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# Motivation

1. The Third Pole region includes some of the highest elevations and most complex terrain in the world, encompassing the Hindu Kush–Himalaya and the Tibetan Plateau.
2. Extreme weather over this region is influenced by the interaction of multiple atmospheric processes, including monsoon flows, westerlies, and orographic lifting.
3. These interacting processes make the prediction of deep convection particularly challenging over the region.
4. Forecast skill is highly sensitive to model grid spacing because of the complex terrain. Therefore, explicitly resolving shallow and deep convection is crucial for improving the simulation of convective events. In this study, we use the newly developed 2TE scheme<sup>1</sup>, which can explicitly represent shallow convection, unlike the traditional TKE turbulence scheme.

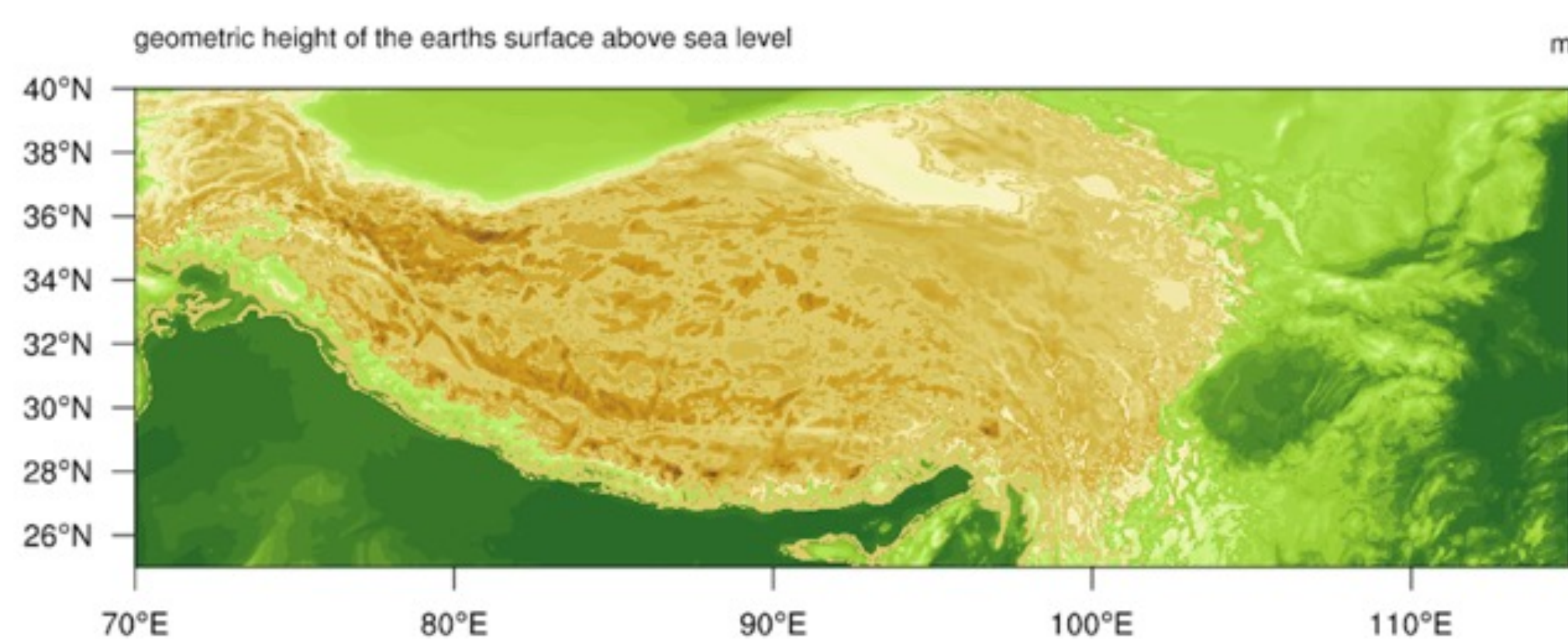


Figure 1. Orography of the study region in the ICON-CLM simulation at 3.3 km horizontal grid spacing.<sup>2-6</sup>

# Model Set-Up

1. ICON-NWP version 2024 was used for all simulations in this study. Most model configurations and tuning parameters are adopted from the ICON-CLM setup used in previous studies<sup>2-6</sup>.
2. For the 1 km grid-spacing simulations, convection parameterization is switched off for both turbulence schemes.
3. The 3.3 km simulations fall within the gray zone of convection parameterization. For the TKE scheme, simulations are performed both with and without shallow convection parameterization, whereas for the 2TE scheme, simulations were performed without convection parameterization.

Table 1. Summary of the ICON-CLM model setup used to simulate deep convective events over the Third Pole region. Only the major differences among the simulations are shown; all other configurations are identical. Further details can be found in Singh and Ahrens (2023, 2025, 2026)<sup>2,3,5,6</sup> Collier et al. (2024)<sup>4</sup>.

|                       |       |       |       |              |    |
|-----------------------|-------|-------|-------|--------------|----|
|                       | 1K2TE | 1KTKE | 3K2TE | 3KTKE        |    |
|                       |       |       |       | S1           | S2 |
| Horizontal resolution | 1 km  |       | 3 km  |              |    |
| Time step             | 10 s  |       | 25 s  |              |    |
| Turbulence            | 2TE   | TKE   | 2TE   | TKE          |    |
| Deep Convection       | No    |       |       | Shallow Only | No |
| Radiation             | ecRad |       |       |              |    |
| Pressure Levels       | 60    |       |       |              |    |

## Evaluation of ICON-CLM at km-Scale

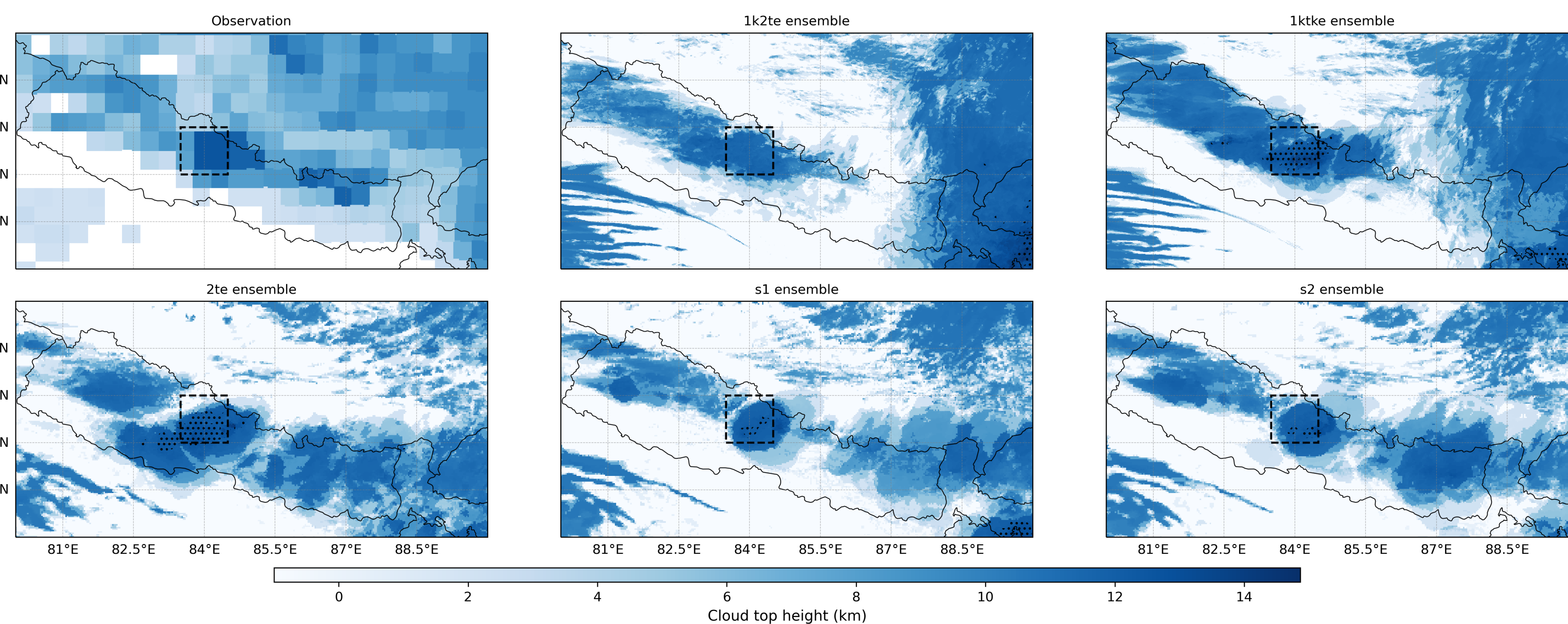


Figure 2. Ensemble mean cloud-top height simulated by different ICON-CLM experiments using the 2TE and TKE schemes at 1 km and 3.3 km horizontal grid spacing, initialized at different times, together with INSAT-3D observations.

1. Km-Cloud-top height: Km-scale ICON-CLM simulations (1 and 3.3 km grid spacing) show good agreement with INSAT-3D observations of the Himalayan deep-convective event.
2. Impact of turbulence scheme: The 2TE turbulence scheme at 3.3 km resolution produces a higher frequency of grid cells with high cloud-top heights compared with the TKE simulations, both with and without shallow-convection parameterization (Figure 2).
3. Precipitation performance: Event-mean precipitation shows good spatial correlation with IMERG observations across all ICON-CLM ensemble members. The 2TE simulation at 3.3 km shows particularly good agreement with IMERG in both spatial distribution and temporal evolution (figure 3).
4. Sensitivity of PBL height: The turbulence schemes exhibit sensitivity in PBL height for individual events. However, ensemble members initialized at different times show consistent behavior, indicating the robustness and stability of the 2TE scheme, comparable to the TKE-based simulations (Figure 4).

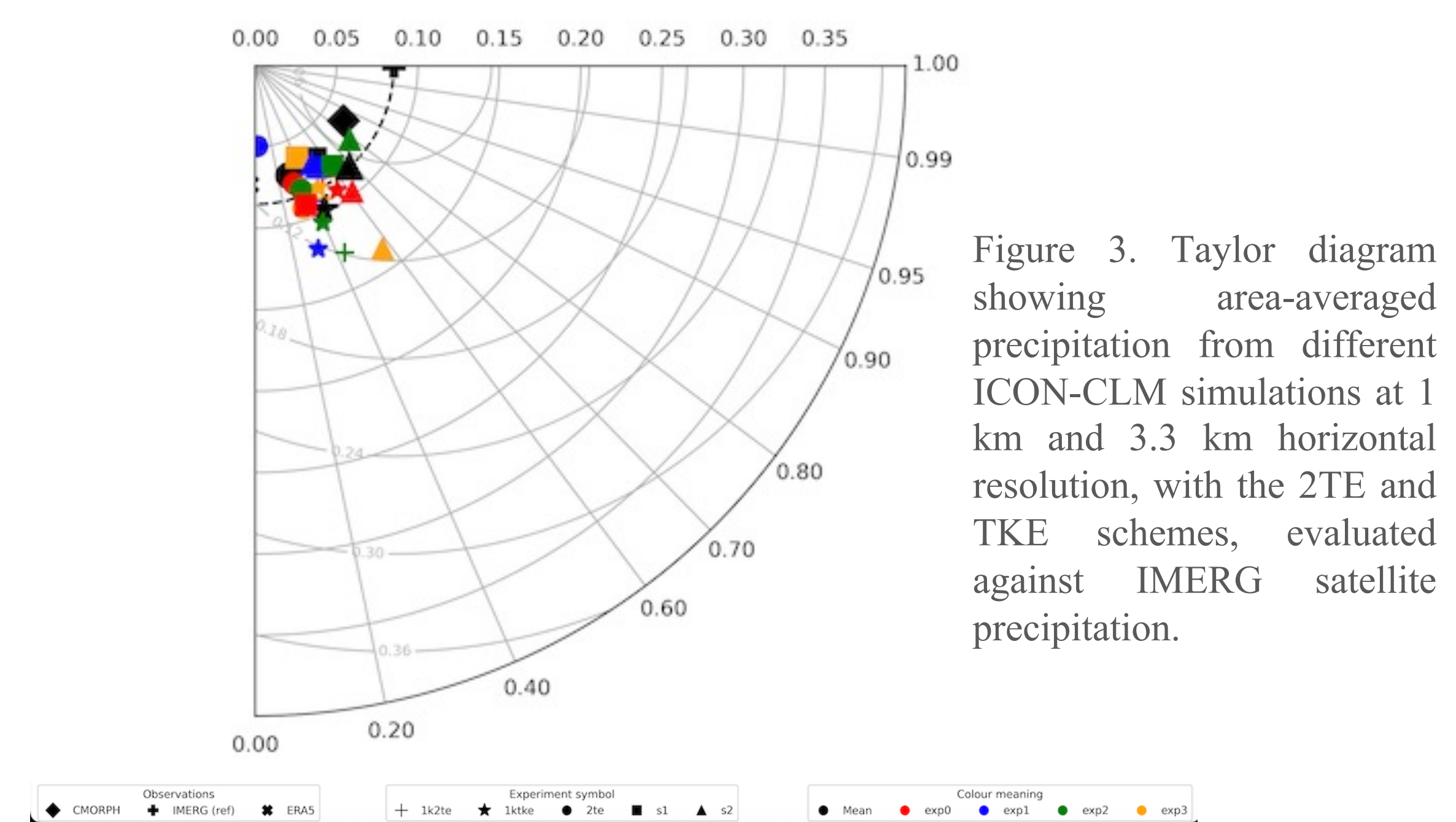


Figure 3. Taylor diagram showing area-averaged precipitation from different ICON-CLM simulations at 1 km and 3.3 km horizontal resolution, with the 2TE and TKE schemes, evaluated against IMERG satellite precipitation.

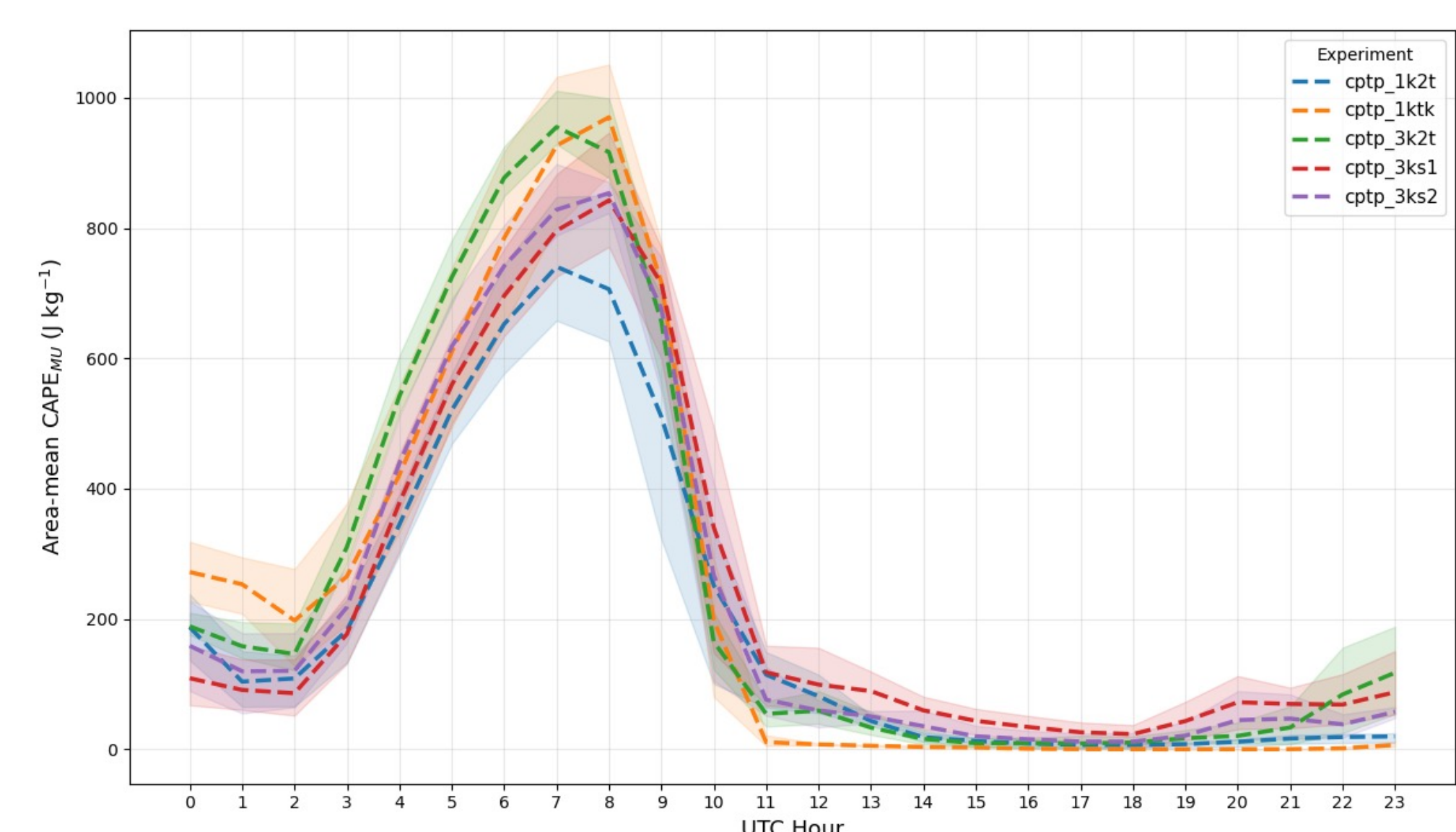


Figure 4. Area-averaged time series of convective available potential energy (CAPE) from different ICON-CLM simulations over the event region, at 1 km and 3.3 km horizontal grid spacing, using the 2TE and TKE turbulence schemes.

## Conclusions

1. Km-scale simulations (1–3.3 km) show good agreement with INSAT-3D and CALIPSO observations, capturing the spatial distribution and cloud-top heights of deep convective clouds over the Indo-Gangetic Plain and Tibetan Plateau. In addition, it shows strong agreement with IMERG precipitation.
2. Despite sensitivity in PBL height and cloud characteristics, simulations initialized at different times show consistent behavior, demonstrating the stability and robustness of the 2TE scheme compared with TKE-based simulations.
3. The 2TE turbulence scheme shows promising performance over the Third Pole region and provides a robust representation of cloud-top structure, precipitation, and boundary-layer processes. Its ability to represent shallow convection at convection-permitting *gray-zone* scales (1–5 km) highlights its potential as an alternative approach to conventional convection parameterization in high-resolution regional climate simulations.

## References

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## Acknowledgement

This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – TRR 301 – Project-ID 428312742. The authors thank Goethe-HLR (Project-ID: 26074) and DKRZ (Project-ID: BB1064) for providing computational resources.

## Convective Transport

1. CALIPSO observations over the Third Pole region identify deep convective clouds over both the Indo-Gangetic Plain (IGP) and the Tibetan Plateau (Figure 5).
2. The observed spatial distribution of deep convection is well reproduced by all three ICON-CLM simulations using the TKE and 2TE turbulence schemes at 3.3 km horizontal resolution.
3. Simulated cloud-top heights (green) show close agreement with CALIPSO observations (red), capturing deep convective clouds over both the IGP and Tibetan Plateau.

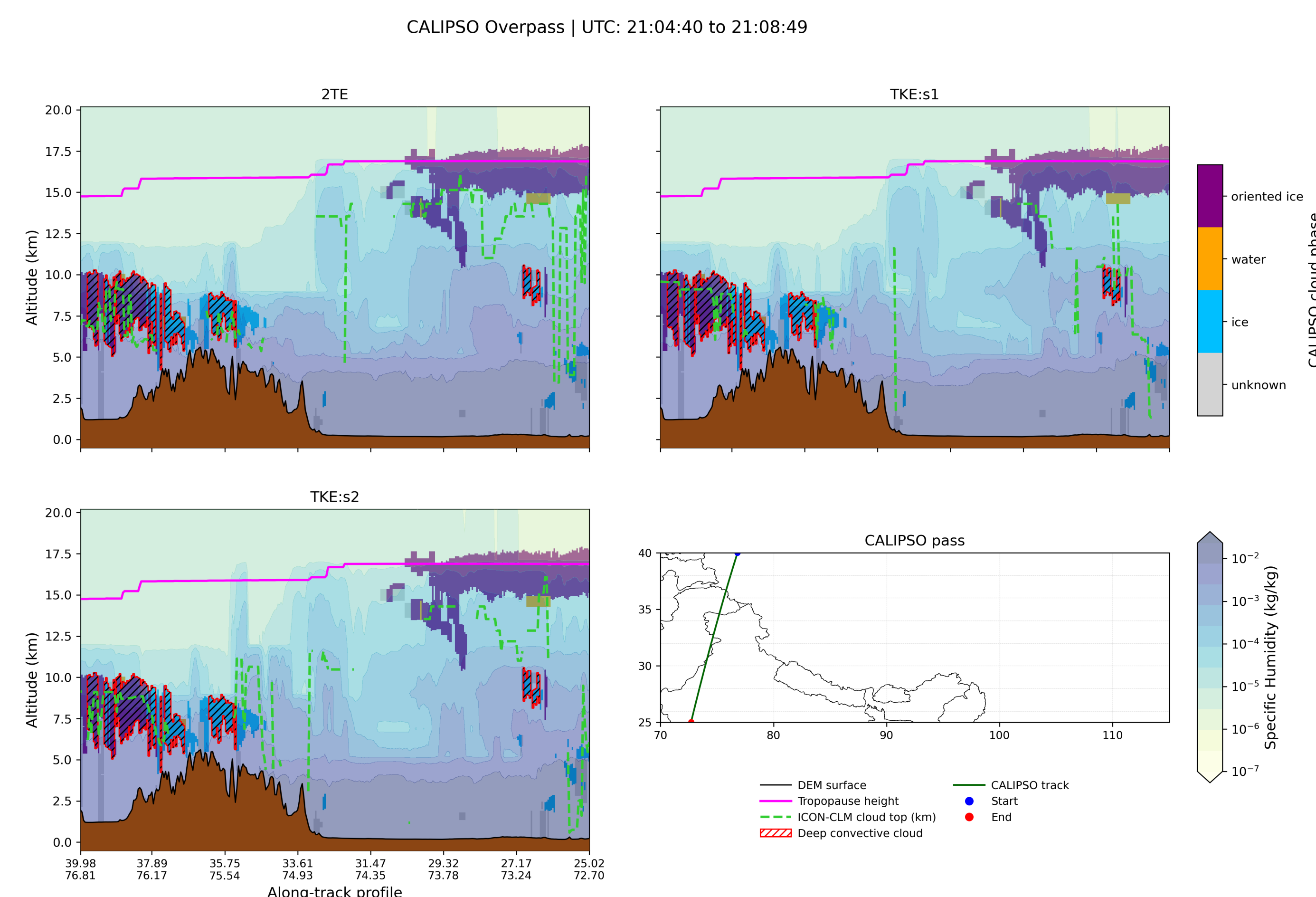


Figure 5. Cross-sections of specific humidity from ICON-CLM simulations at 3.3 km grid spacing along the CALIPSO path, highlighting deep convection in simulations using the 2TE and TKE turbulence schemes, with and without shallow convection parameterization.