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Interactive comment on "Thermal resistances in the Everest Area (Nepal Himalaya) derived from satellite imagery using a nonlinear energy balance model" *by* D. R. Rounce and D. C. McKinney

Anonymous Referee #2

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General Comments

This paper presents an energy balance-based method of mapping thermal resistance (debris thickness divided by thermal conductivity) of supraglacial debris from thermal satellite imagery. This is an important topic as thermal resistance is the most important controlling variable of the melt rate beneath debris cover, and is a vital input to models of glacier mass balance in areas where debris cover is significant, such as the Himalaya. Several methods of mapping supraglacial debris from thermal satellite imagery have previously been proposed. The main innovation here is the application of a multiplying factor to the debris conductive heat flux to account for the nonlinear temperature gradient within debris. This helpful development overcomes an unrealistic assumption of earlier models without adding much model complexity. The proposed method, however, makes several untested simplifying assumptions about the energy budget of debris, lacks a method for extrapolating temperature input data across glaciers and appears to be based on a misunderstanding of the latent heat flux. Furthermore, important information is missing from the methods and on some of the figures which make it difficult for the reader to interpret the results. Hence, it is unclear whether agreement between the model and limited field data is due to good model performance or compensation of different error sources in the model. These are significant issues which should be addressed in a revision of the paper, as detailed below. The paper is generally well written, and has the potential to make a substantial contribution in terms of a relatively simple satellite-based debris thermal resistance mapping tool which other workers may wish to apply.

Finally, all references to 'accurate' results, and 'validation' and 'transferability' of the method need to be removed. No validation has been performed here since only one average value of field thermal resistance measurements is used for comparison with the model output: agreement between model and this datum could be due equally to compensation of errors in the model and good model performance. At best, a largely qualitative evaluation of the final output maps can be made. This problem is not necessarily the authors' fault since field validation of satellite-derived debris thermal resistance is extremely difficult due to the large scale difference between satellite and field data. Similarly, the authors could argue that their method is potentially transferable to other sites, but the transferability has not been tested here.

Specific Comments

1. The following assumptions of the model need to be addressed:

a) Steady state model assumption (p. 895, line 3). At 10.15 LT the debris will be warming rapidly in response to solar heating, hence it is not in a steady state. As the debris warms there is flux of heat energy into the debris, or change of stored heat flux, which is omitted in equation 1. The non-linear temperature profiles in figure 4 show that as you move down the profile, the conductive heat flux decreases markedly, but the model doesn't explain where this missing energy goes, violating the principal of conservation of energy. I suspect that the Gratio multiplier (equation 9) is actually accounting for the omitted change in stored heat flux. This requires a different explanation of how the model represents the surface energy balance.

b) Neglect of a stability correction for the turbulent heat flux/neutral atmosphere assumption (equation 3). Although no surface or air temperature data are presented (see point 3 below), the likelihood is that with relatively high debris temperature and low air temperature there will be a steep vertical temperature gradient and an unstable atmospheric surface layer above the debris. Hence, the sensible heat flux will be strongly underestimated by the neutral atmosphere assumption and a correction for surface layer instability should be applied.

c) Latent heat flux at the debris surface. Latent heat of evaporation is consumed where water evaporates from a surface. There cannot, therefore, be a latent heat flux at a dry debris surface where there is no available water to evaporate. It is likely, however, that water does evaporate (or condense) at the saturated horizon within the debris, which you suggest is commonly at a depth of about 10 cm. Since you effectively use the 10 cm saturation vapour pressure (equation 6) as model input, this 'within debris' latent heat flux is what you model, albeit forced with an atmospheric wind speed that is likely to be much too high. However, since you use (satellite) measured surface temperature as model input, I would suggest that the cooling effect due to within-debris evaporation will already have been accounted for in this surface temperature measurement. My concern is that introducing the latent heat flux term in the model amounts to double-counting of this energy flux. This additional calculated latent heat flux may be compensating for probable underestimation of the sensible heat flux due to neglect of atmospheric instability (point 2 above).

d) Longwave radiation calculation. There appears to be a mistake in the longwave radiation calculation in equation 2 where the measured incoming longwave radiation is multiplied by emissivity. The final term should read +Lincoming – sigma.epsilon.Tsˆ4. I assume this is a typographical rather than model error.

2. How is air temperature extrapolated from Pyramid station across the study area? The distances and elevation ranges are huge (10s of km and 100s or 1000s of m). There doesn't appear to be any method here, not even application of a simple elevation lapse rate. Consequently, air temperatures applied in the model must be unrepresentative of most, possibly all, of the model pixels across the study area. The temperature errors are likely to be much larger than the modest +/- 2 degrees in the sensitivity analysis. Given this, it is questionable whether the turbulent heat flux is modelled accurately at the study basin. Also, can we be sure that decreasing thermal resistances upglacier (figures 5 and 6) represent real patterns on the glaciers and not a gradually increasing error in the sensible heat flux due to progressive air temperature over/under-estimation?

Given the large uncertainties in points 1 and 2 above, there is some question over whether the agreement between model output and measured thermal resistance is actually due to good model performance or fortuitous error compensation in the model.

3. Basic information about the field area and measurements needs to be presented. - Pyramid Station, please show its location on figures 1 and 5 and provide information in Section 2.1 about how far in horizontal and vertical distances it is from the study glacier. Also in Section 2.1 explain what methods were used to extrapolate meteorological variables to the study glaciers, or else make it clear that unmodified data from Pyramid station were applied to all pixels.

- Section 2.3, basic information about the study area is missing. What are the sizes, elevation ranges and aspects of the study glaciers? What are the debris-covered areas? Are there any known patterns in debris cover and debris thickness?

- p. 894 top, what were the debris thicknesses at the 4 thermistor sites?

- p.894 paragraph 2, what is the area of the melt basin and over what area were thickness measurements made? What are the elevations of the measurement points and their elevation difference from Pyramid station?

- you should present some meteorological data from the station and a surface temperature map for at least one of the Landsat images. , the reader would then be able to evaluate the odd statement at p.904, 11-12. If there isn't any variation in surface temperature, then presumably there isn't much variation in debris thermal resistance either?

4. Gratio. The Gratio multiplier is the main innovation in the paper and hence some further analysis and discussion regarding its calculation, variability and transferability is warranted.

- The selection of the upper 10 cm of debris for the 'nonlinear' temperature gradient is fairly arbitrary and seems justified mainly because there happens to be a thermistor at this depth. What happens to the Gratio if different depths, e.g. 1, 2, 3, 4, 5, 15 are used instead? Can you provide a physical justification for the 10 cm depth and would this be universal or would different depths be appropriate for different types of debris cover? What would be the appropriate depth for debris less than 10 cm thick?

- The definition of the Gratio (987, 14-15) seems wrong to me. There is no 'nonlinear' temperature gradient here – both gradients you ratio are linear. Please define carefully what the Gratio actually is.

- can you justify estimating Gratio to 2 significant figures (p. 899)?

5. There appears to be some misunderstanding about the latent heat flux, and indeed range of application of the model, on page 904 lines 21-25. Bare ice faces and ponds don't have any debris on them, so modelling the latent heat flux on these surfaces would require a bare ice energy balance model not a debris model. However, this is not the point here, the effect of water and bare ice areas is to reduce the overall

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temperature the satellite records in an individual pixel leading to a decrease in the thermal resistance estimate. This is a mixed pixel problem, not a problem with the calculation of the latent heat flux.

Tables and Figures

Table 2. What data are shown in this table? Are these averaged field data, model data for part of or the whole of the glacier? Or data for one point with a modified slope angle?

Figure 1. The left panel needs and scale and orientation arrow. The right panel needs some indication of distance. The left panel should be annotated to show the locations of Pyramid station and the outline of Lhotse Shar/Imja glacier and the location of the study melt basin. Main glaciers should be labelled.

Figure 5. Please add glacier outlines so that it is easy to identify glacier and extra-glacial areas. Again, scale and orientation needs to be added, as well as units for the key. Some more discussion of these results is needed in text. Judging from the outlines on Figure 6, the debris cover distribution is rather unusual: high resistance debris on what looks like a tributary glacier flowing from the north and then an abrupt change to very low resistant debris on a west flowing glacier with values rising quite suddenly again on the snout.

Figure 6. Again a total lack of basic annotation (see above).

Technical Corrections

Abstract and throughout paper, remove the terms 'accurate', 'validate' and 'transferable' as none of these claims are justified by the analysis.

888, 2, remove many

888, 4, apostrophe in glacier's

890, 6 LeJeune et al. J. Glaciol., 59(214), 2013 should be added to this list.

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890, 12 and elsewhere, should ASTER be capitalised?

892, 13-14, '. . .above freezing. . .', is this true even at night?

892, 26, '. . .data were taken. . .' (correct data as a plural noun through the paper.

894, 12-13, sentence beginning 'Of the 25. . .' needs rephrasing to avoid ambiguity.

895, 15, justify the emissivity value of 0.95.

897, equation 9, k is not defined.

901, 27, '. . .directly behind the glacier. . .' please clarify.

904, 2-5, there is no basis for this statement. If there is a bias in the difference in meteorological conditions between Pyramid and the glacier, then it doesn't matter how many images you use, they will not compensate for this error.

Interactive comment on The Cryosphere Discuss., 8, 887, 2014.