Review of manuscript “Understanding monsoon controls on the energy and mass balance of glaciers in the Central and Eastern Himalaya” by Fugger et al.

General comments

This manuscript presents measurements and modelling of surface energy and mass balance at 7 sites throughout the central and eastern Himalaya with a view to assessing the how debris cover modifies the effect of the monsoon on glacier fluxes. On-glacier automatic weather station records from the ablation zone of each glacier and a land surface model are used to derive energy and mass fluxes over 4-6 months. The land surface model includes both snow and ice volumes as well as debris cover of various thickness on 5 glaciers where debris cover is observed. The land surface model is optimised and validated against observed melt and surface temperature. The seasonal variation of energy fluxes is presented and differences between pre monsoon and monsoon periods assessed. The commonalities and differences between sites are discussed, especially the role of debris cover in creating differences. The synthesis of 7 sites from a wide geographic area, and analysis in a common framework are a particular strength of the manuscript.

The paper is generally well written and has follows a logical progression. The methods are appropriate and are mostly well described. The results provide new insights into the processes controlling mass loss across these sites. Most statements in the discussion/conclusion/abstract are supported by the results.

The main conclusion that is not shown by the current results is the assertions about lower climate sensitivity for debris covered compared to clean ice glaciers (line 14, 531-542, 572). These results are not demonstrated and should be presented as speculations or hypotheses. A formal analysis of climate sensitivity could be made with this dataset and model, and perhaps this is an area for future research.

The authors appear to have addressed most of the reviewer comments, however further discussion of the role of post monsoon and winter precipitation (Reviewer #1, general comments) in controlling mass balance should be included in the discussion, especially if the authors wish to discuss the significance of the present results (monsoonal controls) on future mass balance i.e. to what extent do monsoonal, pre/post monsoonal and winter mass fluxes determine annual mass balance?

While the authors have reordered the manuscript in response to Reviewer #2, too much material has been placed in the appendix and the appendix needs some more organisation. Some figures and tables could come into main body of text (e.g. diurnal patterns), and the section (text, table, figure) on sensitivity to elevation / debris cover thickness. Organising the appendix into sections with related figures/tables together and text to give context would greatly help the reader.

Further specific comments are given below, but some main points to address are highlighted here.

- Some discussion of the limitations of the study is warranted – this should include the fact that all records cover only one season (how significant is interannual variability?) and that the sites are in ablation areas and that surface energy and mass fluxes (along with their response to the monsoon) will change at higher elevations.
- The sign convention and terms used for changes in fluxes needs clarifying at times
- The methods and results used to regress the turbulent heat fluxes against meteorological forcing needs more description – it looks nice but is hard to interpret meaning of these results.

- The importance of turbulent fluxes at clean ice sites is downplayed more than needed - the change in latent heat flux is similar at clean ice and debris cover sites.

With some reorganisation, clarification to methods and corrections to text this manuscript will make a valuable contribution to the literature.

Specific comments:

131 – the sign convention in Equations 1-3 does not follow that stated in the text - i.e. "The sign convention is such that fluxes are positive when directed towards the surface (line 143)." Thus, all terms should have a + sign in front of them. The exception is M, which is treated as a positive term throughout the text, so should retain a minus sign or appear on the right hand side of equations 1 and 3.

Table 2 – columns describing the mean air temperature, wind speed, RH, precipitation etc of the sites would be very useful in understanding differences in SEB components between sites, particularly the turbulent fluxes.

181 – a brief description of rah, particularly how it relates to deltaT, Ws and z0m, z0h is warranted here given the key role the turbulent fluxes play in the analysis and conclusions.

184 – the assumption of z0h = z0v = 0.1 z0m needs supporting, particularly for large z0m over debris cover where this ratio may become smaller.

211 – the discretisation of subsurface layers in snow/debris/ice is ambiguous - please provide a clear description of the number of subsurface layers used to solve the conduction equations

252 – please introduce the term *In* here (used later but not defined) and provide further details on how the calculation of debris SEB is altered by this term.

290 – please provide NSE (of melt and Ts) for each site for both steps of the optimisation procedure.

Figure 3 – albedo and precipitation observations indicate the YALA glacier had consistent snow cover in the pre-monsoon period, but this is not shown in the modelled results – was this the case, and if so, how might this discrepancy affect the results for YALA?

323 – it is unclear how was the monsoonal period was identified in each record (Figure 3,4). Please add this detail and some discussion of how sensitive the results are to this choice.

323 – also, how were the individual years chosen from the multi-year records at each site? and how sensitive are the results to the chosen years?

355 – some comment on the direction of turbulent fluxes for clean ice glaciers would be useful here

361 – "Reflected shortwave radiation SW↓, which removes energy from the surface, and which is controlled by the surface albedo, follows these changes (Figure 6), becoming less negative by +5:4 (24K, pre: -18:5, mon: -13:8) and up to +164:8 (Parlung No.4, pre: -219:6, mon: -54:8) between sites." This statement is ambiguous – do you mean that the changes in outgoing shortwave follow changes in albedo, or in incoming shortwave? If you mean the later, then this statement is not strictly true – the changes in outgoing shortwave radiation are dominated by changes to albedo at Parlung No 4. Please revise.

364 – "an increase of the flux" – ambiguous (see comment for Figure 8). Suggest changing to" where SW↓ becomes more negative -12:1W m-2 (pre: -60:6, mon: -72:7), as a consequence of…"

374 – some comment on which term in SWnet is causing the increase melt would be useful here.

383 – “glacier-cooling H becomes a smaller flux” – ambiguous (see comment for Figure 8). Suggest “becomes less negative”

385 – “change in LE partly offsets the changes in H, with increases in the flux ranging from…” – ambiguous (see comment for Figure 8). Suggest “LE becoming more negative by…”

387 – following you sign convention (energy input to surface is positive), H is increased (i.e. less negative) and LE is decreased (more negative) in monsoon period. Also, as the changes in radiative and turbulent fluxes do not balance separately, it would better to state that that “reduced SWin and more negative LE are balanced by increased LWin and less negative H.”

Figure 6 – nice figure, but why choose to present only one glacier in the alternate depiction, and not the average of all sites of that type?

397 - Figure A11 – this is an interesting and informative figure and should be described in the main body of the text (Section 4.4) for all surface cover types.

404 – the regression model needs a much better description in its own section of the methods. It is unclear what the timescale of regression is (hourly/daily/weekly/seasonal) and what equations are used to fit the model. Without this it is hard to interpret the meaning of these results. Please revise methods and results.

413 – “Neither RH, gT , or Ws on their own, nor their combination explain the variability of LE across sites with thick debris” – this analysis is not shown here. Please revise

Table A3 – this could be placed in the main body of the manuscript to support these results.

456 – “the turbulent fluxes play a minor role on the clean-ice glaciers” – this statement only applies to sensible heat, as changes in turbulent latent heat fluxes are similar magnitude on clean ice and as debris covered glaciers. Please revise.

489 – this is the first mention of the elevation and debris cover thickness sensitivity experiment and comes as a surprise. The sensitivity experiment could be worked in the main body of the manuscript (methods and results) or at least should be mentioned in the results section.

Figure 8 – the sign convention does not follow the same logic as previous figures: ‘increasing value’ is ambiguous, as it can mean a more or less positive flux. Better to use ‘increasing magnitude’ along with the sign of the flux, or be specific and use ‘positive change’ and ‘negative change’ to refer to changes that increase and decrease the energy available for melt. Please revise here and throughout section 5.3.

535 – “In contrast, the turbulent fluxes ’work for’ the glaciers with debris above the critical thickness, and the melt-equalizing effect of debris under monsoon (Section 4.4.2) would likely remain in place”. and 540 – “Here we confirm this hypothesis [that mass balance of debris-covered glaciers might be less sensitive to climate warming than clean-ice glaciers]” – This effect remains speculative as the sensitivity has not been tested. While the current study does highlight the different roles of turbulent heat fluxes over debris vs clean ice and how these change in monsoonal conditions, it doesn’t assess how this will change in the future. There may be other interactions that change the role of different fluxes in the future e.g. if RH also increases in the future, then the magnitude of evaporative losses during the monsoon may decrease, thereby further increasing the

melt experienced under debris compared to present day. The dataset presents an opportunity to test the sensitivity, but this is not presented here. Please revise.

554 – 'modulated' -> 'increased'?

556 – the cold surface also favours sensible heat exchange into the glacier surface – please revise.

557 – "melt-rates increase compared to the pre-monsoon at the clean-ice glaciers" – this is not significant for Yala – please revise.

563 – "The cooling induced by H at the same time decreases, with the result of unchanged available melt-energy M during monsoon." Increased LWin during the monsoon also helps offset the decreased SWin along with H. Please revise.

570 – it is unclear how the results support a reduced climate sensitivity at debris covered sites. Please provide additional material in the results/discussion or revise.

Section A1 – this could be presented in the main body of the text (methods/results). Also, some features are ambiguous – i.e. was air temperature the only variable modified for elevation (i.e. not incoming longwave radiation and RH?

Figure A12 –Please modify caption as the fourth sentence infers debris cover was varied for all glaciers - Presumably the debris cover thickness was only varied for debris covered glaciers? Also the first sentence could be more instructive e.g. "Sensitivity of changes in the individual fluxes when moving from premonsoon to monsoon, to elevation and debris cover thickness (for debris covered glaciers only). "

Table A3 – the derivation of cloud cover fraction should be described in the methods section.

Editorial comments:

347 – "snow free" -> "snow-free"

350 – "re-emitted" it is perhaps better to say 'lost' as turbulent fluxes do not 'emit' energy, so to speak.

385 – missing negative sign from "to -24.4"

Figure 7 caption. As HAI is excluded from panel (b), the commas should be removed from the last sentence, so it reads "Only debris-covered glaciers where LE is a glacier-cooling flux are shown"

Figure A10 – appears to be missing or perhaps figures need relabelling.