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Improving shortwave radiation schemes in ELM: Sub-grid Topography, Snow Grain Shape, and Light-Absorbing Particles

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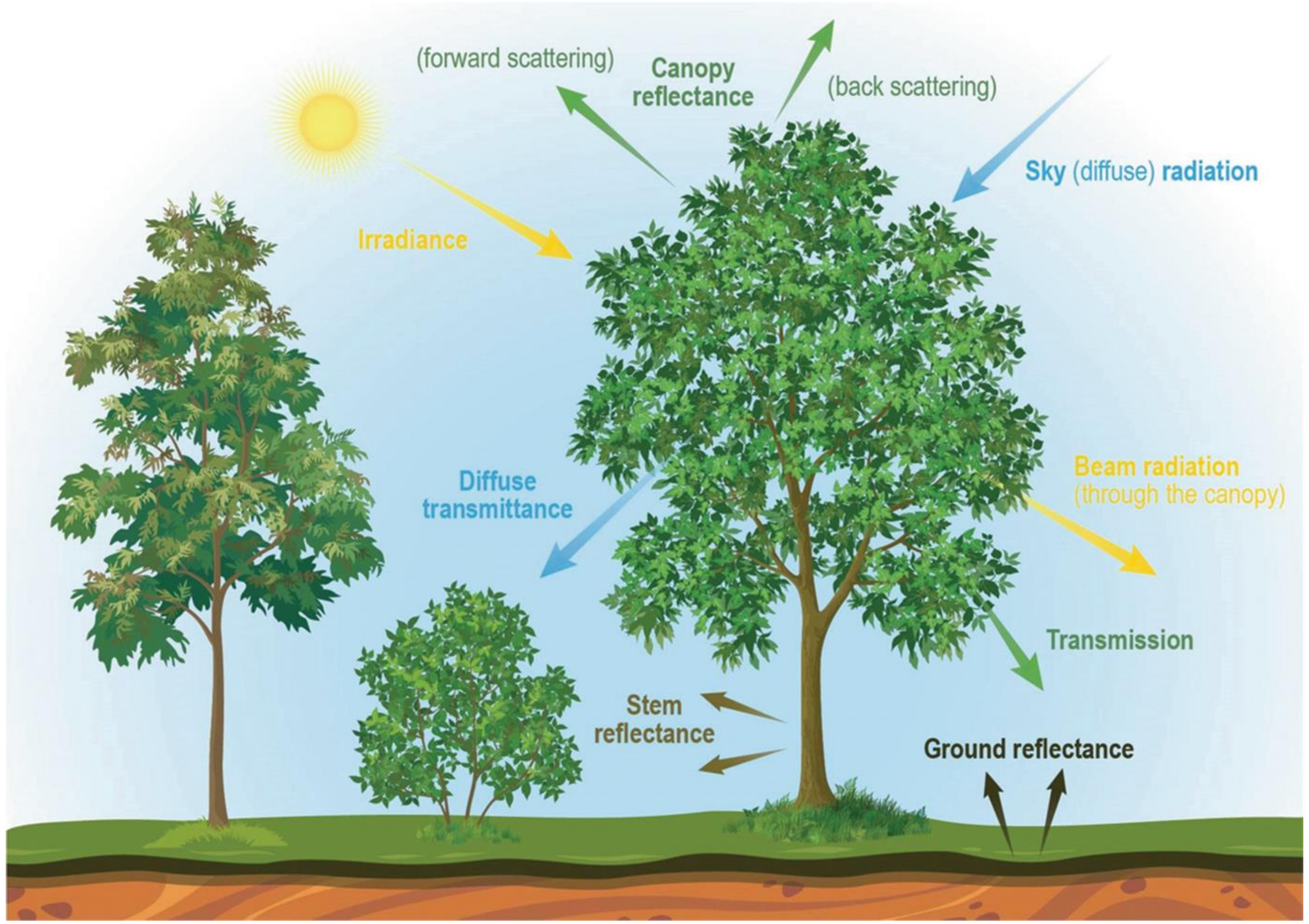
Climate Process Team (CPT)

Project: 3D-Land Energy Exchanges: Harnessing High Resolution Terrestrial Information to Refine Atmosphere-to-Land interactions in Earth System Models

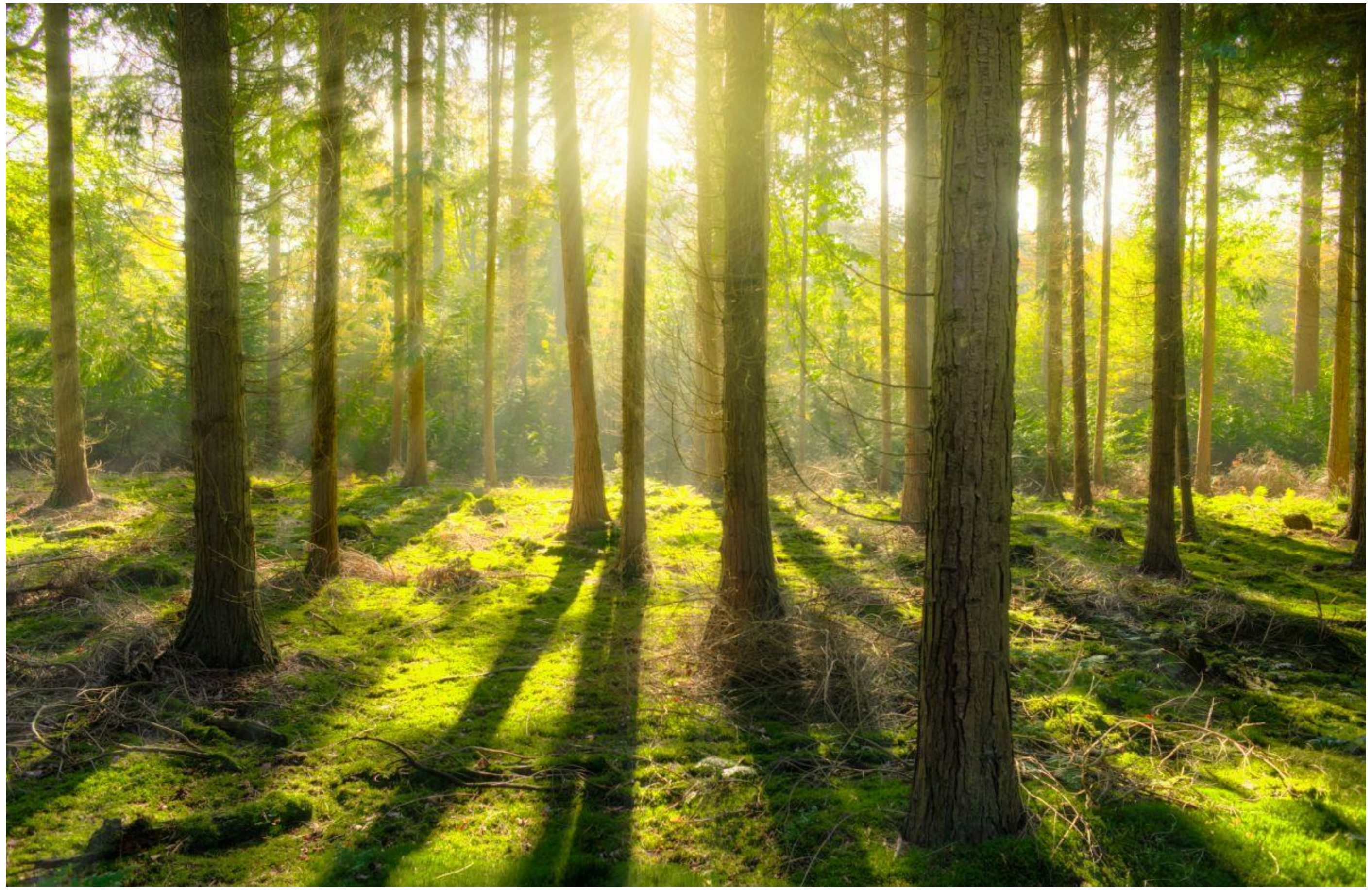
Objective: Advance the representation of atmosphere-to-land radiation exchange processes in the NOAA/GFDL ESM4, **DOE/E3SM**, and NCAR/CESM2:

1. Radiation flux parameterization accounting for the effects of **mountain shading and multiple reflections** between mountains and snow;
2. Parameterizations for **black carbon and dust** mixing in snow and associated light absorption and scattering processes;
3. **Multi-layer** canopy energy transfer accounting for the tracers (e.g. dust and black carbon) in the canopy air space;
4. Interactions of the above improvements with **sub-grid land-heterogeneity**.

Shortwave radiative transfer describes the interactions between sunlight and land surface.



Vegetation radiative transfer process
(Serbin et al. 2020)

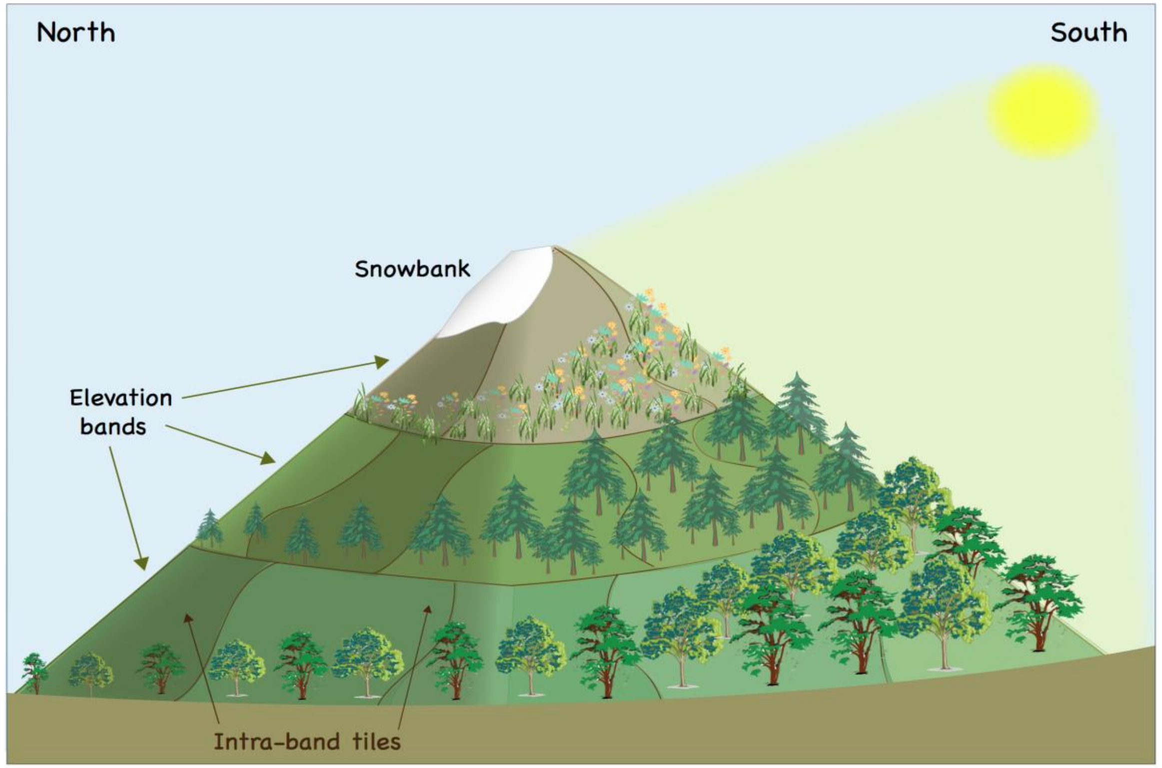


Light distribution in the forests

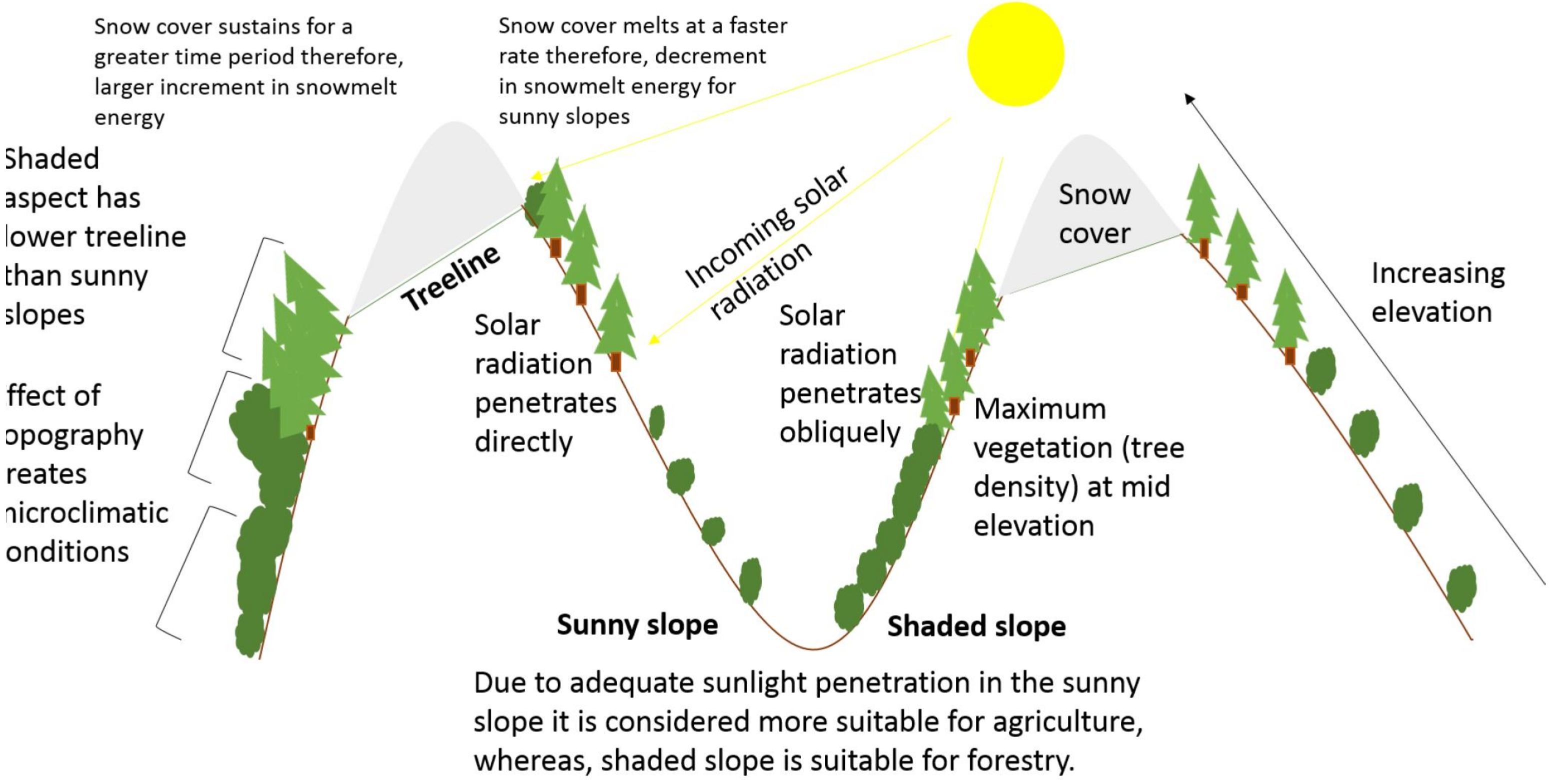
Outline

- Implement a parameterization (TOP) to represent the sub-grid topographic effects on solar radiation in ELM
- Impacts of snow grain shape and mixing state of light-absorbing particles on snow and surface fluxes over the Tibetan Plateau in ELM

Topographic effects on land surface processes



Sunny vs shady slope



Singh 2018

Motivation

- All CMIP6 ESMs use a **plane-parallel (PP)** radiative transfer scheme for atmosphere/land exchange and do not account for the effects of surface topography.
- Evaluate the topographic effects on surface energy balance at different **spatio-temporal scales.**
- Evaluate the performance of the ELM with and without topographic improvements **using remote sensing data.**

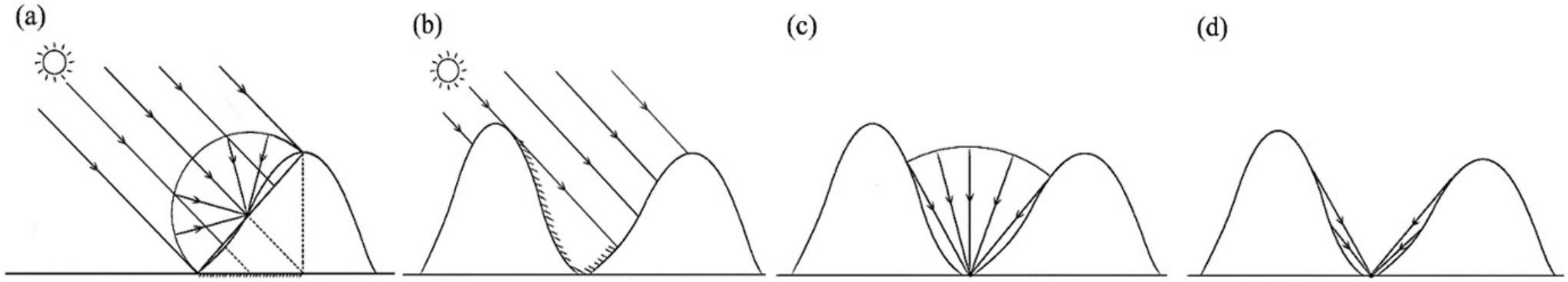
Topography affects solar radiation

a. Effects on direct radiation due to the change of solar incident angle

b. Shadowing effects

c. Reduce the Diffuse sky radiation

d. Reflected radiation from adjacent terrain

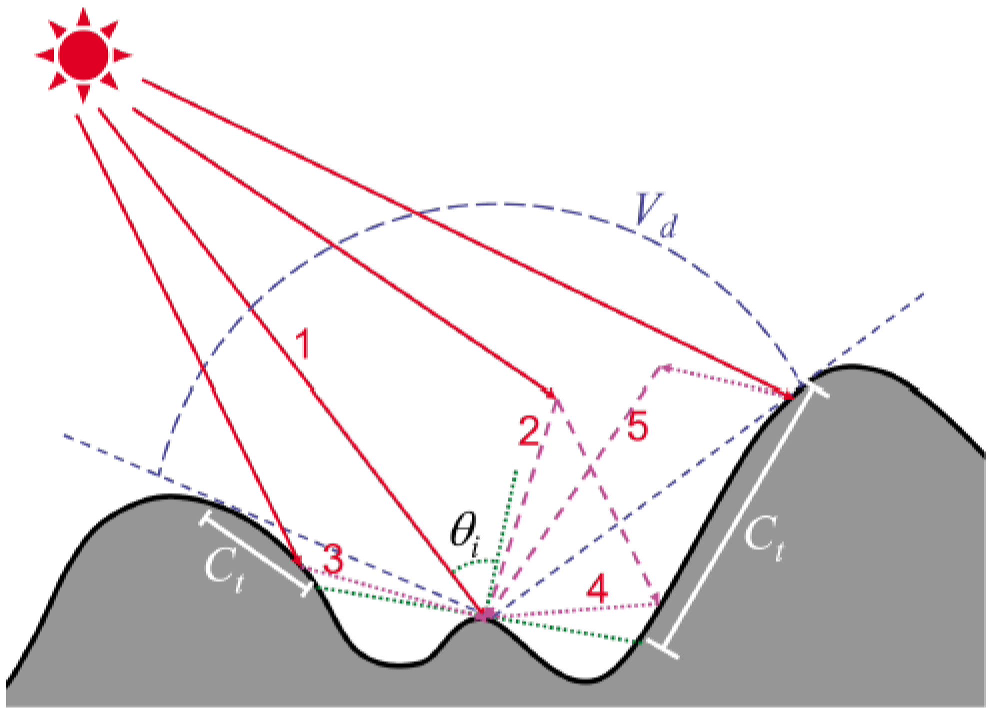


Yan et al., 2018

Included sub-grid topographic effects on solar radiation in ELM

Sub-grid parameterization (Lee et al, 2011)

- DEM (90m)-derived area-averaged topographic information
- 3-D Monte Carlo photon tracing simulations
- Multiple Linear Regression



Lee et al., 2011 in JGR: Atmosphere

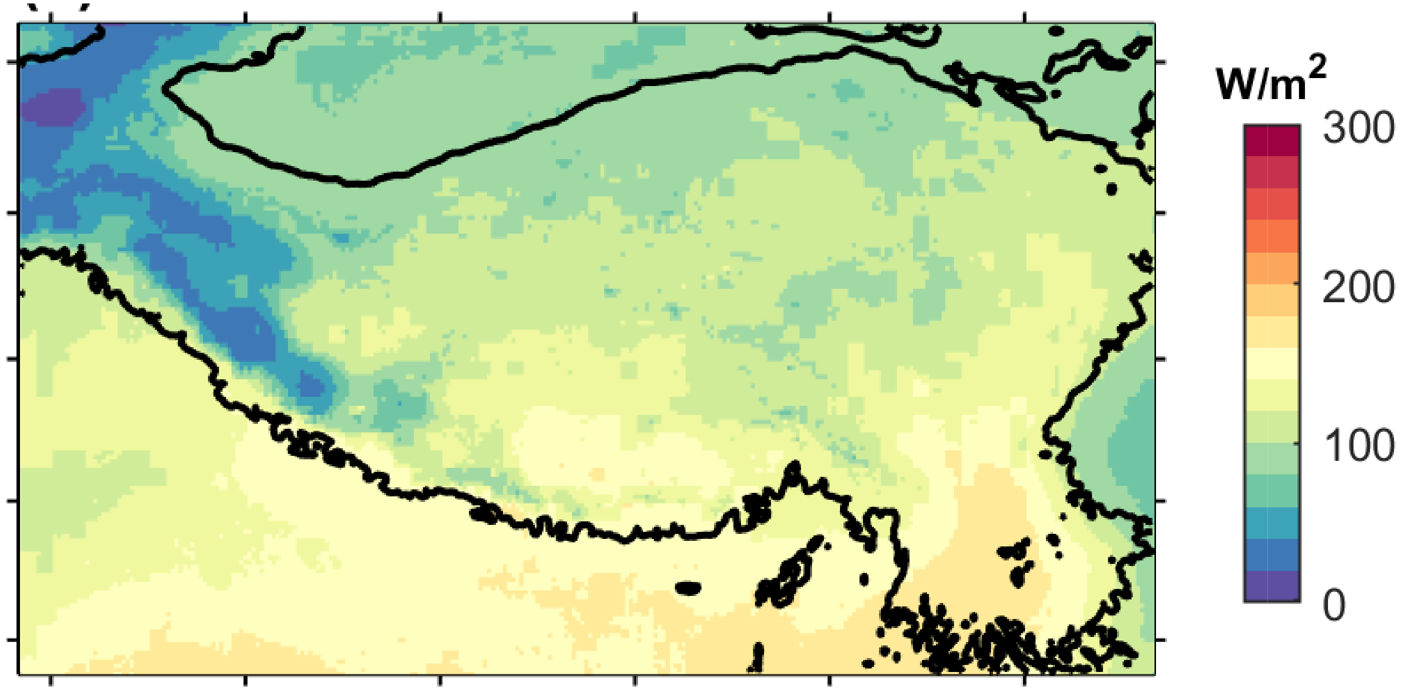
1. Direct
2. Diffuse
3. Direct-reflected
4. Diffuse-reflected
5. Coupled

$$\begin{pmatrix} F'_{\mathrm{dir}} \\ F'_{\mathrm{dif}} \\ F'_{\mathrm{rdir}} \\ F'_{\mathrm{rdif}} \\ F'_{\mathrm{coup}} \end{pmatrix} = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{pmatrix} + \begin{pmatrix} b_{11} & b_{12} & 0 & 0 \\ b_{21} & b_{22} & 0 & b_{24} \\ 0 & b_{32} & b_{33} & 0 \\ 0 & b_{42} & b_{43} & 0 \\ b_{51} & b_{52} & b_{53} & 0 \end{pmatrix} \begin{pmatrix} \langle \tilde{\mu}_i \rangle \\ \langle \tilde{V}_d \rangle \\ \langle \tilde{C}_t \rangle \\ \sigma(h) \end{pmatrix}$$

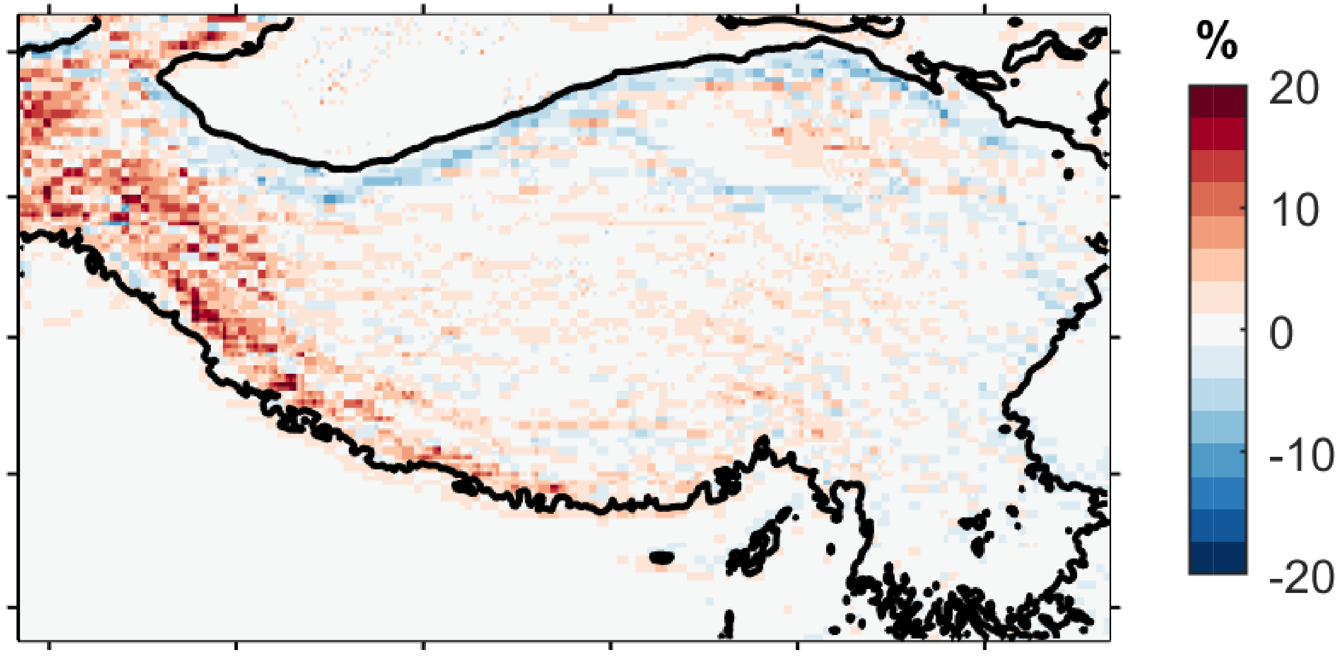
Solar incident angle
Sky view factor
Terrain configuration factor
Std of elevation

Topography has significant effects on surface energy budget

PP

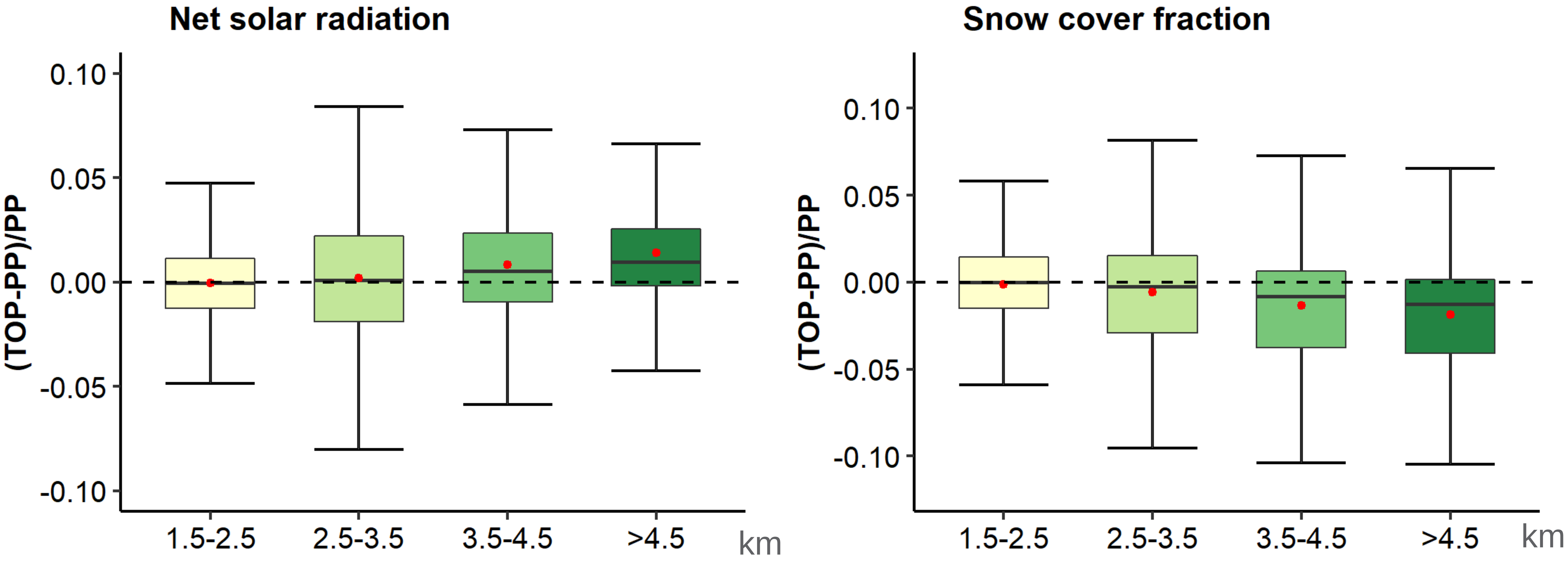


(TOP-PP)/PP



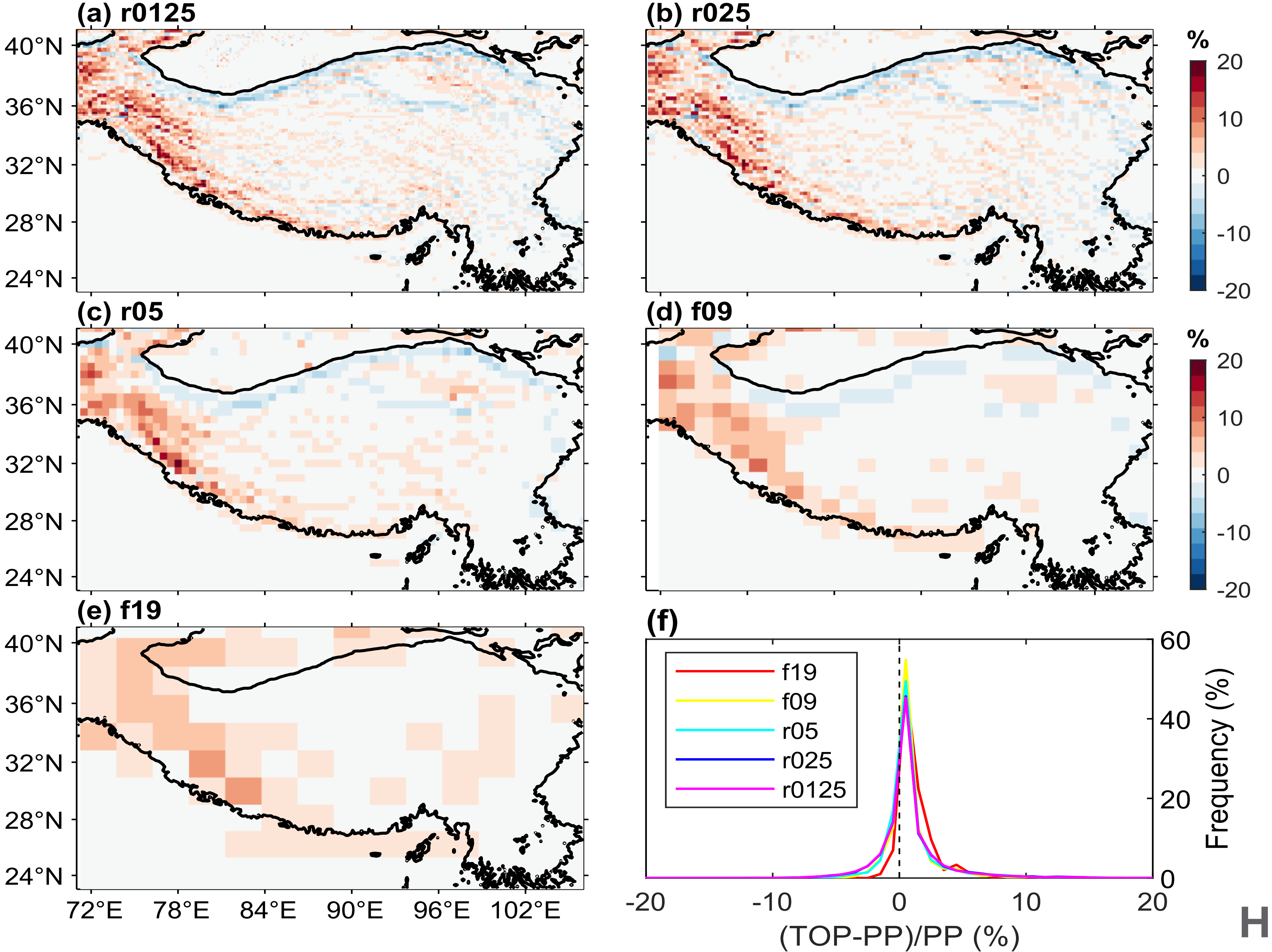
Net solar radiation in winter over the Tibetan Plateau (Hao et al., 2021)

Sub-grid topographic effects show elevation-dependent patterns in winter



Different elevation bands over the Tibetan Plateau (Hao et al., 2021)

The sub-grid topographic effects are sensitive to spatial scales



Hao et al., 2021

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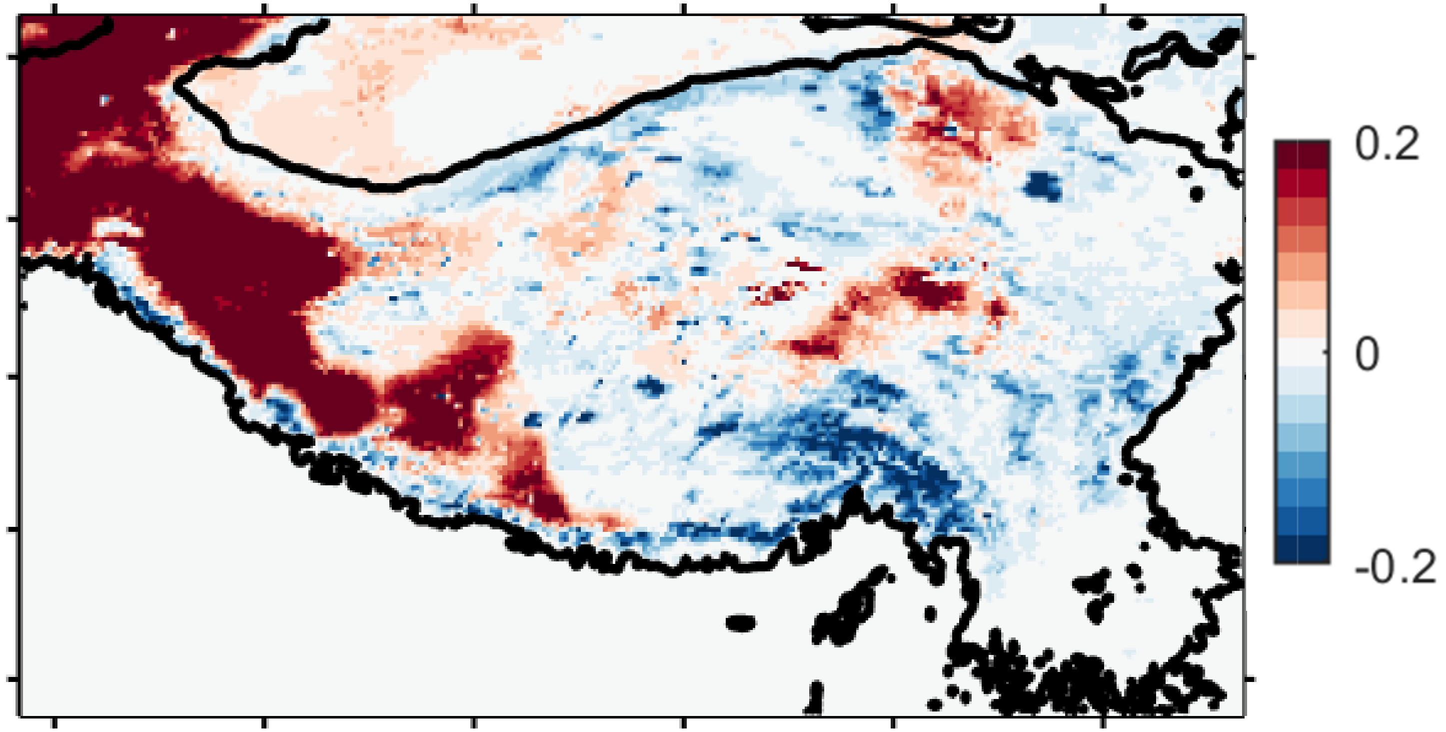
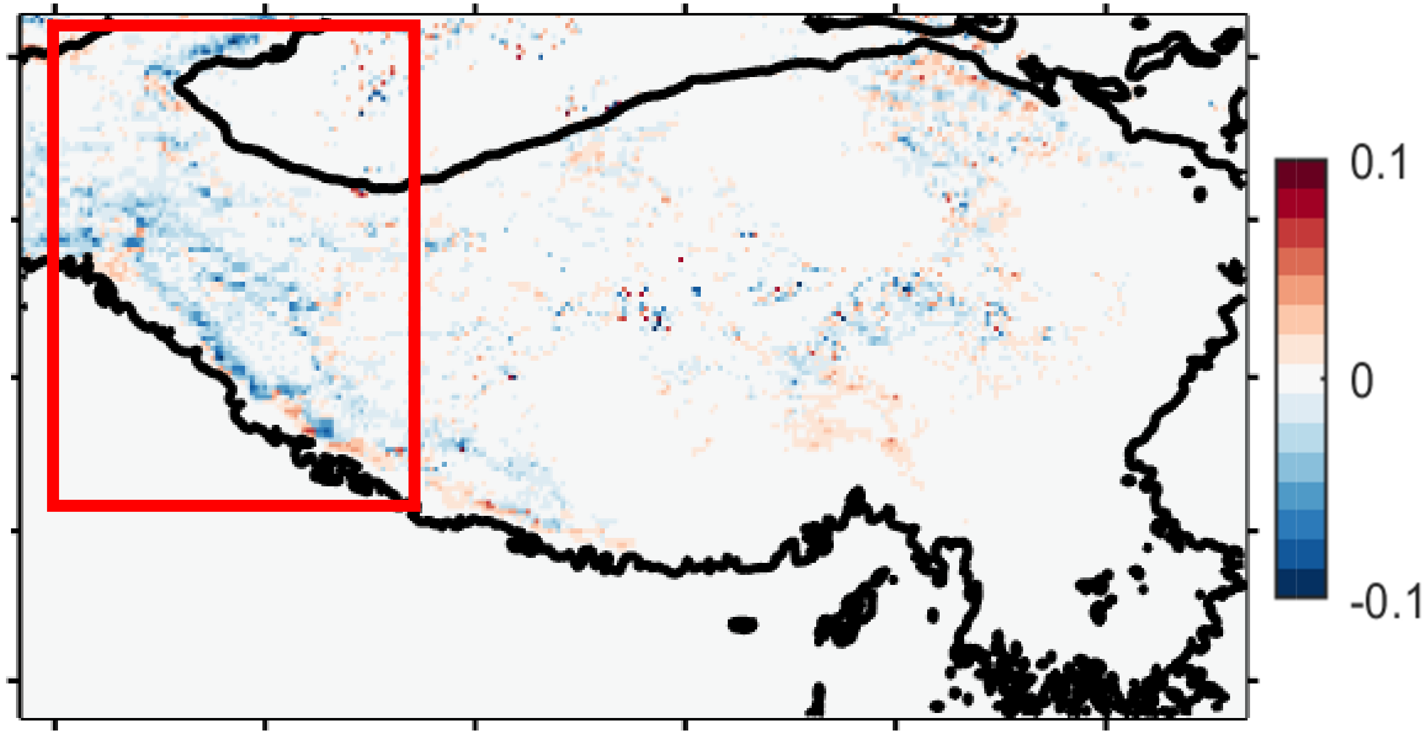
TOP shows better agreements with MODIS data in snow-covered regions in winter

Bias of PP (δ_{PP})



The change in the bias ($|\delta_{TOP}|-|\delta_{PP}|$)



Snow cover fraction over the Tibetan Plateau Hao et al., 2021

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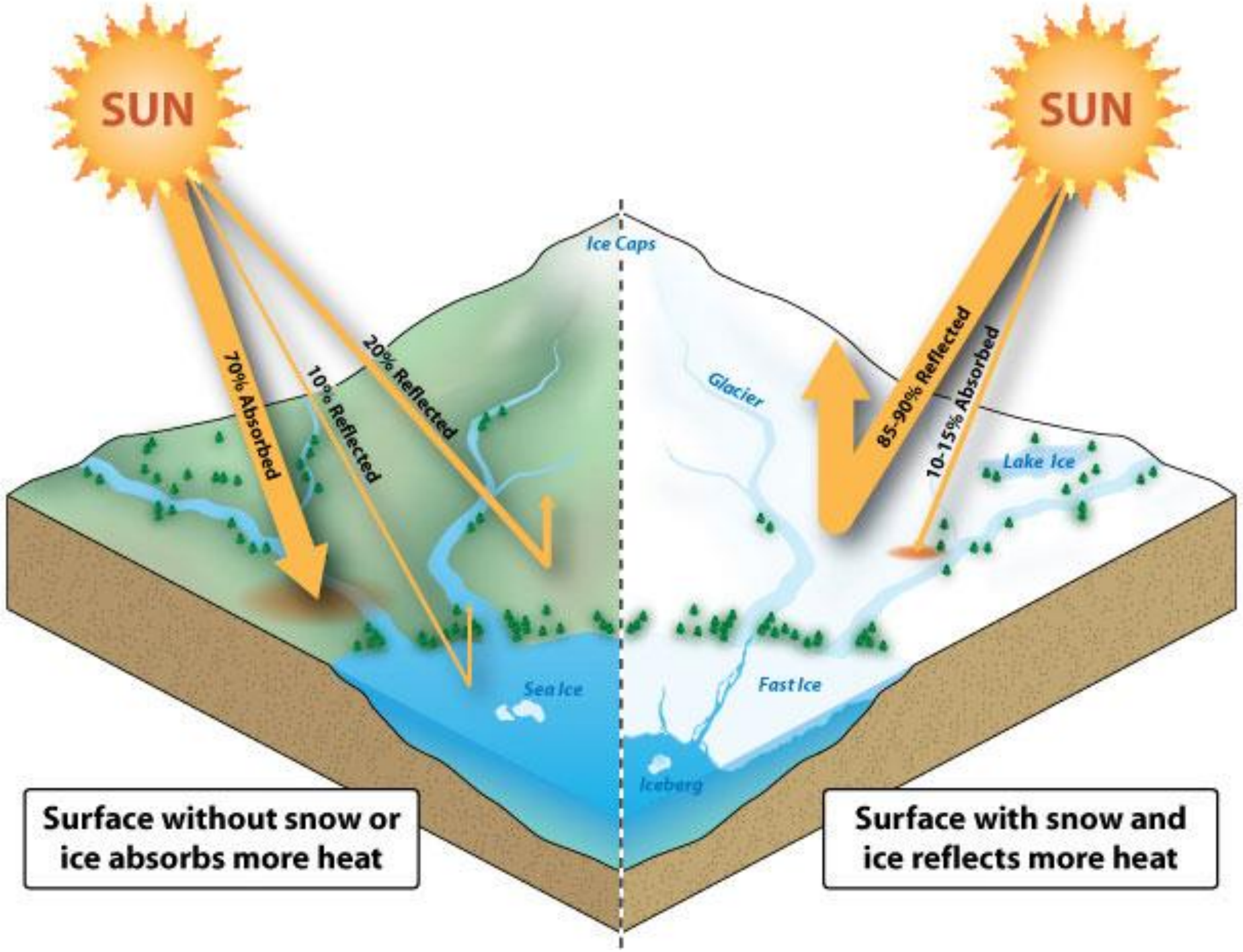
Outline

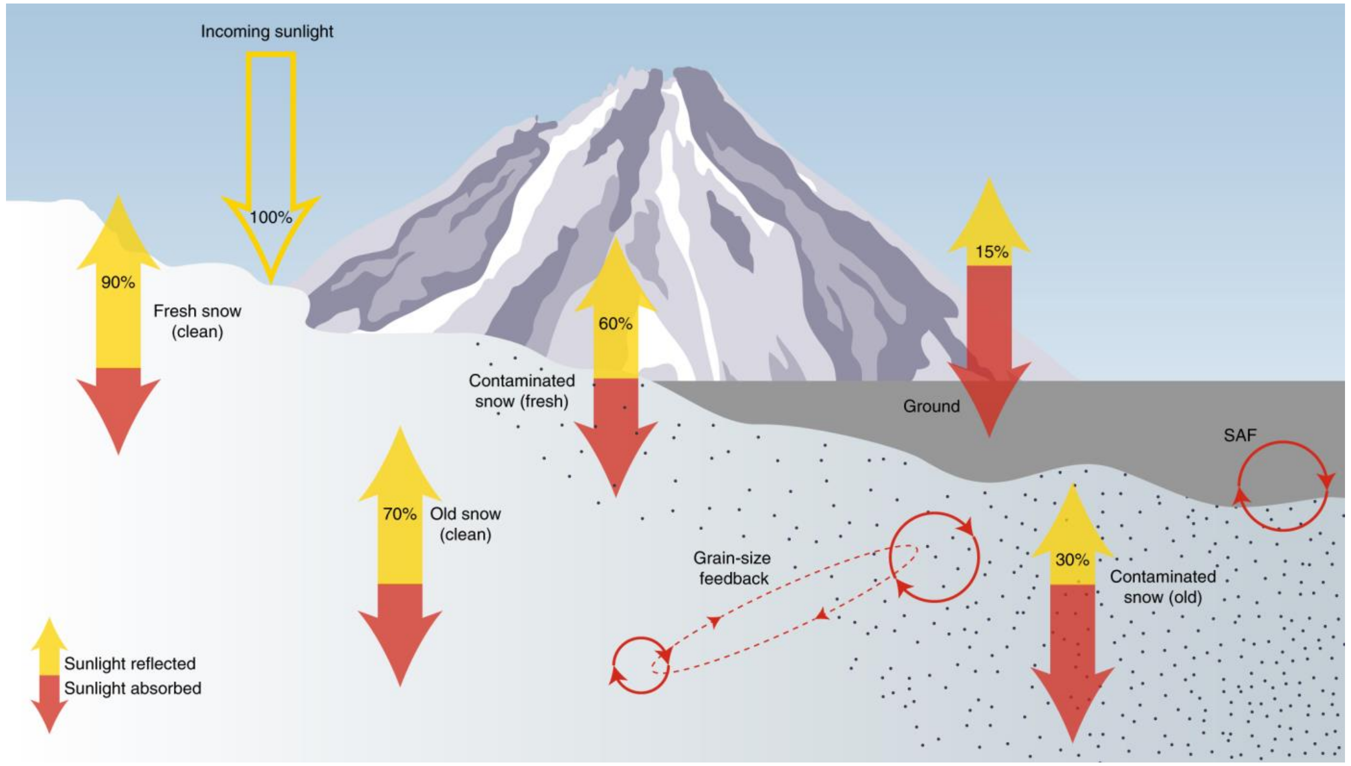
- **Implement a parameterization (TOP) to represent the sub-grid topographic effects on solar radiation in ELM**

- **Impacts of snow grain shape and mixing state of light-absorbing particles on snow and surface fluxes over the Tibetan Plateau in ELM**

Snow plays a vital role in Earth's surface energy and water cycles



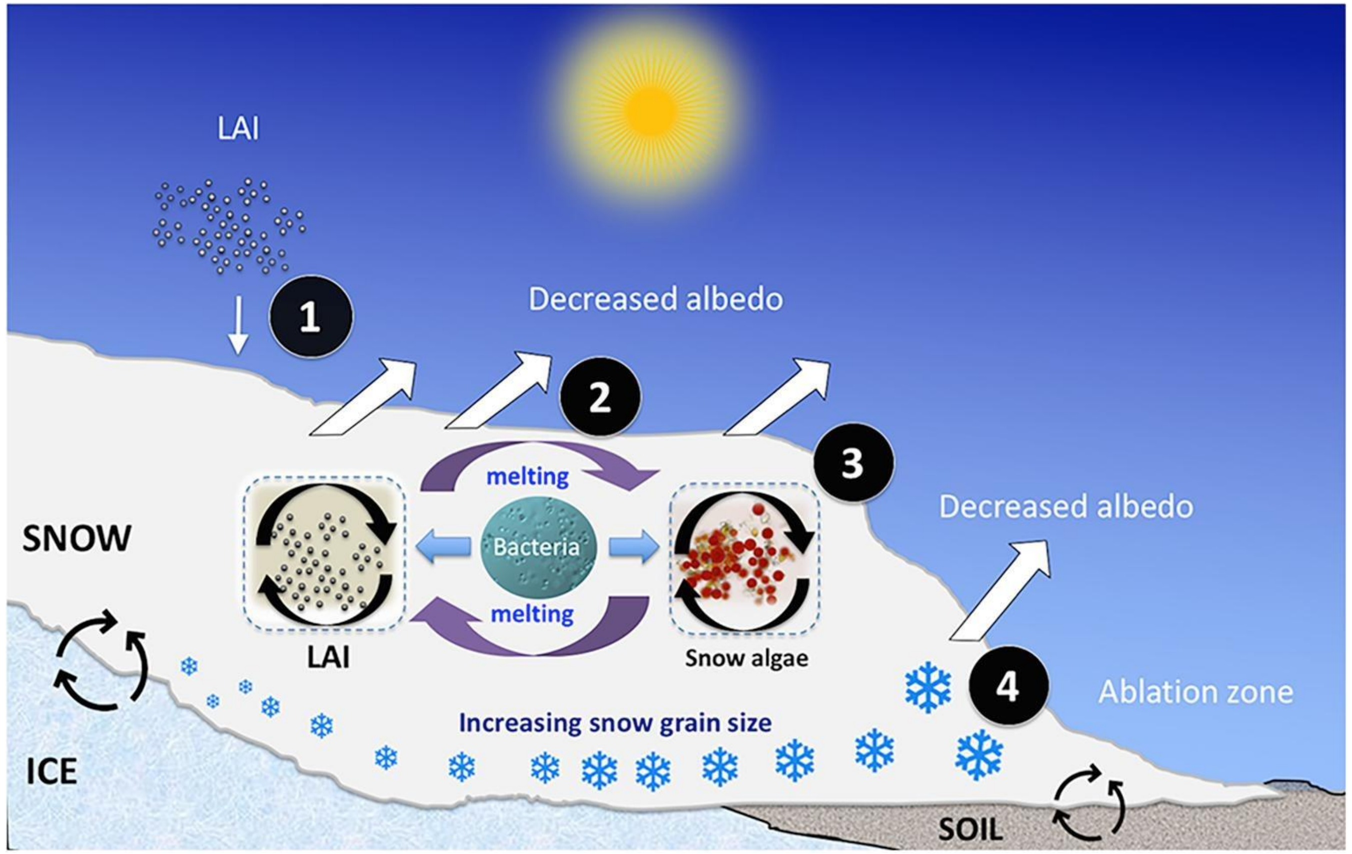
Credit: https://oceanbites.org



Skiles et al., 2018

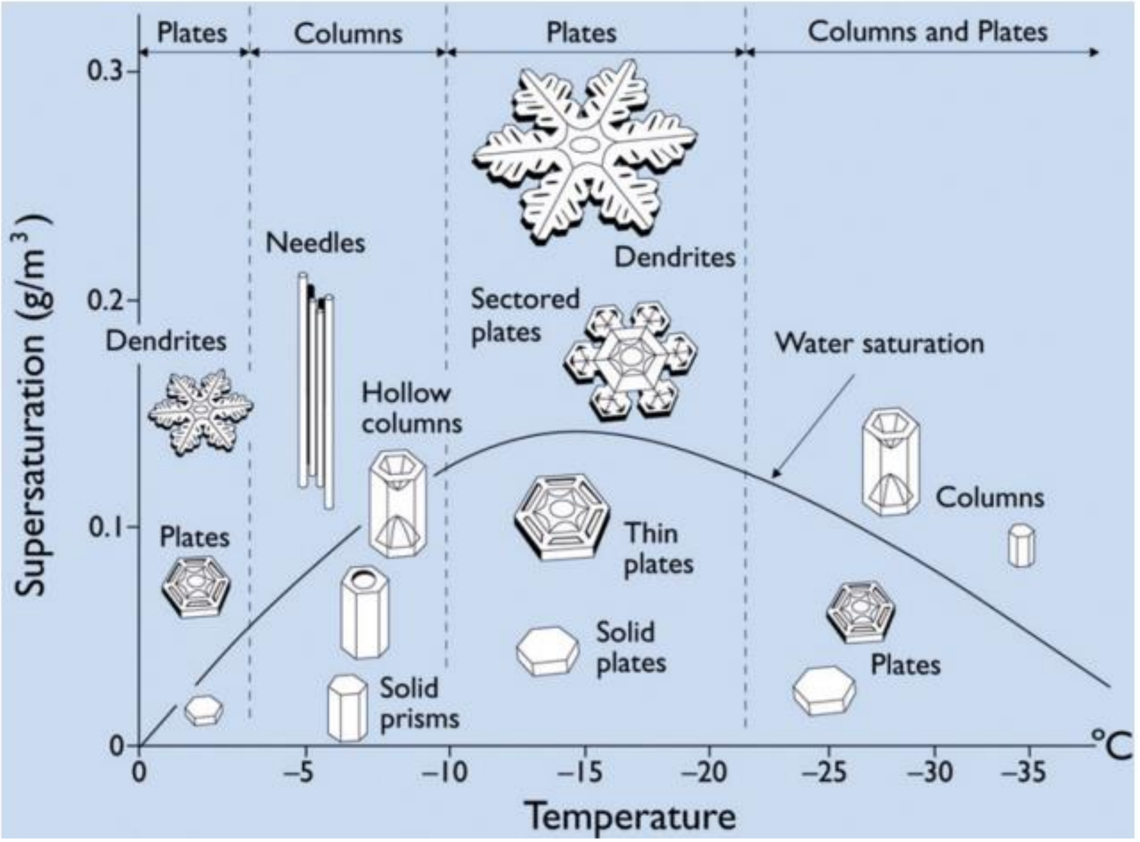
Snow albedo is affected by snow grain properties and light absorbing particles (LAPs)

Credit: www.worldatlas.com

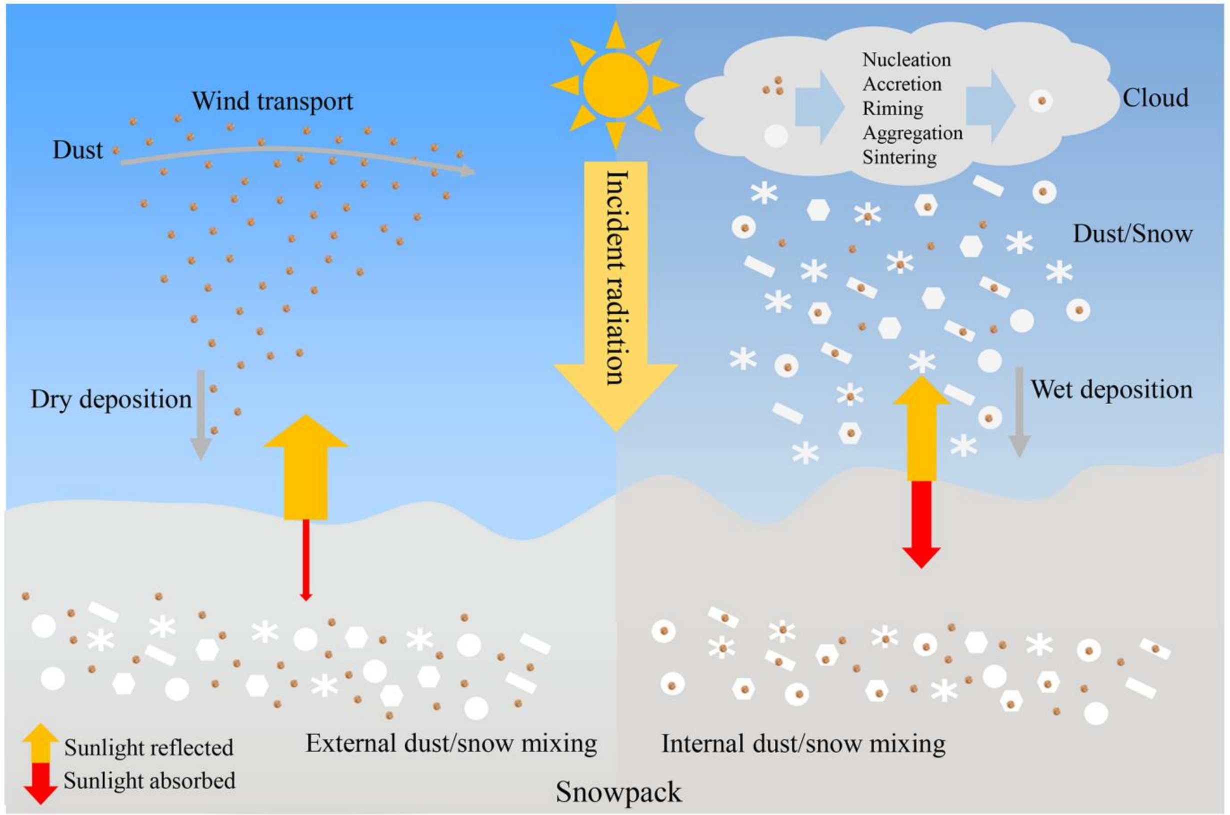


Huovinen et al., 2018

In reality, snow grain is usually irregular and non-spherical, and LAPs can be internally or externally mixed with snow.



Wiebe, 2011



Shi et al., 2021

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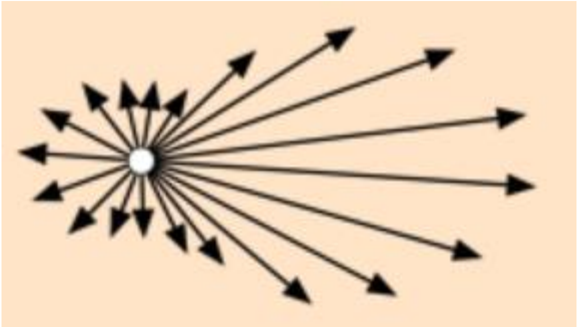
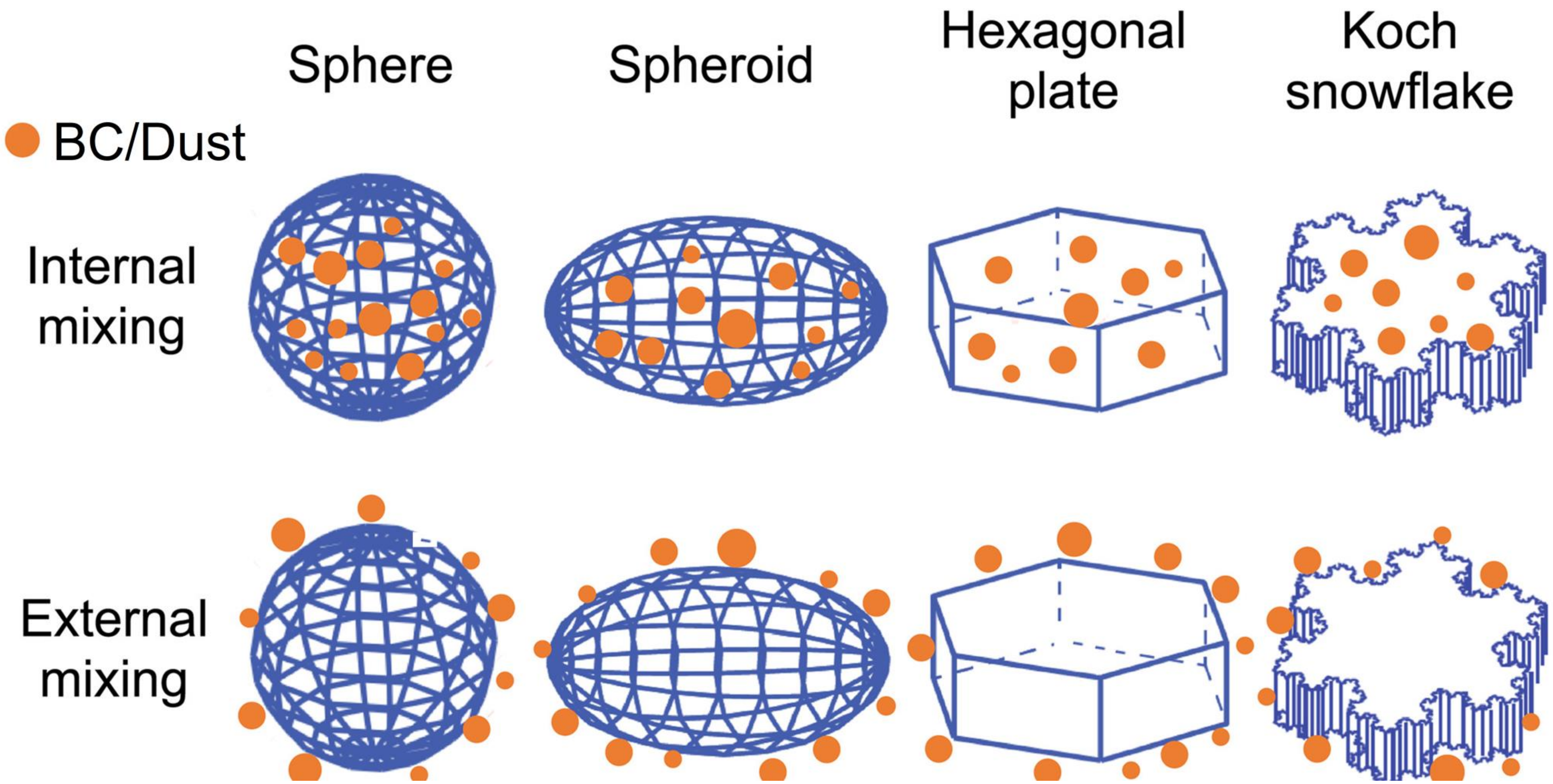
Motivation

- However, most land surface models assume that snow grain shape is **spherical** and LAPs are **externally mixed** with the snow grains.
- The sensitivity of **surface energy and water budgets** to snow grain shape and mixing state of LAPs in snow and the corresponding uncertainties remain underexplored.
- The interactions between snow albedo modeling and **sub-grid topographic effects** on solar radiation are still unknown.

Improving snow albedo modeling in ELM

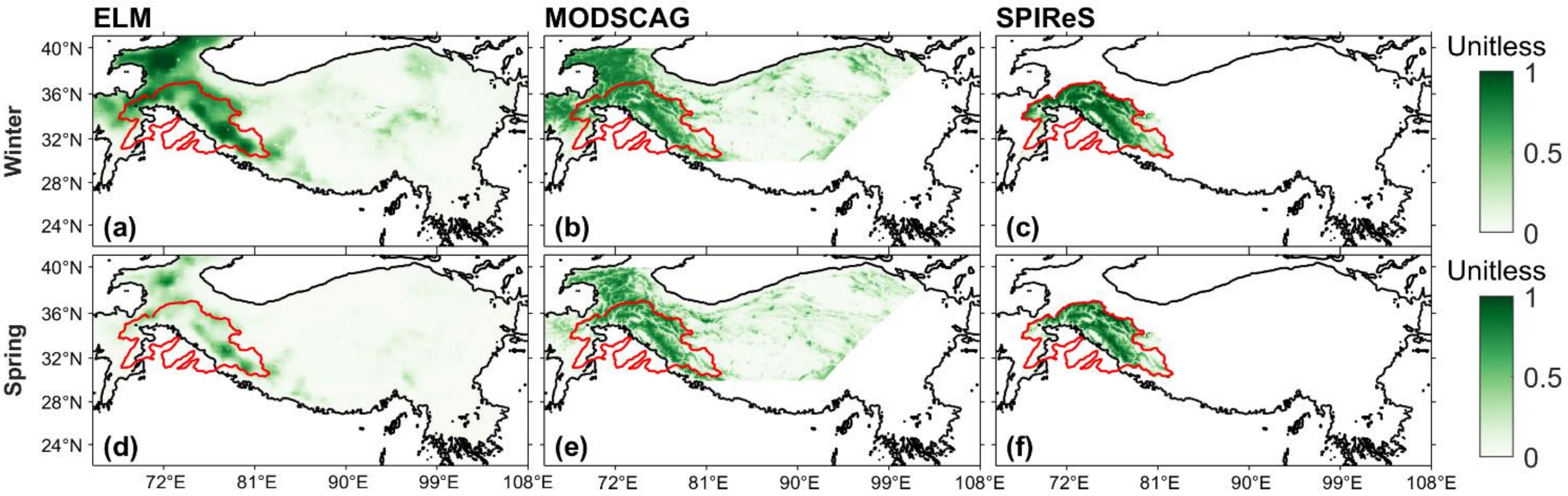


single-scattering albedo and asymmetry factor



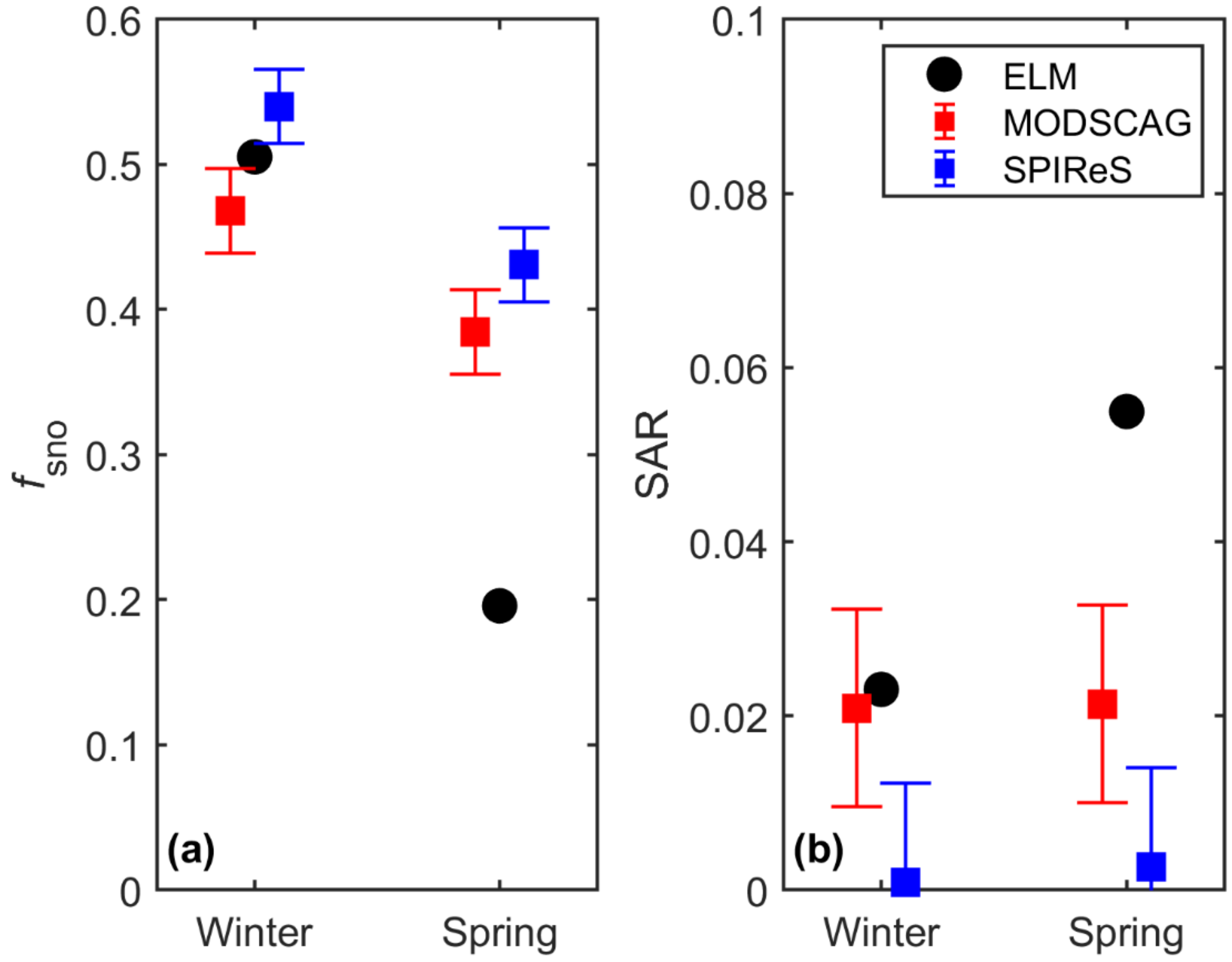
Hao et al., 2022

Snow cover fraction in the control simulation shows good agreements with two MODIS products



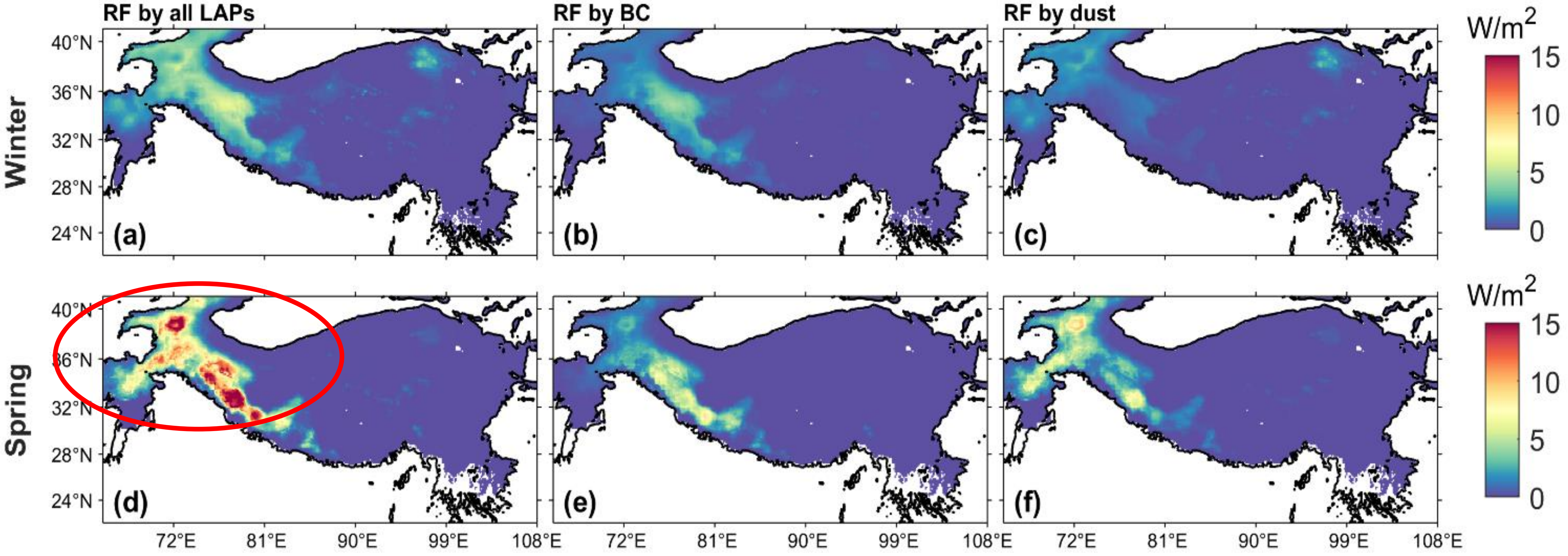
Hao et al., 2022

ELM vs MODIS in snow cover fraction and snow albedo reduction



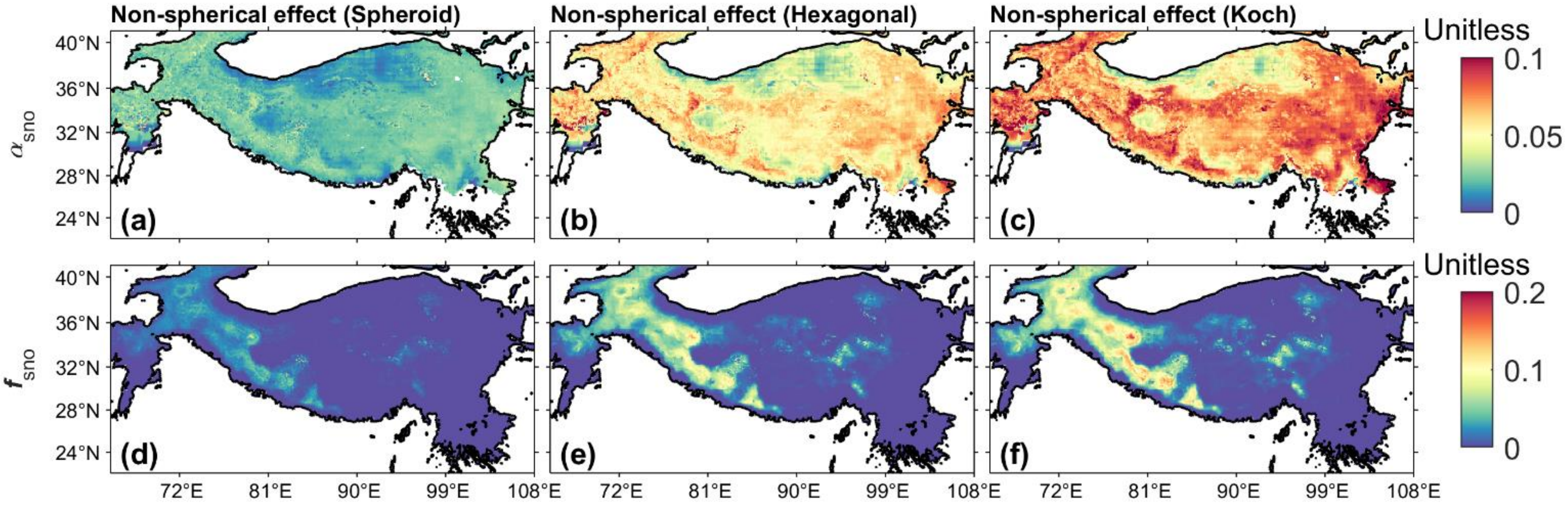
Hao et al., 2022

Radiative forcing induced by LAPs in snow



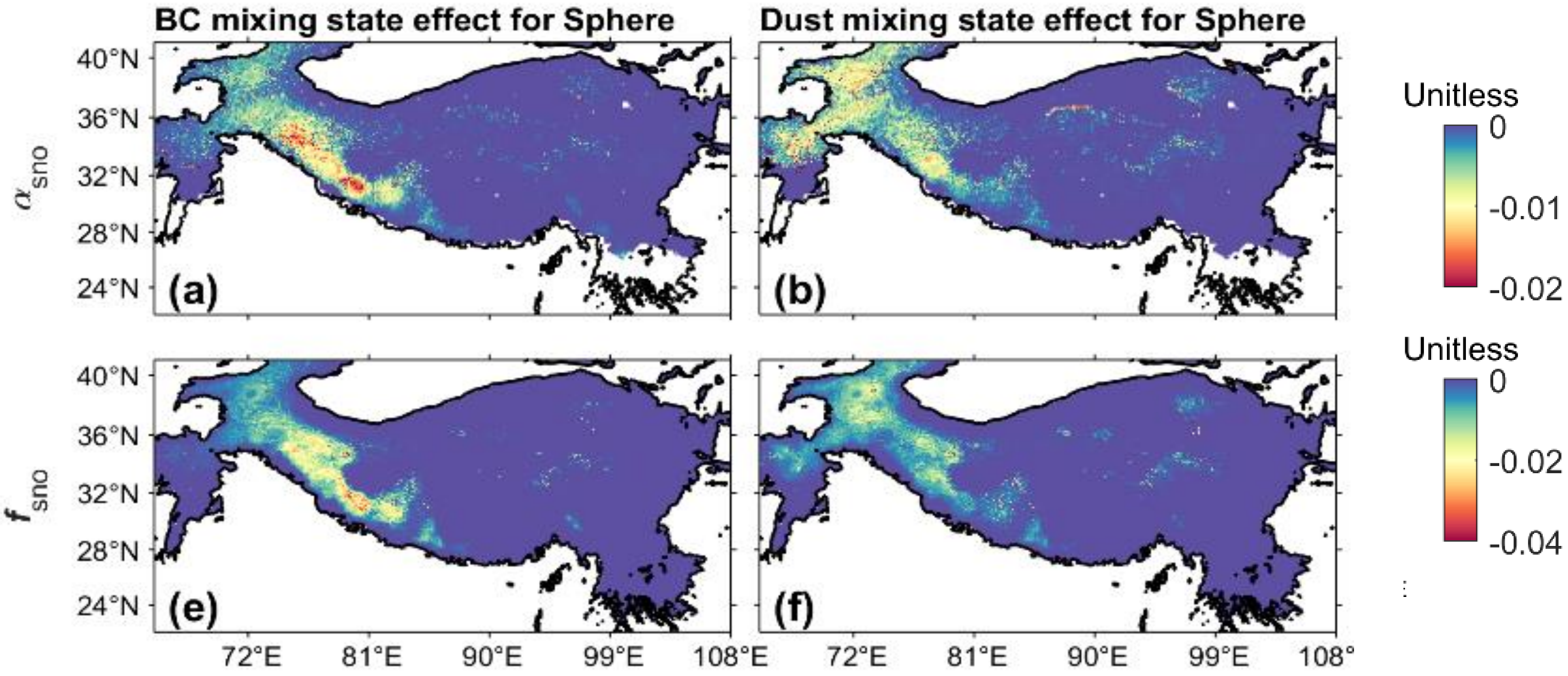
Hao et al., 2022

Impacts of snow grain shape



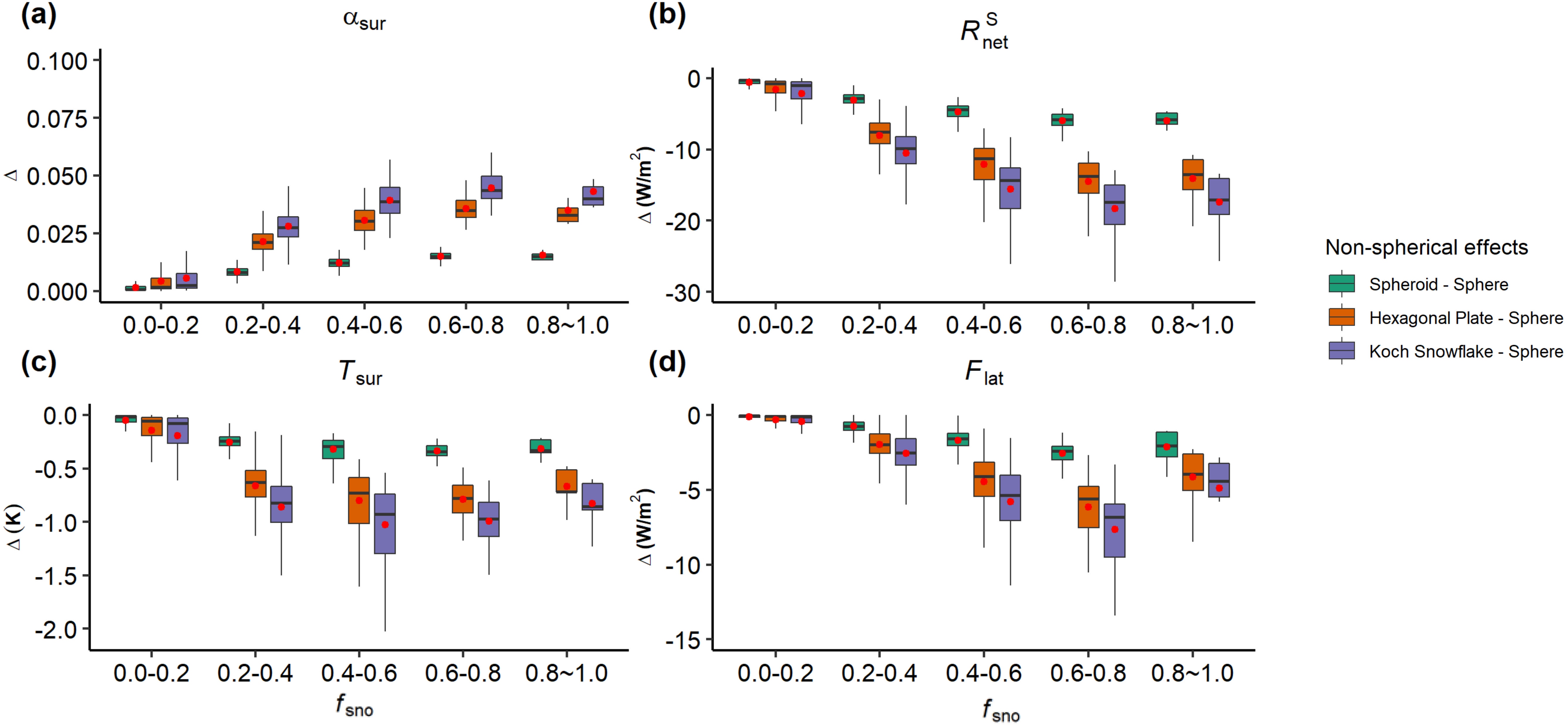
Hao et al., 2022

Impacts of mixing states of LAPs in snow



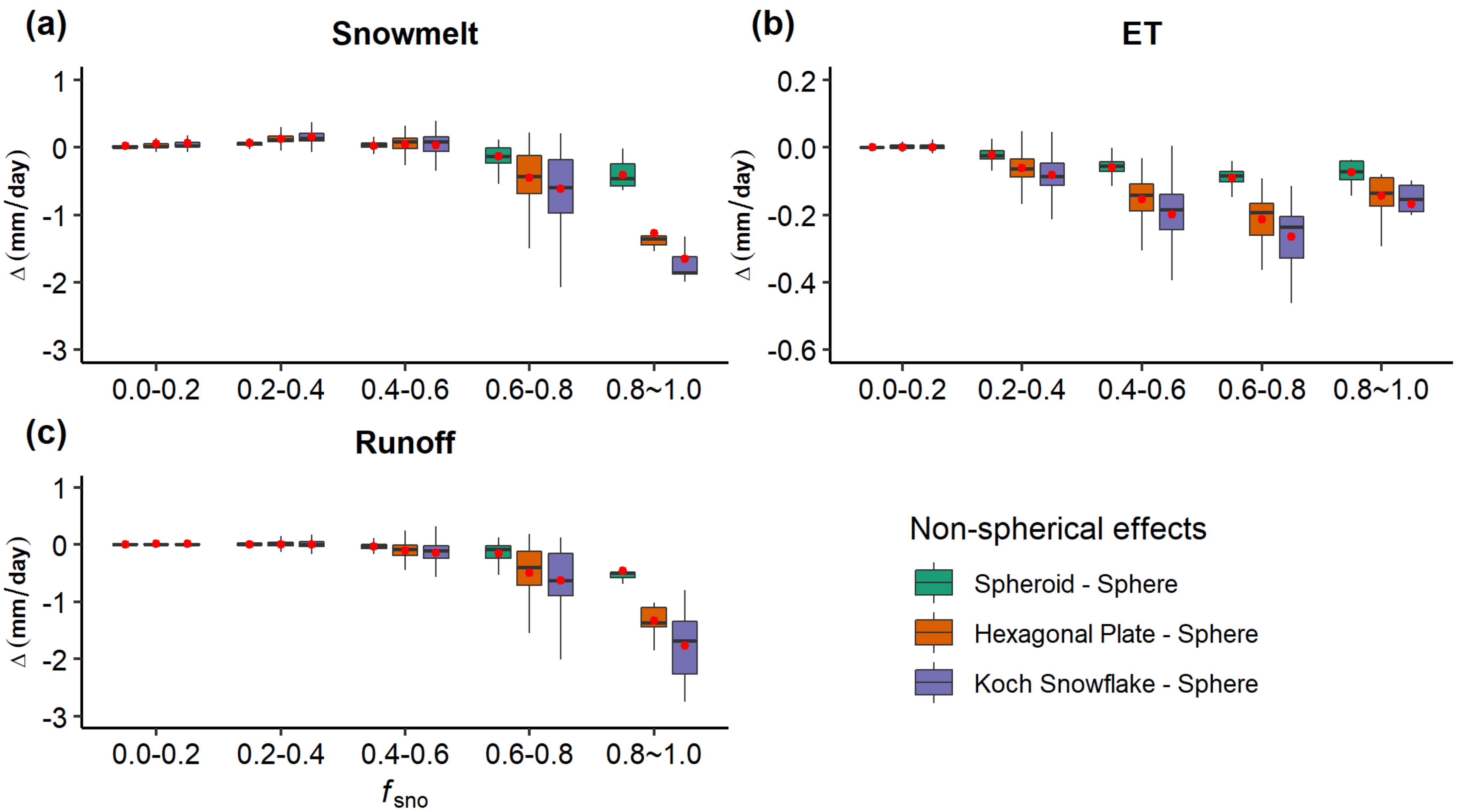
Hao et al., 2022

Large influences on surface energy balance



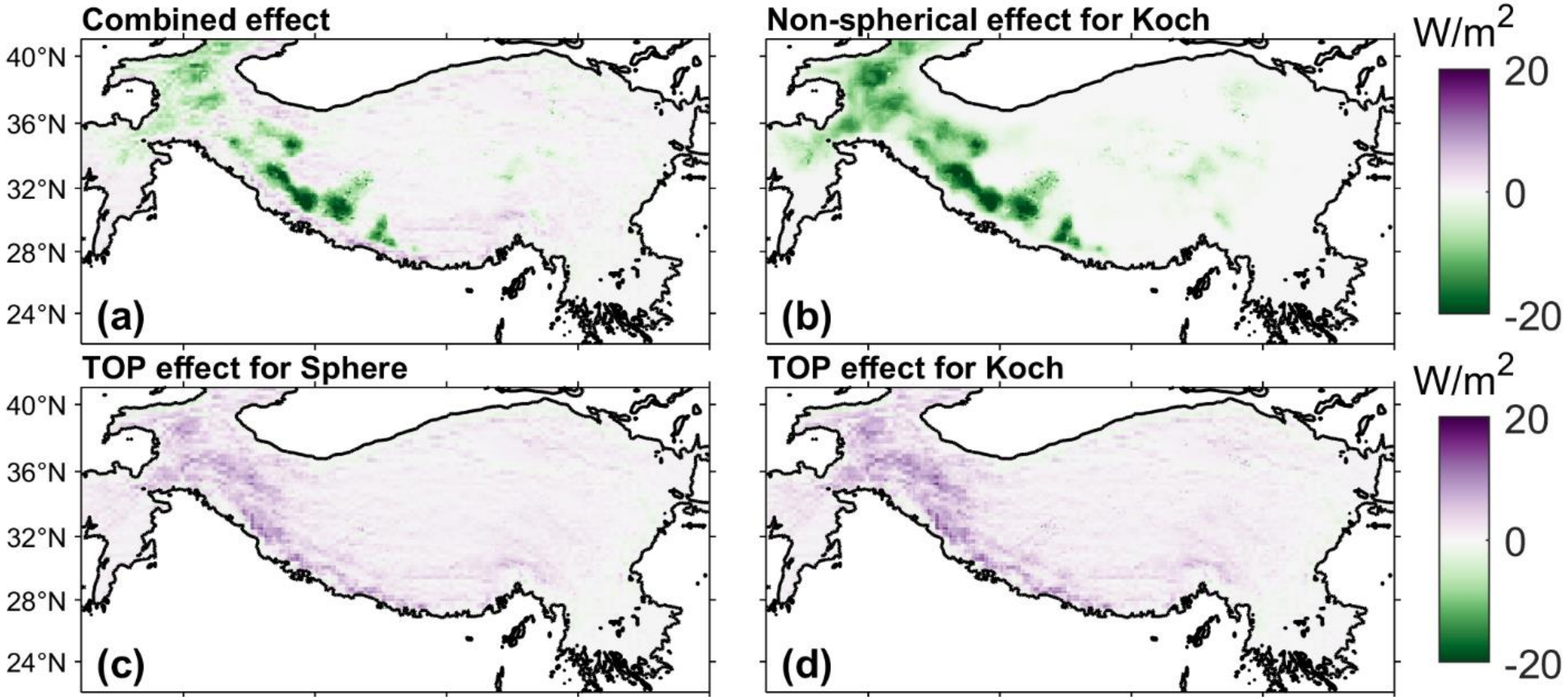
Hao et al., 2022

Large influences on water cycle



Hao et al., 2022

The individual contributions of non-spherical snow shape, mixing state of LAP-snow, and local topography have different signs and magnitudes



Net solar radiation (**Hao et al., 2022**)

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Take-home message

1. Implement a **sub-grid topographic (TOP) parameterization** in ELM to quantify the effects of sub-grid topography on solar radiation flux:
    - Topography can modify **surface energy budget and snow process**.
    - Sub-grid topographic effects are sensitive to **seasons, elevations, and spatial scales**.
    - TOP has better agreements with MODIS data.

2. Improve the snow radiative transfer model in ELM by considering **non-spherical snow grain shapes** and **internal mixing of dust-snow:**
    - **Koch snowflake** shape shows the largest difference from spherical shape.
    - Compared to external mixing, **internal mixing** of LAP-snow can lead to larger snow albedo reduction and snowmelt
    - The **combined effects** of non-spherical snow shape, mixing state of LAP-snow, and local topography can be positive or negetive.

Next Step

- Extend the experiments **from TP to Globe**
- Investigate the climate effects of TOP and LAPs in snow via **land-atmosphere coupling**
- Investigate the impacts of **snow algae** on snow and surface fluxes

Credit: https://en.wikipedia.org/wiki/Watermelon_snow

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Publications

- Hao, Dalei, Gautam Bisht, Yu Gu, Wei-Liang Lee, Kuo-Nan Liou, and L. Ruby Leung. "**A parameterization of sub-grid topographical effects on solar radiation in the E3SM Land Model (version 1.0): implementation and evaluation over the Tibetan Plateau**." *Geoscientific Model Development* 14, no. 10 (2021): 6273-6289.
- Hao, Dalei, Gautam Bisht, Meng Huang, Po-Lun Ma, Teklu Tesfa, Wei-Liang Lee, Yu Gu, and L. Ruby Leung. "**Impacts of Sub-Grid Topographic Representations on Surface Energy Balance and Boundary Conditions in the E3SM Land Model: A Case Study in Sierra Nevada**." *Journal of Advances in Modeling Earth Systems* 14, no. 4 (2022): e2021MS002862.
- Hao, Dalei, Gautam Bisht, Cenlin He, Edward Bair, Huilin Huang, Cheng Dang, Karl Rittger et al. "**Improving snow albedo modeling in E3SM land model (version 2.0) and assessing its impacts on snow and surface fluxes over the Tibetan Plateau**." *Geoscientific Model Development Discussions* (2022): 1-31.

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Thank you