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Interactive comment on "Spatial debris-cover effect on the maritime glaciers of Mount Gongga, south-eastern Tibetan Plateau" *by* Y. Zhang et al.

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General Comments

This study uses Advanced Spaceborne Thermal Emission and Refection Radiometer (ASTER) imagery combined with a distributed surface energy-mass balance model to assess the influence of variable supraglacial debris-cover over a ∼250 km2 area of glaciers on Mount Gongga, south-eastern Tibetan plateau. This is a valuable aim since the impact of debris cover on glacier ablation/mass balance has not been previously assessed at a regional scale using distributed measurements of debris thermal properties. While the energy and mass balance modelling uses a fairly standard approach, the authors attempt to map values of glacier debris thermal resistance (defined as debris thickness divided by thermal conductivity) using a simplified energy-balance modelling approach forced with surface temperature values derived from ASTER ther-

mal imagery. Unfortunately, this methodology is flawed in several ways and generates thermal resistance values which appear to be about an order of magnitude too small (explained in the Specific Comments below). Consequently, the results of the energy-mass balance modelling are unreliable and the inferences about impacts of debris on glaciers cannot be interpreted in any meaningful way. This problem stems at least in part from the fact that much of the important recent work on the topic has not been acknowledged. I am sorry I cannot give a more positive assessment of the paper, but the overly-simplistic approach and unsubstantiated conclusions presented here do not advance our understanding of the response of debris-covered glaciers to climate change.

Specific Comments

Three assumptions are made in the method of deriving debris thermal resistance (R) values which are incorrect and/or unacknowledged and untested:

1. Turbulent fluxes can be ignored in the energy-balance calculation.

2. Net radiation values from NCEP/NCAR reanalysis data are representative of the glacier surface at the time of the satellite imagery acquisition.

3. Debris energy fluxes due to increasing heat stored in a warming debris layer and thawing of frozen water can be ignored.

Each assumption is discussed in turn below.

1. The turbulent fluxes are not negligible in the energy-balance of debris layers. This fact is acknowledged by the authors themselves, as the sensible and latent heat fluxes are included in the energy-mass balance model later used to calculate sub-debris ablation (Equation 4, p.2424). This is a rather obvious inconsistency: either turbulent fluxes over debris can be ignored or they cannot. It isn't acceptable to selectively ignore the turbulent fluxes for the sake of making energy-balance calculations simpler. In fact, several recent field and modelling studies, which should have been consulted (Brock

et al., 2010, Reid et al., 2012, Lejeune et al., 2013), demonstrate that the turbulent sensible heat flux is a large and important component of the debris surface energy budget, particularly under the clear-sky daytime (i.e. insolation) conditions when the satellite imagery were acquired. In defence of the negligible turbulent heat-flux assumption some early studies are referenced (22, 2431) which found daily-averaged turbulent heat fluxes to be close to zero. Aside from the simple empirical formulae with inappropriate transfer coefficients for debris surfaces used in these pioneering studies, daily-averaged fluxes close to zero may result from a reversal in flux direction (sign) between day and night. This does not mean that the instantaneous flux acquired at the time of image acquisition, when the debris has been heated by insolation for several hours, will be zero. Nicholson and Benn (2006) used a more sophisticated approach and found daytime sensible heat flux values of the order of 100 W m-2. Hence, the findings of Nicholson and Benn (2006) are misrepresented (22-3, 2431). The study of Suzuki et al. (2007) only repeats the unsubstantiated assumption of negligible turbulent fluxes and doesn't provide any independent support for this approach.

2. The description of how NCEP/NCAR reanalysis data are used to derive downwardly-directed radiation fluxes is unclear (p. 2422, paragraph 1). As far as I am aware, the highest temporal resolution of the reanalysis is 6-hours and hence there is a significant mismatch between the instantaneous incoming shortwave radiation flux at the surface at the time of image acquisition and the 6-hour average provided by the reanalysis. The imagery were acquired close to midday local time (5, 2418) and during the middle hours of the day the incoming shortwave radiation flux can vary by 100 W m-2 per hour. Hence, using the reanalysis data "…which corresponding to the nearest time … of ASTER acquisition" (6, 2422) introduces a very large uncertainty to the energy balance and R calculations, which is not acknowledged or evaluated. There is also likely to be a large uncertainty in the incoming longwave radiation estimated in this way. A radiative model for incoming radiation would provide a better solution.

3. At the time of ASTER acquisition the debris layer will be warming (under the condi-

tions described) and there will consequently be a significant flux due to the change in heat stored in the debris layer, which is ignored in the methodology (based on Zhang et al. 2011). The magnitude of the heat store flux will be spatially variable, i.e. larger on thicker debris with greater volume, with direct consequences for any interpretation of spatial patterns in R and model calculations of spatially-variable debris effects. While only limited information is provided on meteorological conditions at the time of acquisition (13, 2432), given the presence of cloud-free skies and "high temperatures" in winter it must be a strong possibility that the debris is affected by night-time freezing and daytime thawing of melt water, representing another important, neglected and spatially-variable heat flux. This would also lead to a violation of the assumption of a linear temperature profile with depth, as layers with frozen water will remain at or below zero degrees Celsius until thawed. Note, that there is also the possibility that the debris may remain below zero throughout the day in some areas and depths, violating the assumption that the base of the debris is at zero degrees. Evidence, i.e. ASTER surface temperature maps, should have been presented so that all of these issues could be assessed.

Summarising assumptions 1 and 3 (the sign and magnitude of assumption 2 is difficult to determine although certainly not negligible) several large heat 'sinks' in the debris surface energy balance at the time of satellite acquisition have been ignored. The net effect is to overestimate the conductive heat flux in debris, i.e. the residual from which R is derived (following Zhang et al., 2011). Overestimation of the conductive heat flux leads to an underestimate of R which is manifest in the results shown in Figure 3. Reading from the graph, it can be seen that where debris thickness, h, is 0.8 m, R is approximately 0.08 m2 K W-1, where h is 0.3, R is approximately 0.03 and so on. In other words, the ratio of h to R is roughly 10 to 1. If we substitute these numbers into Equation 1 (R = h/thermal conductivity,) and rearrange to find thermal conductivity we obtain a value of 10 W m-1 K-1. This is far higher than is physically possible from typical rock types which, in solid form, have thermal conductivities in the range of about 1 to 4 W m-1 K-1, but reduce to values around 1 when void spaces filled with much lower-conductivity air and water in debris layers are considered (Nicholson and Benn, 2013). In other words, neglecting these important fluxes in the method generates R values which are around an order of magnitude too small over a wide range of debris thicknesses. In fact, R values calculated in this paper are not the same as thermal resistances in any physically meaningful way and their units are not m2 K W-1.

A compounding problem is that the effects of these neglected fluxes are spatially variable, for example, turbulent fluxes are likely to be higher over thicker, (warmer) debris than cooler (thinner) debris, and similarly for the energy used in thawing frozen layers in the debris. Consequently, it isn't possible to simply scale the results in an attempt to get some physically-meaningful values for R. This fundamentally undermines the main purpose of the paper, which is to assess regional differences in debris cover effect between glaciers. It isn't possible to interpret the spatial patterns in debris-cover influence on mass balance in any significant way. In this respect, an empirical method which simply relates R to ASTER-derived surface temperature, (e.g. Mihalcea et al., 2008) with carefully calibration and testing, would be better than the overly-simplistic energy-balance approach used here. The large number of data presented in Figure 3 suggests that there might be enough data to calibrate such relationships.

However, the best approach would be to do things properly and perform a complete energy-balance calculation forced with ASTER surface-temperature values to derive values of R, including a sensitivity analysis. In fact, such a method has already been demonstrated by Foster et al. (2012) – another important recent study which has been ignored. A much more valuable exercise would have been to look at how the methodology of Foster et al., previously demonstrated on a European Alpine glacier, could be applied in the context of south-eastern Tibetan glaciers. This is a key first step. Only when a scientifically-sound method of extracting R from satellite data has been demonstrated for the glaciers in question, can spatially-variable debris effects be reliably modelled.

While the above discussion implies a fundamental revision of the work, had a reli-

able methodology of mapping R across glaciers been presented, there would have been some other areas where greater clarity and explanation would be needed prior to publication. Most importantly, a stronger demonstration that the gridded climate data used to force the energy-mass balance model are representative of near-surface atmospheric conditions at all glacier elevations (not just at GAEORS).

References cited in the review but not included in the original paper

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