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Implementation and Evaluation of 3D radiative transfer parameterizations to represent topographic effects in the E3SM land model

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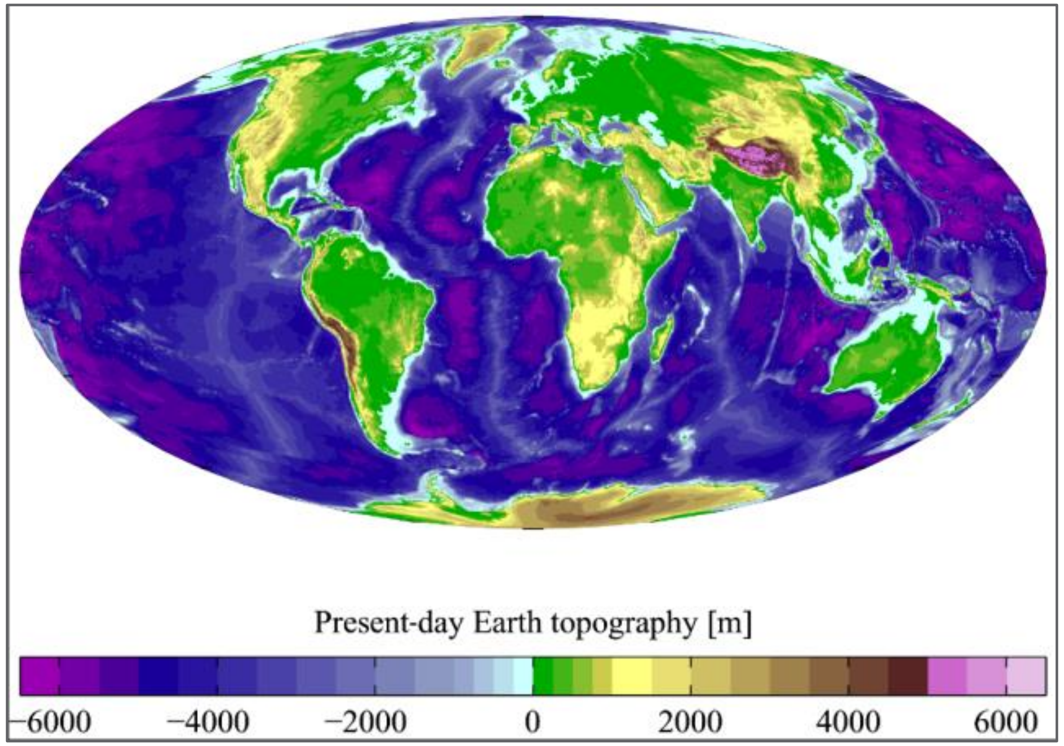
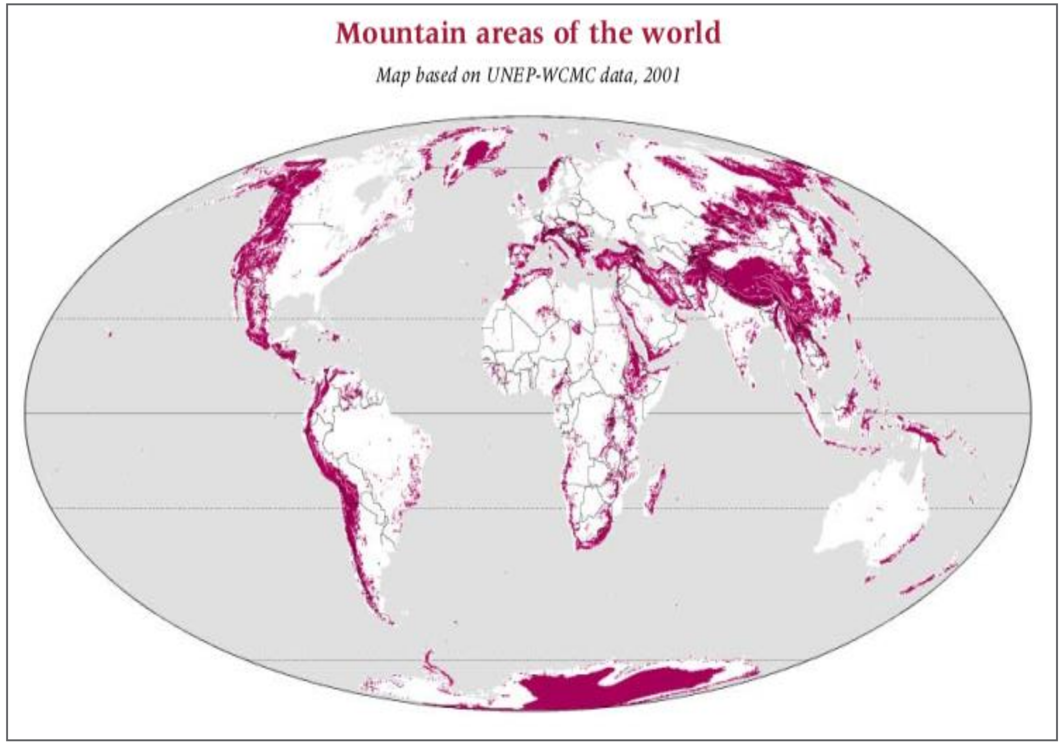
Background & Motivation

- **24%** of the Earth is mountainous.
- All the world's major rivers rise in mountain regions.
- Mountains provide 30 to 60 percent of the fresh water downstream. **(Payne K et al., 2002.)**





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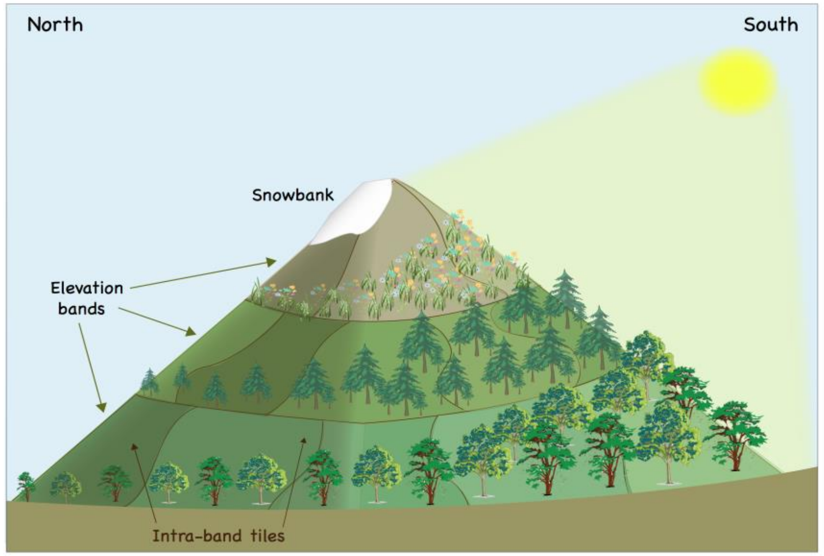
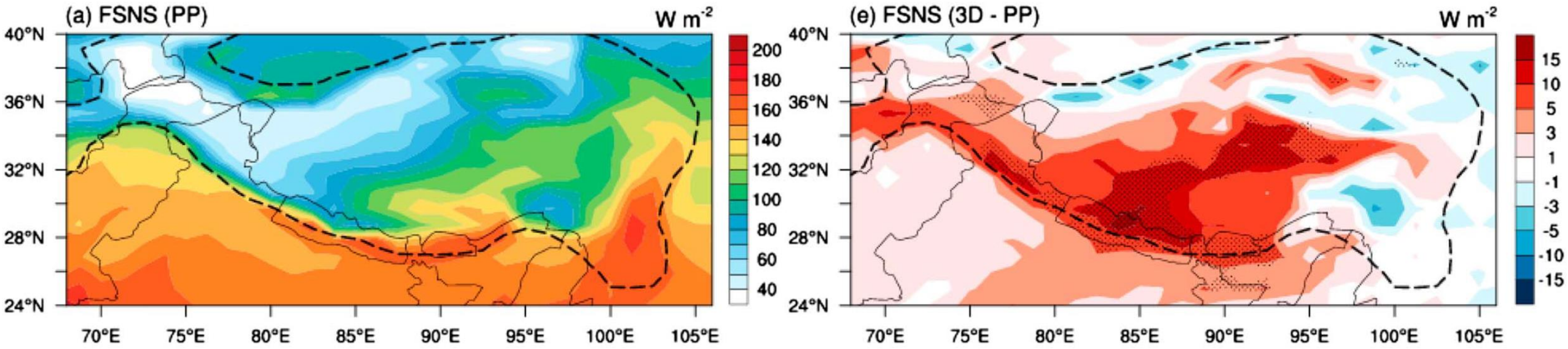
Background & Motivation

- Topographic effects on albedo, snowmelt
  - Updated sun incident geometry
  - Shadowing effects
  - Obstruction for sky diffuse radiations
  - Multi-scattering effects from adjacent terrain



Schematic diagram illustrating topographic effects.



Topography-induced surface net solar flux differences over the Tibetan Plateau (Lee et al., 2019).

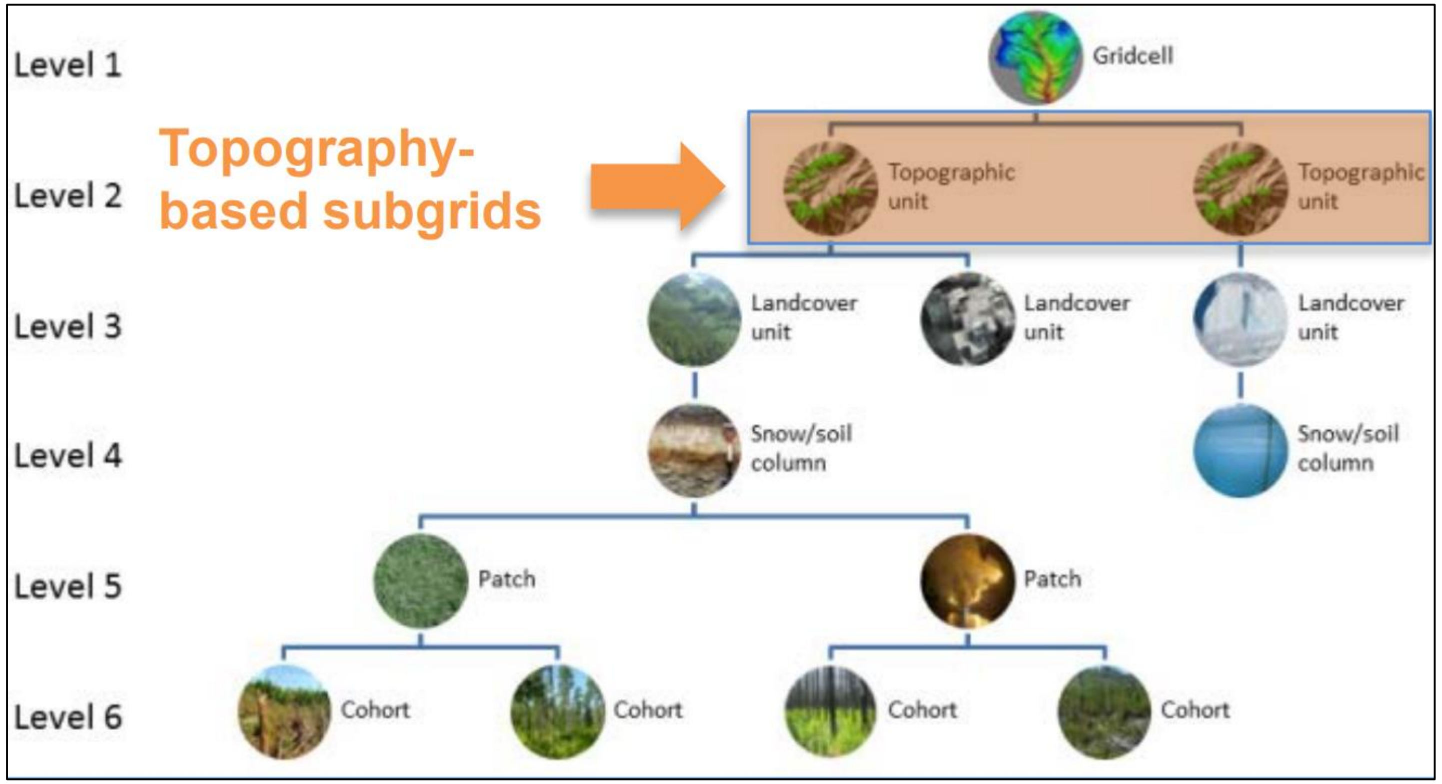
Background & Motivation

- 3D sub-grid parameterizations have been evaluated in stand-alone land, regional, and global atmospheric models.
- All CMIP6 ESMs use a plane-parallel (PP) radiative transfer schemes for atmosphere/land exchange and do not account for the effects of surface topography.

- **Objectives**
- Implement a 3D radiation transfer parameterization to represent the effects of topography, in the E3SM land model (ELM).
- 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.

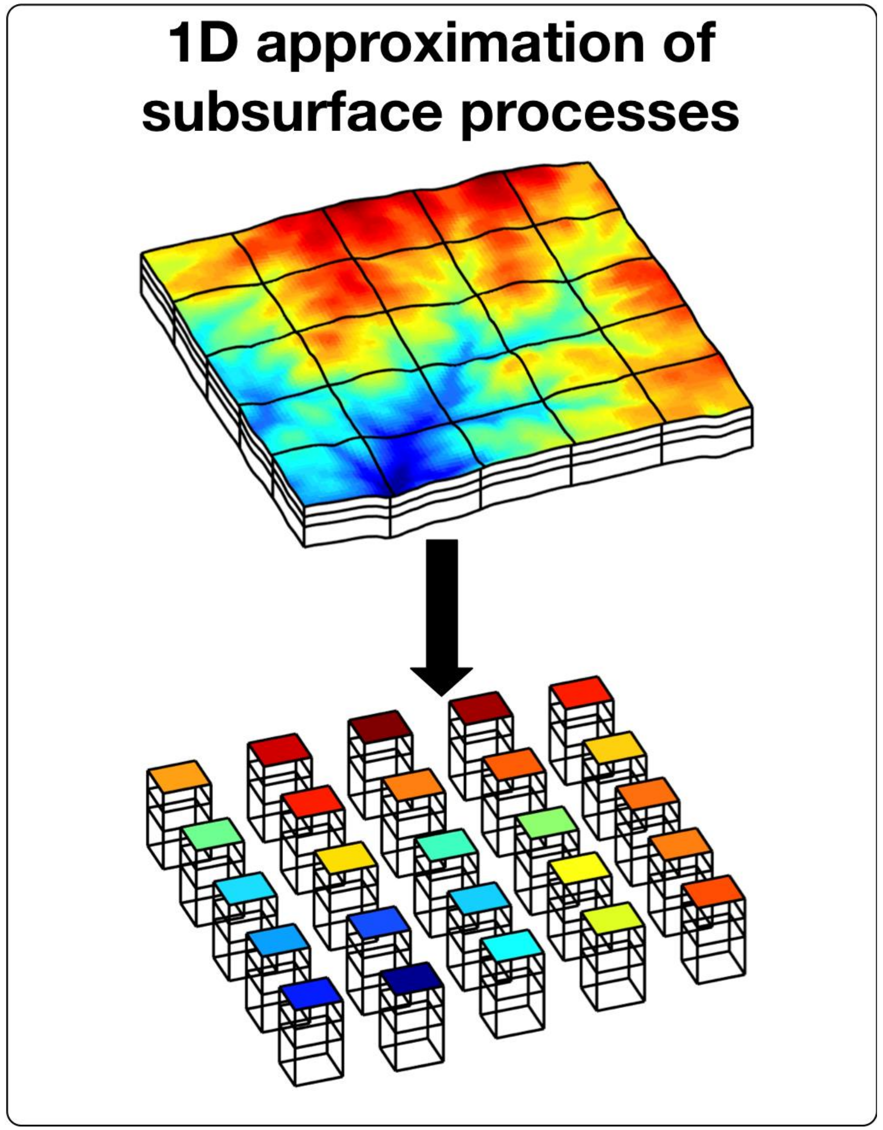
Methodology-Model Description

- Energy Exascale Earth System Model (E3SM)
- The E3SM land model (ELM)



Hierarchical sub-grid structure in ELM

Credit: Teklu et al., in E3SM PI meeting 2019

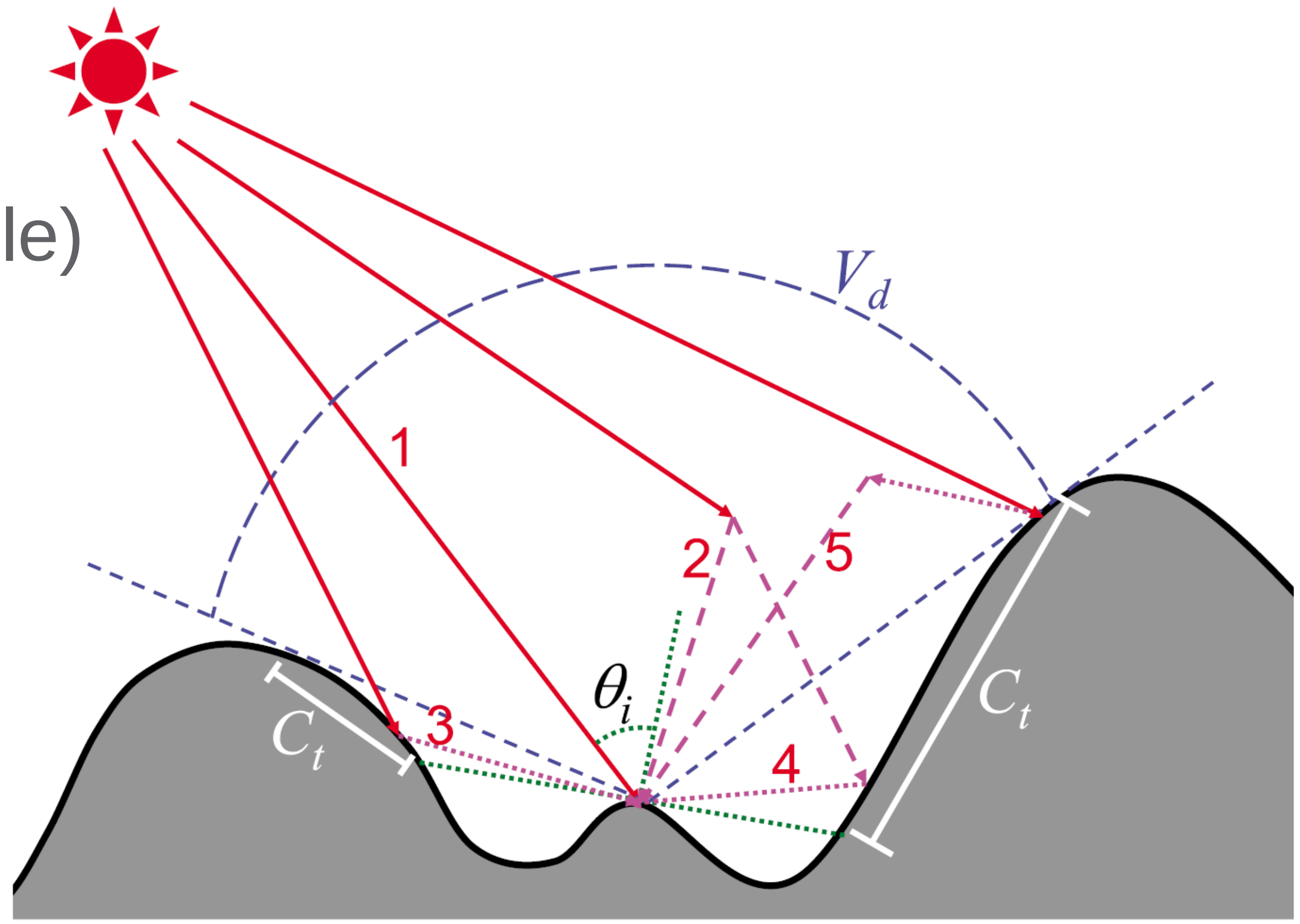


Sub-grid structure in E3SM

Methodology-Model Improvement

Updated radiation flux

1. Direct flux (changed solar incident angle)
2. Diffuse flux
3. Direct-reflected flux
4. Diffuse reflected
5. Coupled-flux



Lee et al, 2011 in JGR: Atmosphere

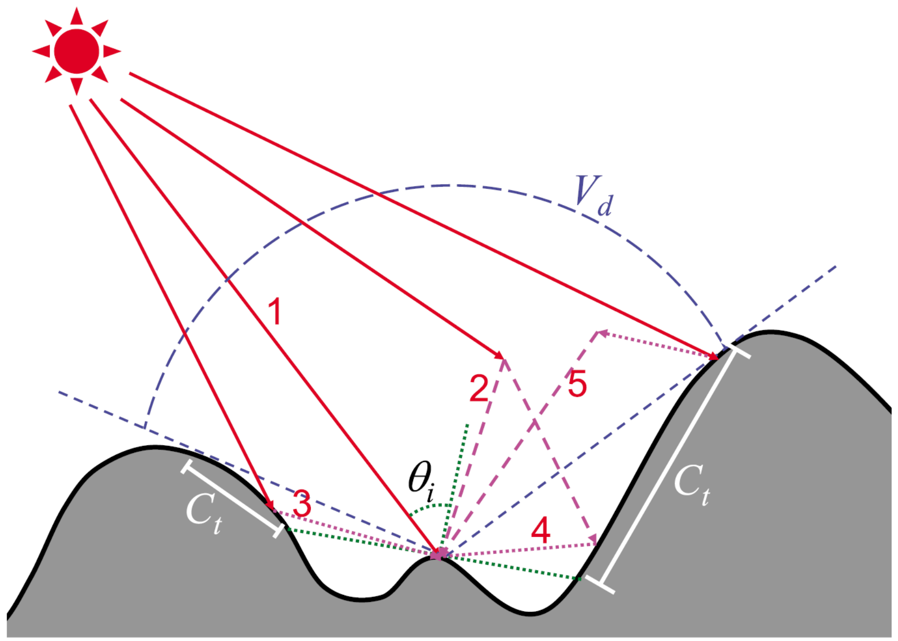
Requirements in ELM

- Considering the influence of arbitrarily fine resolved topography
- without degrading the model's computational performance.

Methodology-Model Improvement

Sub-grid parameterization (Lee et al, 2011)

- 3-D Monte Carlo photon tracing simulations
- Multiple Linear Regression
- DEM (90m)-derived area-averaged topographic information
  - Std of elevation
  - Solar incident angle
  - Sky view factor
  - Terrain configuration factor



Lee et al, 2011 in JGR: Atmosphere

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

Methodology-Experiment Design

- ELM with and without topographic effects (3D and PP) (Land only)
- Forcing data: CLMGSWP3v1
- 11 years run (2000-2010)
- Different spatial resolutions: r0125, r025, r05, f09, f19
- Study areas: **Tibetan Plateau**

- **Determine the variable importance using random forest models and analyze the topographic effects:**
  - Std of elevation
  - Solar incident angle (slope, aspect)
  - Sky view factor
  - Terrain configuration factor
  - Shortwave Albedo

Remote Sensing Data

Data

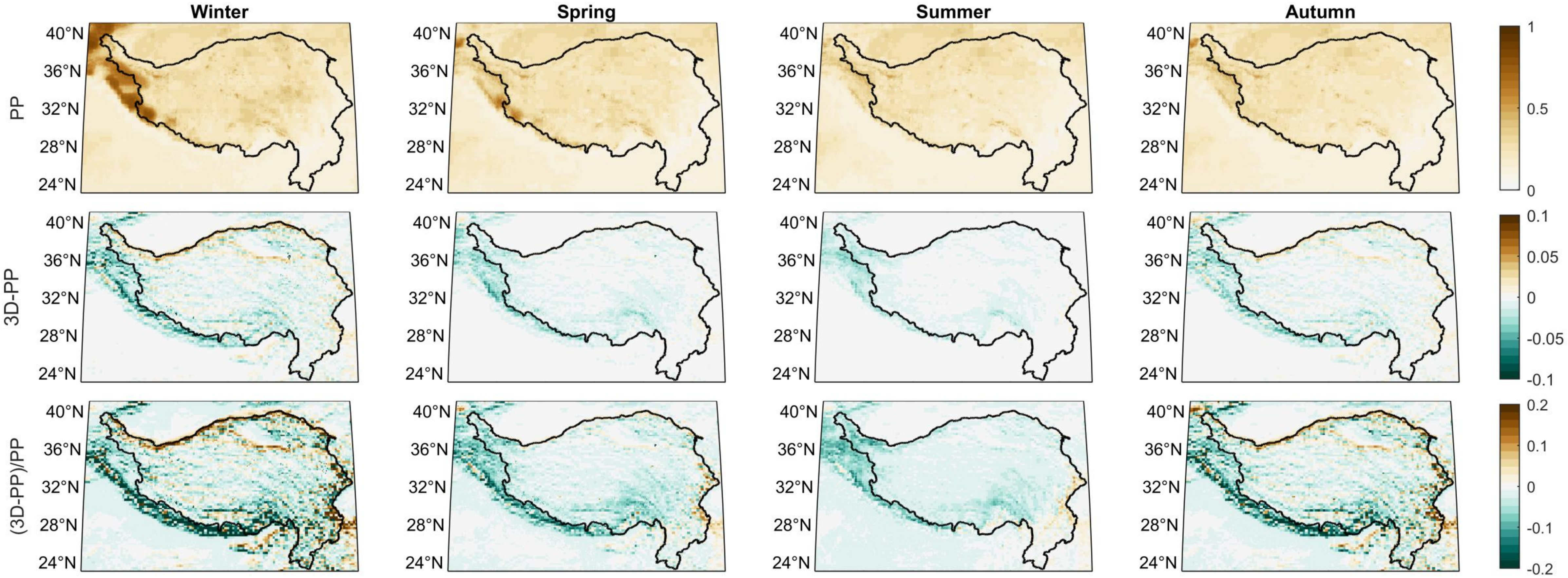
- MODIS albedo (MCD43A3, daily, 500m)
- MODIS surface temperature (MOD11A1, daily, 1km)
- MODIS snow cover (MOD10A1. daily, 800m)
- MODIS latent heat flux (MOD16A2, 8-day, 500m)

Preprocessing

- All data from 2000-2010 were downloaded from the Google Earth Engine (GEE) Platform
- Just used good-quality data (filtered by QA flags)
- Upscaled to grid resolution of r0125, r025, r05, f09 and f19 using area-averaged methods

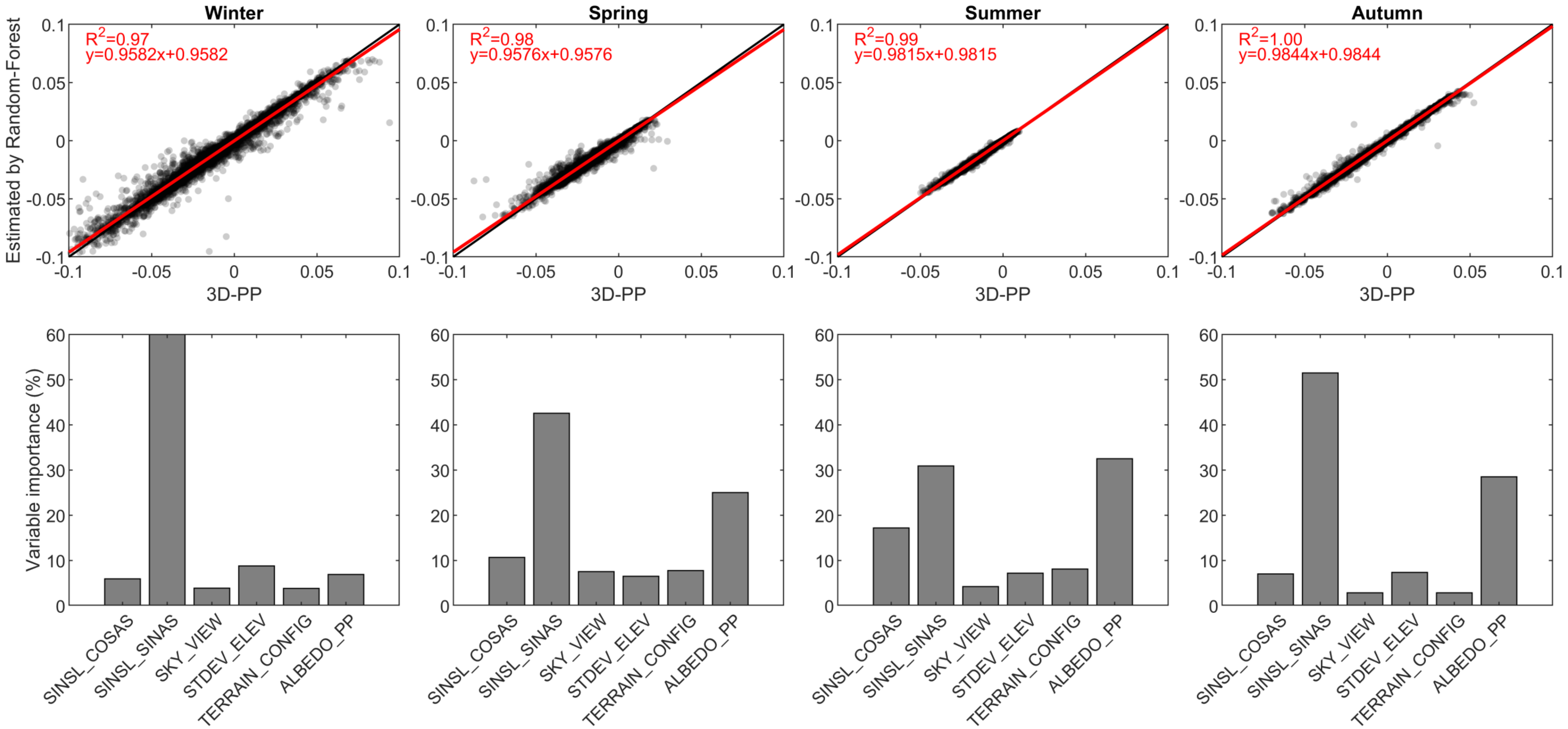
Topographic effects on surface energy balance

- The topography-induced albedo difference (3D-PP) can be larger than ±0.1 (relatively ± 20%) at 0.125 degree resolution.



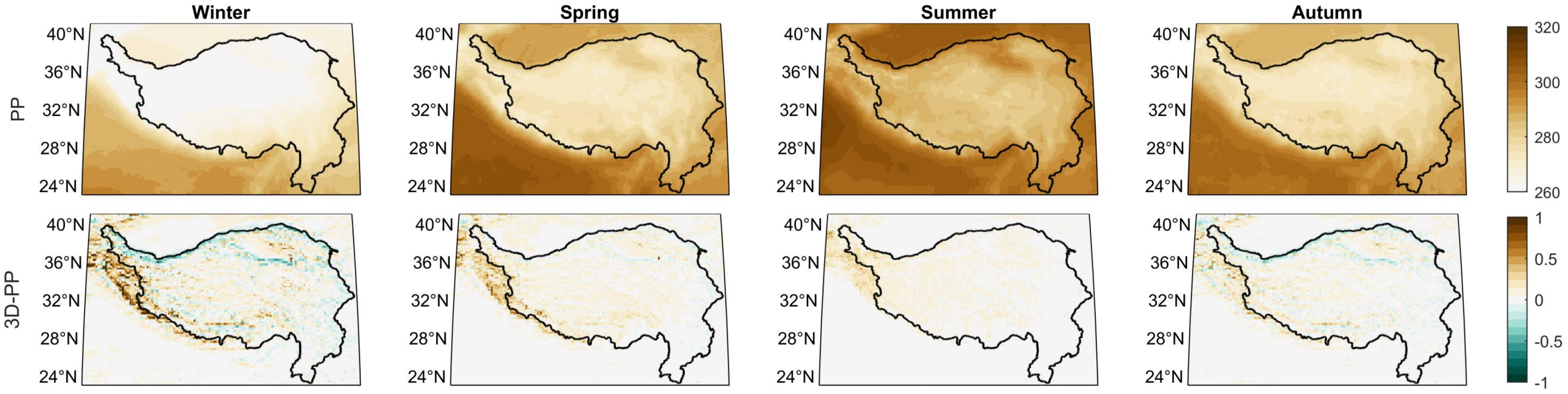
Topographic effects on surface energy balance

Both topographic features (slope, aspect, sky view factor) and albedo can affect the difference of 3D and PP, which is also related to different seasons.



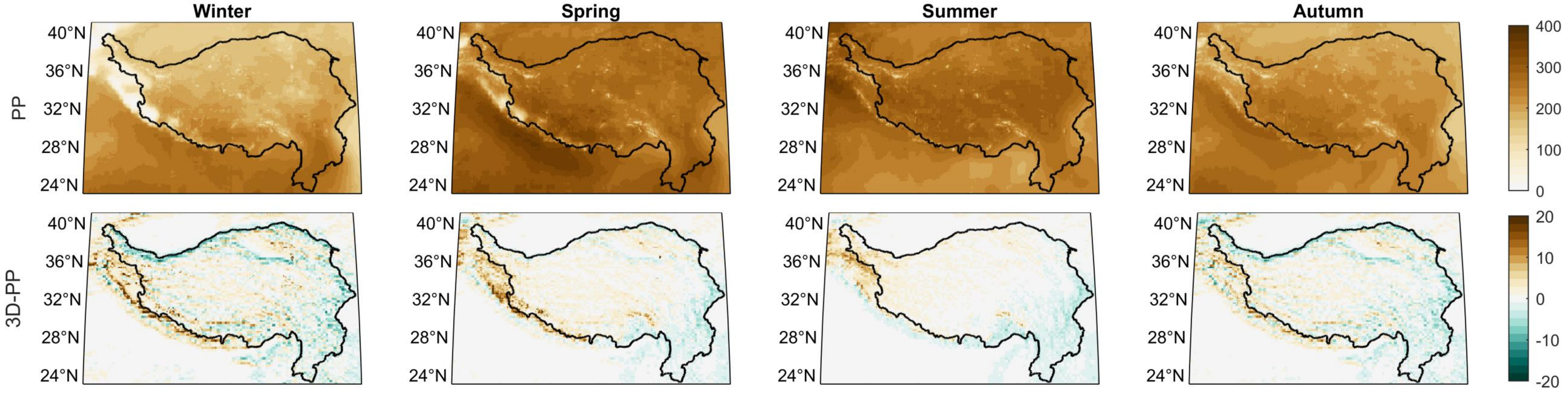
Topographic effects on surface energy balance

The topography-induced surface temperature difference (3D-PP) can be larger than ±1 K at 0.125 degree resolution in Winter.



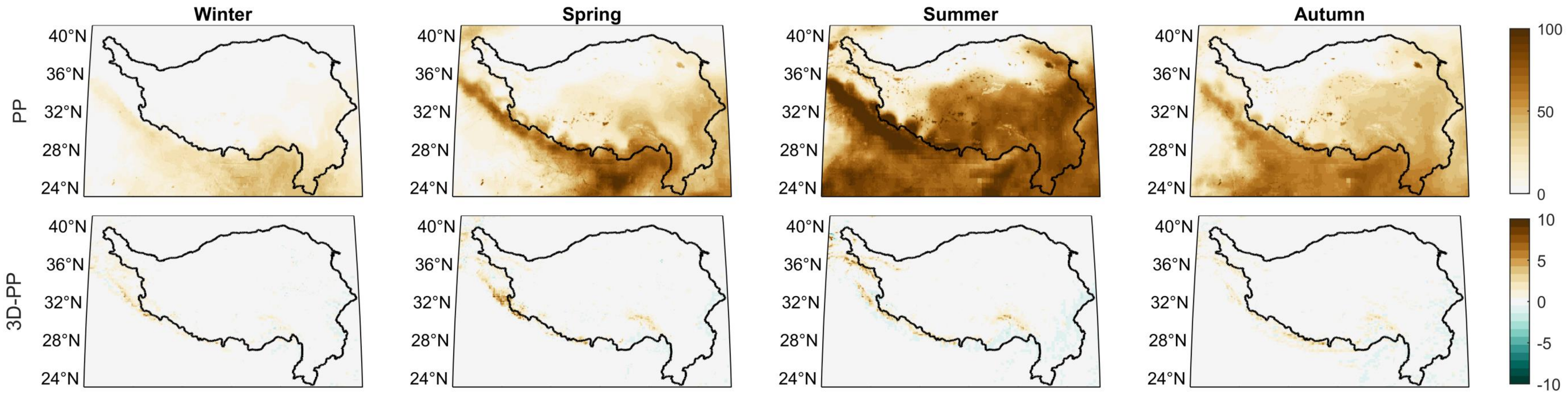
Topographic effects on surface energy balance

The topography-induced net solar radiation difference (3D-PP) can be larger than ±20 W/m^2 at 0.125 degree resolution.



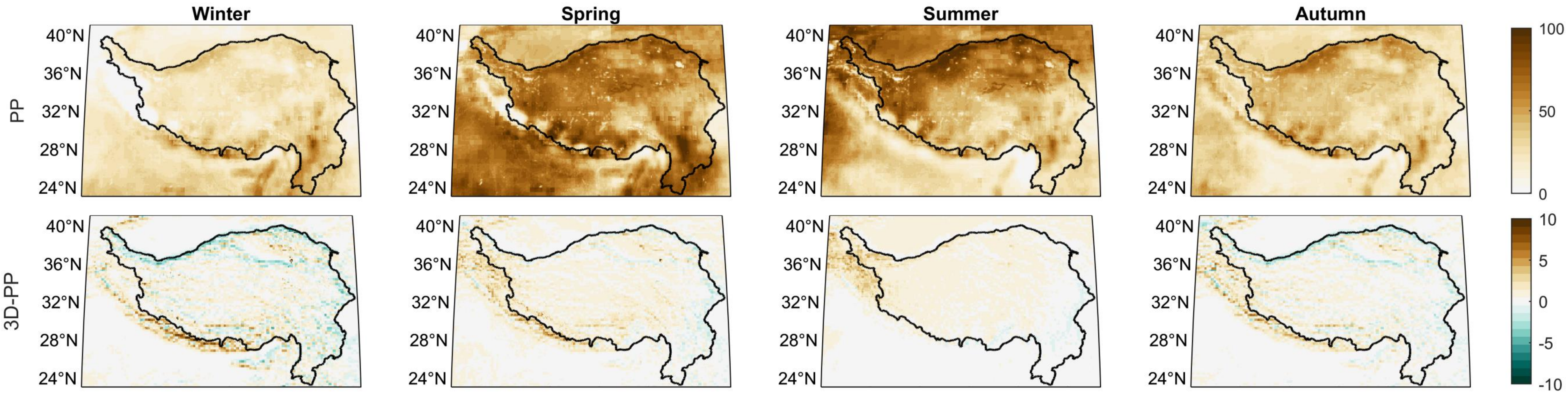
Topographic effects on surface energy balance

The topography-induced latent heat flux difference (3D-PP) is smaller than ±10 W/m^2 at 0.125 degree resolution.



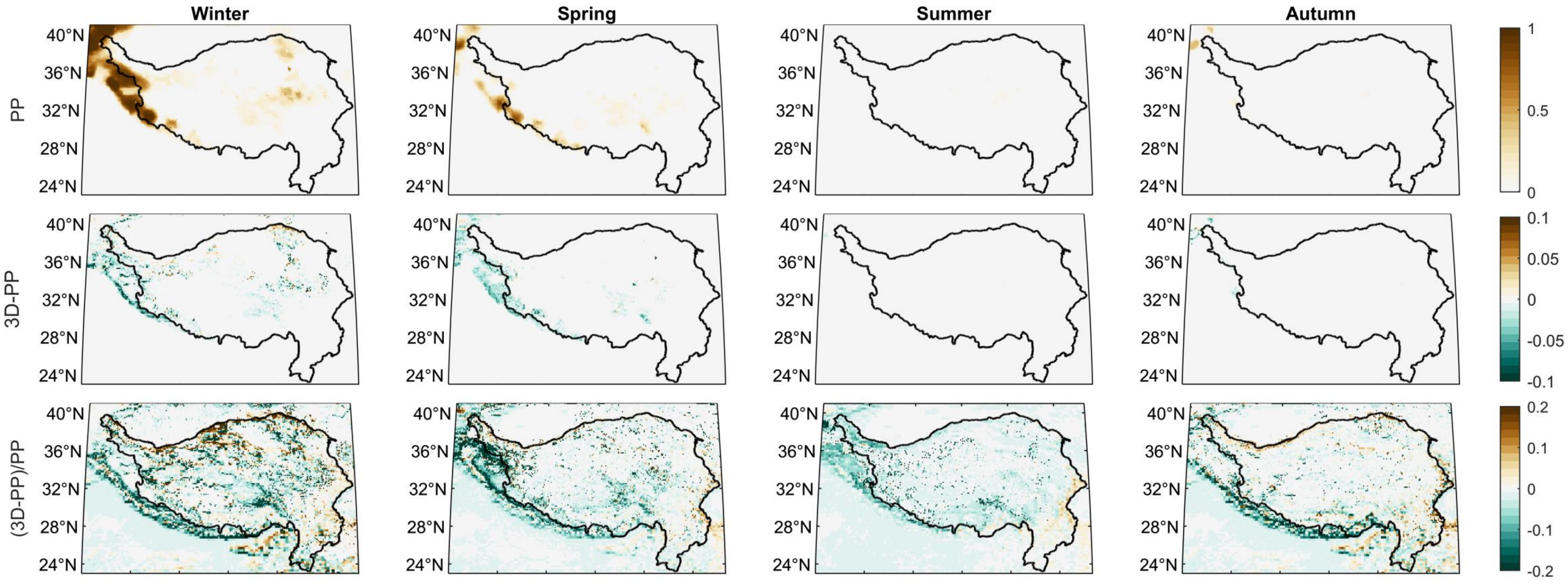
Topographic effects on surface energy balance

The topography-induced sensible heat flux difference (3D-PP) can reach up to ±10 W/m^2 at 0.125 degree resolution.



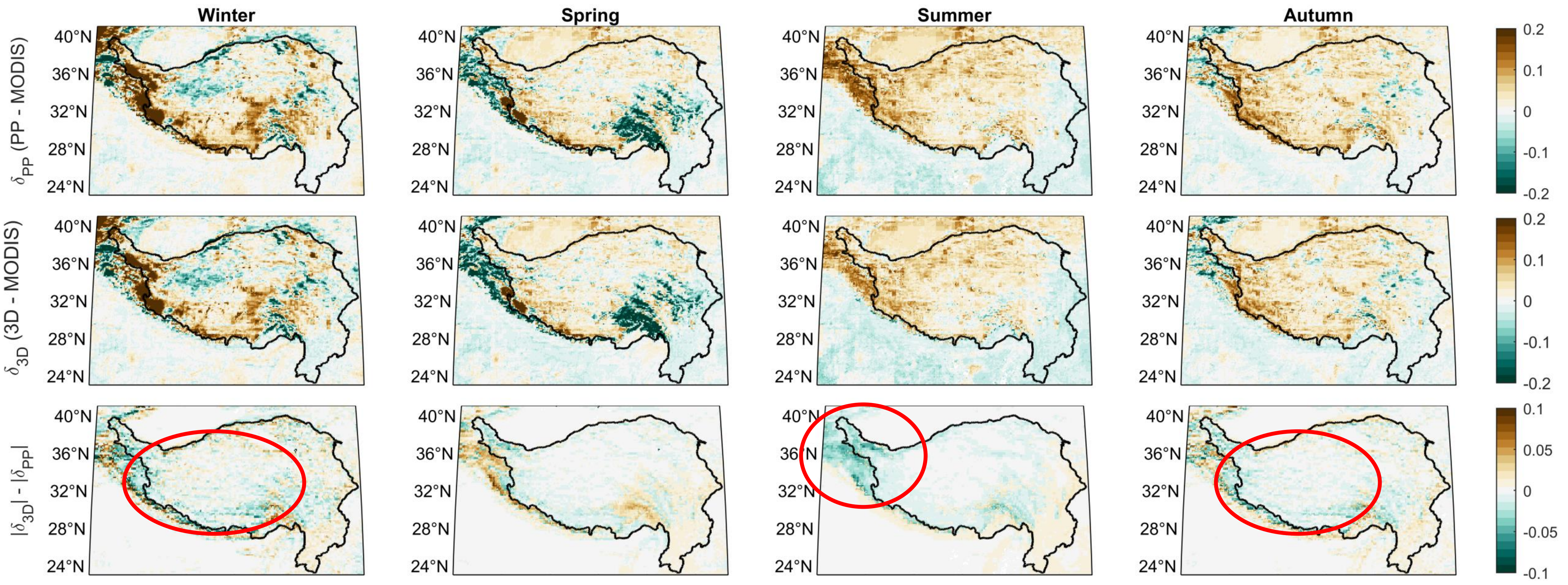
Topographic effects on surface energy balance

The topography-induced snow cover difference (3D-PP) is smaller than ±10% at 0.125 degree resolution.



Comparison with MODIS data

- ELM-PP overestimates direct albedo in most regions.
- Overall, direct albedo in ELM-3D has smaller bias than ELM-PP, compared to MODIS albedo.



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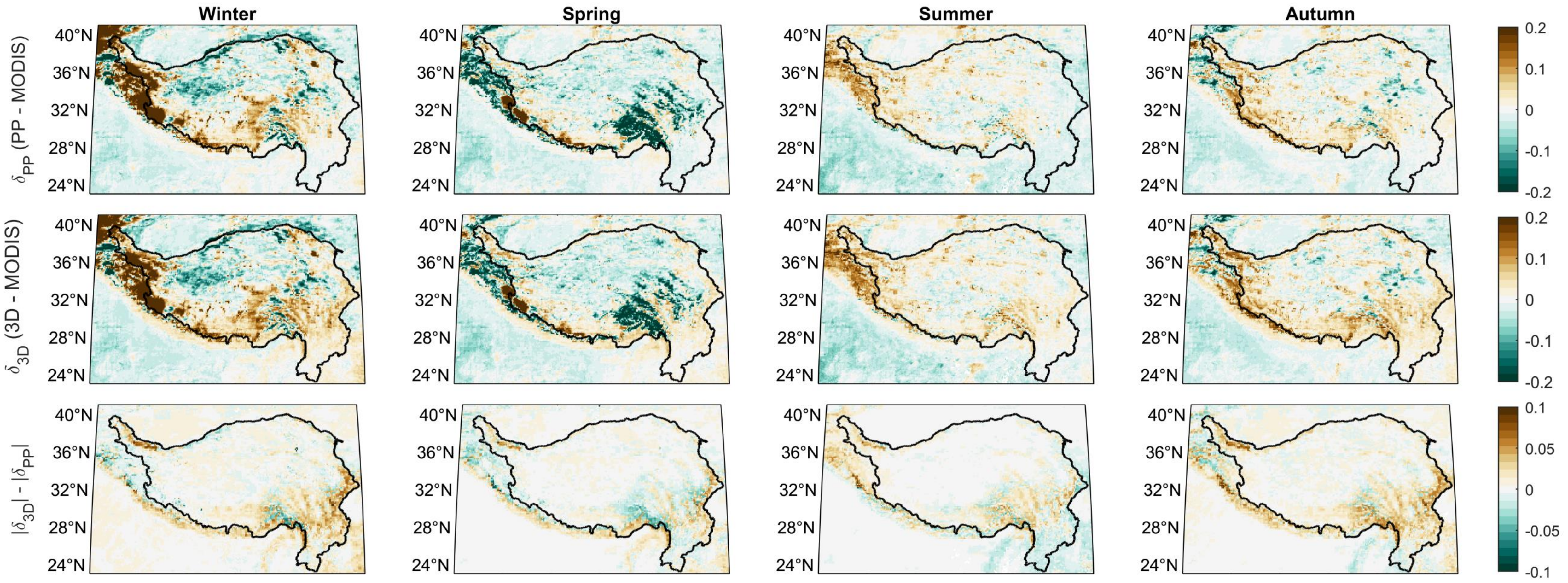
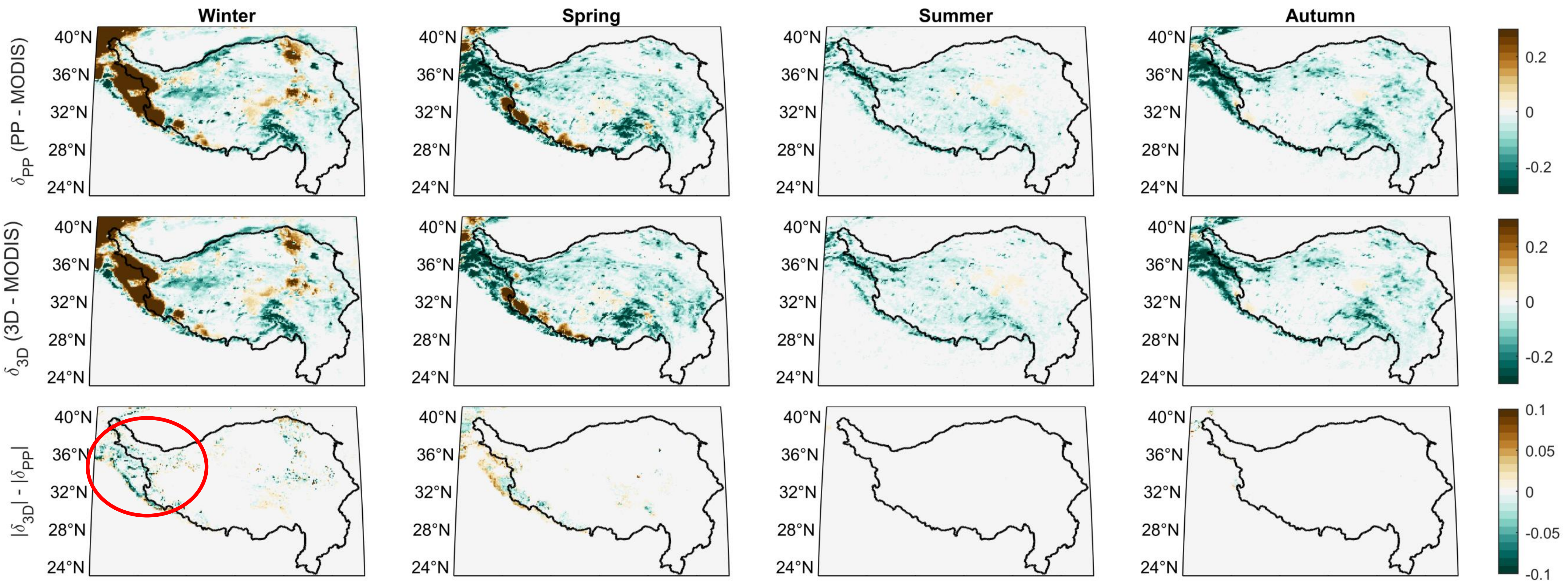
Comparison with MODIS data

- Overall, diffuse albedo in ELM-3D has similar or a little larger bias than ELM-PP, compared to MODIS albedo.



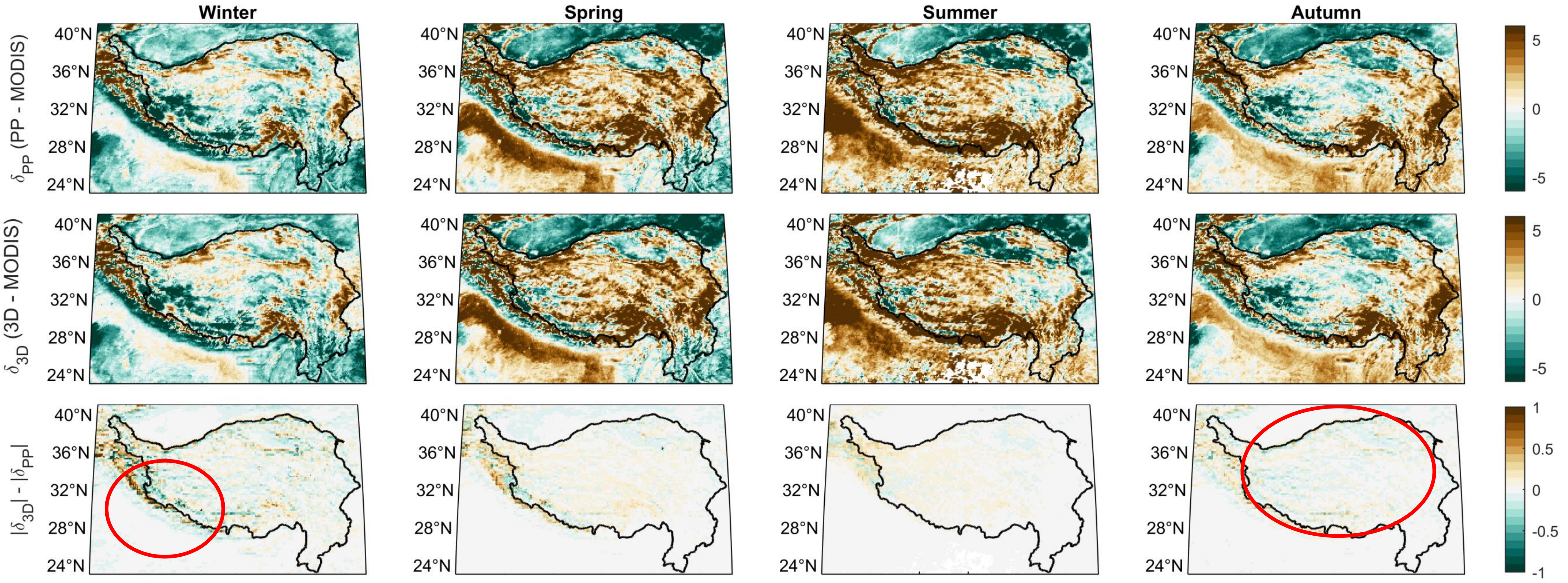
Comparison with MODIS data

- **Snow cover** in ELM-3D are closer to MODIS estimates in Winter.



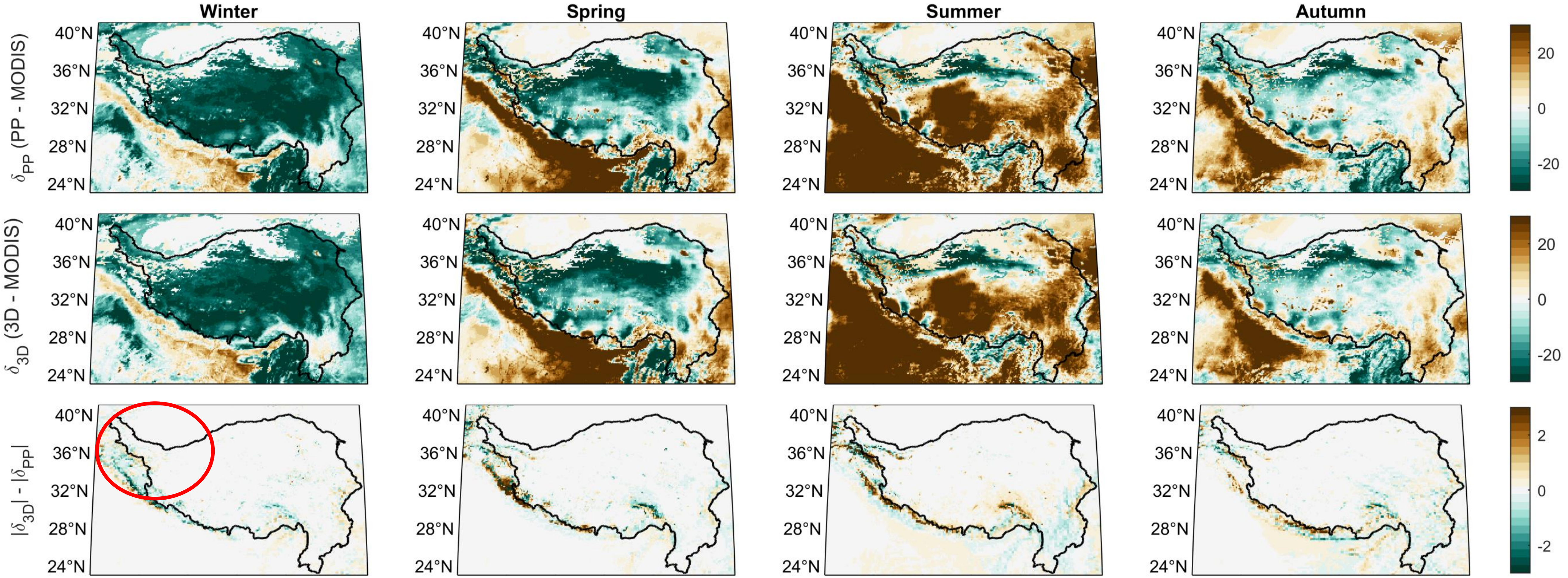
Comparison with MODIS data

- **Surface Temperature** in ELM-3D is slightly better correlated to MODIS estimates in Winter.



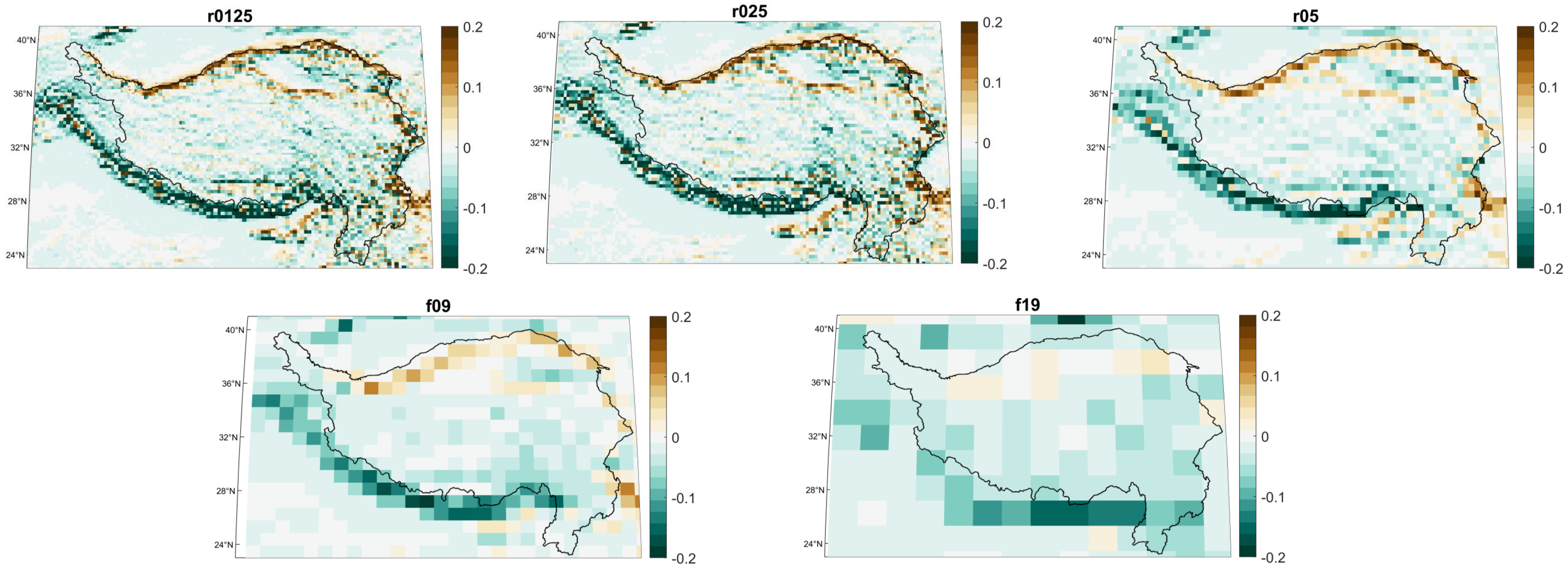
Comparison with MODIS data

- Both ELM-3D and ELM-3D have large biases, compared to MODIS data.
- **Latent heat flux** in ELM-3D is slightly better correlated to MODIS estimates in Winter.



Spatial scale effects

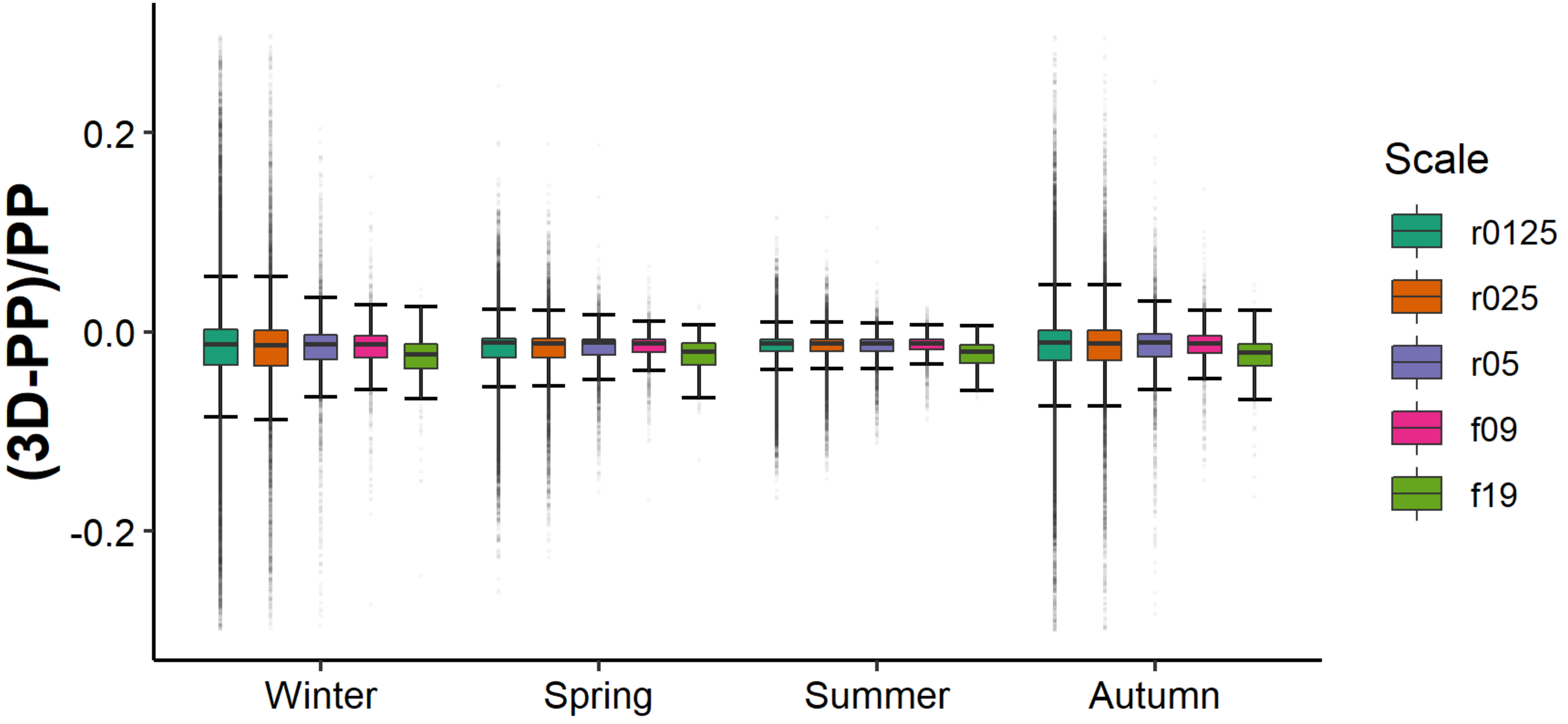
- As the spatial resolution increases, the topographic effects on albedo are more and more obvious.



(3D-PP)/PP of Albedo in Winter at different resolutions

Spatial scale effects

- As the spatial resolution increases, the topographic effects on albedo are more and more obvious, especially in winter.



(3D-PP)/PP of albedo at different resolutions

Conclusions and Prospects

- Topography has non-negligible effects on surface energy balance and snowmelt.
- Topographic effects have seasonal variations and are related to spatial scales.
- ELM with topographic consideration has higher consistencies with MODIS data.

Conclusions and Prospects

- Account for sub-grid topographic heterogeneity in ELM
- Develop parameterizations for black carbon (BC) and dust mixing in snow and associated light absorption and scattering processes.
- Multi-layer canopy energy transfer accounting for tracers (e.g. dust, BC) in the canopy air space.
- Account for topographic effects on longwave radiation
- Perform Land-atmosphere coupled run

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Thank you