Dear Dr. Lindsey Nicholson,

Thank you very much for the valuable comments and suggestions. I would also like to thank you for allowing me to analyze data from Ngozumpa glacier.

General Comments and Questions:

1. Is this 0°C ice temperature condition met according to the ice/debris interface measurements for September? This would be interesting to know as half of your satellite images come from Sept/Oct.

> - The temperature at the debris/ice interface at all 4 sites ranged from 0°C – 0.6°C indicating that the 0°C ice temperature condition was met during our sampling period. The temperature data from Nicholson (2005) was used to justify the range of dates (15 May – 15 October) that were used in this study, where the 0°C ice temperature condition was met.

2. Is the debris thickness range of your 12 samples outside your basin comparable to inside your sampled basin?

> - The debris thickness of the 12 samples outside of the basin ranged from 13 cm to greater than 1 m. Bare ice faces similar to those in the basin were also observed. The same trend with respect to slope was observed outside of the basin, where the thinner debris thicknesses were observed on the steeper slopes and the debris thicknesses that exceeded 1 m were found in the topographic lows.

3. Did you also observe moisture at -0.1m depth in the debris when it was 1 m thick? Was this wetted surfaces of the grains or pore spaces filled with water?

> - The depth at which the debris transitioned from being dry to wet in the debris thickness measurements was not measured. However, this depth did appear to be deeper in debris that was greater than 1 m thick in comparison to the observed -0.1 m depth found in the four sites where thermistors were installed. The observed moisture was mainly the wetted surface of the grains. At the debris/ice interface at some of the sites, there appeared to be a thin layer at the interface with its pore space filled with water.

4. Could the contrasting effective thermal conductivity at -0.1 m be caused by anything other than moisture, such as a change in grain size? Was the debris layer strongly stratified?

> - No significant changes in grain size were observed at the measured sites. In the middle of the basin where the debris thickness was greater than 1 m it was common to find larger boulders/gravel on the surface. However, beneath the surface no stratification or change in grain size was observed. The temperature data and observations of the dry/wet interface in the debris at the four sites

suggest that the contrasting effective thermal conductivity is due to the moisture in the debris.

5. Was this change evident in all 4 sites with thermistors? What were the different debris thicknesses at LT1-4? Do you know if your top 10 cm temperature gradient is robust in different debris thicknesses? If LT1-4 span a range of thicknesses you can examine this point a bit. Or perhaps you can use the data from Ngozumpa to examine this gradient ratio and its consistency in both different debris thicknesses and time?

- The change in effective thermal conductivity at 10 cm was observed at all 4 sites. The debris thicknesses at sites LT1, LT2, LT3, and LT4 were 31, 47, 36, and 40 cm, respectively. The average values of G_{ratio} for these sites were 2.1, 2.9, 2.7, and 3.0, respectively. Based on these values, there appears to be a good relationship between the G_{ratio} and debris thickness ($R^2 = 0.71$) as shown in the figure below. Conway and Rasmussen (2000) measured the temperature profiles in the debris near Everest Base Camp and Lobuche on the Khumbu glacier. They report temperature profiles at 10 cm spacing down to the debris/ice interface of 40 cm for Everest Base Camp from 21-23 May 1999. Unfortunately, no temperature profiles are shown for Lobuche. The values of G_{ratio} at Everest Base Camp for these 3 days ranged from 2.6 to 3.0 with an average value of 2.7. These values agree well with those derived in this study (Figure C1).

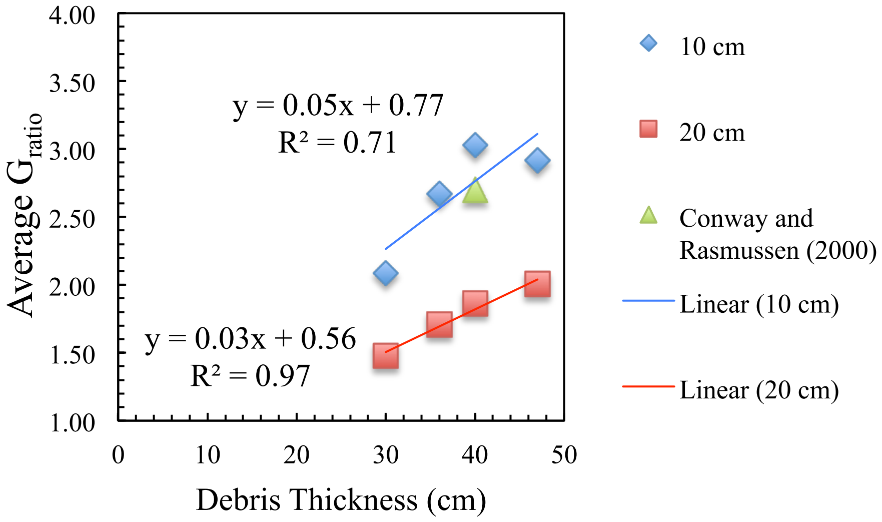

Figure C1. The relationship between average G_{ratio} and depth computing G_{ratio} with the temperature at a depth of 10 cm and 20 cm

The temperature profiles from Nicholson (2005) had a spacing of ~20 cm and the debris thickness was not measured, which makes a comparison to our study difficult. The previously reported value of 2.55 in the discussion paper for Nicholson (2005) was based on temperatures at depths of 10 cm and 76.5 cm and were taken from a figure, which violates the computation of G_{ratio} based on being 0°C and should therefore be disregarded and will be removed from the paper.

However, a comparison with Nicholson (2005) can be made if the debris thickness at their site is assumed to be 2.5 m (Nicholson and Benn, 2012) and if G_{ratio} is computed for 20 cm instead of 10 cm for both studies. Then, the values of $G_{ratio,20cm}$ derived for sites LT1, LT2, LT3, and LT4 were 1.5, 2.0, 1.7, and 1.9, respectively. Once again Figure C1 shows a strong relationship between debris thickness and average $G_{ratio,20cm}$ ($R^2 = 0.97$). The linear regression yields the following empirical relationship between $G_{ratio,20cm}$ and debris thickness:

$$G_{ratio,20cm} = 0.03 * (Debris\ Thickness(cm)) + 0.56$$

Based on data from Nicholson (2005), the value of $G_{ratio,20cm}$ was 5.3 with a standard deviation of 19.1. The standard deviation is largely influenced by a couple of extremely large values. Of the 152 days that $G_{ratio,20cm}$ was computed, 148 fall between the range of 2.3 and 12.6. Based on these 148 days, the value of $G_{ratio,20cm}$ was 6.6 with a standard deviation of 1.6. If the empirical linear relationship derived from sites LT1-4 is extrapolated to a depth of 2.5 m, the value of $G_{ratio,20cm}$ is 8.3. Figure C2 shows that this value agrees very well with those computed in September for Nicholson (2005).

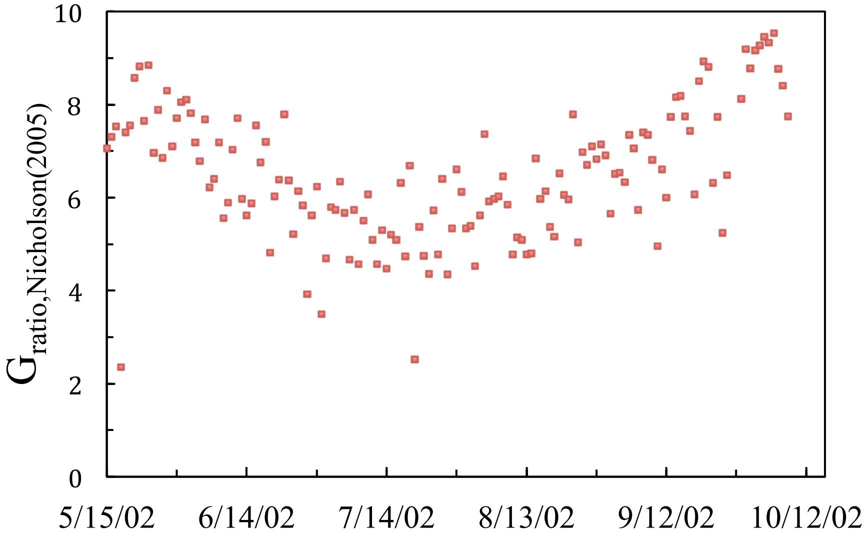

Figure C2. Seasonal variation in $G_{ratio,\ 20cm}$ derived using debris temperature data from Nicholson (2005) on Ngozumpa glacier

The good agreement found using the linear relationship for Nicholson (2005) suggests that G_{ratio} is greatly influenced by depth. Furthermore, the $G_{ratio,20cm}$ computed using data from Nicholson (2005) suggests that G_{ratio} may vary over the course of the melt season reaching a low value during the height of the melt season (July – August) and increasing as one approaches the transition seasons. Future research should explore this relationship and the variability over the melt season to determine if the same trend occurs in the upper 10 cm such that a reliable relationship could be developed.

> For the purposes of this study, 10 of the 12 satellite images were from May, September, or October. The other two images were from June. Therefore, the values of G_{ratio} computed for September should be suitable to apply to all 12 images. It is important to acknowledge that this is a limitation of the study and the analysis above shows that future work should explore how G_{ratio} varies over the melt season. Furthermore, if a parameter like G_{ratio} is used in a glacier melt model, it will be important to capture this variation. In addition, it would be very valuable to know how G_{ratio} varies with debris thickness, especially for thin debris layers.
>
> Foster et al. (2012) noted that the variation in surface temperature is very sensitive to small changes in debris thickness less than 0.5 m and consequently the sub-debris melt rates are also sensitive below this debris thickness. For debris that is greater than 0.5 m thick, the changes in surface temperature are gradual and the sub-debris melt rate is greatly reduced. As a result, they found mapping debris thickness greater than 0.5 m had a high level of uncertainty. In other words, 0.5 m appeared to be the limit for mapping debris thickness from satellite imagery. For estimating the total volume of debris on a glacier this is problematic. However, if debris thickness is used to estimate ablation rates, then a limit of 0.5 m is not a problem because there is little change in the ablation rates above 0.5 m.
>
> The field measurements on Imja-Lhotse Shar glacier showed that a substantial amount of the debris is greater than 0.5 m thick. These results agree well with previous studies on Ngozumpa and Khumbu glaciers, which showed the debris thickness on the tongue of the glaciers was typically greater than 0.5 m and decreases up-glacier (Nakawo et al., 1986; Nicholson and Benn, 2012). Based on these previous studies and the field measurements, it is unlikely that the average debris thickness in one pixel below the confluence of Imja-Lhotse Shar glacier would be less than 31 cm. As 31 cm was the minimum debris thickness of the four sites used to compute G_{ratio}, this lends confidence to the use of G_{ratio} for mapping debris thickness in this study. Furthermore, the difficulty in mapping debris thickness greater than 0.5 m from satellite imagery also lends confidence to the use of G_{ratio} in this study because G_{ratio} was computed from debris thicknesses ranging from 31 cm to 47 cm, which approaches this limit. Above the confluence of the glacier, the slopes of Imja and Lhotse Shar glaciers increase and it is likely that the debris thicknesses in these areas may be less than 31 cm. As this thickness is outside of the thicknesses used to calculate G_{ratio}, it is possible that these thicknesses are overestimated. Future work should collect field measurements to compute G_{ratio} for thin layers of debris.

6. Figure 2 implies Qc is only evaluated through a debris laden ice column, but as I understand the text your model evaluates Qc throughout the debris layer from the surface, and only LE is computed from -0.1m depth? I think you need to redo this figure so that it properly represents your model concept.

- Qc is the ground heat flux at the surface. Previous models estimated this using a linear temperature profile through the entire debris layer. The model in this study uses G_{ratio} to correct for this linear assumption by approximating Qc based on the temperature gradient in the upper 10 cm of the debris. The latent heat flux term was initially included in this study to account for the vapour pressure gradient between the surface and the air. However, after responding to the comments from the other reviewer, the latent heat flux term in our model has been removed.

Figure 2 may be misleading and therefore will be removed from the study. The proper way to describe the updated energy balance is that it is a surface energy balance model where the ground heat flux is approximated by a linear temperature gradient in the upper 10 cm of the debris and the latent heat flux is assumed to be zero.

7. Could you describe the slope correction utilized in your model more fully – for example, in its current form it is unclear whether or not you include shadowing by surrounding terrain or just 'self-shading' of the glacier itself.

- The slope correction accounts for the change in incoming shortwave radiation for each pixel based on the slope and aspect of the terrain in addition to the azimuth and zenith angle of the sun. The hillshade tool in ArcGIS was used to determine if any pixels were shaded from the surrounding terrain based on the position of the sun at the hour that the satellite images were taken. If the hillshade tool showed that a pixel was shaded by the surrounding terrain, then the incoming radiation at that pixel was reduced to 0.15 times the direct incoming radiation at Pyramid Station to account for the diffuse radiation (Hock and Noetzli, 1997).

8. Did you see any systematic change in model performance at different times of year? I would think G_{ratio} will change significantly throughout the year, although it is consistent during your measurement dates.

- In response to comment 5, $G_{ratio,20cm}$ was found to vary throughout the melt season. The Landsat images used in this study were from May (4), June (2), September (2), and October (4). Based on the focus area, the thermal resistances derived from the images acquired in June were the lowest ($TR_{avg} = 0.15$ m^2 K W^{-1}), followed by those in early September ($TR_{avg} = 0.16$ m^2 K W^{-1}) and October ($TR_{avg} = 0.18$ m^2 K W^{-1}). The thermal resistances derived from the images in May were the highest ($TR_{avg} = 0.42$ m^2 K W^{-1}); however, the reason for this large difference is unknown. The good agreement between G_{ratio} values derived in this study for September and those found using data from Conway and Rasmussen (2000) for May 1999 suggest that G_{ratio} would not account for the large difference between May and October.

9. Similarly, you use the temperature at 10 cm depth based on Ts and the temperature gradient measured in September, but this might be quite different to that measured at 10:15 in July. I think this is worth a comment.

> - As discussed in comment 6, the latent heat flux term has been removed from this model after consideration of the other reviewer's comments. As the temperature at 10 cm depth was used to approximate the latent heat flux, this comment is no longer relevant to the paper. Nonetheless, a comparison between the temperature profiles in this paper and those on Ngozumpa glacier, show similar trends to those found in G_{ratio}, where the temperature gradient at 10:15 decreases in the middle of the monsoon season and increases towards the transition seasons.

10. So do you think the negative energy balance instances occur due to the resolution of the satellite images being incompatible with the DEM? This seems to differ from the high temperature causes of model failure reported in Foster et al. (2012), but in your case there could be a clear, scale-based reason. I think you can make this case more clearly in the text linking the discussion on p900 more explicitly with the need to resample at the resolution of the satellite imagery to avoid model errors as detailed on p901.

> -Yes, the instances of pixels having a negative energy balance occur due to the resolution of the thermal band being lower than the resolution of the DEM. Using the slope correction with a high-resolution DEM will cause the incoming shortwave radiation for steep north and west facing pixels to be greatly decreased and vice versa for steep south and east facing pixels. This is realistic based on the orientation of the terrain with respect to the azimuth and zenith angle of the sun. Hence, a high-resolution DEM is useful for modeling thermal resistances because it allows realistic estimations of the incoming solar radiation at each pixel to be made. The problem of having pixels with a negative energy flux is a result of the poor resolution of the thermal band causing a "mixed pixel" effect, which is where the temperatures over the area of a pixel for the thermal band are averaged together. Traditionally, the mixed pixel effect has been used to describe the reduction in surface temperature on debris-covered glaciers due to the presence of bare ice faces and melt ponds. However, for steep north and west facing pixels that do not receive as much incoming shortwave radiation in the morning compared to south and east facing pixels, the mixed pixel effect may actually cause the temperature in these pixels to increase. The increase in temperature will cause the sensible heat flux to significantly increase, thereby causing the net energy flux to be negative. The opposite problem occurs for steep south and east facing pixels, where the mixed pixel effect will decrease the surface temperature on these pixels, which decreases the sensible heat flux. The decrease in sensible heat flux causes the net energy flux to be greater, thereby resulting in lower thermal resistances.
>
> As the reviewer mentions, one way to overcome this problem and decrease the number of pixels that have negative energy balances, is to compute the incoming

solar radiation using a high resolution DEM and then average these values when one resamples to the resolution of the thermal band. This way the values of incoming solar radiation are consistent with the resolution of the thermal band. This change has been made to the model as well and will be clearly stated.

It is difficult to discern if the instances of negative energy balance in this study are different from those reported by Foster et al. (2012). Foster et al. (2012) reported negative thickness values being a problem in their sloped model on pixels with steep slopes and high surface temperatures. These are the same results found in our study, except this only occurred in north and west facing pixels. It is plausible that in Foster et al. (2012) the aspect of these steep slopes was oriented away from the sun thereby reducing the amount of incoming solar radiation, which would cause negative thickness values. However, Foster et al. (2012) does not discuss the aspect associated with these steep slopes is not discussed.

11. Why are wind and T the only meteorological parameters of interest? You mention that negative energy balance can be computed on N and W sloping areas, suggesting that radiation might have a significant impact on the results too.

- Radiation certainly has a large impact on the derived thermal resistances as shown by the relationship between thermal resistance and aspect. Pixels with north and west facing aspects receive less incoming solar radiation, which cause the thermal resistances to increase. It was not included in the sensitivity analysis because the effect that it has on the thermal resistances was previously discussed with respect to aspect. Furthermore, we feel comfortable with the assumption that the incoming shortwave radiation is constant over the study area when the satellite images were taken. The only factor that would cause the incoming solar radiation to greatly vary between the two sites would be the presence of clouds and since all the images used in this study were cloud-free over our study site and Pyramid Station it is unlikely to vary much. However, it's possible that since the surrounding terrain on Pyramid Station is different than that on the debris-covered glacier that the amount of diffuse radiation would vary, which could cause variations in the amount of incoming solar radiation on the glacier compared to the value at Pyramid Station. Therefore, it will be included in the updated sensitivity analysis as shown in response to comment 12.

12. Could you add the impact of the sensitivity test on derived debris thickness as well, I realize this can be easily calculated from the information in your paper, but I think it is a more obvious parameter?

- Yes, the impact of the sensitivity test on the derived debris thickness can be performed as long as a value of effective thermal conductivity is calculated or assumed over the entire site. Table C1 shows the results of the sensitivity analysis in terms of debris thickness using an effective thermal conductivity of 0.96 W m^{-1} K^{-1}. The standard deviation of the effective thermal conductivity was also incorporated into the sensitivity analysis and shows that the debris thickness is very sensitive to the value of effective thermal conductivity. For this reason, the results were previously reported in thermal resistances such that the uncertainty associated with the effective thermal conductivity did not influence the results. However, if one wanted to compare thermal resistances they could back-calculate these values based on the assumed effective thermal conductivity. Therefore, the results in the revised paper will be expressed in terms of debris thickness.

Table C1. Sensitivity analysis showing changes in average debris thickness (m) in the focus area with respect to various meteorological and model parameters

	T_S	G_{ratio}	T_{air}	u	S_{in}	z_0	α	K_{eff}	d avg (m)	Change
Baseline	**-**	**2.7**	**AWS**	**AWS**	**AWS**	**0.016**	**0.30**	**0.96**	**0.29**	**-**
T_S	+ 1	-	-	-	-	-	-	-	0.41	**+ 0.12**
	- 1	-	-	-	-	-	-	-	0.24	- 0.05
G_{ratio}	-	+0.4	-	-	-	-	-	-	0.33	+ 0.04
	-	- 0.4	-	-	-	-	-	-	0.25	- 0.04
T_{air}	-	-	+ 2	-	-	-	-	-	0.24	- 0.05
	-	-	- 2	-	-	-	-	-	0.40	**+ 0.11**
u	-	-	-	+ 1	-	-	-	-	0.45	**+ 0.16**
	-	-	-	- 1	-	-	-	-	0.21	**- 0.08**
S_{in}	-	-	-	-	+ 10%	-	-	-	0.21	**- 0.08**
	-	-	-	-	- 10%	-	-	-	0.45	**+ 0.16**
z_0	-	-	-	-	-	0.010	-	-	0.25	- 0.04
	-	-	-	-	-	0.022	-	-	0.39	**+ 0.10**
α	-	-	-	-	-	-	0.20	-	0.20	**- 0.09**
k_{eff}	-	-	-	-	-	-	-	- 0.33	0.39	**+ 0.10**
	-	-	-	-	-	-	-	+ 0.33	0.19	**- 0.10**

13. I'm not sure you need Figures 3 and 4, as they illustrate essentially the same thing. Figure 5: Does (d) refer to the non-linear slope results? If so specify this in the caption. Also can you restate the scale of the grid points in (d), I think they are 5m grids as per your high resolution DEM, is that correct?

> - Figure 3 will be removed from the paper. Figure 5d does refer to the non-linear sloped results with a 5 m resolution. Scales, north arrows, and coordinates have been added to each image as well.

14: Can you show us debris thickness maps for Ngozumpa and Khumbu glacier as well as TR maps?

> - Yes, in the revised paper all results will show debris thickness assuming that the effective thermal conductivity is 0.96 W m^{-1} K^{-1}, which will help readers understand the results more intuitively.

15: It's interesting to note that expanding Spillway lake identified by Thompson et al. (2012) is identifiable on your thermal resistance maps. Might be worth mentioning?

- Glacial lakes may be detected in the results due to the low surface temperatures. The low surface temperatures cause the derived thermal resistances to be very low, i.e., much smaller than the surrounding debris-covered glaciers, and hence allow them to be identified. However, it is much easier to look at the other bands associated with the Landsat satellite or use the NDWI to outline the lakes. Therefore, while this is a good point, we would prefer not to mention this in the paper to avoid people thinking that the model may be used as another method to derive lake area.

References

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Best regards,

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