Winter snow thermal conductivity and conductive fluxes in the Central Arctic

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Introduction

- Conductive fluxes are important for the winter surface energy budget (SEB) because they link sea ice growth and the atmosphere.
- Calculating conductive fluxes in snow requires knowledge of snow properties, e.g., depth and thermal conductivity, that can have large variability in space and time.
- Despite known variability of snow thermal conductivity (k_{snow}), with measured values of 0.14-0.65 Wm^{-1}K^{-1} [1], most forecast and climate models assume constant k_{snow} ~0.3 Wm^{-1}K^{-1}.

Questions

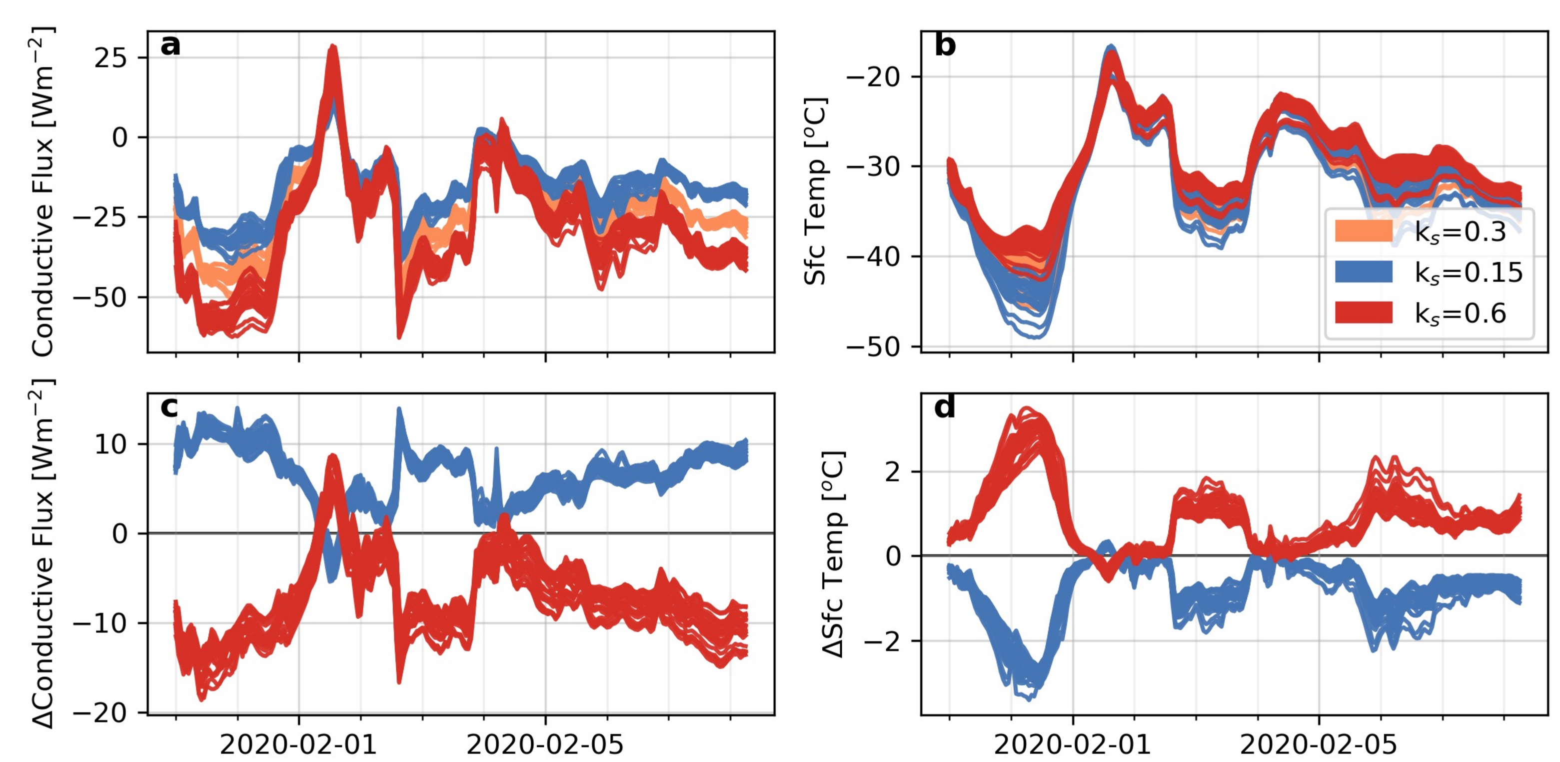
What is the impact of varying snow thermal conductivity in a coupled model?
Can we estimate thermal conductivity and subsurface heat fluxes with time and depth?
What variability can we observe and explain across MOSAiC sites?

SEB sensitivity to snow thermal conductivity in a coupled model

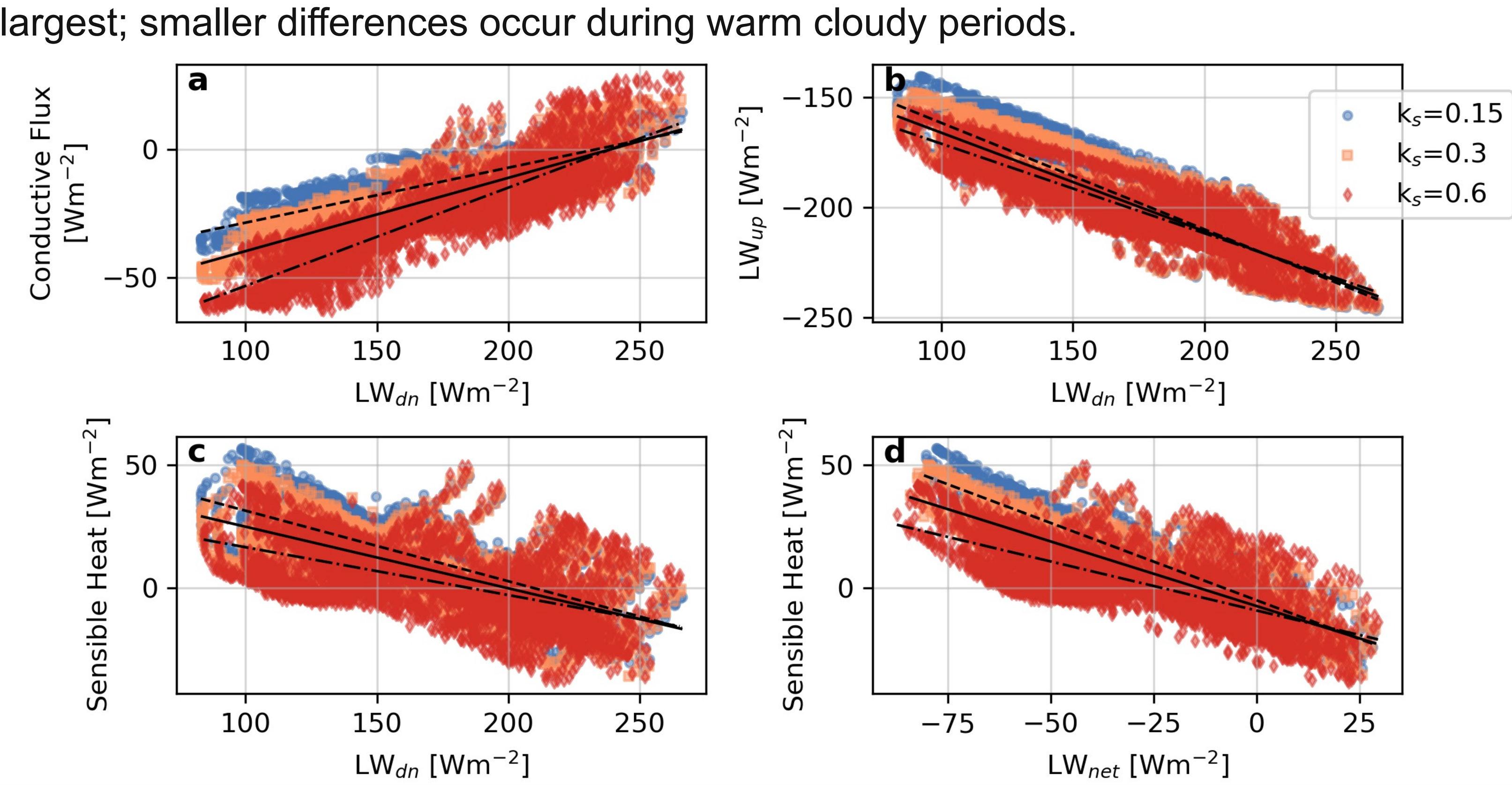
The Coupled Arctic Forecast System (CAFS):

- WRF for atmosphere and CICE for sea ice w/ 3 snow layers, based on RASM
- Simulation run from Jan. 30 to Feb. 8, 2020.
- Fluxes defined as positive when directed down.
- Snow thermal conductivity (k_s) varied over 89.78ºN: 0.15, 0.3 (default), 0.6 Wm^{-1}K^{-1}. Only grid cells where k_s changes are shown.

Varying k_s changes conductive flux *and* upwelling LW and turbulent fluxes through the surface temperature.



Largest impacts of changing k_s are during clear and cold times when conduction is largest; smaller differences occur during warm cloudy periods.



References
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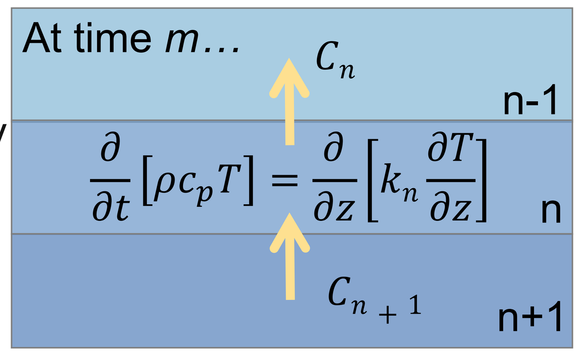
Deriving snow thermal conductivity for conductive fluxes

Temperature changes in time (storage) are set equal to the divergence of vertical conduction [2]. Using smoothed temperature profiles seasonal ice mass buoys (IMBs) [3,4] we can solve for thermal conductivity in winter (no incoming SW). The 13 IMBs have 2 cm vertical resolution and 4 or 6 hourly time resolution.



Approximate 1D heat equation with finite differencing:

$$\frac{\rho c_p}{\Delta t}\left[T_n^{m+1} - T_n^{m}\right] = \frac{1}{\Delta z}\left(\frac{k_{n+1}}{\Delta z}\left[T_{n+1}^{m+1} - T_n^{m+1}\right] - \frac{k_n}{\Delta z}\left[T_n^{m+1} - T_{n-1}^{m+1}\right]\right)$$

Rearrange to solve for thermal conductivity (k_n) in each layer from known temperatures:

$$a_n k_n + b_n k_{n+1} = d_n$$

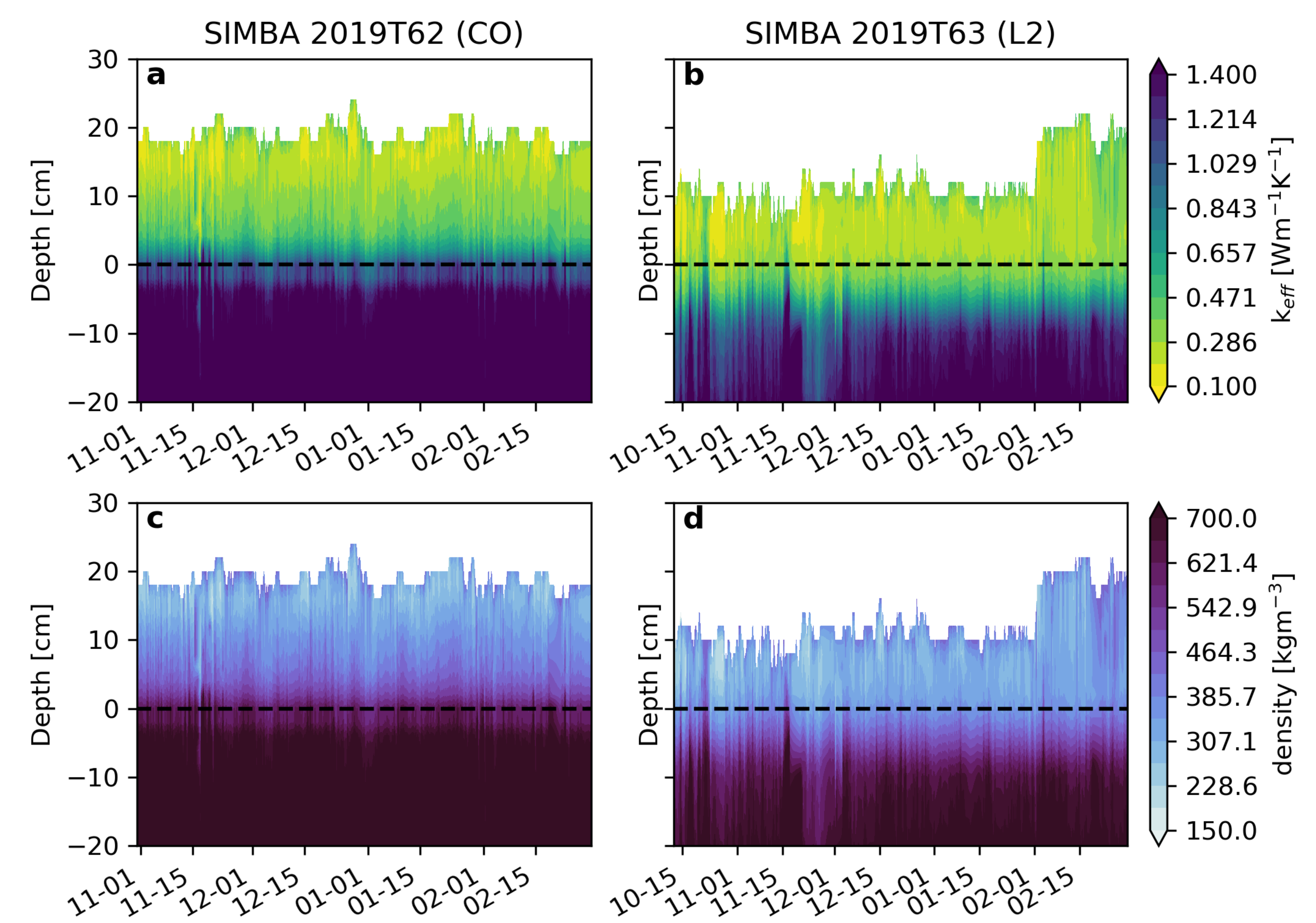
$$\begin{bmatrix} a_{n-1} & b_{n-1} & 0 & 0 & 0 \\ 0 & a_n & b_n & 0 & 0 \\ 0 & 0 & a_{n+1} & b_{n+1} & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots \\ 0 & 0 & 0 & 0 & a_N \end{bmatrix} \begin{bmatrix} k_{n-1} \\ k_n \\ k_{n+1} \\ \vdots \\ k_N \end{bmatrix} = \begin{bmatrix} d_{n-1} \\ d_n \\ d_{n+1} \\ \vdots \\ d_N - k_{ice} b_n \end{bmatrix}$$

$$a_n = T_{n-1}^{m+1} - T_n^{m+1}$$
$$b_n = T_{n+1}^{m+1} - T_n^{m+1}$$
$$d_n = \frac{\rho c_p \Delta z^2}{\Delta t}\left[T_n^{m+1} - T_n^{m}\right]$$

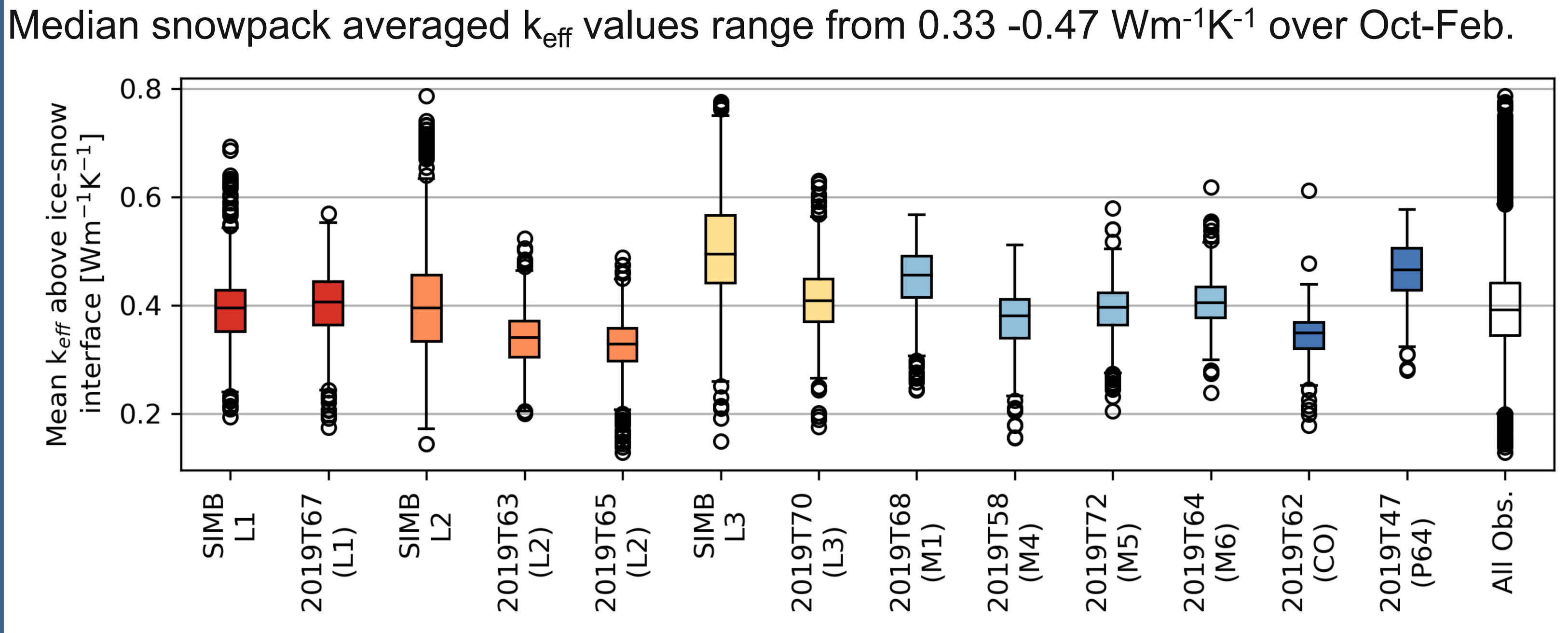
Further assumptions and steps:

- N is set to -30 cm to -100 cm (or 20 cm above sea ice bottom) with k_{ice}=2 Wm^{-1}K^{-1}.
- Initially density (ρ) is constant in snow (300 kgm^{-3}) and ice (900 kgm^{-3}). After first k profile is solved, re-calculate density from [5] and [6]. Remove levels in snow (depth>6 cm) where k_n≥0.6 Wm^{-1}K^{-1}. Re-solve matrices with new density profiles.
- Heat capacity (c_p) only depends on temperature as in [7].

Thermal conductivities are considered "effective" (k_{eff}) because other unaccounted for processes (e.g. ventilation) may influence results.



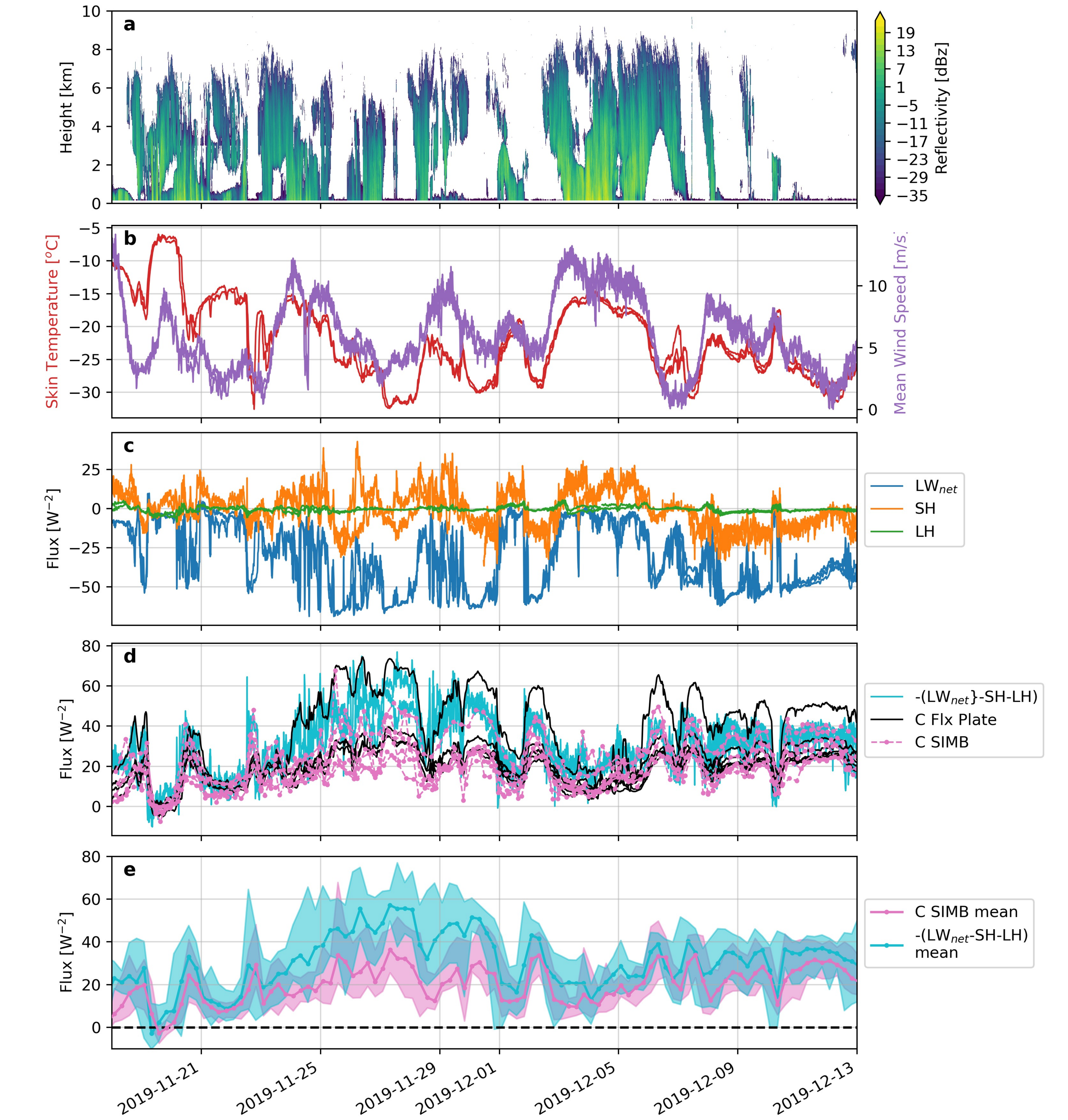
Median snowpack averaged k_{eff} values range from 0.33 -0.47 Wm^{-1}K^{-1} over Oct-Feb.



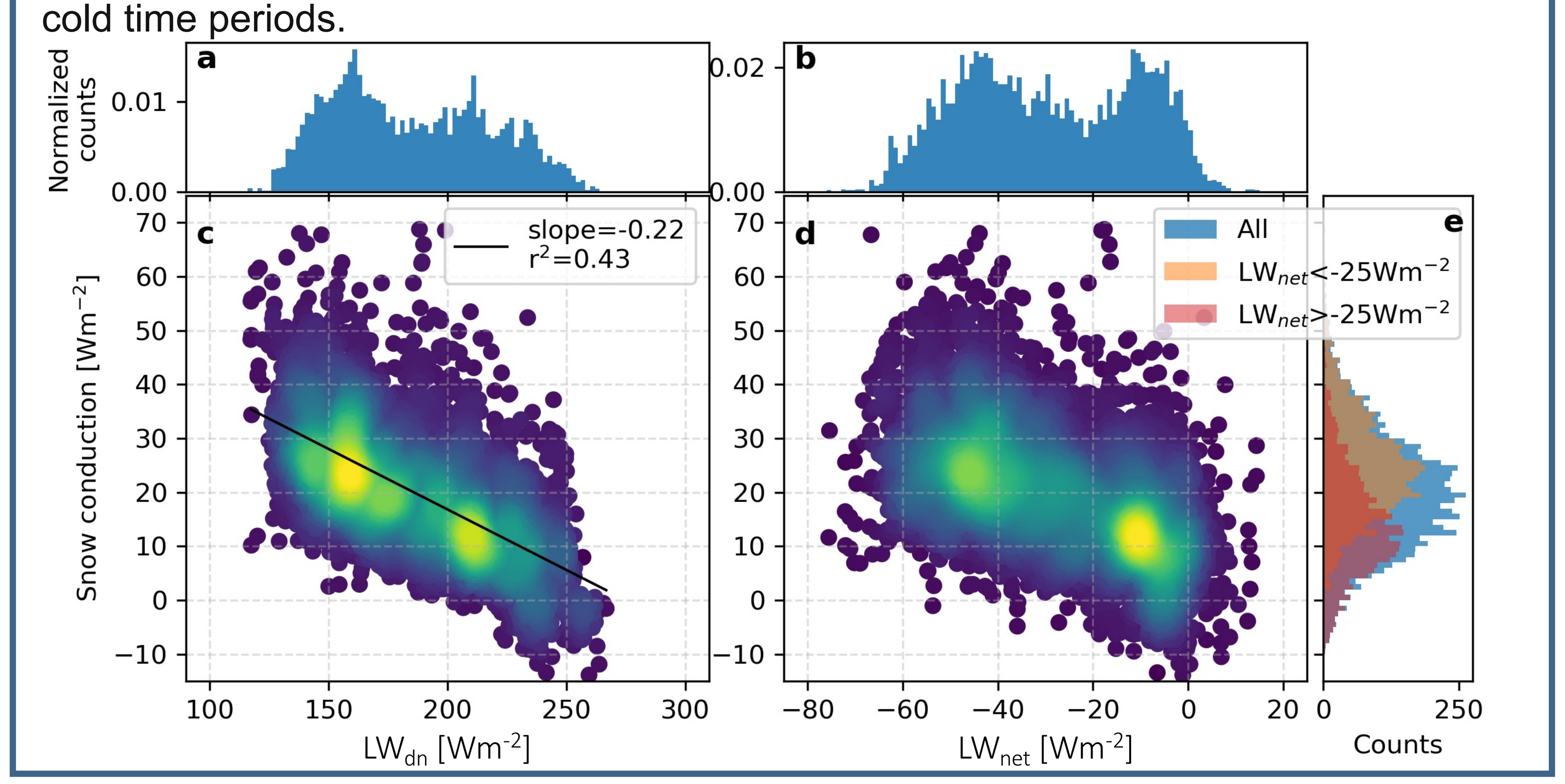
Conductive flux variability and the atmosphere

Conductive fluxes (C) are from 7 nearby SIMBs within the snowpack. Fluxes are averaged over 6 hour windows to speculate about budget closure (bottom) with max. and min. values shown by shading.

Surface fluxes are from three Atmospheric Surface Flux Stations (ASFS) with 10 minute time resolution. Radar reflectivity are derived from the vertically- pointing Ka-band ARM Zenith Cloud Radar.



Larger conductive fluxes are associated with radiatively clear (LW$_{net}$<~-25 Wm^{-2}) and cold time periods.



Conclusions and lingering questions

Vertical profiles of thermal conductivity can be estimated in time from MOSAiC observations.

Does sub-grid scale variability in k_s matter in a coupled model?

Conductive fluxes are variable in space and time and respond to atmospheric forcing.

What causes large residuals in SEB?