by tilt errors of the radiation sensors lead to an erroneous measurement of snow or ice albedo. Consequently, artificial diurnal albedo variations in the order of $1-20\%$ are observed. The present paper proposes a general method to correct tilt errors ~~. In the present paper, these tilt errors~~ of albedo measurements ~~are corrected~~ in cases where tilts of both, the sensors and the slopes are not accurately measured ~~. For this method of correction , a nearby reference measurement with a horizontally levelled sensor is needed to determine atmospheric parameters. Based on that a model is developed that is~~ or known. We demonstrate that atmospheric parameters for this correction model can either be taken from a nearby well maintained and horizontally levelled measurement of global radiation or alternatively from a solar radiation model. In a next step the model is fitted to the measured data to determine tilts and directions of sensors and ~~slopes, which vary daily due to changing atmospheric conditions and snow cover. Once these parameters are determined, the~~ the underlying terrain slope. This then allows to correct the measured albedo, the radiative balance and the energy balance~~can be corrected. The differences~~ . Depending on the direction of the slope and the sensors a comparison between measured and corrected ~~values show an obvious under- or overestimation of albedo, depending on the direction of the slope~~albedo values reveals obvious over- or underestimations of albedo. It is also demonstrated that ~~the difference~~ differences between measured and corrected albedo ~~is highest for high~~ are generally highest for large solar zenith angles.

1 Introduction

~~Reflected solar radiation and hence the~~ The energy balance of snow and ice surfaces ~~strongly depend on snow albedo. The~~ is strongly determined by its shortwave surface reflectivity (albedo). Once the underlying snow/ice is isothermal, the surface energy balance of a ~~glacier surface~~ seasonal snow cover or glacier defines the amount of energy available for ~~the ablation processes, once the underlying snow/ice is isothermal~~melt (Wiscombe and Warren, 1980) .

~~In isolated areas of many glaciers it is difficult to make permanent~~ Depending on their directions, tilted radiation sensors and terrain slopes alter albedo measurements. Most measurement sites on glaciers or seasonal snow fields are more or less operated in remote areas, making it difficult to perform regular manual reference measurements of ~~tilts and directions of sensors and slopes~~sensor and slope tilts. Moreover, the underlying terrain slope may change due to differential melt or changing glacial morphology and ice dynamics, also tilting the radiation sensors within periods of days or weeks and altering the direction of these tilts. This means that the geometry of the measurement site is unknown ~~because of changing physical conditions, inclinations of sensors and changing snow cover. Accurate tilt measurements only make sense when the~~ and changes with time. The use of a dual axis inclinometer to automatically determine the sensor tilts and directions is only possible if the azimuthal direction of the ~~radiation sensor is known (ideally southwards) which is not always possible due to changing conditions.~~

~~In the method described in this paper, measurement errors due to the cosine law as well as other measurement errors and uncertainties are considered~~(tilted) radiation sensors would be constant with time which is unfortunately not the case.

Many ~~publications~~ previous studies note that tilt errors in albedo measurements can ~~be several 100when the sun is low in the sky~~more than double with low sun elevation, especially on snow and glacier surfaces. Large deviations from the expected true diurnal variations of albedo occur due to non horizontally levelled sensors.

In a paper investigating spectral reflected radiation on glacier surfaces, Dirmhirn and Eaton (1975) mention tilt errors of albedo measurements which lead to under- and ~~over-estimations caused by the specular components of daily albedo. The focus of that paper was spectral reflected radiation that varies continuously over time and increases with the number of~~ overestimations caused by specular reflections of melting and refreezing ~~processes. Dirmhirn and Eaton (1975)~~ snow- and glacier surfaces depending on the incident angle of direct incoming radiation. Furthermore, they concluded that incoming shortwave radiation dominated by the direct component is underestimated at low sun angles due to the cosine ~~measurement error (due to imperfections of the glass dome and the reflection properties of the sensor's black paint, l to an underestimation of global radiation at low sun angles and thus overestimating albedo. Also, the direct sun beam, which is the main part of global radiation on clear sky days, and instrumental error due to cosine law cannot be separated. These~~ response error (induced by imperfections of the glass dome of the pyranometers) and the reflection properties of the sensor's black paint, the latter is also noted by Muneer (1997) , leading to an overestimation of albedo. The authors conclude that these errors can be minimized by using instruments with ~~small opening angles~~ a small field of view and deriving the albedo via spatial integration. ~~Dirmhirn~~ Dirmhirn and Eaton (1975) also mentioned difficulties in albedo ~~measurement~~ measurements over non horizontal surfaces and suggested eliminating this problem by using horizontal and uniform surfaces with instruments close to the ground.

Sicart et al. (2001) and Oerlemans (2010) described the same problems of albedo measurements ~~on tiltedsurfaces~~when the glacier surface is tilted, but assumed a horizontally levelled pyranometer and directly measured tilts and directions of the slope to correct albedo values.

Landry et al. (2007) described the influence of both, a tilted slope and an inclined pyranometer, on albedo measurements. They corrected the albedo values by using directly measured tilts and directions.

Ineichen et al. (1987) and Schaaf et al. (1994) described the radiation on a tilted area without snow cover, measured by an inclined pyranometer with known tilts. Measurement with a horizontally levelled pyranometer over a horizontal area served as a comparison. The results showed an apparent diurnal variation of albedo over a forest surface, even the diurnal average albedo showed differences between tilted and horizontal measurements. These results are essential because albedo of a (non snow-covered) forest is expected to be almost constant with time, in contrast to snow albedo ~~which~~ that changes over time due to snow metamorphism (Warren, 1982) .

Allen et al. (2006) used a model of solar radiation on tilted surfaces and integrated analytically over one day, also considering ~~the extinction through the~~ optical properties of the atmosphere. This model was compared to measurements above surfaces with similar tilts and directions, where relative humidity, aerosols and other ~~meteorological~~ influences were considered. By this comparison ~~they estimated the extinction coefficient~~ the diffuse transmissivity was estimated as a function of the measured atmospheric parameters. Furthermore, the irradiance on tilted surfaces based on horizontal measurements was modeled. ~~As opposed~~ Allen et al. (2006) determined the extinction through the atmosphere in a more detailed way using measured data. In contrast to the method described in the ~~following,~~ present paper no horizontal reference measurement ~~was used to estimate the extinction through the atmosphere~~or a high-resolution radiation model is needed to estimate atmospheric parameters.

Mannstein (1985) described a method where tilts and directions of slopes were estimated from the data of the down-facing pyranometer using the measured albedo on ~~preceding clouded day . That paper was used to verify the method described herein (Weiser, 2012) , as tilts and directions were unknown. Since the paper~~ a preceding overcast day where snow albedo has no diurnal variation and a diurnal mean value can easily be calculated. Since Mannstein (1985) did not consider that albedo on ~~clouded~~ cloudy and completely diffuse days is approximately 0.15 higher compared to clear sky days due to the change in the spectral composition of the incoming radiation (Oerlemans, 2010), applying this method ~~can~~ may lead to high ~~inaccuracy~~inaccuracies.

~~With the method described in the present paper , albedo can be estimated from the measured data where tilts and directions of both the slope and the sensor are unknown and a horizontally levelled pyranometer is available in proximity to the measuring site. In contrast to other methods, a model for albedo measurement is developed and fitted to the measured data, considering atmospheric parameters, such as extinction coefficient and the diffuse part of global radiation. Tilts~~ In this paper we present a method to correct measured albedo values with unknown sensor and slope tilts that avoid the before mentioned shortcomings of existing correction methods or the necessity of inclinometer measurements that are difficult to interpret or often simply are not available. The proposed correction method needs either a nearby and horizontally levelled measurement of global and diffuse solar radiation or the output of a solar radiation model to adjust some atmospheric parameters. In this way the method is transferable in space. Thereof, tilts and directions of both~~the~~, the terrain slope and the ~~sensor are derivedthereof. Using this method, the measured diurnal albedo can be corrected with high accuracy as will be demonstrated in the following sections.~~ radiation sensors can be derived, enabling to correct measured albedo values.

A similar measurement setup as Ineichen et al. (1987) and Schaaf et al. (1994) described was made for the presented case study and the results are shown to demonstrate that albedo of a concrete surface, which should be constant, has a strong diurnal variation on clear sky days when only the sensor is tilted.

In the present paper Section 2 details the measurement setup and the derivation and workflow of the albedo correction model. In Section 3 we present the results of the correction method with data from one test site in Vienna, Austria and one remote mountain site located in the central Alpine area of Sonnblick. Section 4 discusses the shortcomings and possible improvements of the described method and Section 5 gives a short summary and the conclusions.

2 Methods

2.1 Albedo over snow and ice surfaces

~~Snow~~ Surface albedo (α)~~is part of the radiative balance (Eq. 26) which in turn, is part of the energy balance that acts as an indicator for the energy available for melting processes of a glacier.~~

~~Albedo in general~~, defined here as the hemispherically averaged broadband reflectance in the spectral range 0.3 – 3 µm, is derived from ~~global~~ incident and reflected solar radiation measured with a horizontally levelled pyranometer by dividing the values of the down-facing sensor ($F^{\uparrow}$, reflected radiation) by those of the up-facing sensor ($F^{\downarrow}$, global radiation):

$$\alpha(t) = \frac{F^{\uparrow}(t)}{F^{\downarrow}(t)} \tag{1}$$

~~Typically,~~

Albedo controls the net shortwave radiation flux at a snow or ice surface and thus the energy available for melt, once the underlying snow or ice is isothermal. Albedo is strongly dependent on snow or ice properties and atmospheric conditions, it can vary over a large range from $\alpha < 0.1$ for dirty glacier ice to $\alpha > 0.9$ for fresh snow (Röthlisberger, 1987 ; Paterson, 1994). While the albedo of pure snow for constant illumination conditions depends only on the effective grain size of the surface snow layers (Wiscombe and Warren, 1980) , the albedo of glacier ice is still less well understood and is a function of light scattering by bubbles and cracks (Mellor, 1977) . Due to its grain size dependance, daily average snow albedo is expected to decrease in periods without snowfall due to metamorphism of the snow ~~cover, such as~~ microstructure induced by temperature changes, melting and refreezing processes ~~.~~

~~However, on clear sky days measured albedo values show a~~ (Dirmhirn and Eaton, 1975) . Generally, albedo increases with increasing solar zenith angle (ϑ_s) due to a higher probability of the photons to be redirected out of the snow cover and due to forward scattering which is enhanced by diurnal freeze-melt cycles (Warren, 1982) . This implies a strong diurnal variation ~~often exceeding the realistic physical range, depending on tilts and directions of slopes and sensors and especially shortly after sunrise and before sunset due to the cosine error of the sensors.~~ of albedo during clear sky days (Oerlemans, 2010) . It is however generally accepted that albedo is largely independent of the solar zenith angle (SZA) for $\vartheta_\mathrm{s} < 50°$ (Wiscombe and Warren, 1980 ; Konzelmann, 1995 ; Brock et al., 2000). In contrast, there is no diurnal variation of albedo on cloudy days that are dominated by diffuse solar radiation, and it is thus reasonable to approximate albedo by a daily average value assuming no metamorphic changes of the snow surface microstructure during the day (Pirazzini, 2004) . Albedo is also known to increase with cloud cover due to spectral variations (Brock, 2004 ; Carroll and Fitch, 1981 ; Cutler and Munro, 1996 ; Oerlemans, 2010). As has been noted by Wiscombe and Warren (1980) , the responses of all commercial pyranometers deviate from a proper 'cosine law' making them usually less sensitive at large incident zenith angles. If not corrected, this causes albedos at low sun elevations to be overestimated (see Eq. (1); Liljequist, 1956 ; Dirmhirn and Eaton, 1975). The surface geometry of a snow cover changes continuously and the tilts of the sensors increase over time, due to glacier movements caused by melting processes and ablation, snow metamorphism and the fact that the automatic weather stations (AWS)~~are~~ , that are used for these methods, are drilled into the glacier. Hence, it makes sense to manually adjust tilts and directions on a daily basis~~to estimate reasonable diurnal mean albedo values~~.

~~The method described in the present paper shows how to correct the true albedo with unknown tilts and directions of both the slope and the sensor.~~

~~Using a model that simulates the direct incoming radiation being reflected diffusely from a tilted surface, the slope of the observed apparent diurnal variation of albedo can be reproduced. To obtain an accurate estimation of the actual albedo when tilts and directions of the slope are unknown, the model is improved and compared to the measured data by fitting the parameters of the model to the measured data, also considering atmospheric parameters~~

2.2 Albedo measurements

The albedo correction method depends on the accuracy of the used instruments and the measurement setup, that are detailed in the following paragraphes.

2.2.1 ~~Albedo measurements~~

Albedo measurements are conducted with two ~~opposite pyranometers (~~opposing pyranometers (also called an albedometer), one facing the upper hemisphere measuring the incoming radiation $F^{\downarrow}$, the other one facing the lower hemisphere measuring the reflected radiation $F^{\uparrow}$.

A pyranometer consists of a thermopile with black coating, absorbing the total solar radiation. The sensors have a glass cover that is transparent defining the exact spectral range and to protect the sensing elements. Radiation is absorbed in the thermopile, producing a voltage output by differential heating.

The used sensors are Kipp & Zonen CNR4 "Net Radiometer" measuring all four radiation components (incoming shortwave radiation SW_{in}, reflected shortwave radiation SW_{out}, incoming longwave radiation LW_{in}, ~~reflected~~ emitted longwave radiation LW_{out}) using separate sensors within the same housing, so all radiation ~~measuring sensors are tilted equally. For an opening angle of~~ sensors exhibit the same tilt. The expanded (95% level) calibration uncertainties given by the calibration certificate are given as 3.4 % for the pyranometers and 6.1 % for the Pyrgeometers. The CNR4 has a field of view of 160° and the cosine error ~~of the "Net Radiometer"~~ is given as $< 5\,\%$ by the manufacturer ~~. The uncertainty of the pyranometer indicates $< 4\,\%$ within a temperature range of $-10\,^{\circ}\mathrm{C} < T < 40\,^{\circ}\mathrm{C}$ and 4 % for $T \leq -10\,^{\circ}\mathrm{C}$.~~ (Kipp and Zonen Manual, 2010) .

The "Net Radiometers" are part of the automatic weather stations (AWS) on the two Sonnblick glaciers Goldbergkees (GOK) and Kleinfleißkees (FLK) (Figure 1 and Table 1), measuring also air temperature, wind speed and direction, relative humidity and air pressure to determine mass- and energy balance of the glaciers. A solar panel ~~serves~~ and battery serve as power supply for ~~the AWS~~ all used sensors. The AWS are drilled into the glacier ice and are located in a remote area where shadows from the surrounding mountains are minimal and the down-facing pyranometer only sees the glacier surface without any nearby mountains.

A MEAS DQG-Series conductometric dual axis inclinometer is attached to each AWS. Four oppositely polarized electrodes are dipped into an electrolytic fluid, producing a voltage that is measured. The conductivity of the electrolyte depends on its depth. When the sensor is tilted, the depth of the electrolyte and consequently its conductivity changes. The uncertainty of the inclinometer given by the manufacturer is $0.5\,\%$ within a temperature range of ~~$-40\,^{\circ}\mathrm{C} < T < 85\,^{\circ}\mathrm{C}$~~ $-40\,^{\circ}\mathrm{C} < \mathrm{T} < 85\,^{\circ}\mathrm{C}$. To use the data of the inclinometer it is necessary to know the orientation of one axis (e. g. southwards). ~~Due to the mounting~~ The orientation of the AWS on the ~~glaciers, the orientation of the sensors changes continuously and~~ glacier changes continuously due to glacier dynamics and snow metamorphism and is therefore estimated with an uncertainty of $\pm 5\,\%$ since the sensor is fixed to the AWS support hardware.

~~One,~~ All radiation data of the AWS were stored with a resolution of one minute, all other values with ten and sixty minute average output~~values of all sensors connected to the AWS are stored.~~. For the used method one minute data of shortwave radiation of the pyranometers connected to each AWS are used and compared to one minute average data of the Suntracker.

~~To determine the optical properties of the atmosphere for the incoming solar radiation , data from a Suntracker , which~~

2.3 Solar radiation reference data

Additionally, high quality solar radiation reference measurements from a nearby Suntracker are used. The latter is part of the ~~Baseline Surface Radiation Network~~ Austrian radiation monitoring network (ARAD) and the Baseline surface radiation network (BSRN) ~~, is used~~to advance national climate monitoring and to support satellite retrievel, modelling and solar energy development. The measurement setup and a detailed uncertainty estimate is shown in Olefs et al. (2015) . The Suntracker is equipped with two ~~Kipp Zonen CMP 21~~ pyranometer and one ~~Kipp Zonen CGR 4~~ pyrgeometer next to each other with ~~opening angles of~~ a field of view of 180°. The tracker follows the sun to shadow one of the pyranometers in order to measure global and diffuse radiation.

To make the albedo correction method more transferable in space, a solar radiation model can be used instead of the nearby reference radiation data. We used the the STRAHLGRID model (Olefs et al., 2013 ;), a parametric solar radiation model. In STRAHLGRID, direct and diffuse solar radiation are calculated considering atmospheric turbidity, cloudiness effects for direct and diffuse radiation and terrain effects (shading, terrain and multiple reflections). Usually, the model is driven with gridded meteorological data from the Integrated Nowcasting through Comprehensive Analysis (INCA) system (Haiden et al., 2011) at 100 m spatial and 15 minutes temporal resolution. In the present case the model was calculated for the location of the AWS in clear-sky mode (no cloudiness) using daily MODIS aerosol optical depth (AOD) and hourly INCA integrated water vapor data as input for aerosol and water vapor transmittances calculated in the model.

Figure 1 and Table 1 show the ~~geographic parameters of the employed measurement stations,~~ location and some details about the measurement stations: Suntracker on Sonnblick Observatory (SBO), AWS Kleinfleißkees (FLK), AWS Goldbergkees (GOK) and Central Institute for Meteorology and Geodynamics (ZAMG) in Vienna, ~~Hohe Warte 38~~ (WHW).

~~The described method was tested with~~ In order to test the albedo correction method we installed a measurement setup on the roof of ZAMG (WHW), over a concrete surface. This experiment was performed to prove that even a constant albedo changes with a tilted sensor and has to be corrected to get realistic albedo ranges, as demonstrated in Figure 2 (right). To determine the exact and presumably constant albedo of the concrete, the pyranometer was ~~levelled horizontally~~first levelled horizontally (2 (left)). In the literature, albedo over a concrete surface is given by $\alpha_{\text{concrete}} = 0.17$–$0.27$ (Santamouris, 2006).

2.4 Model for solar radiation on a tilted surface

2.4.1 Radiation model for a horizontal plane

The ~~model used~~ used model is first demonstrated for the direct solar radiation on a horizontal plane. For this method, which uses the solar position algorithm (SPA)

(Reda and Andreas, 2008) to calculate the solar radiation on top of the atmosphere (TOA), the general form of the Lambertian cosine law is used:

$$\mathrm{d}F = F \cdot \cos\vartheta_{\mathrm{s}} \cdot \mathrm{d}\omega, \tag{2}$$

where F is the irradiance of the incoming radiation, which is determined by the radiant flux per unit area, ~~ϑ the solar zenith angle~~ ϑ_{s} the SZA and ω the solid angle of the sun as seen from the unit area. The irradiance per unit area on TOA is called solar constant, assumed here as $S = 1367\,\mathrm{W\,m^{-2}}$ (Corripio, 2002).

The near-surface incoming direct solar radiation on a horizontal plane (F_{hor}) is given by

$$F_{\mathrm{hor}} = S_{\mathrm{terr}} \cdot \cos\vartheta_{\mathrm{s}}, \tag{3}$$

where S_{terr} is the near-surface, normal incidence direct solar radiation~~and ϑ_{s} the zenith angle of the sun~~.

Solar radiation is weakened by absorption and scattering between TOA and the surface. This process for clear sky days can be described by the Beer–Lambert–Bouger law (Rontu Carlon et al., 2010), which uses the extinction coefficient $\tilde{\varepsilon}$ respectively ε, depending on the condition of the atmosphere (e.g. aerosols and water vapour content):

$$I = I_0 e^{-\tilde{\varepsilon} d} = I_0 e^{-\frac{\varepsilon}{\cos\vartheta_{\mathrm{s}}}}, \tag{4}$$

where I and I_0 are the intensities of the near surface global and TOA incident solar radiation, respectively and d is the optical path length in the atmosphere.

To increase the accuracy of the developed model, a linear factor V is introduced to account for the limited spectral range of the instrument (~~cf. Corripio, 2002 , Eq. 3.7 and Kipp Zonen Manual, 2010) and the varying sun-earth distance is considered~~$0.3-2.8\,\mu\mathrm{m}$) (Kipp and Zonen Manual, 2010) compared to the extra terrestrial solar radiation or solar constant (Corripio, 2002) . Using Eq. (4) S_{terr} can be written as

$$S_{\mathrm{terr}} = \frac{S}{\tilde{r}^2} \cdot V \cdot e^{-\varepsilon \frac{1}{\cos\vartheta_{\mathrm{s}}}}, \tag{5}$$

where $\tilde{r}$ is the ratio of the actual and the mean sun-earth distance. ε and V are two unknown parameters which have to be determined in the first iteration of the correction.

Conclusively, in this model the near-surface incoming direct solar irradiance on a horizontal plane can be expressed from Eqs. (3) and (5) as

$$F_{\mathrm{hor}} = \frac{S}{\tilde{r}^2} \cdot V \cdot e^{-\varepsilon \frac{1}{\cos\vartheta_{\mathrm{s}}}} \cdot \cos\vartheta_{\mathrm{s}}. \tag{6}$$

2.4.2 Radiation model for a tilted plane

As glacier surfaces are located in complex terrain, most glaciological measurements are conducted on tilted surfaces as shown in (~~Fig.~~Figure 3)~~, ϑ~~. ϑ_{s} in the Lambertian cosine law (Eq. 2), ~~is now~~ transforms now to $\vartheta_{\mathrm{tilt}}$, the solar incidence angle of ~~a tilted plane~~ any tilted plane in general, and can be expressed through

$$\cos\vartheta_{\mathrm{tilt}} = \boldsymbol{F}^{\downarrow} \cdot \boldsymbol{n} = \sin\vartheta_{\mathrm{s}} \cos\varphi_{\mathrm{s}} \sin\sigma \cos\gamma + \sin\vartheta_{\mathrm{s}} \sin\varphi_{\mathrm{s}} \sin\sigma \sin\gamma + \cos\vartheta_{\mathrm{s}} \cos\sigma, \tag{7}$$

where $\boldsymbol{n}$ is the ~~n~~ normal vector to the slope, ~~ϑ_{s} is the zenith angle of the sun,~~ φ_{s} the ~~azimuth angle of the sun~~solar azimuth angle, σ the tilt and γ the aspect of the slope.

Consequently, the incoming direct radiation on a tilted plane can be derived from Eqs. (6) and (7) as

$$\begin{aligned} F_{\mathrm{tilt}}^{\mathrm{dir}} &= S_{\mathrm{terr}} \cdot \cos\vartheta_{\mathrm{tilt}} = \\ &= \frac{S}{\tilde{r}^2} \cdot V \cdot e^{-\varepsilon \frac{1}{\cos\vartheta_{\mathrm{s}}}} \cdot (\sin\vartheta_{\mathrm{s}} \cos\varphi_{\mathrm{s}} \sin\sigma \cos\gamma + \sin\vartheta_{\mathrm{s}} \sin\varphi_{\mathrm{s}} \sin\sigma \sin\gamma + \cos\vartheta_{\mathrm{s}} \cos\sigma), \end{aligned} \tag{8}$$

To distinguish between a tilted plane and an inclined pyranometer the indices $\sigma_{\mathrm{t}}, \gamma_{\mathrm{t}}$ for ~~"tilt"~~ the tilted glacier surface and $\sigma_{\mathrm{p}}, \gamma_{\mathrm{p}}$ for ~~"pyranometer"~~ the pyranometer are used from here on.

In an idealized model of a measuring system with exactly horizontally levelled sensors, the incoming radiation hits the pyranometer and the tilted surface and is subsequently reflected back to the upper hemisphere as a function of the true snow albedo. In this idealized case using Eq. (1) the irradiance measured with the down-facing sensor can be expressed as

$$F^{\uparrow} = \alpha_{\text{true}} \cdot F_{\text{tilt}}^{\text{dir}}, \tag{9}$$

where $F_{\text{tilt}}^{\text{dir}}$ is defined in Eq. (8) and α_{true} is the true value of the (still unknown) albedo. ~~In this idealized case it is assumed that~~ For now a hypothetical case is assumed where the total incoming radiation only consists of the direct beam and the diffuse part of the radiation is neglected and described in detail later in the text.

The reflected part of the irradiance is measured by the down-facing pyranometer, so the measured albedo can be written as

$$\alpha_{\text{meas}} = \frac{F^{\uparrow}}{F^{\downarrow}} = \frac{\alpha_{\text{true}} \cdot F_{\text{tilt}}^{\text{dir}}}{F^{\downarrow}}. \tag{10}$$

Combining Eqs. (5), (8) and (10), α_{meas} can be simplified to

$$\alpha_{\text{meas}} = \frac{\alpha_{\text{true}} \cdot \frac{S}{\tilde{r}^2} \cdot V \cdot e^{-\varepsilon \frac{1}{\cos\vartheta_{\text{s}}}} \cdot \cos\vartheta_{\text{tilt}}}{\frac{S}{\tilde{r}^2} \cdot V \cdot e^{-\varepsilon \frac{1}{\cos\vartheta_{\text{s}}}} \cdot \cos\vartheta_{\text{s}}} = \alpha_{\text{true}} \frac{\cos\vartheta_{\text{tilt}}}{\cos\vartheta_{\text{s}}} \tag{11}$$

and the true albedo can be written as

$$\alpha_{\text{true}} = \alpha_{\text{meas}} \frac{\cos\vartheta_{\text{s}}}{\cos\vartheta_{\text{tilt}}}. \tag{12}$$

In Eq. (12) it is assumed that the ~~up-facing~~ pyranometer is levelled horizontally and the reflection of the snow cover is isotropic, which assumes that the surface is completely flat and homogenous.

Figure 4 shows the diurnal albedo variations derived with Eq. (11), where a constant true albedo ($\alpha_{\text{true}} = 0.7$) and a constant tilted slope ($\sigma_{\text{t}} = 7^{\circ}$) are modeled and only the aspect of the slope (γ_{t}) varies.

To improve the described model it has to be considered that the total incoming radiation measured by the up-facing pyranometer consists not only of a direct beam but also of a diffuse component. Consequently, the total incoming radiation can be split into a direct and a diffuse part (p_{dir} and p_{diff}).

In order to simplify the model, incoming diffuse fluxes over a tilted plane are regarded to be isotropic and equal to incoming diffuse radiation on a horizontal surface. Therefore the incoming radiation on a tilted plane can be split into

$$F_{\text{tilt}} = p_{\text{dir}} F_{\text{tilt}}^{\text{dir}} + p_{\text{diff}} F_{\text{hor}}. \tag{13}$$

Thus the measured albedo is

$$\alpha_{\text{meas}} = \frac{\alpha_{\text{true}} \left(F_{\text{dir}} + F_{\text{diff}} \right)}{F^{\downarrow}} \tag{14}$$

where

$$F_{\text{dir}} = \frac{S}{\tilde{r}^2} \cdot V \cdot e^{-\varepsilon \frac{1}{\cos \vartheta_{\text{s}}}} \cdot p_{\text{dir}} \cos \vartheta_{\text{tilt}} \tag{15}$$

and

$$F_{\text{diff}} = \frac{S}{\tilde{r}^2} \cdot V \cdot e^{-\varepsilon \frac{1}{\cos \vartheta_{\text{s}}}} \cdot p_{\text{diff}} \cos \vartheta_{\text{s}}. \tag{16}$$

The total incoming irradiance can be derived by inserting Eqs. (15) and (16) into Eq. (~~13)~~12), using Eq. (14), and finally, the true albedo can be written as

$$\alpha_{\text{true}} = \alpha_{\text{meas}} \frac{\cos \vartheta_{\text{s}}}{p_{\text{dir}} \cos \vartheta_{\text{tilt}} + p_{\text{diff}} \cos \vartheta_{\text{s}}}. \tag{17}$$

Eq. (17) assumes a constant azimuth angle.

2.4.3 Radiation model for a tilted slope with an inclined sensor

~~On a real measuring site~~In practise, pyranometers are not exactly horizontally levelled. The incoming radiation hits the inclined up-facing pyranometer and the tilted surface, from where it is reflected in an isotropic way into the inclined down-facing pyranometer (Figure 5). However, since we assume that the reflection is completely diffuse, the inclination of the down-facing pyranometer is ~~rendered~~ assumed to be irrelevant.

The true snow albedo can now be derived, considering a tilted slope and an inclined pyranometer by using Eq. (10)

$$\alpha_{\text{true}} = \alpha_{\text{meas}} \frac{\cos\vartheta_{\text{p}}}{\cos\vartheta_{\text{tilt}}} \frac{F_{\text{pyr}}}{F_{\text{tilt}}} = \alpha_{\text{meas}} \frac{F_{\text{pyr}}}{F_{\text{tilt}}} = \frac{F^{\uparrow}}{F^{\downarrow}} \frac{F_{\text{pyr}}}{F_{\text{tilt}}} \frac{\cos\vartheta_{\text{p}}}{\cos\vartheta_{\text{tilt}}}, \tag{18}$$

where ϑ_{p}, derived as in Eq. (7), is the inclination angle of the pyranometer, F_{pyr} the incoming irradiance ~~hitting~~ perpendicular to the up-facing pyranometer and F_{tilt} the irradiance hitting the slope.

Figure 6 shows the calculated diurnal albedo using this model with a constant diurnal true albedo ($\alpha_{\text{true}} = 0.7$) for different tilts and inclinations of slope and ~~up-facing~~ pyranometer derived with Eq. (18).

Taking into account the diffuse radiation, F_{pyr} and F_{tilt} have to be split into a direct and a diffuse part analogously to Eqs. (15) and (16). $\cos\vartheta_{\text{p}}$ and $\cos\vartheta_{\text{t}}$ can be derived with tilts and directions of sensor and slope analogously to Eq. (7)~~.~~:

$$\cos\vartheta_{\text{p}} = \boldsymbol{F}^{\downarrow} \cdot \boldsymbol{n} =$$

$$= \sin\vartheta_{\text{s}} \cos\varphi_{\text{s}} \sin\sigma_{\text{p}} \cos\gamma_{\text{p}} + \sin\vartheta_{\text{s}} \sin\varphi_{\text{s}} \sin\sigma_{\text{p}} \sin\gamma_{\text{p}} + \cos\vartheta_{\text{s}} \cos\sigma_{\text{p}}. \tag{19}$$

$$\cos\vartheta_{\text{t}} = \boldsymbol{F}^{\downarrow} \cdot \boldsymbol{n} =$$

$$= \sin\vartheta_{\text{s}} \cos\varphi_{\text{s}} \sin\sigma_{\text{t}} \cos\gamma_{\text{t}} + \sin\vartheta_{\text{s}} \sin\varphi_{\text{s}} \sin\sigma_{\text{t}} \sin\gamma_{\text{t}} + \cos\vartheta_{\text{s}} \cos\sigma_{\text{t}}. \tag{20}$$

Considering these assumptions, the true albedo can be expressed ~~as~~ using the measured albedo α_{meas}, the direct p_{dir} and the diffuse part p_{diff} of the incoming radiation, the solar zenith angle ϑ_s and the tilts of the slope ϑ_t and the sensor ϑ_p:

$$\alpha_\mathrm{true} = \cancel{\frac{F^\uparrow}{F^\downarrow}}\alpha_\mathrm{meas}\left(\frac{p_\mathrm{diff}\cdot\cos\vartheta_\mathrm{s} + p_\mathrm{dir}\cdot\cos\vartheta_\mathrm{p}}{p_\mathrm{diff}\cdot\cos\vartheta_\mathrm{s} + p_\mathrm{dir}\cdot\cos\vartheta_\mathrm{t}}\right) \quad (21)$$

or, using $p_\mathrm{dir} + p_\mathrm{diff} = 1$,

$$\alpha_\mathrm{true} = \cancel{\frac{F^\uparrow}{F^\downarrow}}\alpha_\mathrm{meas}\left(\frac{p_\mathrm{diff}\cdot\cos\vartheta_\mathrm{s} + (1-p_\mathrm{diff})\cdot\cos\vartheta_p}{p_\mathrm{diff}\cdot\cos\vartheta_\mathrm{s} + (1-p_\mathrm{diff})\cdot\cos\vartheta_\mathrm{t}}\right). \quad (22)$$

To correct the albedo with Eq. (22) on clear sky days, ~~the following assumptions and parameters are used:~~ it is assumed that following parameters are constant over one day:

1. extinction coefficient ε~~is constant over one day~~;
2. linear factor V~~, which represents the ratio between the spectral range of the pyranometer and TOA irradiance, is constant over one day~~;
3. ~~diffuse reflection of the incoming radiation by the snowcover is assumed to be isotropic and constant over one day (constant snow albedo over one day); fraction of the diffuse to total incoming radiation during a clear sky day is $p_\mathrm{diff} \approx 10\,\%$;~~ tilt σ_t and direction γ_t of the slope~~are constant over one day~~;
4. tilt σ_p and direction γ_p of the pyranometer~~are constant over one day~~;
5. diffuse part of incoming radiation p_diff.

2.5 ~~Workflow to correct albedo measurements~~

~~The determination of tilts and directions of slopes and sensors are accomplished by fitting the model parameters to~~ The residuals of the results show, that there is almost no diurnal variation between the measured data ~~(Fig. 7). With these, the albedo values can be~~

~~corrected~~and the model where the extinction coefficient ε and the ratio between the spectral range of the pyranometer and TOA irradiance V are considered. The reason for this is that AOD has a small range of values in high altitudes (Weihs et al., 1999) .

The ~~described model, including atmospheric parameters,~~ tilts and directions of both, the slope and the sensor σ_t, ~~is now compared to the measured data to evaluate the differences. To find the smallest difference between model and measured data~~γ_t, ~~the method of least squares is used~~σ_p, γ_p are also considered to be constant over a day, because neither the surface, nor the sensor show relevant changes within small periods. As evidence the residuals of the results are considered, which show no relevant diurnal variations.

For all evaluated clear sky days in the Sonnblick area and in Vienna both, the measured data of the Suntracker and the STRAHLGRID model show a diurnal mean value of the diffuse part of incoming radiation of $p_\mathrm{diff} \simeq 10\%$, therefore this value can be assumed to be constant for clear sky days.

The diffuse reflection of incoming radiation by the surface is assumed to be isotropic and constant for a day. Due to this for the corrected albedo an average value for one day within a SZA of $\vartheta_\mathrm{s} < 50^\circ$ is taken.

2.4.1 ~~Step A:atmospheric parameters for clear sky days~~

2.5 Workflow to correct albedo measurements

The detailed workflow of the albedo correction method is shown in Figure 7 and summarized in the following subsections.

2.5.1 Step A: derive atmospheric parameters for clear sky days

(a) nearby reference measurement

To calibrate the radiation model, the atmospheric model parameters are fitted to nearby reference radiation measurements so as to reduce the residuals between modeled and measured global radiation ~~from BSRN stations SBO and WHW~~using the method of least squares.

~~In Eq. (6), where the direct incoming radiation on a horizontal plane is derived, ε and V are unknown atmospheric parameters, which need to fit the model to~~ **(b) solar radiation model**

Instead of reference measurements, the ~~measured data. The composition of the atmosphere is assumed to be constant during one day over the whole Sonnblick area, where the AWS are drilled into the glaciers and at ZAMG in Vienna, where the Suntracker uses the same coordinates as the measurement setup on the roof~~output of a solar radiation model can be used to derive the atmospheric parameters of the albedo correction model.

2.5.2 Step B: inclination and direction of the pyranometer

After the atmospheric parameters for ~~one specific day~~ clear sky days are estimated, the inclinations and directions of the sensors can be derived by using Eq. (~~13):~~

$$F_\mathrm{p} = \frac{S}{\tilde{r}^2} \cdot V \cdot e^{-\varepsilon \frac{1}{\cos\vartheta_\mathrm{s}}} \cdot ((1 - p_\mathrm{diff}) \cos\vartheta_p + p_\mathrm{diff} \cos\vartheta_\mathrm{s}),$$

~~where ϑ_p, the solar incidence angle of the pyranometer, can be expressed through the scalar product of the direct sun beam and the normal vector to the pyranometer (Fig. 3), which uses cartesian coordinates analogously to Eq. (7):~~

$$\cos\vartheta_\mathrm{p} = \boldsymbol{F}^{\downarrow} \cdot \boldsymbol{n} =$$

$$= \sin\vartheta_\mathrm{s} \cos\varphi_\mathrm{s} \sin\sigma_\mathrm{p} \cos\gamma_\mathrm{p} + \sin\vartheta_\mathrm{s} \sin\varphi_\mathrm{s} \sin\sigma_\mathrm{p} \sin\gamma_\mathrm{p} + \cos\vartheta_\mathrm{s} \cos\sigma_\mathrm{p}.$$

~~The unknown parameters in Eq. (23), σ_p (tilt) and γ_p (direction), are determined by fitting the modeled to the measured data of the up-facing pyranometer with the method of least squares.~~ 15).

~~This method was used for the AWS on Sonnblick glaciers and for the measurement setup on the roof of ZAMG.~~

2.5.3 Step C: tilt and direction of the slope

The process to determine the unknown tilts and directions of the slope out of the measured reflected radiation $F^{\uparrow}$ is more complicated because $F^{\uparrow}$ also depends on the unknown albedo of the surface.

It is assumed that the incoming radiation of the slope is directly proportional to the reflected radiation measured by the down-facing pyranometer with the proportionality factor being the yet unknown albedo α_{true}

$$F^{\uparrow} = \alpha_{\text{true}} \cdot \cos\vartheta_{\text{t}}, \tag{23}$$

where ϑ_{t} is the solar incidence angle on the slope, defined in Eq. (~~7) as ϑ_{tilt}~~ 25) and illustrated in ~~Fig.~~Figure 3.

The task now is to find a combination of σ_{t} (tilt) and γ_{t} (direction) in such a way that the modeled incoming radiation on the tilted slope and the measured values for $F^{\uparrow}$ only differ by a factor C that should be ~~as constant as possible for one day~~ a constant value for the day in progress. First of all, for any combination of σ_{t} and γ_{t}, the constant C is calculated as the average over one day:

$$C = \left\langle \left(\frac{F^{\uparrow}}{\cos\vartheta_{\text{t}}} \right) \right\rangle, \tag{24}$$

where $\cos\vartheta_{\text{t}}$ is expressed ~~analogously to Eqs. (7)and (23):~~

$$\cos\vartheta_{\text{t}} = \boldsymbol{F}^{\downarrow} \cdot \boldsymbol{n} =$$

$$= \sin\vartheta_{\text{s}} \cos\varphi_{\text{s}} \sin\sigma_{\text{t}} \cos\gamma_{\text{t}} + \sin\vartheta_{\text{s}} \sin\varphi_{\text{s}} \sin\sigma_{\text{t}} \sin\gamma_{\text{t}} + \cos\vartheta_{\text{s}} \cos\sigma_{\text{t}}.$$

in Eq. (25).

For every factor C, the method of least squares is used to minimize the difference between modeled and measured reflected radiation with Eq. (25):

$$\left(C \cdot \cos\vartheta_{\text{t}} - F^{\uparrow} \right)^2 \longrightarrow \min. \tag{25}$$

This expression ~~is~~ has to be minimal for the combination of σ_t and γ_t, for which the proportionality factor C is ~~as constant as possible.~~constant for one day in an ideal case and σ_t and γ_t fit the measured data of the reflected measured radiation $F^\uparrow$, calculated with Eq.(23).

2.5.4 Step D: derive true albedo

Now that all inclinations, tilts and directions are estimated for one day, the true albedo can be derived from the measured data with Eq. (22)~~:~~

$$\alpha_\mathrm{true} = \frac{F^\uparrow}{F^\downarrow} \frac{p_\mathrm{diff} \cdot \cos\vartheta_\mathrm{s} + (1 - p_\mathrm{diff}) \cdot \cos\vartheta_\mathrm{p}}{p_\mathrm{diff} \cdot \cos\vartheta_\mathrm{s} + (1 - p_\mathrm{diff}) \cdot \cos\vartheta_\mathrm{t}}$$

~~It is reasonable to use Eq. (22) for an opening angle of the pyranometer of ±80°, so time periods within a flat zenith angle, after sunrise and before sunset, are cut off.~~ .

Compared to Steps A–C, where the results are determined by fitting the model to the measured values with the method of least squares, Eq. (22) is only used with measured ($F^\uparrow$, $F^\downarrow$, p_diff) and derived (σ_p, γ_p, σ_t, γ_t) parameters within a ~~certain time interval~~SZA of $\vartheta_\mathrm{s} < 50°$. The daily mean value ~~as well as the SD~~ and the standard deviation (SD) of α_true are determined.

2.5.5 Step E: derive radiative balance

The ~~effects of corrected~~ purpose of correcting albedo values on ~~the~~ clear sky days is the correction of shortwave radiative balance. The effects are shown by comparing measured and corrected radiative balance in Figure 11.

The ~~shortwave radiative balance~~ net shortwave radiation $\mathrm{SW_{net}}$ is derived as

$$\begin{aligned} \mathrm{SW_{net}} &= \mathrm{SW_{in}} + \mathrm{SW_{out}} \\ &= \mathrm{SW_{in}} - \alpha \cdot \mathrm{SW_{in}} = \mathrm{SW_{in}}(1 - \alpha) \end{aligned} \tag{26}$$

In Eq. (26) the albedo α ~~stands for~~ can be used with both, α_meas and α_corr.

3 Results

3.1 Atmospheric parameters

3.1.1 Nearby reference measurement

To determine the described ~~atmospheric parameters~~ parameters that depend on the composition of the atmosphere, the data of the Suntracker are compared to the model of TOA for each location, in this case the roof of ZAMG in Vienna and the Sonnblick Observatory. In both cases the ranges of ε and V are within the same intervals, shown in Tables 2 and 3.

The ~~weighted extinction coefficient ranges~~ determined extinction coefficients resulting from model adaptions range between $\varepsilon = 0.001$–0.2, which ~~occurs due to~~ concur well with known ranges (DeWalle and Rango, 2008) , as a result of several influences, such as ~~temperature,~~ water vapour, aerosols and other meteorological parameters that vary continuously.

The ratio between the spectral range of the pyranometer and the irradiance on TOA ranges between $V = 0.8$–1, which underestimates the known ranges of $V \simeq 0.98$ (Corripio, 2002) , caused by model errors.

3.2 ~~Roof of ZAMG~~

3.1.1 Solar radiation model

~~With the described method, the model was fitted to the measured data (Step Bof the workflow to correct albedo measurement~~If there is no reference measurement nearby, a solar radiation model such as STRAHLGRID can be used. The benefit of the use of a radiation model is that it can be used for every grid point provided, that data on AOD and integral water vapor are available. The results of ε and V show values within similar ranges, shown in Tables 2 and 3.

As can be seen in Figure 8 the STRAHLGRID model overestimates the AOD leading to different albedo values. The mean bias error (MBA) and the mean ~~albedo over one clear sky day was taken~~absolute error (MAE) for measured and corrected albedo values of both correction procedures, the reference measurement (Suntracker) and the STRAHLGRID model are shown in Table 4.

~~Subsequently~~

3.2 Roof of ZAMG

To demonstrate the performance of the albedo correction method and its validity also for large inclinations, the pyranometer was horizontally leveled on 4 July 2014 and intentionally inclined with $\sigma_\mathrm{p} \approx 25°$ in westerly direction with ($\gamma_\mathrm{p} \approx 270°$) on 19 July 2014 over a horizontal concrete plane. ~~As described above, the upper and the lower pyranometer used the same housing and therefore had the same inclination and direction.~~

The differences between measured and corrected albedo values are shown in ~~Fig.~~Figure 2 and Table 2.

~~In Fig.~~In Figure 2 (left) the fitted and measured data show an almost constant diurnal albedo on 4 July 2014, where the pyranometer was horizontally levelled. The anomalies shortly after sunrise and before sunset occur due to the cosine error of the up-facing sensor at ~~flat zenith angles~~large SZA and are outside the SZA ranges of $\vartheta_\mathrm{s} < 50^\circ$ that are used for the correction model.

Figure 2 (right) shows that with an inclined pyranometer the incoming and reflected radiation change unequally, resulting in a modified, wrong surface albedo that is not constant anymore during one clear sky day. After sunrise, the reflected radiation is higher than the incoming radiation which is the result of the westerly inclination of the sensor because the down-facing sensor also receives direct incoming radiation due to the flat zenith angle after sunrise. Even within the taken SZA limits of $\vartheta_\mathrm{s} < 50^\circ$ the measured albedo shows a diurnal variation, which has to be corrected.

In both cases it is apparent that the model ~~that was presumed with a diurnal constant albedo fits the measured data for a horizontal as well as for an inclined sensor .~~

~~Furthermore, it is reasonable to use the daily mean albedo for both, the~~ of both, the horizontal and the inclined sensor fits the measured data and the corrected ~~model, within a zenith angle of $\vartheta_s = \pm 80°$, which is marked by the grey vertical lines~~albedo values are within the same ranges.

~~After comparing the Suntracker data of several clear sky days all over the year on the WHW and Sonnblick observatory, it is reasonable to assume the diffuse part of the total incoming radiation on a horizontal surface $p_{diff} \approx 10\,\%$.~~

The accuracy of the correction method can be demonstrated by comparing the ~~corrected albedo α_{corr} for~~ measured albedo α_{meas} as of 4 ~~July with the one for~~ July 2014 (horizontally levelled sensors) with the corrected albedo α_{corr} as of 19 ~~July in Table~~ July 2014 (tilted sensors) in Table 2. The deviation between these two results is less than 1 %, whereas the deviation between the measured albedo ~~α_{meas}~~ α_{meas} for both days is $\approx 16\,\%$.

3.3 ~~AWS on Sonnblick glaciers~~

~~Depending on the direction of the slope and the sensor, the true value of the diurnal mean albedo can either be larger or smaller than the measured one~~As shown in Figure 8, the corrected albedo with the STRAHLGRID model is $\approx 1\,\%$ higher than with the data of the Suntracker. Though the deviations between the two observed days are within the same ranges of 1 % for the corrected albedo and $\approx 16\,\%$ for the measured albedo.

~~In Fig.~~

3.3 AWS on Sonnblick glaciers

In Figure 2 as well as in ~~Fig.~~Figure 9 it is apparent that the model can be fitted to the measured data for highly inclined and differently directed sensors and slopes. As the figures show, the model differs from the measured values by ~~approximately 1for acceptable zenith angles. The acceptable~~ $\approx 1\,\%$ for a SZA of $\vartheta_s < 50^{\circ}$. The daily mean albedo within a ~~zenith angle of $\vartheta_s = \pm 80°$~~ SZA of $\vartheta_s < 50°$ is marked by the gray vertical lines.

The correction for a clear ~~winter day~~ day in March is demonstrated for the southwesterly directed Kleinfleißkees where the corrected diurnal mean albedo is 0.11 less than the measured one~~.~~, even when the period of correction within a SZA of $\vartheta_s < 50°$ is very small in this season due to astronomical reasons.

In contrast, the correction for a clear ~~summer day~~ day in June is demonstrated for the northeasterly directed Goldbergkees where the corrected diurnal mean albedo is 0.03 higher than the measured one (see ~~Fig.~~Figure 9 and Table 3). The actual tilts and directions were directly measured repeatedly when the sensors were maintained at field works and matched well with the determined results. The results of the AWS on the Sonnblick glaciers were also verified with the method of Mannstein (1985) and lead to the same values.

These results lead to the conclusion that it depends on the direction of the slope ~~whether the~~ and the sensor whether the true value of the diurnal mean albedo is over- or underestimated, demonstrated in Figure 10, where measured and corrected albedo values for clear sky days on FLK and GOK in the observed time period are presented.

Furthermore, the absolute value of over- or underestimations in summer months are smaller than in winter months due to ~~a different solar zenith angle~~generally lower SZA.

3.4 Shortwave radiative balance

As shown in the previous sections the ~~directly~~ measured albedo differs from the corrected ~~(true)~~ albedo. This means that the amount of shortwave radiation absorbed by the glacier varies likewise. For example, using data from Table 3, directly measured values for Kleinfleißkees indicate that 14 % of the incoming shortwave radiation SW_{in} are absorbed by the glacier. On the other hand, the corrected values show that 25 % of the incoming shortwave radiation are absorbed during those days.

The correction of the radiative balance using Eq. (26) is demonstrated in ~~Fig.~~Figure 11 for the two sample days, where on 5 March 2011 on Kleinfleißkees the corrected radiative balance SW_{corr} is roughly 55 % higher than the measured one SW_{meas} and on 27 June 2011 on Goldbergkees SW_{corr} is roughly 7 % smaller than SW_{meas}.

~~Over the year~~ An average over the years 2011 and 2012 the corrected radiative balance SW_{corr} on Kleinfleißkees is $\approx 8\,\%$ higher than the measured one (SW_{meas}). On Goldbergkees the corrected radiative balance SW_{corr} is $\approx 6\,\%$ smaller than the measured one. ~~The~~ These relatively small absolute values of the relative corrections result from the fact that there are more cloudy than clear sky days over the year at those locations.

4 Discussion

The ~~described method can be used on clear sky days and on days with a short period of clear sky, with a minimum of 2–3h. On these days, the clouded part has to be cut off when fitting the model~~ atmospheric parameters of the albedo correction model consist of two single numbers (ε and V) which does not allow to account for eventual diurnal variations of the clear-sky transmittances. However, the fitting of the albedo correction model to measured or modelled clear-sky reference data in order to derive those bulk atmospheric parameters revealed a small SD and diurnal variation of the residuals at both sites, Sonnblick and WHW for all selected and presented days. We attribute this to ~~the measured data. Also shadows of nearby mountains have to be cut off to use just the clear sky part with direct incoming radiation. The advantage of this method is that it is not limited to completely clear sky days, which are relatively rare in mountainous areas.~~ generally low AOD and water vapor values at the remote and high elevated site Sonnblick, which has been noted in previous studies already (e.g. Weihs et al., 1999). For the urban test site WHW, AOD values were especially low during the selected days and showed little diurnal variation as given by a low SD of direct normal irradiance measured with the Suntracker during those days. We also note that calculated values of V (ratio of spectral range) are too low compared to radiative transfer model experiments carried out by Corripio (2002) . We explain this by the fact that other errors of the fitting procedure are also lumped into this coefficient. For the correction model we further assumed a constant ratio of diffuse to global radiation $p_{\text{diff}} \simeq 10\%$. This number is based on data analysis of multiple clear-sky days during different seasons at stations, Sonnblick and Vienna and is also strengthen by the results of the STRAHLGRID model which gives a similar number.

~~The differing optical path length through the atmosphere due to the curvature of the earth has to be considered, especially when the zenith angle is flat at sunrise and sunset, hence it is reasonable to neglect these time intervals.~~ The described method can be applied on days with a minimum of 2-3 hours of nearly clear-sky conditions. Although this might imply a large limitation of the method as cloudy days predominate at least in the climate of the European Alps, highest daily sums of melt energy for snow and ice are strongly correlated with direct solar radiation and thus low cloudiness. In other words the correction method is applicable when most melt energy is available and corrections are most needed.

~~When the inclinations of the sensors are too large, the down-facing sensor receives parts of the incoming radiation after sunrise or before sunset, depending on~~ We introduced a SZA limit of $\vartheta_s < 50^\circ$ for the albedo correction method as it assumes a diurnal constant albedo which is reasonable only for this SZA range. Due to astronomical reasons, in the Sonnblick region this condition can only be satisfied in the ~~direction. For these days a correction for the albedo is less useful because incoming and reflected radiation are not clearly separated any more.~~ period from mid-March to mid-September as minimum daily SZA values do not fall below this value outside of this period. Again, we do not see this as a major shortcoming of our method, as main melt energy is available within the time between March and September. Future work will investigate whether the diurnal variation of albedo outside of this period has significant implications for the applicability of our method.

~~On days after snowfall it can happen that the up-facing sensor is still covered with snow and after melting periods there are water drops on the~~ The tilts of both the sensors and the slope are also assumed to be constant over one day. From field observations and residual analysis of the correction model this assumption appears justified. Under seldom conditions of extreme sensor tilt $\sigma_p > 25^\circ$ the down-facing ~~sensor.~~ sensor can receive parts of the incoming radiation which makes it difficult to separate incoming from reflected radiation. In those rare situations the correction model obviously doesn't work.

~~Sometimes the solar panel attached to the AWS is covered with snow, so the self-contained power supply is not guaranteed. Especially in winter months the AWS cannot take measurements for longer time periods due to their isolated locations.~~

~~The atmospheric parameters, as well as tilts and directions of slopes and sensors have to be calibrated every daywhich is very time consuming and cannot be fully automated due to different cut-offs. If there is no reference measurement nearby, this method cannot be applied. As a further consequence, an improvement of this~~ A further improvement of our method would be to ~~use a model that finds atmospheric parameters without a reference measurement , using meteorological parameters, such as aerosol concentration, water vapour, temperature, etc.~~

~~To minimize tilt errors in albedo measurement, the sensor can be adjusted parallel to the slope, such that the incident radiation is identical for both.Ideal measurement setups are over flat surfaces with horizontally levelled sensors, which is difficult in mountainous areas on glaciers.~~directly use a solar radiation model instead of fitting the atmospheric parameters of the albedo correction model to a reference measurement or model. To be successful this would require (a) more accurate AOD data than those used from MODIS satellite here, which is a problem that is still under debate (e.g. Ruiz-Arias et al., 2013 ; Gueymard, 2012) and (b) the integration of an automated clear-sky detection algorithm which is available from e.g. Marty and Philipona (2000) and requires records of longwave incoming radiation.

5 Conclusions

~~Directly measured snow albedo variations on clear sky days can be relatively high~~

Automatically measured snow or ice albedo values in complex terrain on days with low cloudiness are often incorrect due to tilted ~~slopes and inclined pyranometers, hence it is challenging to determine a diurnal mean albedo from directly measured data. The tilts and directions~~ radiation sensors or the underlying terrain slope. This leads to the conclusion that albedo has to be corrected during those days.

The presented albedo correction method calculates tilts and aspects of sensors and ~~slopes were unknown and it was difficult to make permanent manual reference measurements due to the isolated location of the measuring sites. To compensate for this problem, a model was developed with the aim to allow accurate estimations of measurement site's tilts and orientations of slope and sensors~~of the terrain slope during periods of clear-sky.

~~For this model, atmospheric parameters~~ Atmospheric parameters of the correction model are determined using ~~a nearby~~ data from a nearby Suntracker as reference measurement with a horizontally levelled pyranometer~~to find the difference between TOA and near surface incoming shortwave radiation . With these~~ . In case no nearby radiation reference measurement exists, a solar radiation model can be used to determine these atmospheric parameters. The results show that the solar radiation model is accurate enough for the correction method to be successful.

With the determined atmospheric parameters, the model is fitted to the measured data. The results of these fitting procedures are ~~tilts and directions~~ the tilts and aspects of both, the sensors and the slopes.

With these tilts and directions, the true albedo can be derived from the measured ~~data. Especially in winter months (September to June) and in polar areas, where the zenith angle of the direct sun beam is flat, the differences are relatively high.~~ one.

To ~~prove this~~ validate our method, an experimental measurement was ~~taken for~~ setup on a horizontal concrete surface ~~with a pyranometer with and without inclination. The results show a different diurnal mean albedo . The atmospheric parameters, the inclination and the direction of the sensor were determined with the described method . Furthermore, the true albedo was derived and~~ to show that even a constant albedo shows strong artificial diurnal variations and a wrong daily average value when the sensor is inclined which has to be corrected to get physically correct values.

For the case of the automatic weather stations (AWS) on two glaciers the method showed large albedo corrections leading to radiative balances that are up to 55% higher or lower compared to the ~~diurnal mean albedo measured by a horizontally levelled pyranometer over~~

~~the same surface. The difference between these values was less than 1 %, whereas the difference between the directly measured values by an inclined pyranometer was ≈ 16 %.~~

~~Consequently, the difference between the directly measured and the corrected radiative balancecan be significant on single clear sky days especially with a flat zenith angle~~(wrongly) measured value for single days. On average over two years the correction factors of the radiative balance ranged in the order of 6% to 8%. These results indicate that albedo corrections are strongly needed in order to correctly quantify the energy balance, especially in case of AWS in remote locations. Our method is a first step towards such a correction and is easily reproducible and transferable in space.

Acknowledgements. This work was financed by the FEMtech programme of the Österreichische Forschungsförderungsgesellschaft (FFG) and the Central Institute for Meteorology and Geodynamics (ZAMG).

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Table 1. Geographic latitude ϕ~~and~~, longitude $\cancel{\vartheta}$ θ, altitude above sea level, tilts and ~~direction~~ aspects of the used measurement ~~stations~~sites.

	SBO	FLK	GOK	WHW
ϕ	$12°57'28''$	$12°56'42''$	$12°57'50''$	$16°21'23''$
$\cancel{\vartheta}$ θ	$47°3'14''$	$47°3'15''$	$47°2'38''$	$48°14'55''$
~~altitude~~ (m a.s.l.)	3111	2829	2678	198
~~direction~~ tilt		$8° - 12°$	$11° - 15°$	
aspect		SW	NE	

Table 2. ~~Results of measured~~ Measured and ~~corrected~~ retrieved sensor inclinations and directions and daily average albedo, including all standard deviations, at WHW on 4 and 19 July ~~2014.~~ 2014 on a horizontal concrete surface.

	4 Jul 2014	19 Jul 2014
ε	0.102 ± 0.001	0.111 ± 0.002
$\varepsilon_{\mathrm{mod}}$	0.129 ± 0.001	0.118 ± 0.002
V	0.86 ± 0.03	0.84 ± 0.04
V_{mod}	0.81 ± 0.03	0.80 ± 0.04
σ_{p}	$0.3° \pm 0.0003°$	$24.0° \pm 0.024°$
γ_{p}	$5.0° \pm 0.025°$	$265.0° \pm 1.325°$
$\sigma_{\mathrm{p(meas)}}$	$1.27° \pm 0.01°$	$23.33° \pm 0.12°$
$\gamma_{\mathrm{p(meas)}}$	$170.44° \pm 0.85°$	$264.32° \pm 1.32°$
$\cancel{\alpha_{\mathrm{meas}}}$ $\alpha_{\mathbf{meas}}$	$\cancel{0.1791 \pm 0.0063}$ 0.1791 ± 0.0063	$\cancel{0.2083 \pm 0.0696}$ 0.2083 ± 0.0696
$\cancel{\alpha_{\mathrm{corr}}}$ $\alpha_{\mathbf{corr}}$	$\cancel{0.1789 \pm 0.0064}$ 0.1789 ± 0.0064	$\cancel{0.1773 \pm 0.0082}$ 0.1773 ± 0.0082

Table 3. Results of measured and corrected inclinations and directions and daily average albedo~~on~~, including all standard deviations, at the AWS sites Kleinfleißkees on 5 March 2011 and on Goldbergkees on 27 June 2011.

	FLK, 5 Mar 2011	GOK, 27 Jun 2011
ε	0.051 ± 0.001	0.071 ± 0.002
$\varepsilon_{\mathrm{mod}}$	0.071 ± 0.001	0.081 ± 0.002
V	0.95 ± 0.03	0.93 ± 0.04
V_{mod}	0.91 ± 0.03	0.90 ± 0.04
σ_{t}	$10.57^\circ \pm 0.05^\circ$	$13.51^\circ \pm 0.11^\circ$
γ_{t}	$225.00^\circ \pm 5.60^\circ$	$41.43^\circ \pm 4.93^\circ$
σ_{p}	$4.72^\circ \pm 0.11^\circ$	$3.93^\circ \pm 0.08^\circ$
γ_{p}	$247.62^\circ \pm 3.37^\circ$	$9.68^\circ \pm 0.68^\circ$
$\sigma_{\mathrm{p(meas)}}$	$4.29^\circ \pm 0.02^\circ$	$7.77^\circ \pm 0.39^\circ$
$\gamma_{\mathrm{p(meas)}}$	$305.43^\circ \pm 1.53^\circ$	$52.54^\circ \pm 0.26^\circ$
α_{meas}	0.86 ± 0.07	0.51 ± 0.06
α_{corr}	0.75 ± 0.01	0.54 ± 0.01

Table 4. Mean bias error (MBA) and mean absolute error (MAE) for corrected albedo values between modeled and measured data determined with reference measurement (Suntracker) and radiation model (STRAHLGRID).

		Suntracker		STRAHLGRID	
		MBE	MAE	MBE	MAE
5 Mar 2011	FLK	-0.08	2.44	-3.30	3.55
27 Jun 2011	GOK	0.25	1.86	-1.87	2.50
4 Jul 2014	WHW	1.51	3.55	4.07	6.52
19 Jul 2014	WHW	2.88	6.29	3.64	6.32

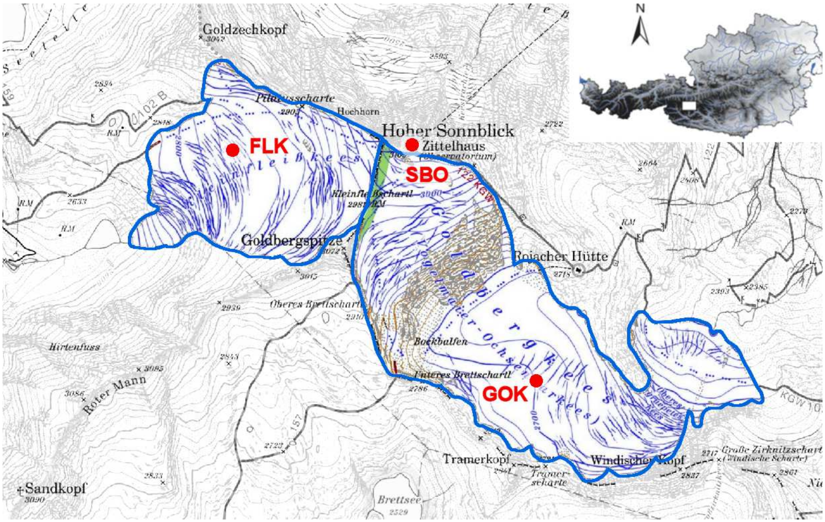


Figure 1. Map of Sonnblick area (taken from Alpenvereinskarten digital 2007, Vers. 2.0.9.0, DAV (Munich), ÖAV (Innsbruck)). The red marks indicate the positions of the AWS and SBO.

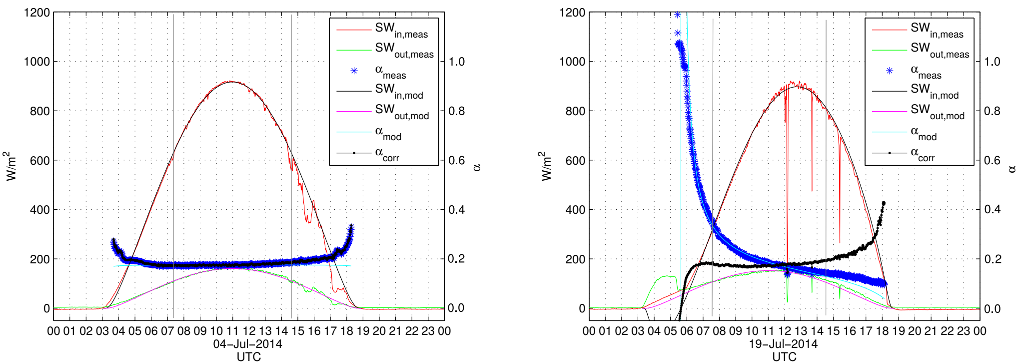


Figure 2. ~~Geometric account of~~ Measured, modeled and corrected SW_{in}, SW_{out} and α with a ~~tilted surface.~~ horizontally levelled (left) and an intentionally inclined pyranometer (right) at WHW for two days in July 2014.

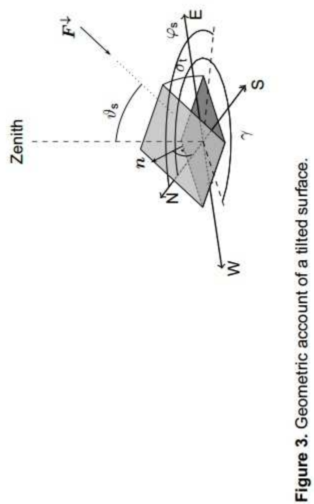


Figure 3. Geometric account of a tilted surface.

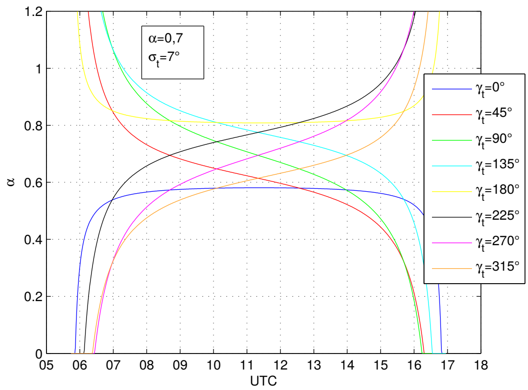


Figure 4. Diurnal variations of albedo with a constant true albedo, a constant tilt of the slope but differing aspects.

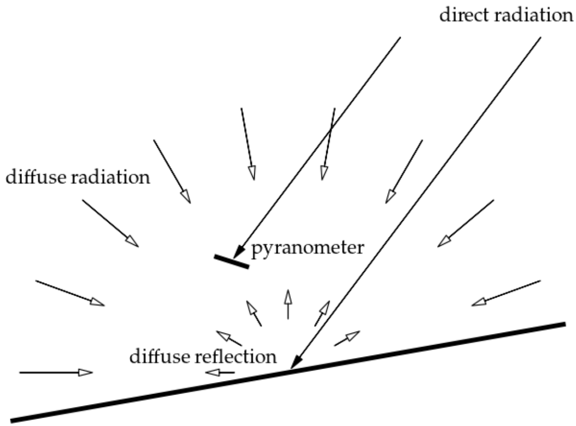


Figure 5. Isotropic reflection from a tilted slope with an inclined pyranometer.

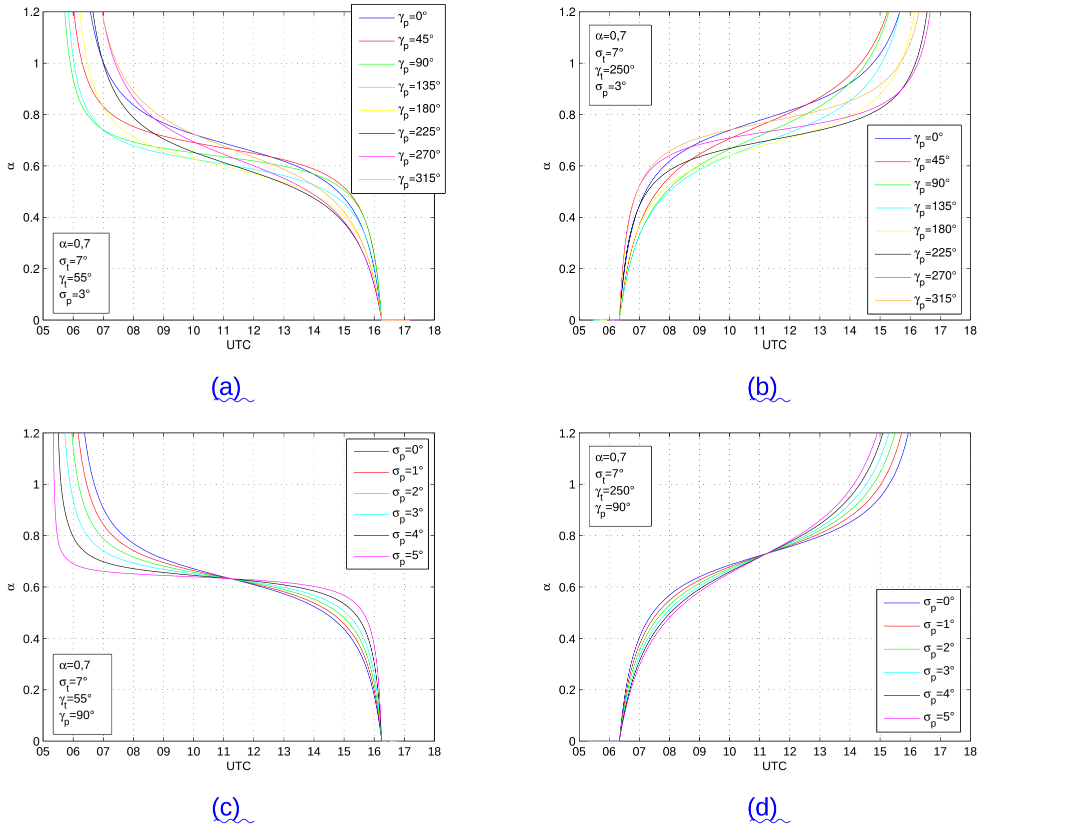


Figure 6. Calculated albedo with a constant diurnal true albedo for (**a** and **b**) differently oriented (γ_p) and (**c** and **d**) inclined (σ_p) pyranometers, different tilted (σ_t) and directed (γ_t) slopes.

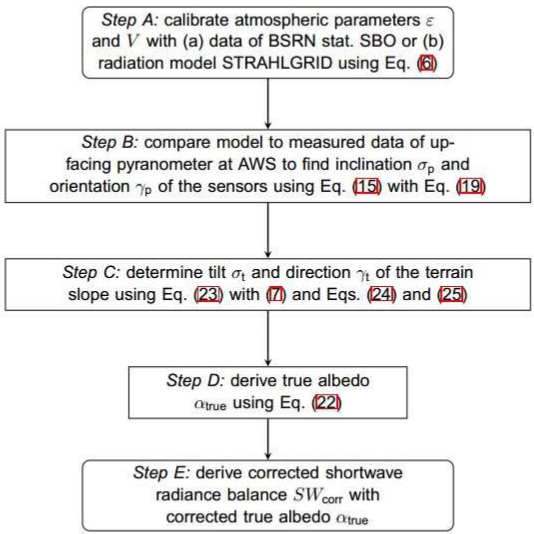


Figure 7. Workflow to correct daily albedo values.

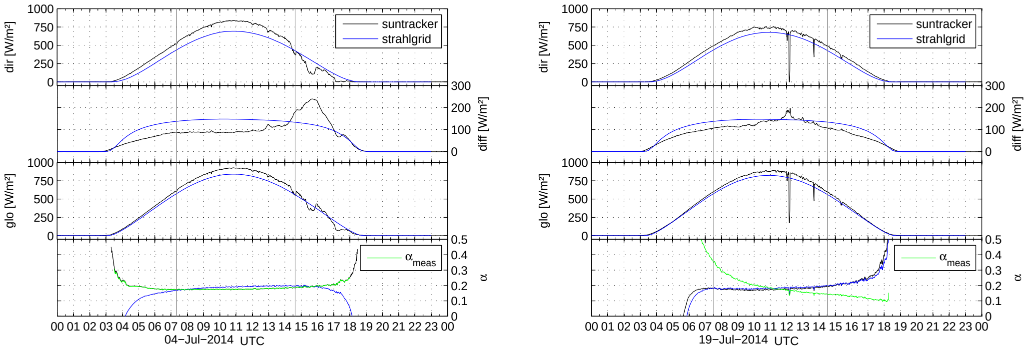


Figure 8. ~~Measured, modeled~~ Comparison of the radiation data of the Suntracker and ~~corrected SW_{in}, SW_{out} and α with~~ the STRAHLGRID model for the two example days at the roof of ZAMG for a ~~-~~horizontally levelled (left) and an ~~intentionally~~ inclined pyranometer (right)~~at WHW for two days in July 2014.~~, including the difference of the corrected albedo.

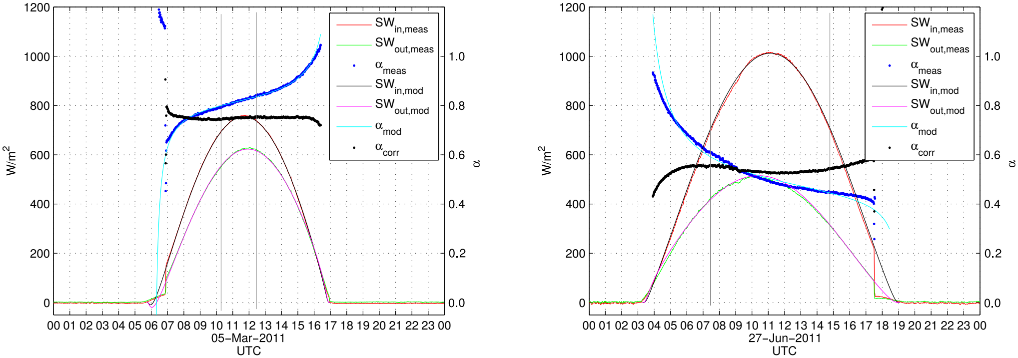


Figure 9. Directly measured (blue dots), modelled (cyan) and corrected (black dots) albedo calculated from data of an inclined pyranometer and a tilted slope at the location of the AWS on Kleinfleißkees on 5 March 2011 (left) and Goldbergkees on 27 June 2011 (right).

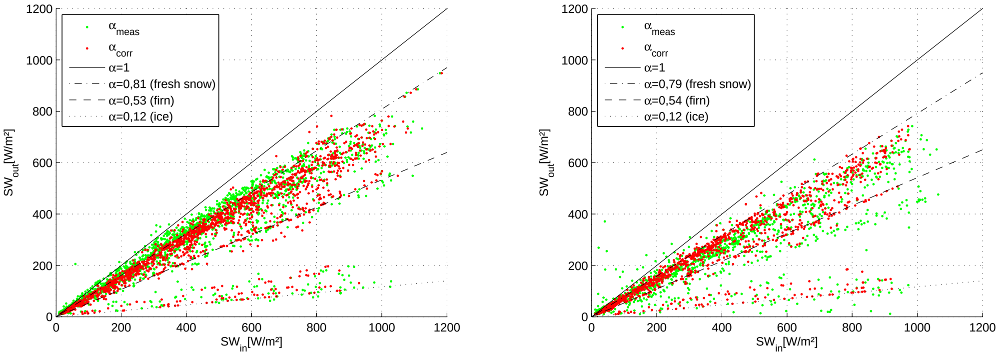
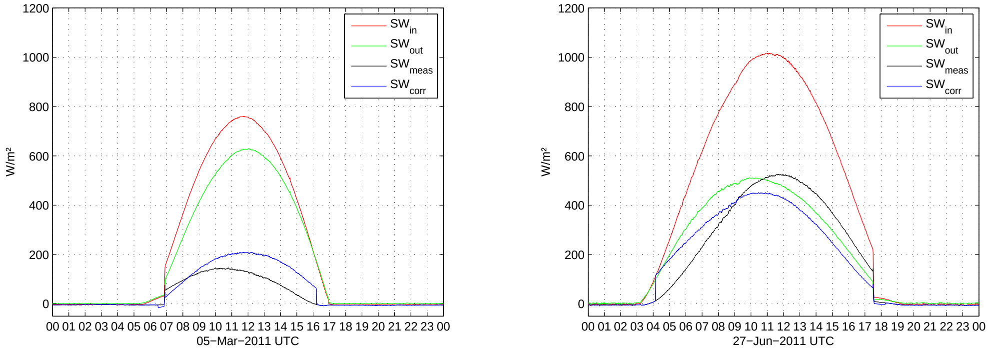


Figure 10. Measured (green) and corrected (red) albedo values on Kleinfleißkees (left) and Goldbergkees (right) for ~~all~~ the ~~year 2011.~~years 2011 and 2012.



1200
1000
800
600
400
200
0
W/m²
SW_in
SW_out
SW_meas
SW_corr
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00
05−Mar−2011 UTC
27−Jun−2011 UTC

Figure 11. Measured (SW_{meas}) and corrected (SW_{corr}) net shortwave ~~radiative~~ radiation balance on Kleinfleißkees on 5 March 2011 (left) and on Goldbergkees on 27 June 2011 (right).

Appendix A: Used Symbols

[C]	constant factor	[1]
[d]	optical path length in the atmosphere	[m]
[F]	irradiance	[Wm^{-2}]
[F_{diff}]	diffuse part of irradiance	[Wm^{-2}]
[F_{dir}]	direct part of irradiance	[Wm^{-2}]
[$F^{\downarrow}$]	measured incoming irradiance of up-facing pyranometer	[Wm^{-2}]
[$\boldsymbol{F}^{\downarrow}$]	vector of direct incoming irradiance	[Wm^{-2}]
[$F^{\uparrow}$]	measured incoming irradiance of down-facing pyranometer	[Wm^{-2}]
[F_{hor}]	near-surface incoming direct solar irradiance on a horizontal plane	[Wm^{-2}]
[F_{pyr}]	incoming irradiance in up-facing pyranometer	[Wm^{-2}]
[F_{tilt}]	incoming irradiance on a tilted plane	[Wm^{-2}]
[$F_{\text{tilt}}^{\text{dir}}$]	direct part of incoming irradiance on a tilted plane	[Wm^{-2}]
[I]	intensity of near-surface global incident solar radiation	[Wm^{-2}]
[I_0]	intensity of TOA incident solar radiation	[Wm^{-2}]
[$\boldsymbol{n}$]	normal unit vector	[1]
[p_{diff}]	diffuse part of global radiation	[%]
[p_{dir}]	direct part of global radiation	[%]
[r]	actual sun-earth distance	[m]
[$\bar{r}$]	mean sun-earth distance	[m]
[$\tilde{r}$]	ratio of $r/\bar{r}$	[1]
[S]	solar constant (1367Wm^{-2})	[Wm^{-2}]
[S_{terr}]	near-surface direct solar radiation	[Wm^{-2}]
[SW]	general global radiative balance (measured, modelled or corrected) with $SW_{\text{in/mod/corr}} + SW_{\text{out/mod}}$	[Wm^{-2}]
[SW_{corr}]	with corrected values calculated global radiative balance $SW_{\text{in,corr}} + SW_{\text{out}}$	[Wm^{-2}]

$[SW_{\text{in}}]$	incoming measured shortwave radiation	[Wm^{-2}]
$[SW_{\text{meas}}]$	with measured data calculated global radiative balance with $SW_{\text{in}} + SW_{\text{out}}$	[Wm^{-2}]
$[SW_{\text{out}}]$	reflected measured shortwave radiation (negative sign)	[Wm^{-2}]
$[T]$	temperature	$[^{\circ}C]$
$[t]$	time	[s]
$[V]$	ratio between spectral range of pyranometer and TOA irradiance	[1]
$[V_{\text{mod}}]$	ratio between spectral range of pyranometer and TOA irradiance, determined with radiation model	[1]
$[\alpha]$	general name of albedo	[1]
$[\alpha_{\text{concrete}}]$	albedo of concrete	[1]
$[\alpha_{\text{corr}}]$	corrected albedo	[1]
$[\alpha_{\text{meas}}]$	with measured data direct calculated albedo	[1]
$[\alpha_{\text{mod}}]$	modelled albedo	[1]
$[\alpha_{\text{true}}]$	true albedo	[1]
$[\gamma]$	direction of a tilted plane (north=0°)	[°]
$[\gamma_{\text{p}}]$	direction of pyranometer (north=0°)	[°]
$[\gamma_{\text{t}}]$	direction of tilted slope (north=0°)	[°]
$[\varepsilon]$	extinction coefficient	[m^{-1}]
$[\varepsilon_{\text{mod}}]$	extinction coefficient, determined with radiation model	[m^{-1}]
$[\tilde{\varepsilon}]$	extinction coefficient	[m^{-1}]
$[\theta]$	longitude	[°]
$[\vartheta_{\text{p}}]$	angle between normal vector to the tilted pyranometer and vector of incoming direct irradiance	[°]
$[\vartheta_{\text{s}}]$	solar zenith angle (SZA)	[°]
$[\vartheta_{\text{t}}]$	angle between normal vector to the tilted slope and vector of incoming direct irradiance	[°]

[$\vartheta_{\mathrm{tilt}}$]	angle between normal vector to any tilted slope in general and vector of incoming direct irradiance	[°]
[σ]	angle of inclination of a tilted plane	[°]
[σ_{p}]	angle of inclination of the pyranometer	[°]
[σ_{t}]	angle of inclination of the tilted slope	[°]
[ϕ]	latitude	[°]
[φ_{s}]	azimuth of the sun	[°]
[ω]	solid angle	[°]