Review of: High-resolution debris cover mapping using UAV-derived thermal imagery: limits and opportunities, Gök et al.

General comments:

Gök et al. present a comprehensive study investigating the derivation of debris thickness from thermal imagery at different times throughout a day using two approaches: solving of a SEBM using reanalysis data, and a least squares regression method that utilises in-situ debris thickness measurements. This study advances knowledge by investigating the diurnal changes in debris thickness estimations and addresses the impact of thermal drift due to the use of uncooled microbolometers by applying a manually calibrated drift compensation. My line specific minor comments to improve clarity in the manuscript are below and any major issues to be addressed are in bold.

Specific comments:

ABSTRACT

L10: Specify what LST you use (i.e. LST over debris layer)

L15: Can you specify which method is the most appropriate.

L18: Please state recommendation for which time of day best represents the most accurate debris thickness estimations.

INTRODUCTION

L22: I would disagree with the statement that debris thickness is generally rather thin, debris thickness is highly variable! – please rephrase and/or add a supporting reference.

L26: Change heavily to extensively or similar word.

L37: Provide references for these processes – e.g. Kirkbride and Deline, 2013; Hartmeyer et al. 2022a,b.

L38: Provide reference for ‘debris thickness varies with time’ and ‘recent studies document changes…’

L43: Reword sentence for clarity.

L52: Add Gibson et al. 2017 as reference for empirical estimation of debris thickness using in situ debris thickness measurements.

L61: Westoby et al. 2020 use UAV optical imagery to estimate debris thickness and changes, so perhaps rephrase to emphasize that debris thickness estimation using UAV thermal imagery has remained elusive.

STUDY AREA

L70: Units for coordinates.

L76: Detail the specific dimensions of the study area here and replace ‘numerous’ with the specific number of flights.

MATERIALS AND METHODS

L90: Change pre-define to pre-defined.

L92: Can you state the resolution of your imagery here too? I.e. … has a resolution of 640x512 pixels, equating to a thermal image resolution of XXm x XXm over the study site.

L103: Add a statement that reflects the inherent bias of making in-situ manual hole measurements (i.e. the presence of a large boulder/ thick debris makes it less likely that it will be chosen it as a spot to dig).

L108: Can you provide a bit more detail about what unbalanced thermal conditions are? Spell it out for the reader.

L119: Why is there a reduced framerate?

L130: Define FPA acronym used in figure in caption.

L137: Change 'asserting' to 'assuming' – this is an assumption that you have made for the final calibration, the ice surface may be 0°C but ice surface temperatures can be colder than 0°C and this should be acknowledged. It is also apparent that after your correction, some ice surfaces are now pushing 10°C (frame number ~250 (c)) where the spline interpolation was not super effective, this should be explained and acknowledged too.

L145: State number of thermal and optical images used in this sentence.

L155: State size of test sight so comparison with the footprint of the reanalysis data is possible.

L166: Do you mean 'by *accounting* for the water vapor content…'?

L168: Why/how are they the best classification results?

L169: Add statement to end of sentence along the lines of 'thus data from this time stamp were used to classify the thermal imagery'.

L172: I'm not sure I understand how ΔS is a rate of change if the right hand side of Eq. 2 is fluxes in W m^{-2}?

L198: Can you comment on the accuracy of wind speed data taken from reanalysis products and the impact this will have on your subsequent debris thickness estimates (see Schauwecker et al 2015; Stewart et al 2021)?

L203: State what your definition of 'thin' debris thickness is.

L229: Can you please justify why the debris thickness was estimated by solving a quadratic rather than previously documented methods such as that in Rounce and McKinney, 2014? The exclusion of sites for which there is not a real or positive solution to the quadratic equation means that a large proportion of your data is excluded from further analysis – which poses quite a large problem when your study area is already quite small.

L230: Change testing to training.

RESULTS

L236: I think it is the estimation of debris thickness that changes rather than the relationship between LST and debris thickness, no? i.e. when hotter LSTs are observed, thicker debris will be estimated?

L240: A key problem for me with this figure is the lack of consistency between the areas of ice and debris in each subplot – theoretically, these areas should remain consistent throughout the day, the time scale of this study is not large enough to observe actual

change in the cliff geometries. This then throws into question the accuracy of the data in each time stamp if cliffs are not consistently detected. Can you provide an explanation / justification for this?

L243: Can you show a linear regression line and an R2 value on each subplot to support this statement?

L270: Are these LST ranges using raw LST or offset corrected LST?

L295: In caption (or next to the color bar in the figure) state what aspect degrees refer to (i.e. N S E W). Also, is the debris thickness manually measured debris thickness? Make this clear.

L310: To support this statement, include a histogram of manually measured debris thicknesses for comparison with the modelled debris thicknesses in Fig. 7.

L312: I am concerned about how much data is not valid in Fig7a-d, and I'm not convinced that 'no valid solution' is a sufficient explanation for the lack of data. A surface energy balance model should not be unsolvable. To compare data from different time stamps, the data needs to be (and should be) spatially consistent.

L318: Quantify 'pattern of thin debris predictions'.

L343: Sentence beginning 'Predicted debris thicknesses…' does not make sense.

DISCUSSION

L374: underestimates compared to what?

L406: Figure units! X axis and also mean debris thickness in top right.

L417-421: My takeaway from this is that 1) wind speed is not modelled well with ERA-5 data, 2) if wind speed is increased to 'realistic' values then the amount of 'valid' debris thickness pixels decreases significantly? Can you discuss what implications this has in terms of the methodology? I.e. would you recommend that SEBM are not used in conjunction with thermal data to estimate debris thickness?

L434: Can you quantify 'in parts more accurate'?

L451-452: Westoby et al 2020 do this with optical imagery and a geodetic based debris thickness estimation.

L455: It would be good to see a debris thickness difference map (i.e. rational curve – sebm debris thickness) to quantify the differences between the two methods as panels c and d visually look very different. Are the differences between the two methods significant on a pixel by pixel basis?

L512-520: I would like to see a recommendation of 1) which method is the better predictor of debris thickness, and 2) at which time of day the method appears to be the most accurate. This seems to be missing from the discussion and the paper in general.

Technical corrections:

Ensure LST and not LST's throughout the paper.

Rounce and McKinney, 2013 – should this be Rounce and McKinney, 2014, see reference below?

L150: Check section numbers here and throughout (i.e. where they're referenced, such as in L187).

L362: Figureb?

L364: that thin debris should be than thin debris.

REFERENCES

Gibson, M.J., Glasser, N.F., Quincey, D.J., Mayer, C., Rowan, A.V. and Irvine-Fynn, T.D., 2017. Temporal variations in supraglacial debris distribution on Baltoro Glacier, Karakoram between 2001 and 2012. *Geomorphology*, *295*, pp.572-585.

Hartmeyer, I., Delleske, R., Keuschnig, M., Krautblatter, M., Lang, A., Schrott, L. and Otto, J.C., 2020. Current glacier recession causes significant rockfall increase: the immediate paraglacial response of deglaciating cirque walls. *Earth Surface Dynamics*, *8*(3), pp.729-751.

Hartmeyer, I., Keuschnig, M., Delleske, R., Krautblatter, M., Lang, A., Schrott, L., Prasicek, G. and Otto, J.C., 2020. A 6-year lidar survey reveals enhanced rockwall retreat and modified rockfall magnitudes/frequencies in deglaciating cirques. *Earth Surface Dynamics*, *8*(3), pp.753-768.

Kirkbride, M.P. and Deline, P., 2013. The formation of supraglacial debris covers by primary dispersal from transverse englacial debris bands. *Earth Surface Processes and Landforms*, *38*(15), pp.1779-1792.

Rounce, D.R. and McKinney, D.C., 2014. Debris thickness of glaciers in the Everest area (Nepal Himalaya) derived from satellite imagery using a nonlinear energy balance model. *The Cryosphere*, *8*(4), pp.1317-1329.

Schauwecker, S., Rohrer, M., Huggel, C., Kulkarni, A., Ramanathan, A.L., Salzmann, N., Stoffel, M. and Brock, B., 2015. Remotely sensed debris thickness mapping of Bara Shigri glacier, Indian Himalaya. *Journal of Glaciology*, *61*(228), pp.675-688.

Stewart, R.L., Westoby, M., Pellicciotti, F., Rowan, A., Swift, D., Brock, B. and Woodward, J., 2021. Using climate reanalysis data in conjunction with multi-temporal satellite thermal imagery to derive supraglacial debris thickness changes from energy-balance modelling. *Journal of Glaciology*, *67*(262), pp.366-384.

Westoby, M.J., Rounce, D.R., Shaw, T.E., Fyffe, C.L., Moore, P.L., Stewart, R.L. and Brock, B.W., 2020. Geomorphological evolution of a debris-covered glacier surface. *Earth Surface Processes and Landforms*, *45*(14), pp.3431-3448.