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Interactive comment on "A global high-resolution map of debris on glaciers derived from multi-temporal ASTER images" *by* Orie Sasaki et al.

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General Comments

The study of Sasaki et al utilises multi-temporal satellite thermal imagery from the ASTER sensor and radiation data from the CERES project, combined with glacier outlines in the Randolph Glacier Inventory, to estimate: (1) the global distribution (excluding polar regions) of supraglacial debris cover at 90 m resolution; and (2) the distributions of 'thick' (ablation inhibiting) and 'thin' (ablation enhancing) debris cover over the same areas. These are ambitious aims, but such a global dataset would be of enormous value to earth science, and studies of glacier response to climate change in particular. Unfortunately, the study contains basic flaws in the methodology, relating to mistaken and untested assumptions about the surface energy balance of debris

cover. These render the estimates of 'thick' and 'thin' debris cover distributions unreliable, while a much more rigorous evaluation of the critical threshold between clean ice and debris-covered ice would be needed to support the estimates of total debris covered area. These issues are explained in more detail below. Due to these significant problems, it would be misleading if the outputs from this study were incorporated into global glacier models to assess the effect of debris on glacier melt, as intended by the authors.

Specific Comments

Key Issue 1: Assumptions regarding the surface energy balance of supraglacial debris

Section 2.2 of the paper introduces several important assumptions which undermine the so called 'energy balance' approach in this study. Only one of these assumptions (that the debris-ice interface is at 0 degrees C.) is assessed later in the paper, although its implications are not fully realised in the discussion. The values of thermal resistance, R, which are the basis of the mapping methodology, are derived as an energy balance residual and in order to do achieve this, the energy balance needs to be as complete, consistent and as accurate as possible. The methodology fails to achieve this.

The assumptions of a) instantaneous linear temperature gradient, and b) no heat storage in the debris layer are known to be incorrect from several studies (e.g. Nicholson and Benn, 2006; Brock et al., 2010, Reid and Brock, 2010; Rounce and McKinney, 2014). These processes are spatially and temporally variable in magnitude, depending on debris thickness, thermal properties and weather conditions before and at the time of satellite imaging and yet these important assumptions are not revisited in the paper. This undermines the attempt to estimate areas of debris cover with different melt impacts (i.e. 'thick' and 'thin' debris) made in the paper.

The next assumption which is not evaluated is that the emissivity of debris = 1. Given rock forming minerals all have emissivity < 1 this assumption is clearly wrong, and even very small changes in emissivity of 0.01 have a significant impact on the calculated longwave radiation flux estimated from the Stefan-Bolzmann relationship (equation 3). There is no acknowledgement of this problem or attempt to evaluate its impact on debris cover estimations in the paper.

Probably most critical is the assumption that turbulent fluxes = 0. The 4 references given here are selective, dated and do not provide support for this assumption. Recent, and more rigorous, field and modelling studies of the energy balance of supraglacial debris have been ignored (e.g. Nicholson and Benn, 2006; Brock et al., 2007, Brock et al., 2010, Reid et al., 2012; LeJenue et al., 2013; Collier et al., 2014; Fyffe et al., 2014; Rounce et al., 2015). These studies clearly demonstrate the opposite, i.e. that the sensible heat flux is a very large flux of energy away from the debris surface, particularly under the conditions when the imagery will have been captured, i.e. debris is being warmed strongly by insolation leading to a steep debris-air temperature gradient. Furthermore, the importance of including turbulent fluxes when mapping debris cover from thermal satellite imagery using an ‘energy balance residual’ approach has been demonstrated by several studies (Foster et al., 2012; Rounce and McKinnery, 2014; Schauwecker et al., 2015).

The assumption of zero turbulent fluxes creates an energy imbalance and a large underestimate of the thermal resistivity of debris covers (R; equation 4). This problem can be demonstrated by substituting the resulting R values (e.g. figures 3-5) into equation 1, using possible thermal conductivity (lambda) values of between 0.5 and 2, to estimate debris thickness. The resulting debris thickness is only in the range up to a maximum of 14 cm for lambda = 2, and 7 cm for a more realistic value of lambda = 1 (or 3.5 cm for lambda = 0.5). For example, on Baltoro glacier debris is estimated to be only a few cm over the majority of the glacier ablation zone (Figure 3) while it is known to exceed 100 cm on the lower tongue. The other examples in figures 3 to 6 show similarly unrealistically low debris thickness values if realistic thermal conductivity values are used.

Crucially, errors due these assumptions will be spatially and temporally variable due to

variable meteorological conditions (particularly wind speed and air temperature) and debris thickness and thermal properties. This renders not only the resulting R values physically meaningless and unusable, but also makes relative comparisons between different glaciers, and even different sites on the same glacier, impossible. Hence, the key aim of the paper, to produce a global map of the thermal resistance of debris for use in global glacier models is not achieved. The ’headline’ claim that the global area of thick debris (ablation inhibiting) is two times the area of thin debris (ablation enhancing) is unsupported by the analysis.

Key Issue 2: Threshold thermal resistance between clean ice and debris-covered ice

This threshold R value is set to 0.01 mˆ2 K Wˆ-1 (p. 5, line 15). Note that, given the problems discussed under Key Issue 1, there is large uncertainty in derived R values and this critical value will not provide a globally-consistent clean ice-debris cover threshold between different glaciers and regions. Given that this threshold value is critical to the estimates of total debris covered area, there is surprisingly little discussion of what this value means in terms of actual debris cover, and what the implications of uncertainty in the critical threshold are. What is the effect of changing the R threshold to 0.02, or to 0.001, for example? The value of 0.01 sounds like a convenient number, rather than one that is based on sound scientific reasoning. The upper ablation zones of debris covered glaciers typically have large areas of dirty ice, patchy debris, and thin debris cover which grades into mostly continuous debris cover down glacier. It is not clear what the 0.01 threshold corresponds to in this transition. This is an important issue as thin and patchy debris is likely to lead to increased melt rates compared with clean ice, whereas continuous debris will normally lead to a reduction in ablation. Uncertainty in where this cut-off lies undermines the estimates of total debris covered area, and further weakens the attempt to calculate relative areas of ‘thick’ and ‘thin’ debris.

Other issues

The evaluation of debris covered areas in figures 3-6 shows some general agreement between the present study and earlier work, but also important discrepancies, particularly missing medial moraines. The explanation for the ‘missing’ debris cover at Koxkar Glacier (some 18 km^2 of debris and 60% of the ablation zone according to Juen et al., 2014) discussed in Section 4.3 is reasonable, but this does demonstrate the problem that, for high elevation continental glaciers, overnight freezing of debris is common (particularly under clear sky conditions) which is a significant issue for the energy balance method of debris thickness estimation as it leads to non-linear temperature profiles in debris and significant changes in energy stored debris (both sensible and latent) as the debris warms in the morning (when satellite data are acquired). These processes are unaccounted for in the methodology.

Technical corrections

Overall, the study is well presented and concisely written. Given the significant problems with this work discussed above, however, I have not included a list of technical corrections in this review.

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