Author's response to reviewer comments: Impacts of topographic shading on direct solar radiation for valley glaciers in complex topography

First, we would like to thank The Cryosphere for their unique open review process, and in particular, our editor for extending the deadlines for this paper. We sincerely appreciate the comments and suggestions received from Geoffrey Evatt, and Anonymous Referee #2. We address each of the comments below, and believe the paper is significantly improved because of their feedback.

Reviewer Comments: **Bold**
Author's Response: AR: Regular text
Added Text: Blue

<u>Response to Referee #1, Geoffrey Evatt</u>

<u>Overall concerns:</u>

1. **The paper is generally well written and presents an interesting flag of how important topographic shading is. My main concern is that this point is reasonably well known, and even if it were not, the methodology presented here does not present an easily replicable rectification.**

AR: Although we agree that the importance of topographic shading is generally well known, it is often excluded or oversimplified in many glaciology studies. Additionally, the magnitude of impact topographic shading can have on the direct solar radiation and overall energy balance of a glacier has only narrowly been discussed in detail, and has not been addressed in the uniquely complex topographic region of the Himalayas. This paper aims to clarify any misunderstandings regarding modeling methods for shading, show the magnitude of importance shading can have, and generate ideas into further improving the accuracy of surface energy balance models in complex terrain.

In order to improve the replication of this approach, we clarify the model and equations in the text and create a new diagram (Figure 3). See following comments.

2. **The authors say at the end of the manuscript, future work should consider terrain-emitted/reflected energy; in my view this paper should also have considered this, for the decrease in SW energy from shading is partly offset by the increase in topographic reflectance/LW energy emittance, and thus the degree to which shading effects the surface energy balance is not established.**

AR: In section 4.2 we explain the importance of including these energy fluxes in future work, as noted by the reviewer. However, we disagree that these additional components are required to address the impacts of topographic shading. The goal of this paper is to explore the magnitude to which direct shortwave radiation may be altered if topography is not incorporated correctly, as has historically been the case for many glaciological studies. Direct shortwave radiation is by far the largest energy flux during the summer months, and is directly affected by shading from surrounding terrain. While it is important to include other energy fluxes for a complete surface energy balance, it is beyond the scope of this paper and would not improve our understanding of the role of topographic shading on direct solar radiation. As such, we feel that this paper includes valuable information and discussion regarding the impact of topography as it relates to direct solar radiation.

<u>Main points:</u>

1. **Novelty: Whilst true that people have overlooked the precise role topographic information has on SW fluxes, most of the work I am familiar with uses field data for calibrating SW fluxes. In so doing, this already has the topographic information built in. This is less the case if one is purely using a computational approach with no in-situ field data. But if one is doing that, then one certainly also needs to worry the size of offset from SW reflection from terrain and the associated LW fluxes, which this paper does not.**

AR: Calibrating SW fluxes with field data is generally preferred over a solely model based approach. Unfortunately, there is little existing data in remote glacierized regions of the world, particularly in the Himalaya. Due to this fact, the community must rely heavily on elevation data obtained via satellite and modeled climate data in order to estimate the glacier surface energy balance. Additionally, even with adequate field measurements, the spatial coverage is often insufficient to properly determine the fully distributed impact of topographic shading over the entire coverage of a glacier. The topographic information is included at the location on a glacier in which measurements were taken, however, the impact of topography is extremely spatially variable. Figures 3b and 4b show the spatial heterogeneity of cast shadowing across the surface of two different glaciers in the Himalaya, and highlight this point. In addition to improving modeled SW fluxes, incorporating this shading algorithm will indeed improve the accuracy of field calibration data across the surface of a glacier. Models are also requisite for projecting glacier changes under future climate scenarios, as the role of shading shifts over time as the glacier thins and retreats (or thickens and advances). Thus, while field data are invaluable, models are also necessary for many glaciological research questions.

We add discussion in the introduction to the paper at P3:L11 addressing this directly, as this may be a question other readers have as well.
P3:L11– "Improving glacier models is essential in order to predict melt, particularly in remote regions where little data exists. Additionally, point field measurements generally lack the spatial heterogeneity of energy flux values across the surface of a glacier, and consequently require additional topographic information and integrative modelling."

2. **Replication/utility: Equations 3-6 need much more explanation and certainly a diagram, showing where all the angles/fluxes are acting. In terms of replication, it**

would have be very useful to see how these quantities (or the fluxes they then produce) compare when one using mean topographic information. Mean topographic information is much easier to estimate/use than using exact elevation data. A comparison between the exact and mean fluxes would then be very useful: if close, then that gives people an easy fix; if quite different, then it shows a fine grained approach, as advocated by this paper, is required.

AR - equations: P5:L15-16 mentions that for Equations 3-6 "We use variations of Eq. (2) in order to determine the daily mean change in solar radiation from specific topographic parameters shown in Fig. 1." The flowchart in the bottom right corner of Figure 1 explains how each term in Equation 2 is associated with each topographic parameters. This equation and terms are well known among individuals interested in energy balance within the glaciology community. Essentially equations 3-6 calculate the difference between Equation 2 and a model that excludes the topographic parameter of interest, which is then integrated throughout the day.

We have added an additional diagram (Figure 3) to illustrate the derivation of Equations 3-6 and define the topographic parameters of interest. Text is also added at P5:L27.
P5:L27 - "Figure 3 shows the derivation of these equations with respect to Equation 2 (Model 1), and illustrates the topographic parameters of interest. In order to parse out the influence of each parameter, a second model is created excluding the parameter of interest. Equations 3-6 calculate the difference between Equation 2 (Model 1) and a model that excludes the topographic parameter of interest, which is then integrated over the course of a day. The result of these equations is a change in irradiance due to a specific topographic parameter."

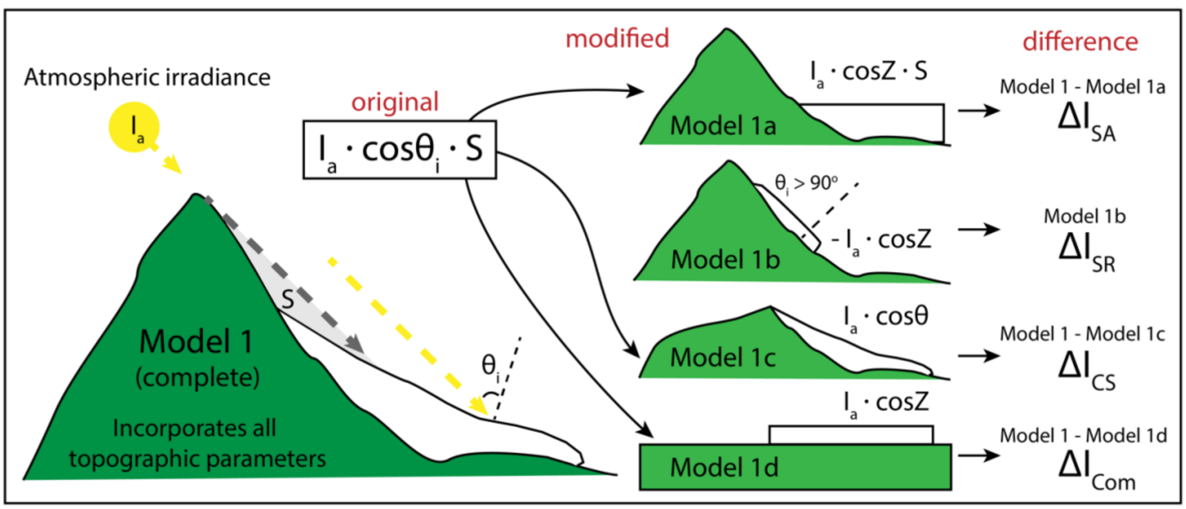

Figure 1. Diagram illustrating the derivation of Equations 3-6. Model 1 (same as Equation 2) is the base model and incorporates both methods of topographic shading (S) and the effect of slope and aspect (θ_i). Additional models are also created, each excluding some component of topography. The difference between Model 1 and Model 1a shows the change in irradiance due to slope and aspect on the surface of the glacier. Model 1b calculates the sum of irradiance that would arrive on a flat surface at locations on the glacier where the incidence angle (θ_i) is greater than 90°. Model 1b is the only scenario not dependent on Model 1. The difference between Model 1 and Model 1c shows the change in irradiance due only to cast shadows. Model 1d removes surrounding terrain and assumes the glacier surface is a flat plane, the difference between this and the original model shows the combined effect of removing all topographic information from the DEM.

AR - replication: Rather than compare our fluxes against the result of a mean topographic proxy, we opted to focus on the impact of DEM resolution in section 4.1 and Figure 9. These results show that in regions of complex topography, topographic effects can drastically alter energy fluxes. As such, some amount of distributed elevation data is much more useful than mean topographic information. Due to this fact, we considered the question of DEM resolution to be a more pertinent comparison than mean topographic fluxes.

Minor Points

1. **P3 L10. Here, and elsewhere in the paper, the use of 'slope and aspect' is a little confusing. As the authors say, cast shadows contain both slope and aspect already, so what exactly does the different 'slope and aspect' refer to? A diagram would be nice, for these distinctions need to be effortlessly clear.**

AR: The vocabulary used to describe the topographic parameters in this paper is very literal of the physical processes altering the energy arriving at the surface. As such, the term 'slope and aspect' refers to the slope and aspect of the surface, which we include as one of our topographic parameters altering the amount of irradiance on a glacier. P3:L12-14 states that we include this parameter as a comparison against the impact of our two shading methods. However, previously on P2:L2-4, we note that shaded relief also relies on information about the slope and aspect of the surface in order to determine whether a given cell is in shade. Figure 1 illustrates the two main types of shading, shading based on the relief and positioning of the surface topography (shaded relief), and shadows cast from the surrounding terrain (cast shadows). Although shaded relief relies on obtaining information about the slope and aspect, it is still a component of topographic shading. The reviewer claims that the paper states, "cast shadows contain both slope and aspect already," We are not positive where this reference comes from and do not believe such a statement exists, as it would be an incorrect statement. However, we believe that the confusion is between 'slope and aspect' as a separate parameter, and the fact that information about slope and aspect is used in determining areas of shaded relief.

We added text at the end of the paragraph at P3:L14 defining the term 'slope and aspect' and edited the caption on Figure 1 to include information about this term and the other topographic parameters of interest. Additionally, we feel that Figure 3 in conjunction with Figure 1 now clarifies any other confusing terminology throughout the paper. We thank Referee 1 for helping us see that this needed further clarification.
P3:L14 - "Hereafter, 'slope and aspect' will refer to a topographic parameter responsible for changing irradiance values based on the orientation and slope of the surface in unshaded areas of the glacier."
Figure 1 caption addition - "Red coloring indicates areas 'in sun' that are impacted by a change in irradiance due to the slope and aspect of the surface. Cast shadow, shaded relief, and 'slope and aspect' are the three topographic parameters compared in this paper."

2. **Equation 4, missing a dt?**

AR: Yes, thank you for catching that.

3. **P9:L5, change 'won't' to 'will not'.**

AR: Changed, much appreciated.

Response to Anonymous Referee #2

Overall concerns

1. **I agree with the review comments that have already been made. This isn't a new insight but it is helpful to be reminded of its potential significance. The modelling section needs to be clarified - equations (3) - (6) are not easy to understand as they are, and would certainly benefit from diagrams to show how things are defined.**

AR: This was addressed in the previous review response. A diagram (Figure 3) has now been included to aid in explaining the equations.

Major points

1. **The use of the secant approximation for the air mass (eq. 1) is discussed, and the fact that it will introduce bias into the results is correctly identified, but I was left wondering why the authors didn't simply fix the problem with a better approximation.**

AR: We have removed this sentence from the paper due to the fact that this bias is considered to be insignificant to our results and detracts from the main goals of this paper.

2. **As the previous reviewer, I feel that the lack of explicit consideration of diffuse radiation is also a significant omission.**

AR: This was addressed in the previous response under section 2 of the Overall Concerns.

3. **The discussion of the impact of DEM resolution in section 4.1 is certainly relevant, but needs to acknowledge the fact that, while the sampling interval of GDEM is 30 m, its actual spatial resolution is coarser than that. There is relevant literature on this, e.g. Hengl & Reuter 2011 in general, Rees 2012 for polar environments, no doubt others, showing that the actual spatial resolution is more like 100 m so that some at least of**

the trend noted in fig 9 can be attributed to the characteristics of the DEM not the terrain.

AR: Reviewer 2 points out the issues in spatial resolution associated with the ASTER GDEM. Section 4.1 advocates the need for higher spatial resolution when determining the impact of topographic shading. Figure 10 shows that the influence of shading diminishes as resolution decreases, assuming the provided resolution of the GDEM. Although the actual spatial resolution might be less than the sampling resolution of the terrain, the coarsening of the DEM in Figure 10 illustrates that spatial resolution (actual or sampled) affects the results. As this is largely a theoretical study, we feel that this issue is less of a concern, however, we agree that this information is useful to other readers.

We added discussion in section 4.1 at P15:L20 addressing possible issues with the GDEM, as this could be useful information for those interested in incorporating this research into their models.
P15:L20- "It should also be noted that although the sampling interval of the GDEM is 30 m resolution, the spatial resolution may be up to 3 times coarser in some regions (Hengl and Reuter, 2011). Despite the shortcomings of this DEM product, the findings in this study still demonstrate clearly the impacts of DEM resolution on incoming shortwave radiation."

Minor Points

1. **And as a minor comment, the lower limits for the integrals in these expressions have to be zero, not 1, surely?**

AR: Thank you for catching that. We have corrected the limits for the integrals on equations 3-6.