Response to G. Evatt, Referee #2

Dear Dr. Evatt,

Thank you for your helpful review of our manuscript. We made the typesetting corrections you suggested in the manuscript. We also greatly expanded and better organized the methods section, to further clarify the model code, physics and parameterizations. Please find our responses to your other comments (bold) below, along with the relevant amendments to the manuscript text.

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 at the end of this document after our response.

Best regards,
Emily Collier & co-authors

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.

(3) Added paragraphs about (i) uncertainty in estimating the surface vapour pressure, (ii) 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."

<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 $\left|F_{NET}\right| < 1E-3$.* 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."*

Updated results for the transition season of fall 2011

Page 1590, line 18 (abstract): *"In combination with surface heat extraction by QL, sub-debris ice melt is reduced by 3.1% in 2008 and by 7.0% in 2011 when moisture effects are included. However, the influence of the parameterization on the total accumulated mass balance varies seasonally. In summer 2008, mass loss due to surface vapour fluxes more than compensated the reduction in ice melt, such that the total ablation increased by 4.0%. Conversely, in fall 2011, the modulation of basal debris temperature due to the presence of ice resulted in a decrease in total ablation, of 2.1%. Although the parameterization is a simplified representation of the moist physics of glacier debris, it is a novel attempt at including moisture in a numerical model of debris-covered glaciers and opens up additional avenues of future research."*

Sect 3.3 has been amended to: *"Two freezing events occur during the 2011 simulation, between 18 September 23:00 LT—19 September 14:00 LT and between 7 October 9:00 LT--9 October 9:00 LT, at the tail end of two precipitation events with sub-zero air temperatures (cf. Fig. 4d). Net longwave and shortwave radiation are reduced, due to cooler surface temperatures and to small amounts of snowfall that increase the surface albedo (Fig. 10a). Rapid melt of the thin overlying snow cover (< 0.5 cm}) and infiltration of rainfall at the beginning of the precipitation events provide the source water for refreeze in the debris (Figs. 10b and 11a). During the first event, a maximum of 1.0 kg m*$^{-2}$ *of ice is produced, which persists in the basal debris layer for a further three days after the last time step with refreeze. In the second event, the debris ice content reaches 1.4 kg m*$^{-2}$*, and does not melt away before the end of the simulation.*

The bulk presence of liquid water and ice in the debris layer influences the vertical temperature profile in two competing ways (Fig. 11b-d). Latent heat release due to refreezing warms the subsurface, on average by 0.3K but exceeding 0.7K for the hourly time steps with the greatest refreeze. However, the presence of ice in saturated basal layers constrains the debris temperature to the melting point. In combination with a reduction in the effective thermal diffusivity of saturated layers, the modulation of debris temperature results in a decrease in sub-debris ice melt of 7.0% in CMB-RES compared with CMB-DRY.

The accumulated mass balance between 14 September--11 October 2011 is -172.4 kg m^{-2} *for CMB-DRY and -168.8 kg m*$^{-2}$ *for CMB-RES. Changes in water and ice storage again have a negligible impact on simulated mass balance, resulting in a further ablation of 0.2 kg m*$^{-2}$*. Thus, for the fall transition season, surface vapour fluxes do not compensate for the reduction in sub-debris ice melt due to the thermodynamic influence of ice in the debris. However, considering the same summer period in 2011 as in 2008 (20 July--11 August), the percent changes in accumulated mass balance and sub-debris ice melt are +4.0% and -3.2%, respectively, consistent with the findings of the 2008 simulation. Therefore, the influence of the reservoir parameterization varies seasonally."*

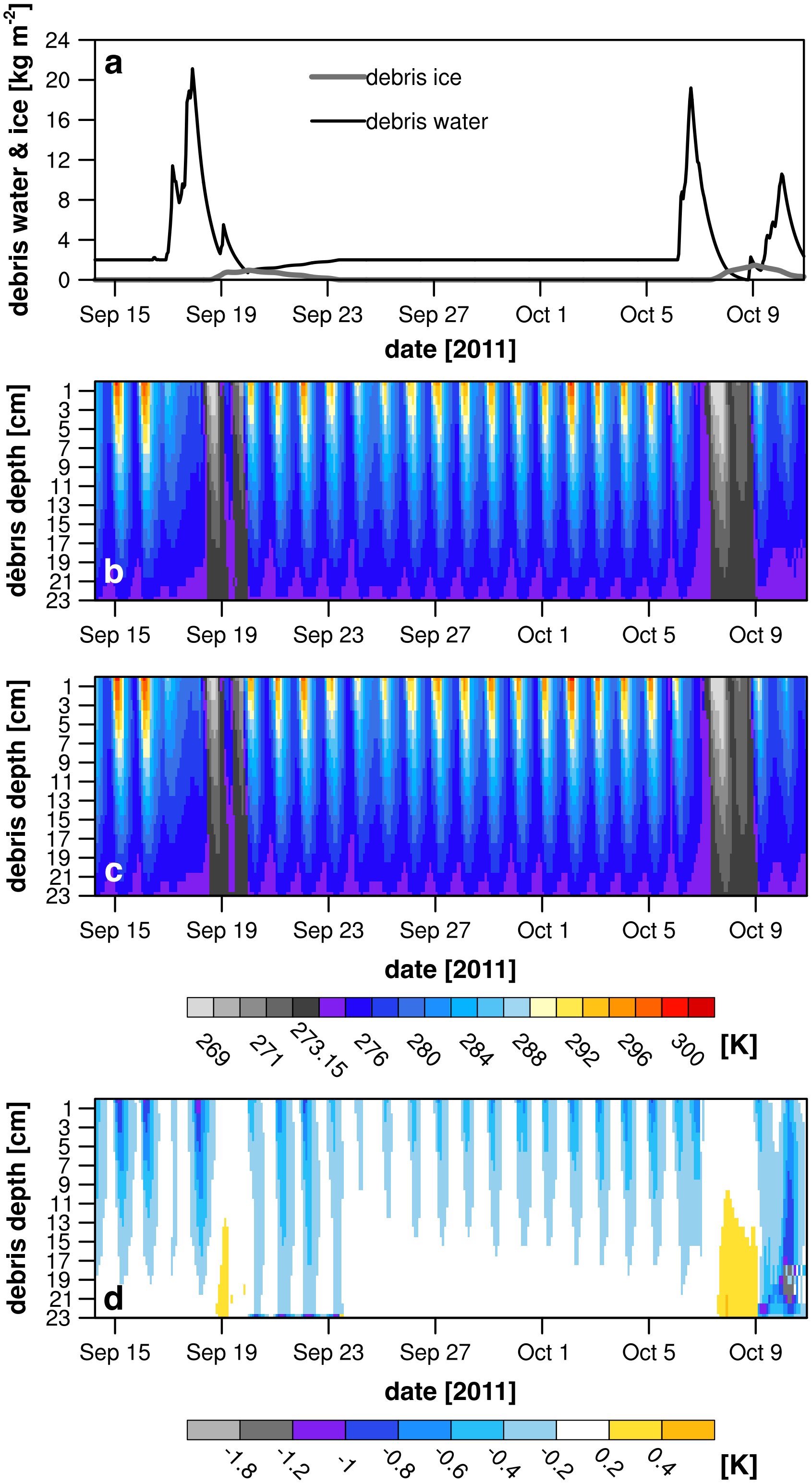

Figure 11: (a) Time series from the 2011 simulation of the debris water (black line) and ice (grey line) content [kg m^{-2}]. Temporal and depth variation of the debris temperatures in (b) CMB-RES and (c) CMB-DRY, and (d) the difference between the model runs (CMB-RES minus CMB-DRY). Units are K.