GFDL Land-Atmosphere-Snow Scheme: formulation and evaluation of a new snow model for Earth system science applications

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NOAA Climate Program Office
Climate Process Teams project
“3D-Land Energy Exchanges”

NASA’s High Mountain Asia Team 2
Collaborative research to study water and cryosphere changes in High Mountain Asia.

Main objective

- Enhance understanding of **cryosphere-climate interactions** through improved fidelity of snow component in GFDL ESM4.1, and improved representation of **land heterogeneity and topography**

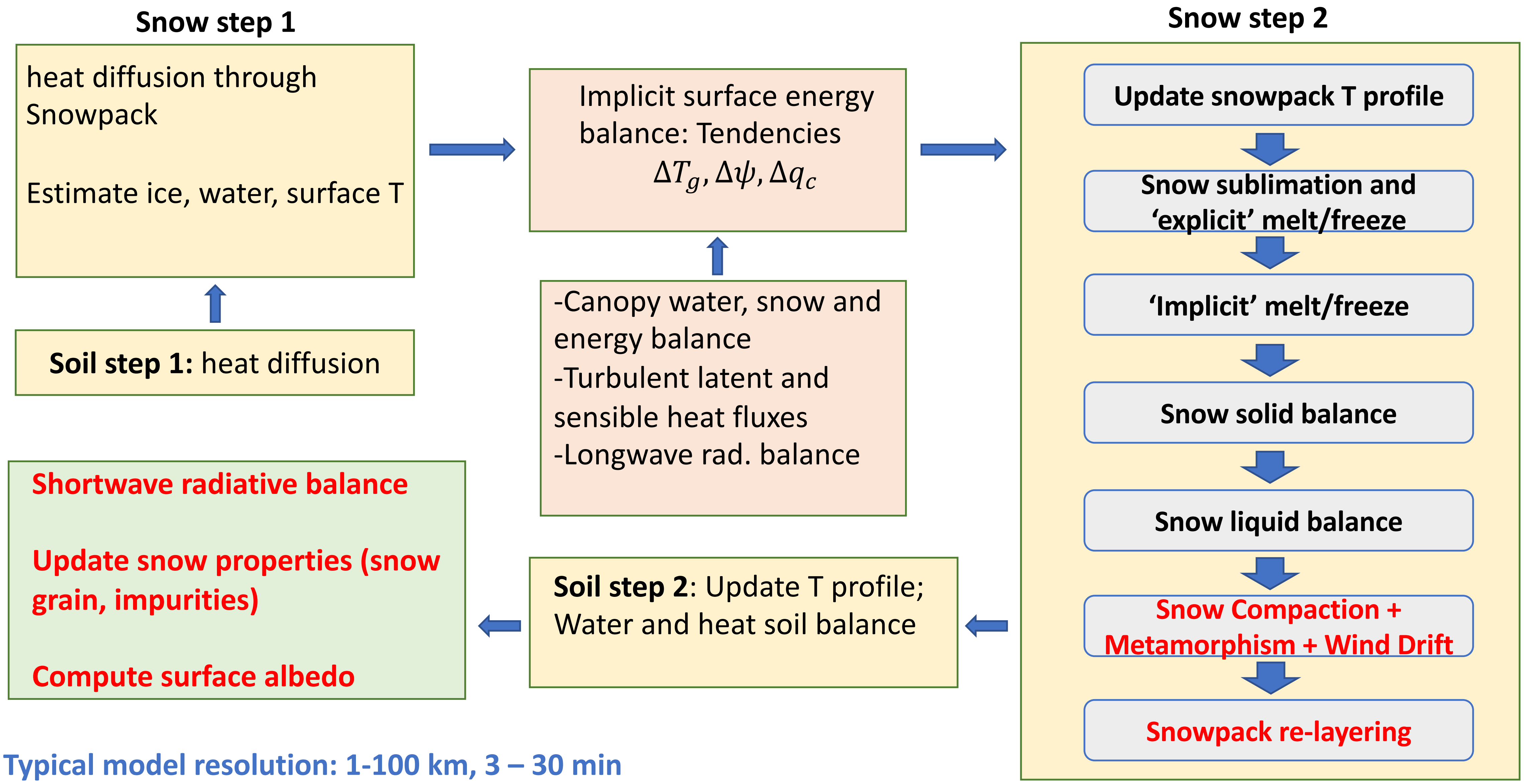
Outline

- Challenges of existing models
- The new **GFDL Land-Atmosphere-Snow Scheme (GLASS)**
- Evaluation over Snow Model Intercomparison Project (SnowMIP) sites
- Implications for climate modelling

Challenges and trade-offs in current ESM snow modelling

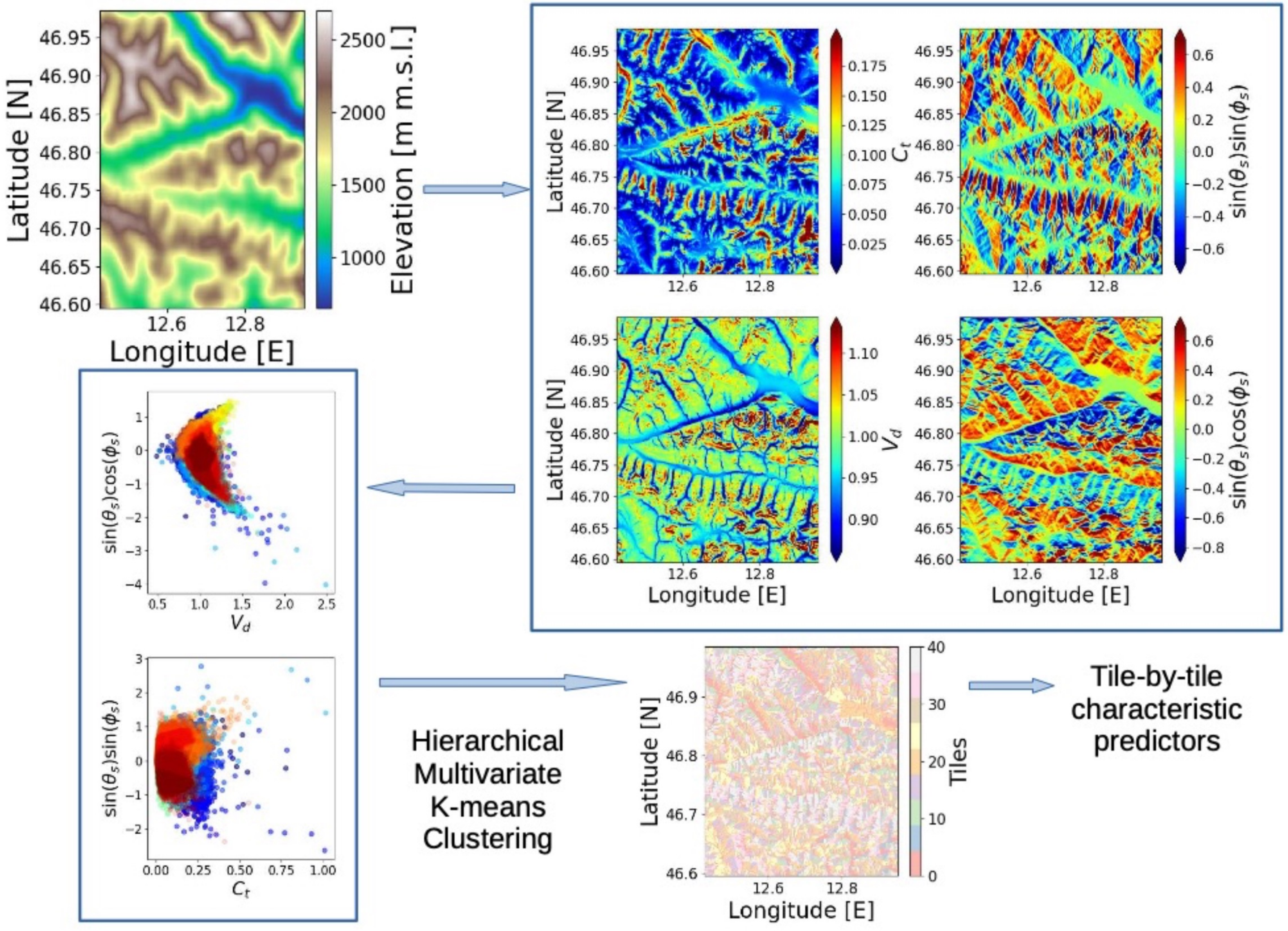
- Must be global, run over centuries
- Interaction with atmosphere, soils, and biosphere
- Conserves energy, mass and tracers
- Must be fast: linearized energy balance, coarse vertical discretization
- Should properly capture surface albedo feedbacks on climate

Overview of GLASS in GFDL ESM framework



Typical model resolution: 1-100 km, 3 – 30 min

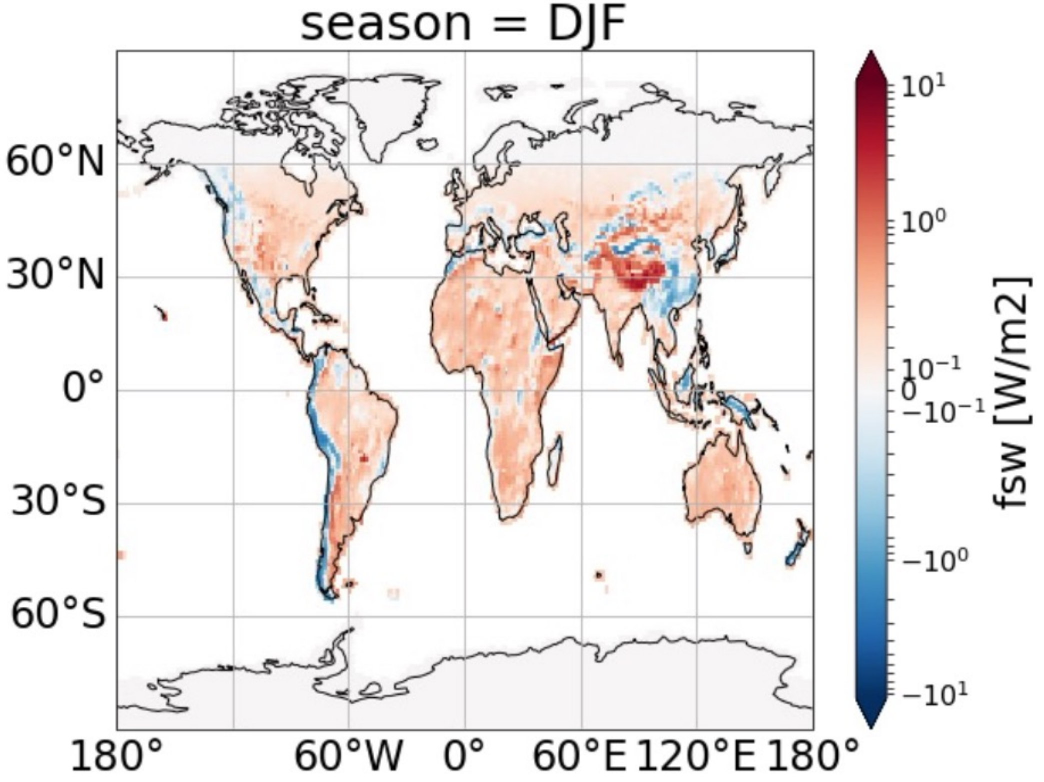
3D Topography – radiation interactions in the GFDL land model



CLASP Climate Process Team

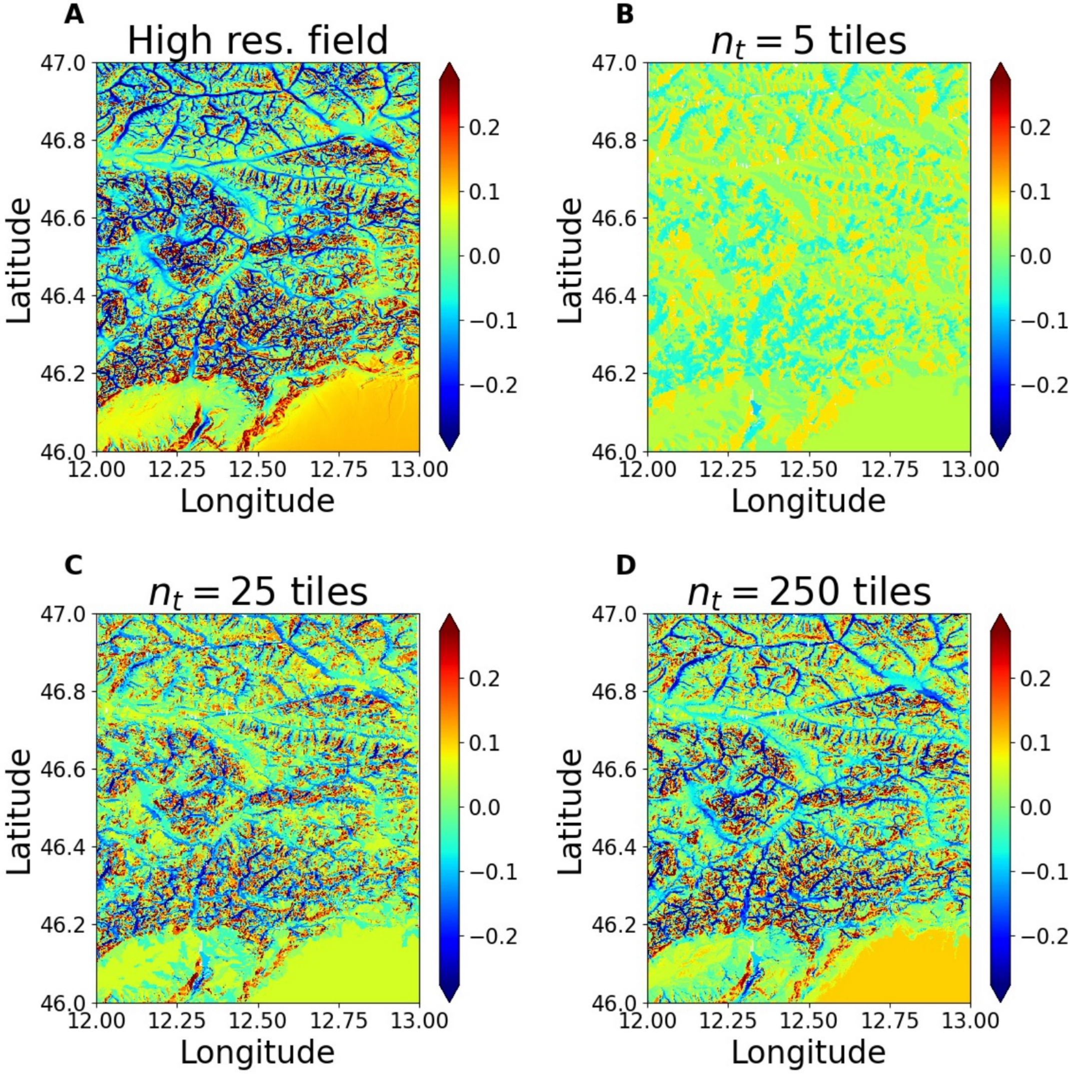
Coupling of **L**and and **A**tmospheric **S**ubgrid **P**arameterizations

Winter differences in sensible heat flux between flat and 3D historical model runs

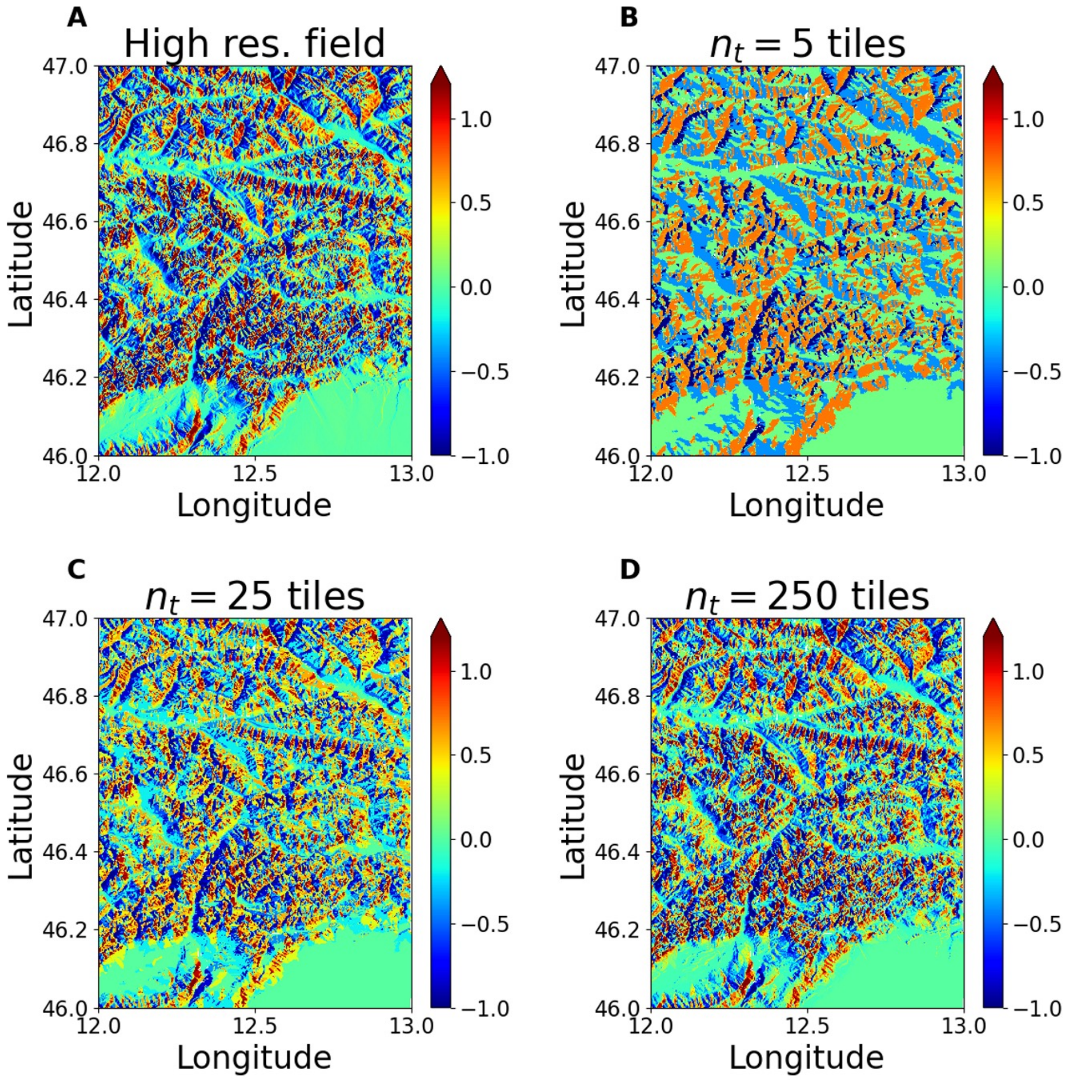


Convergence to high-resolution radiation fields

20 tiles recover 50-70% of spatial variance vs 1E6 points…



Direct radiation



Diffuse radiation

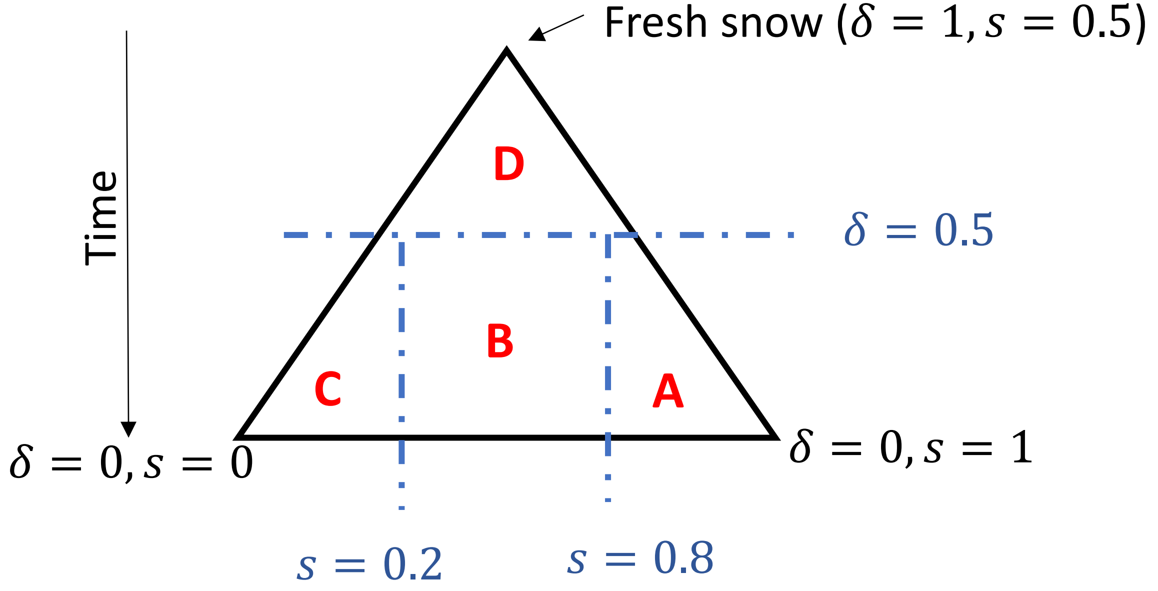
Snow metamorphism and albedo in GLASS

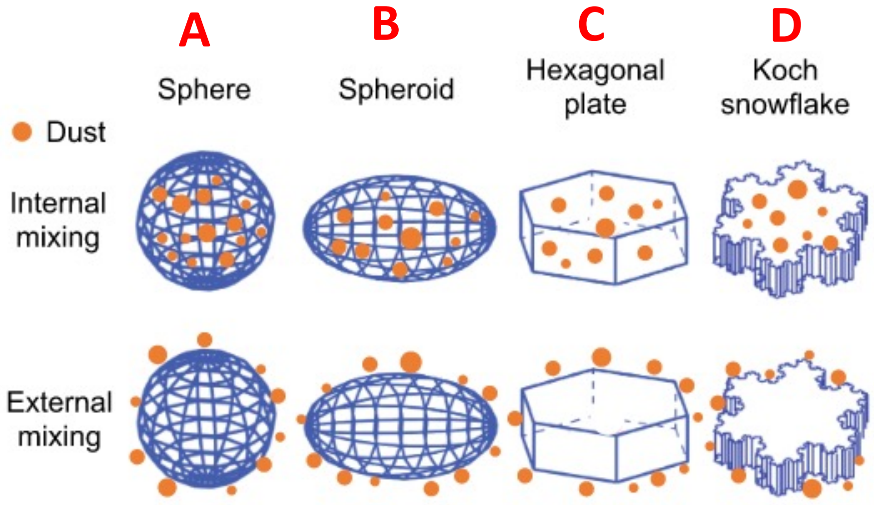
GLASS prognostic equations for the evolution of

- **Dendricity δ** – wet + dry process as in CROCUS (Brun et al., 1992)
- **Sphericity s** – wet + dry process as in CROCUS (Brun et al., 1992)
- **Optical diameter d_{opt}**: wet metamorphism (Brun et al., 1992) and dry (Flanner and Zender, 2006)

Novel feature: link between grain properties and albedo parameterization

Prognostic shape of snow: we classify snow in one of these four shape classes based on the prognostic δ, s, d_{opt}





Albedo parameterization by He et al., 2017 JGR-A

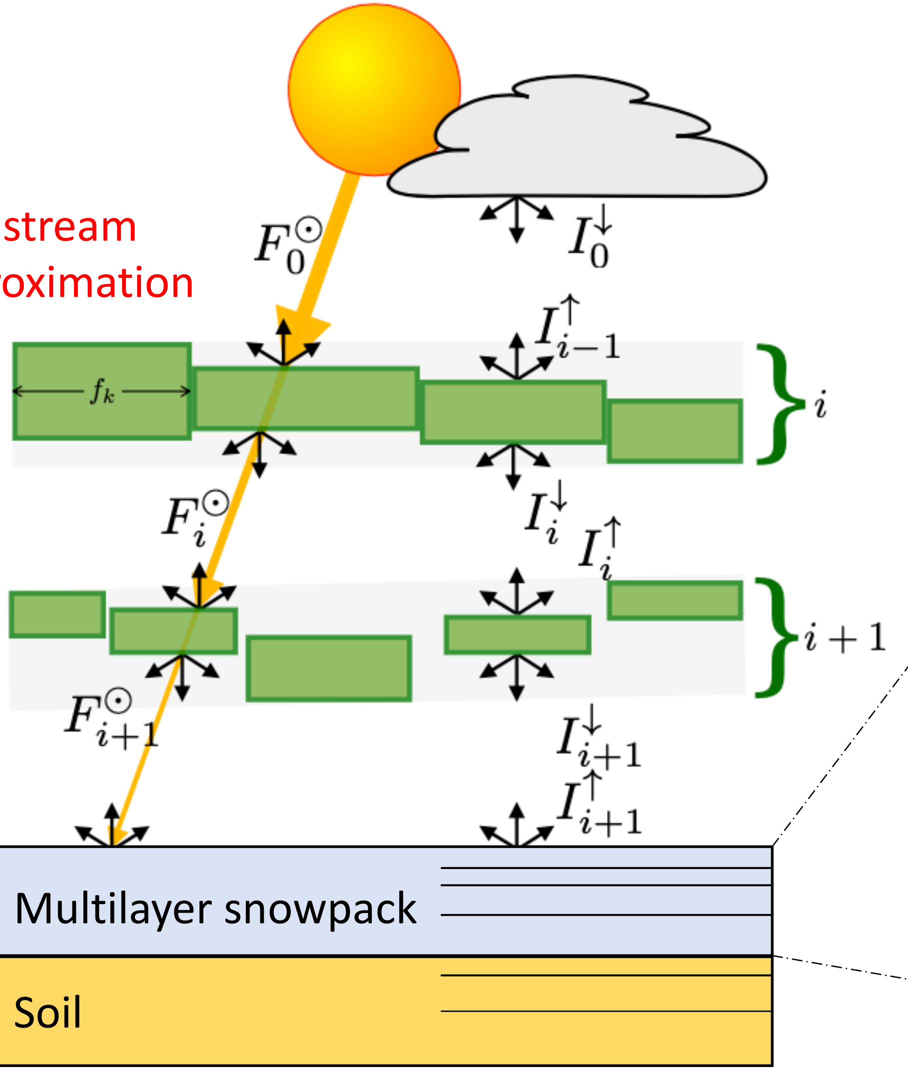
Radiative balance of canopy and snow

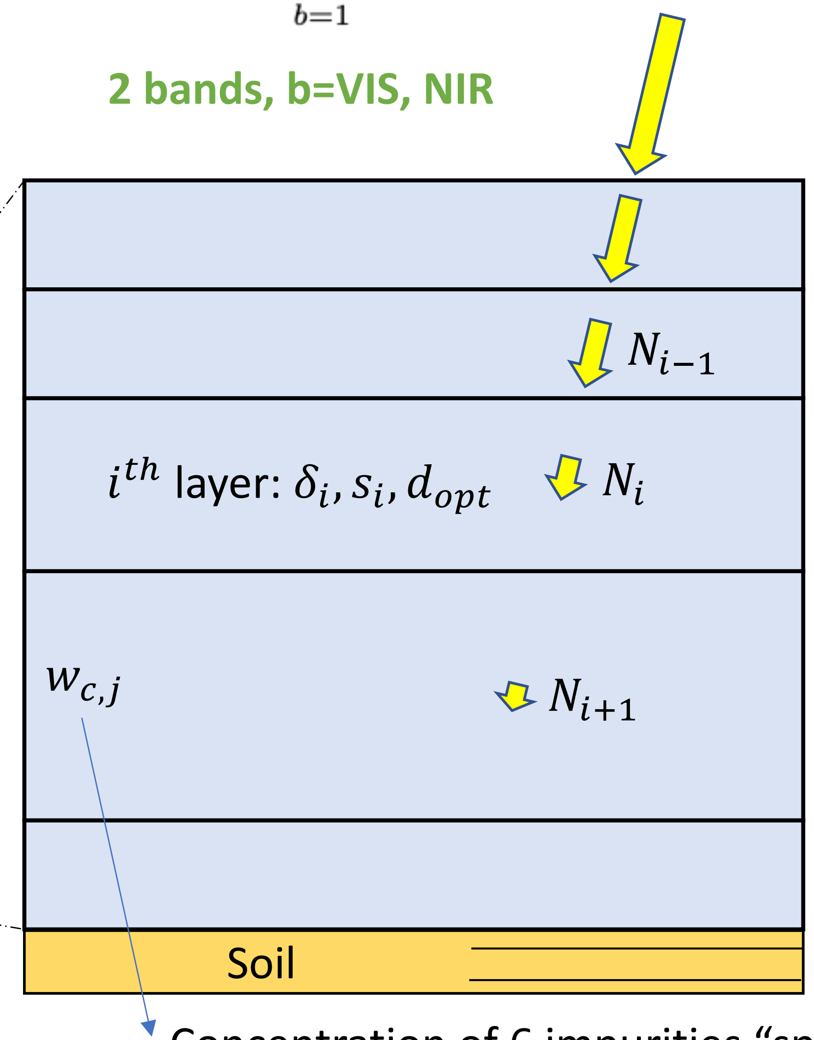
Empirical parameterization: exponential absorption of light in the snow; $\beta_b = f(d_{opt})$

$$Q_s(z) = \sum_{b=1}^{2} (1 - \alpha_b) R_{s,b} e^{-\beta_b z}$$

2 bands, b=VIS, NIR

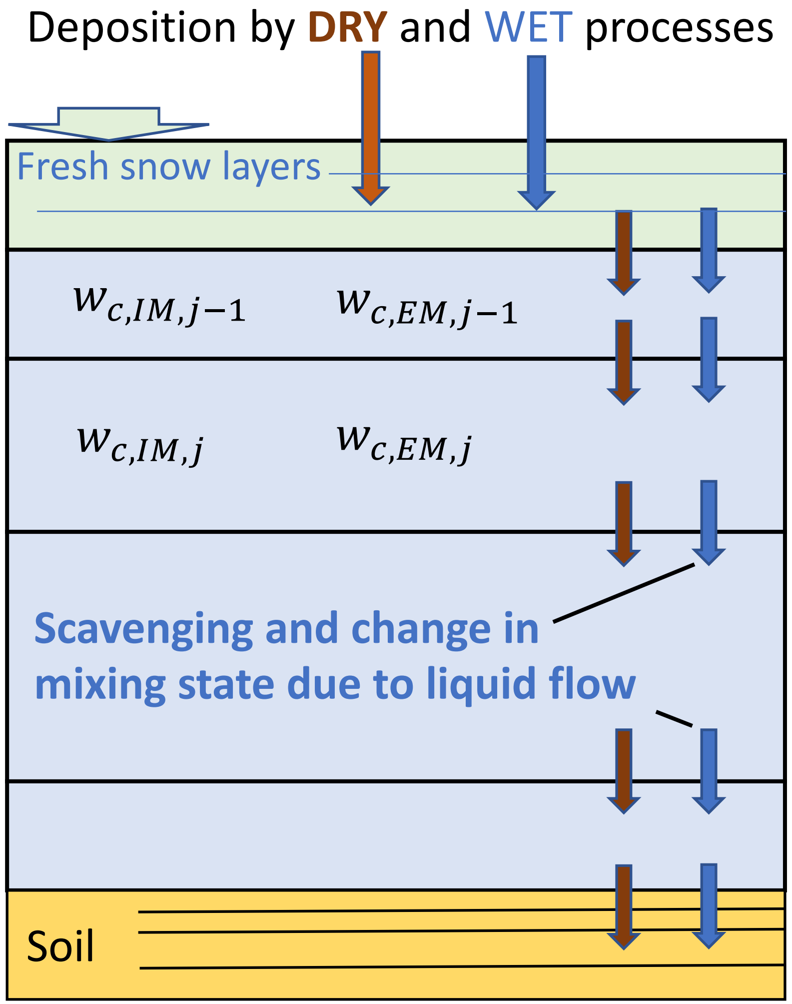
Two stream approximation





Concentration of 6 impurities “species”: Mineral Dust, Black Carbon and Organic Carbon, in internally or externally mixing states

Albedo model and light-absorbing impurities



Mass balance of LAPs (OC, BC, MD)
In the snowpack

Near surface concentration of LAPs:

$$c_{eq,BC} = c_{BC} + c_{MD}\frac{\sigma_{abss,MD}}{\sigma_{abs,BC}} + c_{OC}\frac{\sigma_{abss,OC}}{\sigma_{abs,BC}}$$

Albedo model (function on optical diameter, and grain shape)
Formulation from He et al., 2017

$$\alpha_s = b_0(\delta_p, s_p) + b_1(\delta_p, s_p)R_n + b_2(\delta_p, s_p)R_n^2$$

$$R_n = \log_{10}\left(\frac{R_e}{R_0}\right)$$

Radiative effect of impurities

$$\Delta\alpha_s = d_0\left(C_{eq,bc}\right)^k$$

$$k = d_1\left(\frac{R_e}{R_0}\right)^{d_2}$$

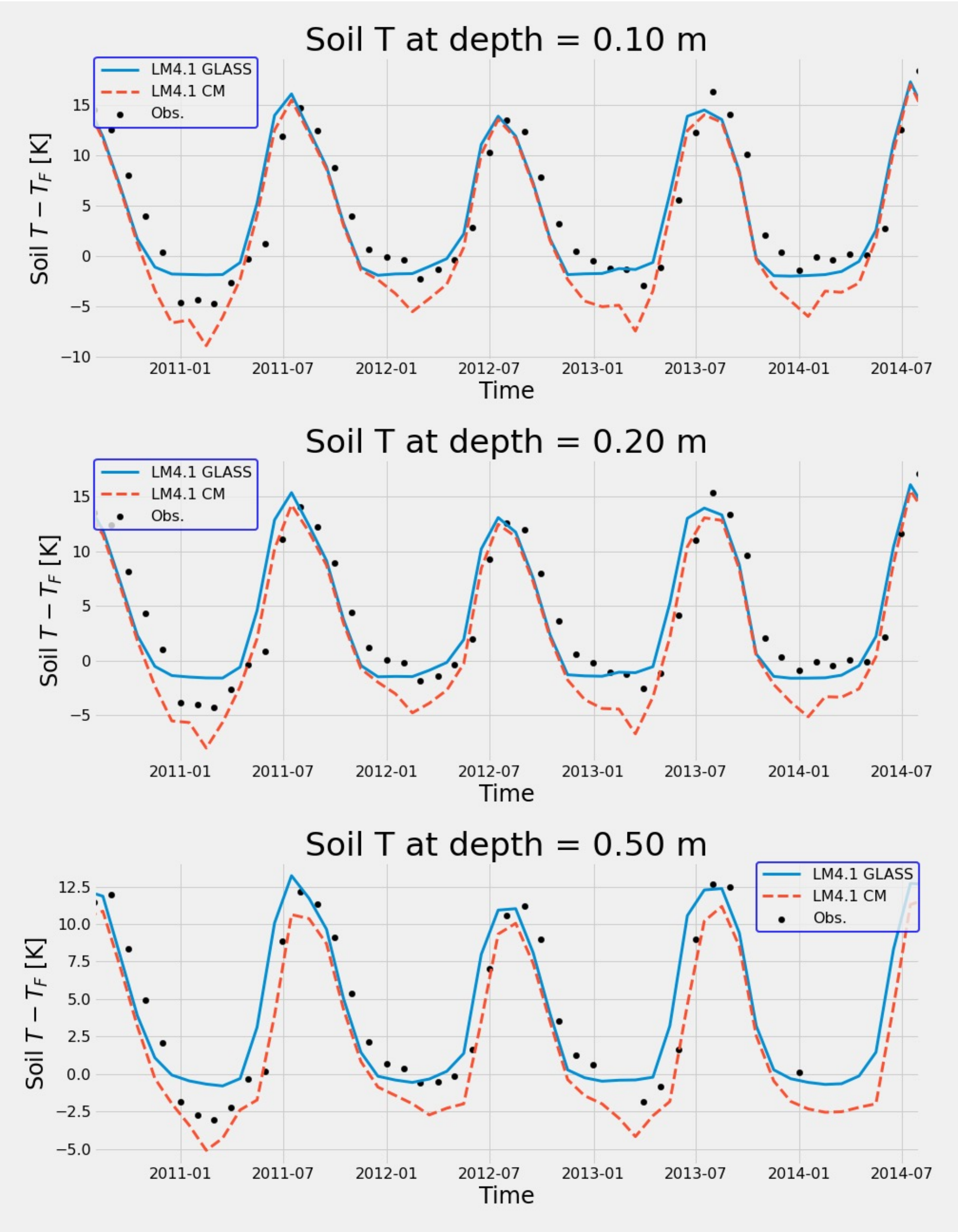
Experimental setup for model validation

Runs for each reference site
A] Spin-up 1880-1980 cycling through GSWP3 [1980-1990] forcing
B] Historical run, 1981 – to Start of in-situ data [1990s or 2000s]
C] Experiment run forced by in-situ data

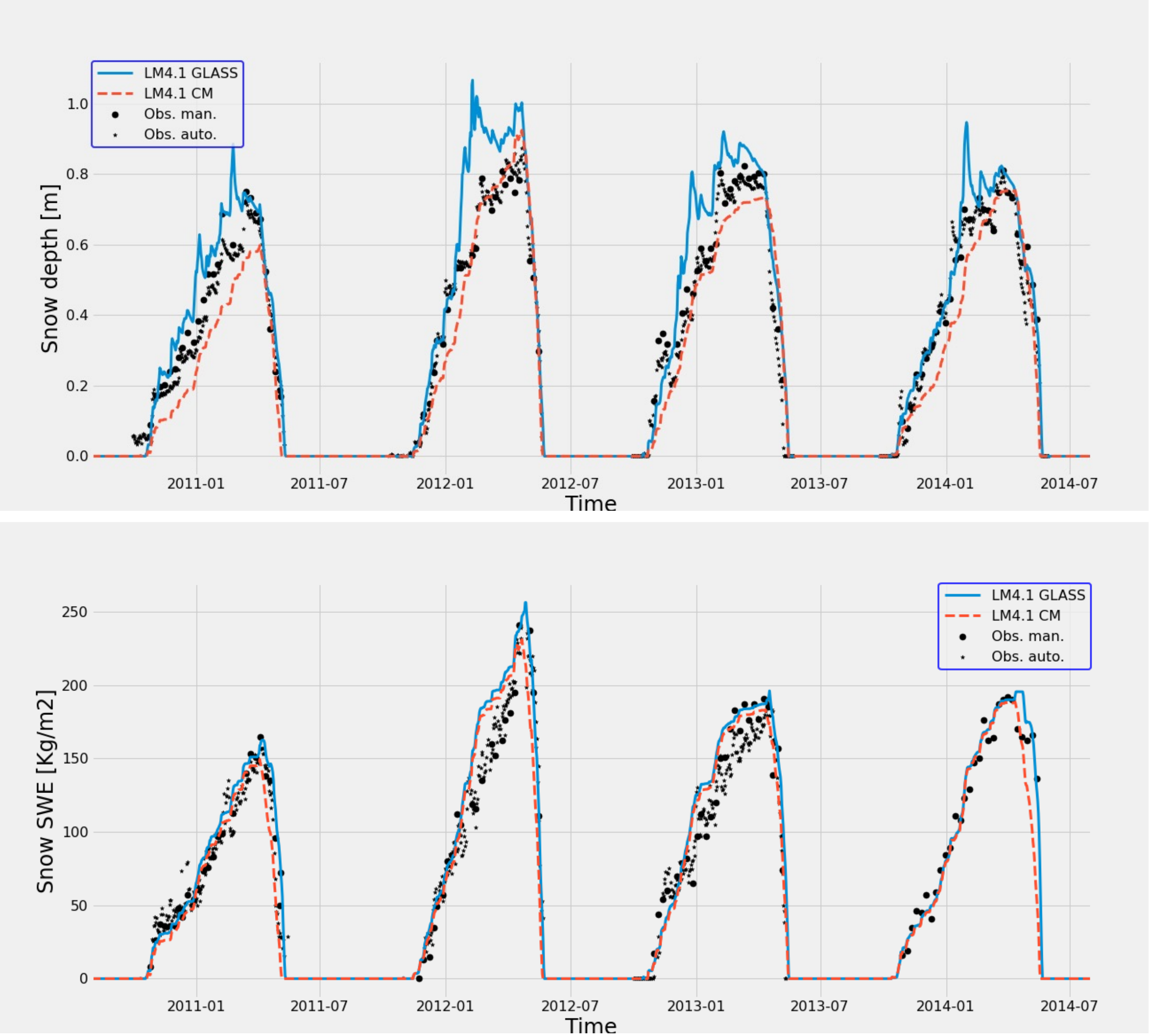
We compare 3 snow model configurations:

- **LM4.1 CM** current component of GFDL ESM 4.1
- **LM4.1 GLASS** No impurities, LM4.1 CM albedo
- **LM4.1 GLASS LAP** New albedo model with impurities

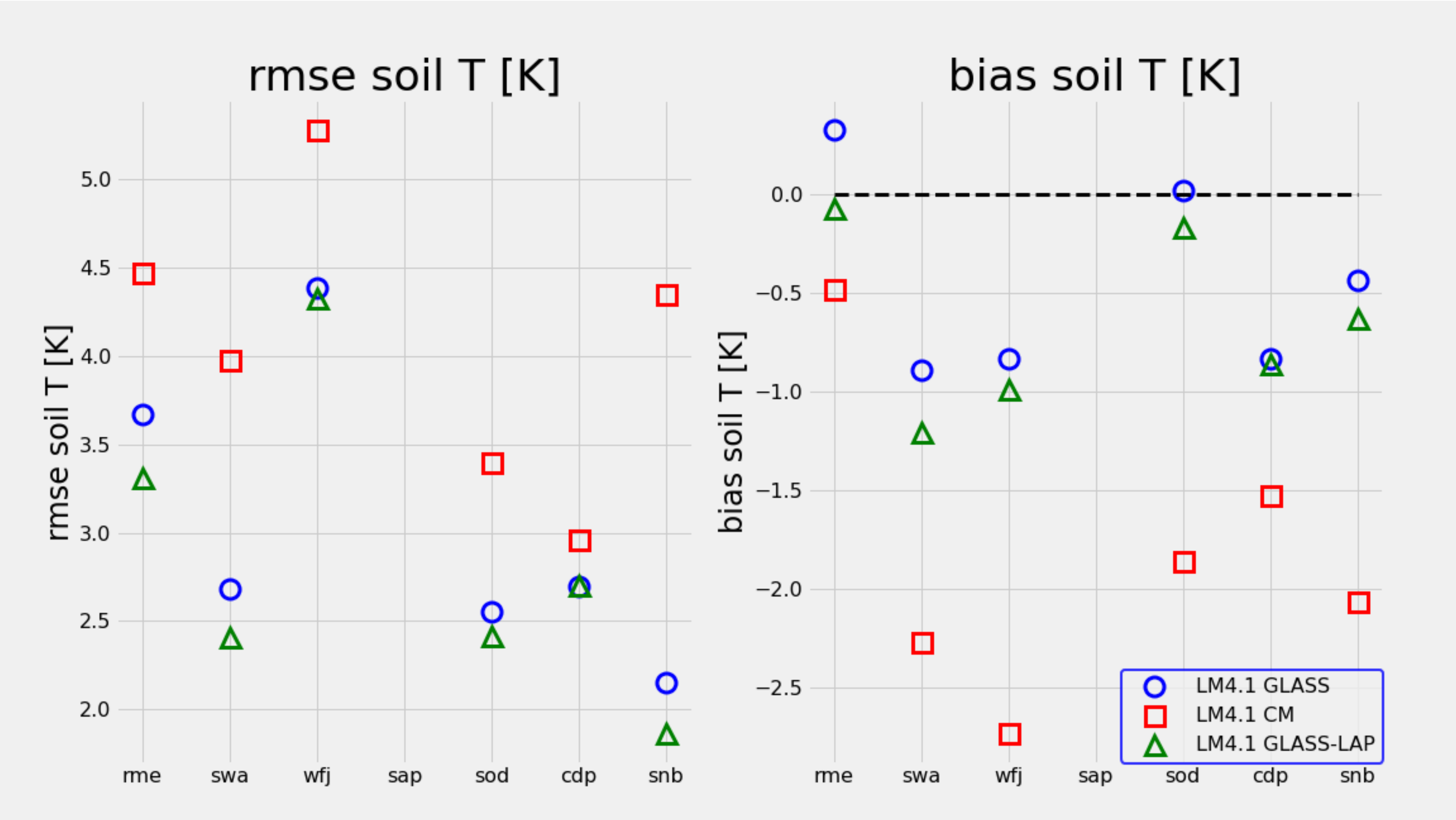
SnowMIP reference sites
Image from
https://doi.pangaea.de/10.1594/PANGAEA.897575



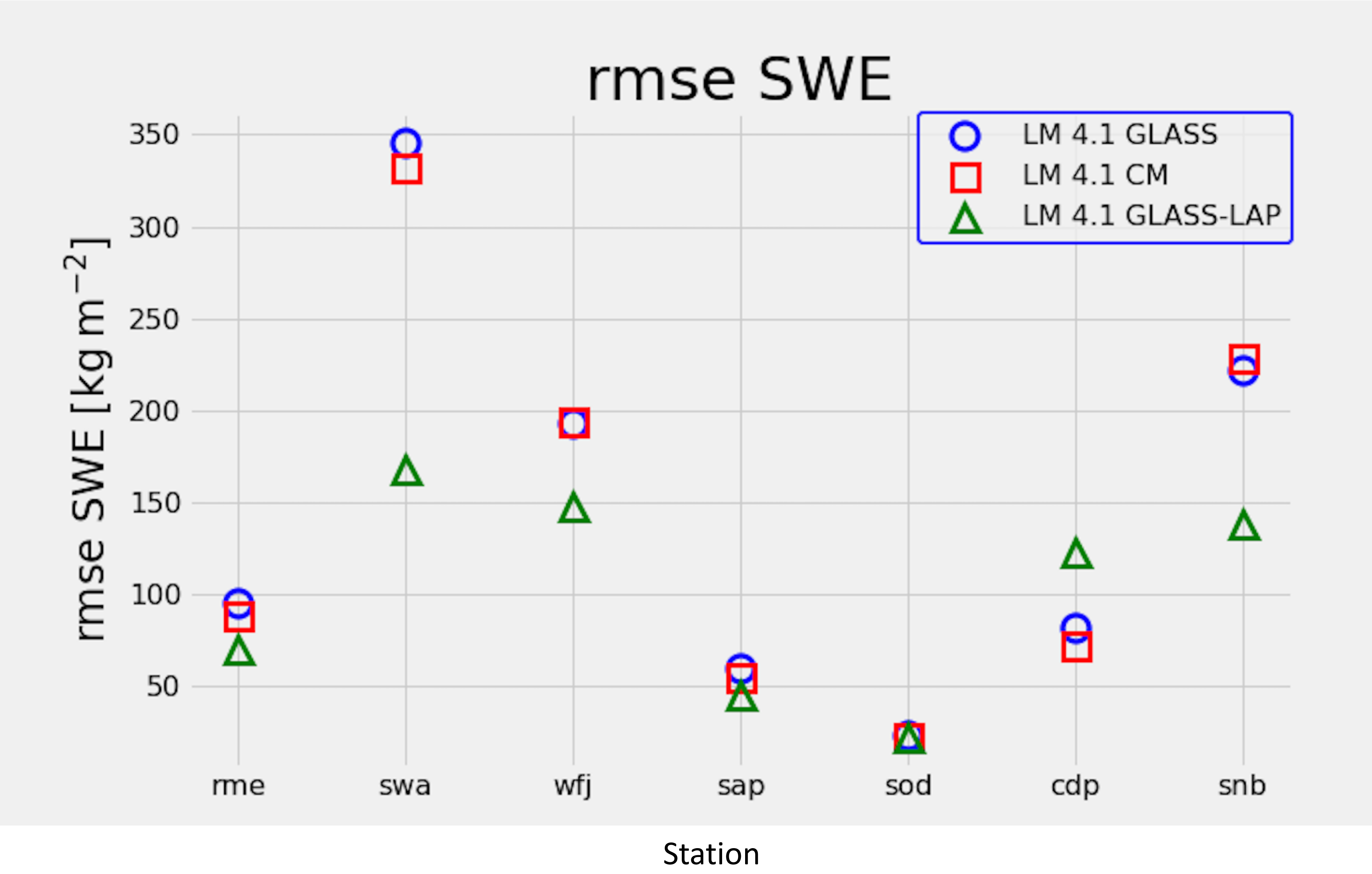
Significant Improvement in modelled soil temperature for the Sodankyla site (SOD), Finland, despite modest changes in Snow water equivalent



Results for soil temperature



Results for snow bulk variables



From Zorzetto et al. 2022, in preparation

Conclusions

- The detailed snow scheme GLASS was developed for GFDL LM4.1

- GLASS overcomes limitation of ESM4.1 snow scheme, and in particular offers
  - Optimized dynamic number of vertical layers
  - Snow heat conductance which depends on density & grain properties
  - Albedo explicitly depends on grain properties and impurities content

- The model exhibits improved performance over SnowMIP sites, especially for snow albedo and soil temperature

- Future work: Global-scale analysis and climate implications

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