Dear Dr. Radic,

Please find our responses to the reviewer comments (bold) below, along with the relevant amendments to the manuscript text. **Please note that the line numbers correspond to the TCD manuscript and not the final revised version.**

We have addressed the referee comments to the best of our abilities, with helpful improvements to the CMB model that did not alter the core findings and results of the discussion paper. However, please note that during the review process we also fixed an important error in the ice melt calculation within the debris layer. Formerly, the debris porosity was not taken into account. Now, the melt amount, M_d, in each 1-cm saturated debris layer when the temperature exceeds the melting point is given by

$$M_d = \frac{1}{L_F}\left(\phi \, \Delta T \, \rho_{ice} \, c_{ice} \, \Delta z\right) \qquad (1)$$

where L_F is the enthalpy of fusion of ice, ϕ is the porosity of the layer, $\Delta T = \left(T_d - 273.15\right)$ is the excess temperature of the layer, and Δz=1cm. Fixing this error affected the behaviour of the model during the transition season of fall 2011. As the debris ice melts more slowly, the debris temperature in basal saturated layers is constrained to the melting point for longer. Therefore, surface vapour fluxes do not compensate for decreased sub-debris ice melt during the fall period, although for summer 2011 that finding remains intact. The changes to the abstract and Sect 3.3 of the results are included in the revised version of the manuscript.

Best regards,
Emily Collier & co-authors

Response to T. Reid, Referee #1

p1597, line 2: 'a minimum debris water content of 2 kg mˆ-2' – I'd like more detail on why this figure was chosen. What field measurements were taken, and how?
The value of 2 kg m^{-2} is the amount of water required to saturate the lowest 1-cm layer in the debris given its porosity of 20%. The value was chosen as a first guess, since field measurements were not available and, in general, debris water contents are poorly constrained. Since we do not explicitly represent the actual processes that transport moisture into and within the debris (i.e., percolation, capillarity and water flow in response to hydraulic gradients), the minimum water content provides a small "source" term for debris moisture. The value of 2 kg m^{-2} gives a volumetric water content of ~ 0.01, which is in agreement with empirically derived residual water contents of soils composed of more than 10% of "large" gravel clasts (5-10 mm in size; θ_W ~ 0.00 to 0.03; Wang et al. 2013).

Amended page 1597, line 1 to:
"In addition, when the ice-debris interface reaches the melting point, a minimum debris water content is imposed to reflect field observations of a basal saturated layer during the ablation season (e.g., Nakawo and Young, 1981; Conway and Rasmussen, 2000; Kayastha et al., 2000; Reznichenko et al., 2010; Nicholson and Benn, 2012). As the water content of glacier debris cover is poorly constrained and no measurements are available, the minimum value is set to the amount of water needed to saturate the lowest layer in the debris, given its porosity and ice content."

Appended to the paragraph on porosity in Sect. 2.3:
The porosity value of 20% in the lowest 1-cm layer in the debris gives a minimum water content of 2 kg m^{-2} that is imposed only when the sub-debris ice is at the melting point. Sub-debris ice melt changes by ±1.8% if the minimum value is removed or doubled in the 2008 simulation.

Eq. 5 and related text: This is an interesting approach for estimating surface vapour pressure. However I feel it needs a more firm justification here in terms of theory and/or data. Is the linear relationship backed up by any field measurements, or theory e.g. from soil science or other fields?
A widely used approach in the soil sciences to estimate the actual vapour pressure within the pore space is the thermodynamic relationship of Edlefson and Anderson (1943) (e.g., Wilson et al. 1994; Karra et al. 2014), wherein the relative humidity is expressed as an exponential function of the pore liquid pressure. The solution for liquid pressure is computed for each grid cell in the computational domain (S. Karra, personal communication, May 2014). However, since the CMB model is missing many physical processes (e.g., capillary action, water vapour diffusion, instantaneous infiltration), this formulation would provide zero vapour pressure in the pore space above the saturated horizon.

We tested two additional approaches: (1) computing the saturation vapour pressure at the saturated horizon and (2) using an exponential relationship. The first approach produced a very small latent heat flux, since the saturated horizon is mainly located near the base of the debris and therefore temperature fluctuations are constrained by the proximity to the underlying ice. The second approach was implemented as follows

$$e_{sfc} = e_{sfc\_sat} \exp\left(\frac{-\theta_{air}}{\phi_{bulk}}\right)$$

where θ_{air} is the void fraction of the bulk layer that is occupied by air and ϕ_{bulk} is the bulk porosity (please see the following response for the calculation of these terms). However, this produced an excess of condensation and changed QL from an energy sink to a source, on average.

Therefore, the estimate of the surface vapour pressure when debris is exposed at the surface represents an important source of uncertainty. The approach we adopted in the manuscript is not consistent with conventional approaches employed in the unsaturated soil science literature However, such approaches are often based on studies of finer texture material than glacier debris cover (e.g., as coarse as fine gravel, with a grain size of 2-5 mm). Furthermore, their implementation often requires empirical relationships based on extensive laboratory data (for example, to convert the soil water content to a variable that can be used in the Edelfson and Anderson (1943) approach). Such studies are absent for glacier debris cover.

We feel that the simplified approach adopted in this paper, while perhaps not best suited for a detailed examination of moisture distribution within the debris, compares favorably to the available field data and is appropriate for our intended future research goals in the absence of more detailed evaluation data. There is also some support for a linear treatment in coarser grain soil, as Yeh et al. 2008 found that the effective degree of saturation in sand decreased approximately linearly in the top two meters above the water table.

Based on this comment, we added three paragraphs to the discussion section, about the uncertainty in the surface vapour pressure and missing physical processes in CMB-RES:
"The simulated QL and surface vapour fluxes depend on the estimate of the surface vapour pressure, which is an important source of uncertainty in the CMB-RES model. In unsaturated soil sciences, the relative humidity is often treated as an exponential function of the liquid water pressure in the pore space using the thermodynamic relationship of Edelfsen and Anderson (1943) (e.g. Wilson et al. 1994; Karra et al. 2014). However, testing an exponential relationship with the moisture content of the debris in CMB-RES resulted in strong in QL (MD = 28; MAD = 96 W m^{-2}) and a shift from QL as an energy sink to a gain, which was inconsistent with the EC data. For simplicity, we employed a linear approach, and there may be some support for this treatment in coarser texture soil, as Yeh et al. (2008) found that the effective degree of saturation in sand decreased approximately linearly in the top two meters above the water table.

In reality, water vapour fluxes occur at the saturated horizon, either at the surface or within the debris layer. However, in the 2008 simulation, the mean depth of the saturated horizon was 21.5 cm, where the proximity of glacier ice damped temperature fluctuations and constrained the mean temperature to ~275 K. Therefore, computing vapour fluxes at this level produced a very small latent heat flux, of -3.1 W m^{-2} on average, that was also not in agreement with the EC data. CMB-RES likely provides an underestimate of the simulated location of the saturated horizon, since capillary action was not taken into account. For fine gravel soils (grain size of 2—5 mm), capillary rise is on the order of a few cm (Lohman 1972), while for coarser, poorly sorted glacier debris, the effect may be smaller. Underestimation of the height of the saturated horizon, and therefore of both the debris temperature and the saturation vapour pressure, is consistent with the small latent heat flux when vapour fluxes are computed at this level. As a part of future work, there is a need to accurately compute the vapour fluxes at the level of the saturated horizon.

In addition to neglecting capillary action, CMB-RES also does not account for many internal physical processes that have been highlighted in unsaturated soil sciences, including water vapour flow due to gradients in concentration and temperature; liquid water flow in response to hydraulic gradients; volume changes due to changes in the degree of saturation (e.g. Sheng 2011); deposition of water vapour and its contribution to the formation of thin ice lenses (e.g. Karra et al. 2014); and heat or moisture advection as a result of airflow (e.g. Zeng et al. 2011). However, incorporation of these processes into CMB-RES is currently limited by a lack of appropriate evaluation data. Instead, we focus on including processes related to phase changes, *which have been demonstrated to have an impact on the subsurface temperature field and ablation rate (Reznichenko et al. 2010; Nicholson and Benn 2013). As a part of future work, CMB-RES could be improved by distinguishing the location of debris ice and water separately within saturated layers, thus potentially improving the simulated debris temperature profiles as the melting point constraint would only be applied to saturated layers containing ice."*

It seems that using the fractional fullness of the reservoir (F_res) might not be appropriate for layers of different thickness. E.g. a 1m layer with F_res=0.6 would have a distance of 40cm between the top of the reservoir and the debris surface, whereas in a 10cm layer with the same F_res it would only be 4cm away. Wouldn't the reservoir then have a much bigger effect on the surface vapour pressure in the thinner debris layer? It seems to me that debris thickness should be included in the equation and not just F_res.
Excellent point. To address this issue, we replaced F_{res} in Eq. 5 as follows,

$$e_{sfc} = e^{*}_{sfc} + \left(e_{sfc\,sat} - e^{*}_{sfc}\right) \cdot \left(1 - \frac{\theta_{air}}{\phi_{bulk}}\right)$$

where θ_{air} is the void fraction of the bulk layer that is occupied by air, given by

$$\theta_{air} = \sum_{i=1}^{m_K - 1} \frac{\phi_i}{N}$$

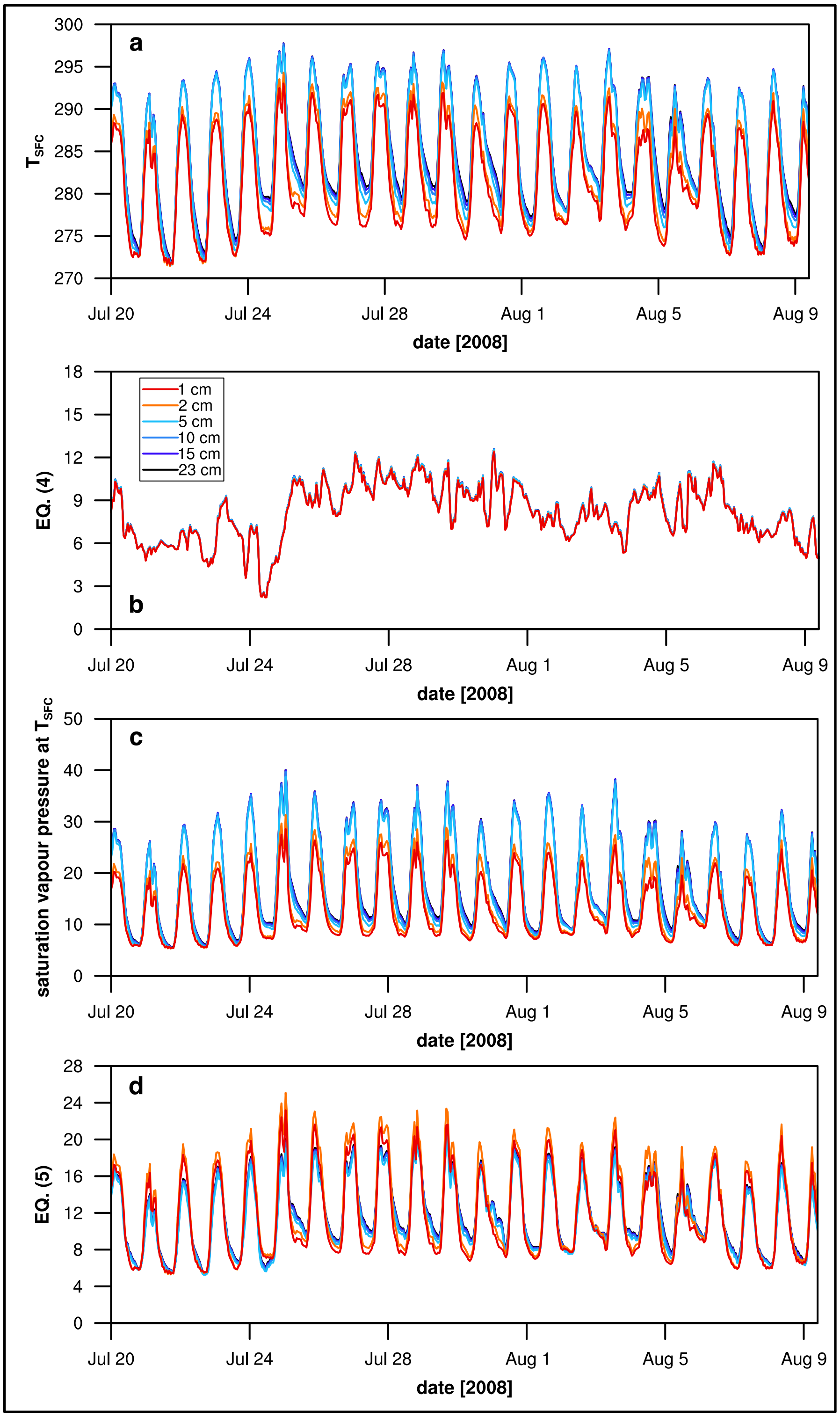
where m_K is the level of the saturated horizon and N is the total number of layers in the debris. ϕ_{bulk} is the total bulk porosity, given by

$$\phi_{bulk} = \sum_{i=1}^{i=N} \frac{\phi_i}{N}$$

which is invariant under different debris thicknesses, due to the linear specification of the debris porosity. When the debris is completely unsaturated, $\theta_{air} = \phi_{air} = 0.3$, and when the saturated horizon reaches the upper layer, $\theta_{air} = 0$. Here we assume that θ_{air} is a suitable representation of the changing distance from the height of the saturated horizon in the debris to the surface.

To illustrate the influence of this correction factor for varying debris thickness, we re-ran the 2008 CMB-RES simulation with debris thicknesses of 23, 15, 10, 5, 2 and 1 cm, and artificially set the debris water (ice) content to 50% (0%) of its capacity at each time step. Below is a figure showing time series of (a) debris surface temperature T_{sfc} [K], (b) the result of Eq. 4 [hPa], (c) the saturation vapour pressure at T_{sfc} [hPa], and (d) the result of Eq. (5), namely the final surface vapour pressure used in the CMB-RES model [hPa].

As one would expect, a water content of 50% produces a larger surface vapour pressure during the day in thinner debris layers compared with thicker ones, despite the higher surface temperatures and therefore saturation vapour pressure of thicker debris layers. The text of the manuscript has been updated to reflect these changes.



a
b
c
d
T_{SFC}
EQ. (4)
saturation vapour pressure at T_{SFC}
EQ. (5)
1 cm
2 cm
5 cm
10 cm
15 cm
23 cm
date [2008]
Jul 20
Jul 24
Jul 28
Aug 1
Aug 5
Aug 9

p1600, line 16-18: I have some data from a thermistor profile that might back up this model finding, I'll be in touch separately.
After careful consideration, we changed the approach used to prognose the glacier surface temperature. The eventual goal of this research is to couple the debris model with a high-resolution atmospheric model. For that application, determining an appropriate representative-surface-layer depth with time evolving snow cover is computationally expensive and impractical over large model domains. Therefore, we decided to follow the approach adopted in previous studies, in which the surface temperature is calculated iteratively such that there is zero residual energy in the surface energy balance equation (Eqn 1; e.g., Nicholson and Benn, 2006; Reid and Brock, 2010; Reid et al., 2012; Zhang et al. 2011). The results do not differ significantly from the previous approach, however the model is now more widely applicable.

Page 1595, paragraph 3 has been replaced with:
"*Consistent with previous modelling studies of debris-covered glaciers (Nicholson and Benn 2006; Reid and Brock 2010; Reid et al. 2012; Zhang et al. 2011), the model employs an iterative approach to prognosing surface temperature, with the solution yielding zero residual in the surface energy balance (Eq. 1). The model employs the Newton-Raphson method to calculate T_{SFC} at each time step as implemented in Reid and Brock (2010), with a different termination criteria of* $|F_{NET}| < 1E-3$*.* When snow or ice are exposed at the surface, the resulting T_{SFC} is reset to the melting point if it exceeds this value, and energy balance closure is achieved by using the residual energy for surface melt.

Page 1600, paragraph 2 (which gave further details about the former approach for the Miage glacier) has been removed.

p1600, line 20: I've never tried to measure this, but 60% porosity seems very high for the piles of clasts I've seen on Miage! If I were to guess I'd have said it couldn't be more than 40%, definitely not more than 50% because surely that would defy some mathematical stacking laws (and I don't think the clasts themselves are very porous)? I'd like to see more detail on how the authors made these measurements to justify such a high number, and if indeed it is too high then they could do a small sensitivity analysis to see how it affects their final numbers on mass balance.
As we needed to re-run the simulations to address the comment on the estimation of the surface vapour pressure, we decided to change the upper bound on the porosity to 40%. While measurements indicated porosity values up to 60% (Brock et al. 2006), using the range of 20—40% gave better agreement in the bulk porosity value with measurements reported by Nicholson and Benn (2012) for other debris covers. While the actual amount of sub-debris ice ablation is sensitive to the choice of porosity range, the model behaviour and main findings presented in the paper are unaffected.

Amended p1600, paragraph 3 to read:
"For both CMB-DRY and CMB-RES, we assumed that the debris porosity is a linear function of depth in the debris, decreasing from 40% at the surface down to 20% at the debris-ice interface. A range of 19 – 60% percent void space by volume was measured on the Miage glacier, by placing a known volume of surface debris in a graduated bucket and measuring the volume of water required to fill the air spaces (Brock et al. 2006). For this study, we used an upper-bound of 40%, such that the bulk porosity (30%) was consistent with other reported values for glacier debris (Nicholson and Benn 2012). A sensitivity study using the measured upper bound of 60% showed that while sub-debris ice melt was strongly affected (it decreased by ~17% in both simulations), the CMB model behaviour and the main results presented in Sect. 3 remained intact.

p1602, line 15: Should it say 'source' rather than 'sink' for QPRC? (I suppose this depends on whether air or surface temperature is higher?)
We think sink is correct here. On average, QPRC is ~ -17 W m^{-2} in the CMB models during daytime rainfall events, i.e. the surface temperature is higher. During nighttime rainfall, QPRC has a mean value of ~ +2 W m^{-2}.

Table 1: A third column showing some sources for these numbers would be nice.
The column mainly pays homage to Brock et al. (2010), but done.

Fig. 3b: It's not clear if the line for the first period (modelled wind speed I presume) is grey or black. Also the caption would benefit from an explanation that this was modelled from ERA.
We changed the line color to green for the ERA data, reduced the line thickness to make the plots clearer, and amended the legend to say *"ERA Interim (temporally downscaled)."*

Fig. 6b&10b: I'm curious as to how deposition is modelled? This isn't mentioned in the text and it could benefit from a sentence or two.
Page 1594, line 7 added: *Surface vapour fluxes (Q_v; i.e., sublimation or deposition [kg m^{-2}], depending on the sign of QL) at each time step Δt are calculated according to*

$$M_V = \frac{QL\ \Delta t}{L_H}$$

where L_H is the latent heat of sublimation (2.84×10^6 J kg^{-1}) or vapourization (2.51×10^6 J kg^{-1}), depending on the surface temperature.

Fig. 8a-c: Would these look more intuitive with flipped axes?
The plot of specific heat capacity is a bit squished, but it is more intuitive and consistent with previous figures.

Fig. 9b is an excellent illustration of how moisture cools the debris. I wonder if you could make the colour scale a bit wider so that the small differences are highlighted better?
We changed the shading for panel b, as well as moved and inverted the sign of the QL curve, since it obstructed the difference plot.

Fig. 11: No units on y axes. I like this figure as a demonstration of refreeze, but it is quite difficult to understand – I think it would benefit from showing the full CMB-DRY temperature profile, as well as CMB-RES and the difference between the two.
We added the units and an additional panel showing the full CMB-DRY temperature profile.

Please give a detailed explanation of what happens to precipitation in CMB-DRY.
Added on page 1596, line 27: *"For CMB-DRY, rainfall or other liquids water inputs are instantaneously removed as runoff from the debris layer and do not accumulate or contribute to vapour exchange between the debris and the atmosphere, similar to previous modelling studies (e.g., Reid and Brock 2010; Lejeune et al. 2013)."*

I’d like a more detailed explanation of how mass balance is calculated, taking into account these three factors:
- Mass gain due to debris being wet and thus lowering sub-debris ice melt
- Mass loss due to vapour fluxes at surface
- Mass gain due to precipitation

For the first factor, debris moisture in CMB-RES reduces the effective thermal diffusivity, resulting in less heat transfer to the underlying ice and therefore less melt, rather than a mass gain. We hope that this result is explained sufficiently on the last paragraph of page 1603.

To clarify the other two factors, we added a separate section about the mass balance calculation to the methods section (see below). Given that liquid precipitation is neglected in CMB-DRY and not accounted for in the accumulated mass balance calculation of CMB-RES, it is consistent that the mass balance of CMB-DRY is less negative than CMB-RES, since QL is neglected.

“The total mass balance calculation in CMB-DRY and CMB-RES accounts for the following mass fluxes [kg m^{-2}] each time step: solid precipitation; surface and vertically integrated subsurface melt; meltwater refreeze and formation of superimposed ice in the snowpack; changes in liquid water storage in the snowpack; and surface vapour fluxes. The contribution of surface vapour fluxes to or from the debris layer is zero when overlying snow cover is present and in CMB-DRY. In CMB-RES, these fluxes also contribute to changes in the debris water and ice content of the reservoir. For both models, sub-debris ice melt is calculated as the vertical integral of melt in the ice column underlying the debris.

Liquid precipitation contributes indirectly to the mass balance through changes in storage in the snowpack in both CMB models and directly in CMB-RES via reservoir storage. However, changes in the debris water and ice content in CMB-RES are not included in the mass balance calculation, so as to allow for a more direct comparison between CMB-RES and CMB-DRY of the influence of including the latent heat flux. The impact of changes in the storage of water and ice in the debris is quantified in Sect. 3. and has a negligible influence on the total accumulated mass balance.”

References

Edlefsen, N.E., and Anderson, A.B.C.: Thermodynamics of soil moisture, Hilgardia, 15, 31-298, 1943.

Wang, H., Xiao, B., Wang, M., and Shao, M.: Modelling the soil water retention curves of soil-gravel mixtures with regression method on the Loess Plateau of China, PLOS One, 8, DOI: 10.1371/journal.pone.0059475, 2013.

Response to G. Evatt, Referee #2

If we look at the conservation of heat equation (2), we see that z is not defined. This might appear a simple oversight. However, if the computer package has the z coordinate taken from a fixed reference point (as one would probably choose if writing the code for a non-debris covered glacier), then equation (2) would be incorrect.
We agree this needed clarification in the paper.
Added to page 1594, line 23: *"Both versions of the CMB model prognose the temperature distribution in the upper subsurface following the conservation of energy. The vertical levels selected for the case study in Sect. 2.3 are defined in Table 2, and are set at fixed depths in the subsurface, from 0.0 to 9.0 m, that track the glacier surface as it moves due to mass loss or gain. On this grid, the 1-D heat equation becomes*

$$\rho c \frac{dT}{dt} = \rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k \frac{\partial T}{\partial z}\right) + \frac{\partial Q}{\partial z}$$

where ρ is the density [kg m^{-3}]; c is the specific heat capacity [J kg^{-1} K^{-1}]; T is the englacial temperature [K]; k is the thermal conductivity [W m^{-1} K^{-1}]; and Q is the heat flux due to non-conductive processes (penetrating shortwave radiation) [W m^{-2}]."

Another example of my concern is given on page 1595, in which the model only appears to be able to deal with 1cm step sizes. Is this true? In which case the model may not be amazingly appropriate for examining the debris layer of a glacier. If it is possible to run further simulations, it would be good to see a convergence test conducted, where the grid size is deceased to the mm level.
The grid spacing Δz in the debris layer was chosen to be 1-cm to be consistent with previous studies that explicitly model heat diffusion through the debris (e.g., Reid and Brock 2010; Reid et al. 2012; Lejeune et al. 2013). To test the convergence of the model, we performed three simulations with both versions of the model for the 2008 period, using grid spacings of 1 cm, 0.5 cm and 1 mm throughout the whole column down to a depth of 9.0 m. For the finer resolution simulations, the time step was reduced concurrently by the same factors of 1/2 and 1/10. Forcing data was produced by linearly interpolating the hourly mean AWS data.

Below are some results, temporally averaged over the full 2008 simulations including the spin-up period. The results from the 0.5-cm and 1-mm cases do not differ strongly from 1-cm case, although the computational expense was much higher.

		Δz=1 cm Δt=3600 s	**Δz=0.5 cm Δt=1800 s**	**Δz=0.1 cm Δt=360 s**
ice ablation rate [mm w.e. hr^{-1}]	CMB-DRY	11.0	12.6	13.4
	CMB-RES	10.7	12.2	12.9
bulk debris temperature, T_B [K]	CMB-DRY	280.6	280.6	280.4
	CMB-RES	280.3	280.2	280.0
amplitude of diurnal cycle of T_{sfc} [K]	CMB-DRY	26.1	26.3	26.7
	CMB-RES	25.2	25.3	25.7

Added to page 1595, line 7: *"The convergence of the numerical solution down to a vertical grid spacing of 1-mm was checked; however, the results did not strongly differ from the 1-cm case."*

Technical Comments:
-1598. Programming error - of what?
Amended line 1598 to “programming error in the AWS.”

-1600 second para. You say boundary conditions are given by a temperature. You may find a flux better to use (i.e. temperature gradient), as this will be less sensitive to the arbitrary choice of depth.
Since we have no information about either ice temperature or temperature gradients at the bottom boundary located at N=9.0 m, to implement this suggestion we assumed a zero-flux boundary condition. The prognosis of the basal temperature at time step j+1 is therefore given by,

$$k\frac{\partial T(z,t)}{\partial z}\bigg|_{z=N} \approx k\left(\frac{T_N^{j+1} - T_{N-1}^{j+1}}{\Delta z}\right) = 0$$

which is satisfied if $T_N^{j+1} = T_{N-1}^{j+1}$.

Amended page 1595, line 15: “*The CMB models explicitly simulate heat conduction throughout the glacier column. Therefore, the ice temperature is a prognostic variable at all levels except the bottom boundary, where a zero-flux condition is imposed.”*

-1603. At this point I’m unsure as to how the thermal conductivity is calculated. Presumably it is a function of z, thus reflecting the moisture within the lower part of the debris? A clear equation showing how k is determined is certainly needed.
We introduced a new sub-section in the methods section, entitled “Physical and thermal properties”
“The important physical properties of the glacier subsurface in Eq. (3) -- density ρ, thermal conductivity k, and specific heat capacity c -- are non-uniform with depth. Defining m_S and m_D as the levels corresponding to the bottom of the snowpack and debris layers (cf. Fig. 1), respectively, the column properties (generalized as $f(z)$) are specified as

$$f(z) = \begin{cases} f_{snow} & z <= m_s \\ f_{deb} & m_s < z <= m_d \\ f_{ice} & z > m_d \end{cases}$$

Standard values are selected for snow and glacial ice properties (Table~1), with the exception of snow density, which is a prognostic variable. Within the debris layer, the properties of each 1-cm layer are a weighted average of the depth-invariant whole-rock values f_{wr} and the content of the pore space f_ϕ, as determined by an assumed linear porosity function, ϕ

$$f_{deb}(z) = \phi(z) \cdot f_\phi(z) + (1 - \phi(z)) \cdot f_{WR}$$

For CMB-DRY, the debris pore space contains only air ($f_\phi = f_{air}$), while the weighted average in CMB-RES also considers the bulk water and ice content of the debris of saturated layers. The porosity function is discussed further in Sect. 2.3”

-The discussion section does not seem to discuss much! It would be nice to see warts-and-all suggestions about the model limitations/ appropriateness/further work.
We made the following modifications to the discussion section to address this comment.

(1) Shortened and moved the paragraph on the influence of water percolation to the methods section:
"Congruent with the simple nature of the single-reservoir parameterization, the heat flux from precipitation is only applied at the surface in CMB-RES, and subsurface heat transport as a result of water percolation is not included. This treatment is consistent with the findings of Sakai et al. (2004), namely that the heat flux due to rainfall percolation contributes minimally to sub-debris ice melt, although its influence may depend on debris permeability (Reznichenko et al. 2010)."

(2) Removed the paragraph discussing the latent heat flux treatment in Rounce et al. (2014), as the authors of this study removed this component of their model during the review process.

<u>(3) Added paragraphs about (i) uncertainty in estimating the surface vapour pressure, (ii) missing physical processes in CMB-RES:</u>
"The simulated QL and surface vapour fluxes depend on the estimate of the surface vapour pressure, which is an important source of uncertainty in the CMB-RES model. In unsaturated soil sciences, the relative humidity is often treated as an exponential function of the liquid water pressure in the pore space using the thermodynamic relationship of Edelfsen and Anderson (1943) (e.g. Wilson et al. 1994; Karra et al. 2014). However, testing an exponential relationship with the moisture content of the debris in CMB-RES resulted in strong in QL (MD = 28; MAD = 96 W m^{-2}) and a shift from QL as an energy sink to a gain, which was inconsistent with the EC data. For simplicity, we employed a linear approach, and there may be some support for this treatment in coarser texture soil, as Yeh et al. (2008) found that the effective degree of saturation in sand decreased approximately linearly in the top two meters above the water table.

In reality, water vapour fluxes occur at the saturated horizon, either at the surface or within the debris layer. However, in the 2008 simulation, the mean depth of the saturated horizon was 21.5 cm, where the proximity of glacier ice damped temperature fluctuations and constrained the mean temperature to ~275 K. Therefore, computing vapour fluxes at this level produced a very small latent heat flux, of -3.1 W m^{-2} on average, that was also not in agreement with the EC data. CMB-RES likely provides an underestimate of the simulated location of the saturated horizon, since capillary action was not taken into account. For fine gravel soils (grain size of 2—5 mm), capillary rise is on the order of a few cm (Lohman 1972), while for coarser, poorly sorted glacier debris, the effect may be smaller. Underestimation of the height of the saturated horizon, and therefore of both the debris temperature and the saturation vapour pressure, is consistent with the small latent heat flux when vapour fluxes are computed at this level. As a part of future work, there is a need to accurately compute the vapour fluxes at the level of the saturated horizon.

In addition to neglecting capillary action, CMB-RES also does not account for many internal physical processes that have been highlighted in unsaturated soil sciences, including water vapour flow due to gradients in concentration and temperature; liquid water flow in response to hydraulic gradients; volume changes due to changes in the degree of saturation (e.g. Sheng 2011); deposition of water vapour and its contribution to the formation of thin ice lenses (e.g. Karra et al. 2014); and heat or moisture advection as a result of airflow (e.g. Zeng et al. 2011). However, incorporation of these processes into CMB-RES is currently limited by a lack of appropriate evaluation data. Instead, we focus on including processes related to phase changes, which have been demonstrated to have an impact on the subsurface temperature field and *ablation rate (Reznichenko et al. 2010; Nicholson and Benn 2013). As a part of future work, CMB-RES could be improved by distinguishing the location of debris ice and water separately within saturated layers, thus potentially improving the simulated debris temperature profiles as the melting point constraint would only be applied to saturated layers containing ice."*

<u>(4) Modified the paragraph on the Ostrem curve, given that enhanced melt was not produced for any debris thickness value when the sub-debris ice depth in the column was held constant:</u>
"There are no ablation measurements available for either of the two simulation periods. To examine the general behaviour of the CMB models, the 2008 simulation was repeated with debris thicknesses of 1 to 20 cm, holding the sub-debris ice depth constant and scaling the minimum debris water content as 3% of the reservoir capacity (consistent with the 23-cm simulation; Fig. 12). Total column melt is suppressed for all debris thicknesses compared with the clean-ice melt rate, with less melt in CMB-RES than CMB-DRY due to heat extraction by QL and the reduced thermal diffusivity discussed in Sect. 3.2. Therefore, the CMB models do not reproduce the typical Østrem curve, wherein melt is enhanced below a critical debris thickness that ranges between 1.5—5 cm (e.g. Loomis 1970; Fujii 1977; Inoue and Yoshida 1980; Mattson et al. 1993) and suppressed above this value. The rising limb of the Østrem curve is not reproduced for several reasons. First, in the clean-ice and thinly debris-covered simulations, lower night-time air temperatures in the beginning of the evaluation period (20—24 July 2008; cf. Fig. 4a) produce freezing events that cool the subsurface. Averaged over the entire evaluation period, a non-negligible amount of energy is expended to warm the ice column as a result. For example, in the clean-ice simulation, this heat flux amounts to 3.7 W m^{-2}. For CMB-RES (CMB-DRY) with debris thicknesses of 1 and 2 cm, the average energy required is 4.4 (5.3) and 3.1 (3.5) W m^{-2}, respectively. In addition, sub-zero englacial temperatures in the clean-ice simulation are eradicated more quickly, since penetrating shortwave radiation is considered. Finally, other processes that are not treated in the CMB models may be important to fully reproduce the rising limb of the Østrem curve, such as (1) changes in the surface albedo as the debris cover becomes more continuous, as in the albedo "patchiness" scheme introduced by Reid and Brock (2010), and (2) wind-driven evaporation inside the debris layer (Evatt et al., working paper, 2014)."

Specific Comments:

-Page 1592. Line 15. Clarification of what actually 'total input' means, is required.

Sentence amended to: "*In addition, percolation of rain through a debris layer, which can reach as high as 75% of the total rainfall at the surface (Sakai et al. 2004) and other inputs of moisture can influence the thermal regime by heat advection (Reznichenko et al. 2010), and by providing a source of moisture for evaporation that cools the debris and therefore reduces heat transmission to the ice."*

-page 1595. Third paragraph down. More information and a significantly clearer explanation is required.

After careful consideration, we changed the approach used to prognose the glacier surface temperature. The eventual goal of this research is to couple the debris model with a high-resolution atmospheric model. For that application, determining an appropriate representative-surface-layer depth with time evolving snow cover is computationally expensive and impractical over large model domains. Therefore, we decided to follow the approach adopted in previous studies, in which the surface temperature is calculated iteratively such that there is zero residual energy in the surface energy balance equation (Eqn 1; e.g., Nicholson and Benn, 2006; Reid and Brock, 2010; Reid et al., 2012; Zhang et al. 2011). The results do not differ significantly from the previous approach, however the model is now more widely applicable.

Page 1595, paragraph 3 has been replaced with:
"*Consistent with previous modelling studies of debris-covered glaciers (Nicholson and Benn 2006; Reid and Brock 2010; Reid et al. 2012; Zhang et al. 2011), the model employs an iterative approach to prognosing surface temperature, with the solution yielding zero residual in the surface energy balance (Eq. 1). The model employs the Newton-Raphson method to calculate T_{SFC} at each time step as implemented in Reid and Brock (2010), with a different termination criteria of* $|F_{NET}| < 1E-3$*.* When snow or ice are exposed at the surface, the resulting T_{SFC} is reset to the melting point if it exceeds this value, and energy balance closure is achieved by using the residual energy for surface melt.

Page 1600, paragraph 2 (which gave further details about the former approach for the Miage glacier) has been removed.

-page 1596 (or maybe earlier). A clear definition of what a 'single reservoir' model means.
Changed the manuscript to refer solely to a "reservoir" rather than a "single-reservoir." Modified page 1596, line 27, *"For CMB-RES, a reservoir is introduced for moisture accumulation and phase changes (Fig. 1). The reservoir depth for each column is calculated as the sum of the debris porosity over the debris thickness. Thus, the pore space in the debris is represented as a single reservoir rather than treating the storage in each 1-cm layer individually."*