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Supplement of

The surface energy balance in a cold and arid permafrost environment, Ladakh, Himalayas, India

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Table S1: Comparison between observed and ESOLIP estimated precipitation from 1 September 2015 to 31 August 2017 at South-Pullu (4727 m a.s.l.).

| Year  | Annual Sum | Field Obs. (mm w.e.) | ESOLIP Est. (mm w.e.) |
|-------|------------|----------------------|----------------------|
| 2015-16 | 120.3      | 92.2                 |
| 2016-17 | 190.6      | 292.5                |
| Total  | 310.9      | 384.7                |

Table S2: Comparison of estimated mean monthly surface energy balance components (W m$^{-2}$) for low (2015-16) and high (2016-17) snow years at South-Pullu (4727 m a.s.l.), in the upper Ganglass catchment, Leh.

| Month | $R_n$ [W m$^{-2}$] | LE [W m$^{-2}$] | H [W m$^{-2}$] | G [W m$^{-2}$] | $F_{surf}$ [W m$^{-2}$] |
|-------|-------------------|----------------|---------------|---------------|---------------------------|
|       | 2015-16 | 2016-17 | 2015-16 | 2016-17 | 2015-16 | 2016-17 | 2015-16 | 2016-17 | 2015-16 | 2016-17 |
| Sep   | 55.7     | 50.7    | -6.2       | -5.1       | -47.1     | -40.9     | -1.9     | -4.7     | -2.4     | -4.7     |
| Oct   | 20.4     | 29.5    | -1.2       | -0.5       | -22.9     | -33.2     | 3.8      | 4.2      | 3.8      | 4.2      |
| Nov   | 1.5      | 5.3     | 0.3        | 0.5        | -15.3     | -18.2     | 13.5     | 12.5     | 13.5     | 12.5     |
| Dec   | -25.8    | -11.8   | 2.5        | 0.5        | -1.3      | -4.7      | 24.6     | 16.0     | 24.6     | 16.0     |
| Jan   | -37.9    | -20.2   | -3.4       | -6.8       | 24.1      | 10.9      | 16.5     | 16.1     | 17.2     | 16.1     |
| Feb   | -34.0    | -22.7   | -7.6       | -3.8       | 32.9      | 22.1      | 8.4      | 4.5      | 8.7      | 4.4      |
| Mar   | -2.2     | -12.6   | -17.8      | -7.3       | 17.6      | 16.9      | 4.7      | 3.8      | 2.4      | 3.0      |
| Apr   | 40.2     | 0.7     | -17.4      | -12.8      | -11.7     | 14.5      | -2.3     | 0.4      | -11.1    | -2.4     |
| May   | 92.7     | 80.2    | -29.9      | -26.4      | -42.9     | -2.0      | -19.9    | -11.2    | -19.9    | -51.8    |
| Jun   | 81.0     | 88.2    | -7.9       | -39.7      | -52.4     | -29.8     | -20.8    | -17.9    | -20.8    | -18.6    |
| Jul   | 78.9     | 99.6    | -6.9       | -48.5      | -54.7     | -30.7     | -17.4    | -20.4    | -17.4    | -20.4    |
| Aug   | 72.4     | 75.8    | -8.1       | -14.5      | -53.3     | -49.2     | -10.8    | -12.1    | -11.0    | -12.1    |
| Annual Av. | 28.6 | 30.2 | -8.6       | -13.7      | -18.9     | -12.0     | -0.1     | -0.7     | -1.0     | -4.5     |
Performance statistics for evaluation of outgoing longwave radiation

For the evaluation of outgoing longwave radiation, we prefer the statistics mean bias difference (MBD) and the root mean square difference (RMSD) (Badescu et al., 2012; Gubler et al., 2012; Gueymard, 2012). These statistics indicate model prediction accuracy (Stow et al., 2003).

The MBD (Eq. S1) is a simple and familiar measure that neglects the magnitude of the errors (i.e. positive errors can compensate for negative ones) (Gubler et al., 2012):

\[
MBD = \frac{1}{n} \sum_{t=1}^{n} (y_t - y_t^*)
\]  

(S1)

Here, \(y_t\) is the modelled output variable, and \(y_t^*\) is the corresponding measured variable. The MBD ranges from \(-\infty\) to \(\infty\). The perfect model is the one with an MBD value equal to 0.

The RMSD (Eq. S2) is calculated as (Gubler et al., 2012):

\[
RMSD = \frac{1}{y} \sqrt{\frac{1}{n} \sum_{t=1}^{n} (y_t - y_t^*)^2}
\]  

(S2)

The RMSD takes into account the average magnitude of the errors and puts weight on larger errors, but neglects the direction of the errors (Gubler et al., 2012). The RMSD ranges from 0 to
The perfect model is the one with an RMSD value equal to 0. The formulae (Eq. S1 and S2) used for estimation of MBD and RMSD respectively provide dimensionless quantities since their right-hand side has been divided by the mean of the measured variable (Badescu et al., 2012). Hence, they are expressed in per cent throughout the manuscript for clarity.

**Coefficient of determination** ($R^2$, Eq. S3): is defined as the squared value of the coefficient of correlation which indicates the amount of variation in the modelled variable predictable from the measured variable:

$$R^2 = \left( \frac{\sum_{t=1}^{n}(y_t - \bar{y})(y_t - \bar{y}^*)}{\sqrt{\sum_{t=1}^{n}(y_t - \bar{y})^2(y_t - \bar{y}^*)^2}} \right)^2$$  \hspace{1cm} (S3)

Where $\bar{y}^*$ is the mean of the measured variable.

**Performance statistics for evaluation of snow depth and near-surface ground temperature**

For the evaluation of near-surface ground temperature and snow depth apart from the coefficient of determination ($R^2$), different statistical measures have been used such as mean bias (MB), and root mean square error (RMSE).

**Mean Bias (MB):** The MB (Eq. S4) provides a good indication of the mean over or underestimate of predictions (Carslaw and Ropkins, 2012). MB is in the same units as the variables being considered.

$$MB = \frac{1}{n} \sum_{t=1}^{n} (y_t - y_t^*)$$  \hspace{1cm} (S4)

The optimal value of MB is equal to zero. The positive and negative MB values indicate model over-estimation and under-estimation bias, respectively.

**Root Mean Square Error (RMSE):** The RMSE (Moriasi et al., 2007) is a commonly used statistic that provides a good overall measure of how close modelled values are to predicted values and is given below (Eq. S5):

$$RMSE = \sqrt{\frac{1}{n} \sum_{t=1}^{n}(y_t - y_t^*)^2}$$  \hspace{1cm} (S5)

**Nash-Sutcliffe efficiency (NSE):** The Nash-Sutcliffe efficiency (NSE) (Eq. S6) is a normalized statistic that determines the relative magnitude of the residual variance (“noise”) compared to the measured data variance (“information”) (Moriasi et al., 2007; Nash and Sutcliffe, 1970).
\[ NSE = 1 - \frac{\sum_{t=1}^{n}(y_t - y_t^*)^2}{\sum_{t=1}^{n}(y_t - \bar{y})^2} \] (S6)

NSE indicates how well the plot of observed versus simulated data fits the 1:1 line.

Figure S2: Comparison of hourly observed and GEOtop simulated snow depth at 4727 m a.s.l. in the upper Ganglass catchment, Leh from September 2015 to August 2017. The solid red line is the 1:1 line.
Figure S3: Comparison of hourly observed and GEOtop simulated near-surface ground temperature at 4727 m a.s.l. in the upper Ganglass catchment, Leh from September 2016 to August 2017. The solid red line is the 1:1 line.
Figure S4: Comparison of hourly observed and GEOtop simulated outgoing longwave radiation at 4727 m a.s.l. in the upper Ganglass catchment, Leh from September 2016 to August 2017. The solid red line is the 1:1 line.
Figure S5: Comparison of hourly observed wind speed (m s\(^{-1}\)) as a function of hourly wind direction (°) at 4727 m a.s.l. in the upper Ganglass catchment, Leh from September 2015 to August 2017.

**Seasonal diurnal variability of SEB components**

The seasonal response of diurnal variation of modelled SEB components (\(R_n\), LE, H and G) for both years are shown in Figures S6 and S7, respectively. The seasons chosen were pre-winter (Sep to Dec), winter (Jan to Apr), post-winter (May-Jun), and summer (Jul to Aug).

In the 2015–16 year (Figure S6), the amplitude of \(R_n\) and the G during pre-winter, post-winter and summer season were the largest and smallest in winter. The G peaks earlier than those of the LE and H during the pre-winter, post-winter and summer season. The LE and H show strong seasonal characteristics such as (a) during the pre-winter season, the magnitude of diurnal variation of H was greater than LE depicting lesser soil moisture content because of freezing conditions at that time, (b) during the winter season, the amplitude of LE was slightly greater (sublimation process) than H, (c) during the post-winter, the amplitude of H was greater than LE and, (d) during the summer season, again the amplitude of H was greater than LE, which is
similar to that of the pattern seen during the pre-winter season. In the 2015-16 year, the amplitude of LE in comparison to H was smaller in summer season due to the lesser precipitation and lesser moisture availability. The $R_n$ and G increased rapidly after the sunrise and changed the direction during pre-winter, post-winter and summer seasons. After sunset, the $R_n$ and G again change sign rapidly, but the LE and H gradually decreased to lower values. The LE and H in the morning increased 1 to 2 hours after the $R_n$ during pre-, post-winter and summer season.

In the 2016–17 year (Figure S7), the pre-winter, winter and summer were the same as that of the 2015–16 year except for the amplitude of LE in was larger in summer season due to the more precipitation and more moisture availability. However, during the winter and post-winter season of the 2016–17 year, the main difference in diurnal changes was found because of the extended snow cover till May during that year. The amplitude of $R_n$, LE, H and G were smaller compared to the 2015-16 year.
Figure S6: The diurnal change of modelled surface energy fluxes on (A) pre-winter, (B) winter, (C) post-winter, and (D) summer seasons for the 2015-16 year at South-Pullu (4727 m a.s.l.), in the upper Ganglass catchment, Leh.
Figure S7: The diurnal change of modelled surface energy fluxes on (A) pre-winter, (B) winter, (C) post-winter, and (D) summer seasons for the 2016-17 year at South-Pullu (4727 m a.s.l.), in the upper Ganglass catchment, Leh.
APPENDICES

APPENDIX-I

Table A1: Snow characterisation parameters used as input to the GEOtop model.

| GEOtop parameter name       | Description                                                                 | Units   | Value |
|-----------------------------|-----------------------------------------------------------------------------|---------|-------|
| MaxWaterEqSnowLayerContent  | Maximum water equivalent admitted in a snow layer                           | kg m$^{-2}$ | 7     |
| SWEtop                      | Maximum snow water equivalent per unit area of the snowpack in the top region | kg m$^{-2}$ | 3000  |
| SWEbottom                   | Maximum snow water equivalent per unit area of the snowpack in the bottom region | kg m$^{-2}$ | 3000  |
| MaxSnowLayersMiddle         | maximum number of layers admitted in middle region                          | -       | 50    |
Table A2: Snow characterisation parameters used as input to the GEOtop model. The parameter values were adopted from Gubler et al. (2013) and Engel et al. (2017).

| GEOtop parameter name       | Description                                                                 | Units | Value |
|-----------------------------|-----------------------------------------------------------------------------|-------|-------|
| SnowCorrFactor              | Correction factor on fresh snow accumulation                                | -     | 1.8   |
| RainCorrFactor              | Correction factor on rain                                                    | -     | 1.0   |
| DewTempOrNormTemp           | Use dew temperature (1) or air temperature (0) to discriminate between snowfall and rainfall | -     | 0     |
| ThresTempRain               | Air temperature above which all precipitation is rain                        | °C    | 3     |
| ThresTempSnow               | Air temperature below which all precipitation is snow                        | °C    | -1    |
| SnowEmissiv                 | Emissivity of snow                                                           | -     | 0.98  |
| IrriducibleWatSatSnow       | Irreducible water saturation. It is the ratio of the capillarity-hold water to ice content in the snow. | -     | 0.07  |
| MaxSnowPorosity             | Maximum snow porosity allowed. This parameter prevents excessive snow densification | -     | 0.7   |
| DrySnowDefRate              | Snow compaction (% per hour) due to destructive metamorphosis for snow density < SnowDensityCutoff and dry snow | -     | 1     |
| SnowDensityCutoff           | Snow density cut off to change snow deformation rate                          | kg m\(^{-3}\) | 175   |
| WetSnowDefRate              | Enhancement factor in presence of wet snow                                   | -     | 1.5   |
| SnowViscosity               | Viscosity of snow                                                            | N s m\(^{-2}\) | 6.E6  |
| AlphaSnow                   | Freezing characteristic soil for snow                                       | -     | 1.E5  |
| FreshSnowReflVis            | Visible band reflectance of fresh snow                                       | -     | 0.85  |
| FreshSnowReflNIR            | Near infrared band reflectance of fresh snow                                 | -     | 0.65  |
| AlbExtParSnow               | Albedo extinction parameter (aep): if snow depth < aep, albedo is interpolated between soil and snow | mm    | 10    |
| SnowRoughness               | Roughness of snow surface                                                    | mm    | 2     |
| SnowAgingCoeffVis           | Reflectance of the new snow in the visible wave length                       | -     | 0.2   |
| SnowAgingCoeffNIR           | Reflectance of the new snow in the infrared wave length                      | -     | 0.5   |
Table A3: Soil parameters for different groups used as input to the GEOtop model. The parameter values were adopted from Gubler et al. (2013).

| GEOtop parameter name       | Description                                | Units   | Clay  | Silt  | Bedrock |
|-----------------------------|--------------------------------------------|---------|-------|-------|---------|
| AlphaVanGenuchten           | Van Genuchten parameter $\alpha$           | m$^{-1}$| 0.001 | 0.001 | 0.001   |
| NVanGenuchten               | Van Genuchten parameter $n$                | -       | 1.6   | 1.4   | 1.2     |
| ThermalConductivitySoilSolids| Thermal conductivity of the soil solid     | W m$^{-1}$ K$^{-1}$ | 2.5 | 2.5 | 2.5 |
| ThermalCapacitySoilSolids  | Thermal capacity of the soil solid         | 10$^6$ J m$^{-3}$ K$^{-1}$ | 2.25 | 2.25 | 2.25 |
| ThetaSat                    | Saturated water content                    | %       | 0.49  | 0.47  | 0.47    |
| ThetaRes                    | Residual water content                     | %       | 0.06  | 0.07  | 0.002   |
**Table A4:** Soil and ground surface characterisation parameters used as input to the GEOtop model. The parameter values were adopted from Gubler et al. (2013).

| GEOtop parameter name         | Description                                                                 | Units | Value                          |
|------------------------------|-----------------------------------------------------------------------------|-------|--------------------------------|
| SoilLayerThicknesses         | vector defining the thickness of the various soil layers                     | mm    | 19 layers with thickness increasing from the surface to the deeper layers |
| Simulation depth             |                                                                             | m     | 10                             |
| InitSoilTemp                 | Initial soil temperature                                                    | °C    | -0.5                           |
| BottomBoundaryHeatFlux       | Incoming heat flux at the bottom boundary of the soil domain (geothermal heat flux) | W m⁻² | 0                              |
| SoilRoughness                | Roughness length of soil surface                                            | mm    | 10                             |
| ThresSnowSoilRough           | Threshold on snow depth to change roughness to snow roughness values with d₀ set at 0, for bare soil fraction | mm    | 2                              |
| SoilAlbVisDry                | Ground surface albedo without snow in the visible - dry                     |       | 0.20                           |
| SoilAlbNIRDry                | Ground surface albedo without snow in the near infrared - dry               |       | 0.20                           |
| SoilAlbVisWet                | Ground surface albedo without snow in the visible - saturated               |       | 0.18                           |
| SoilAlbNIRWet                | Ground surface albedo without snow in the near infrared - saturated         |       | 0.18                           |
| SoilEmissiv                  | Ground surface emissivity                                                   |       | 0.88                           |
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