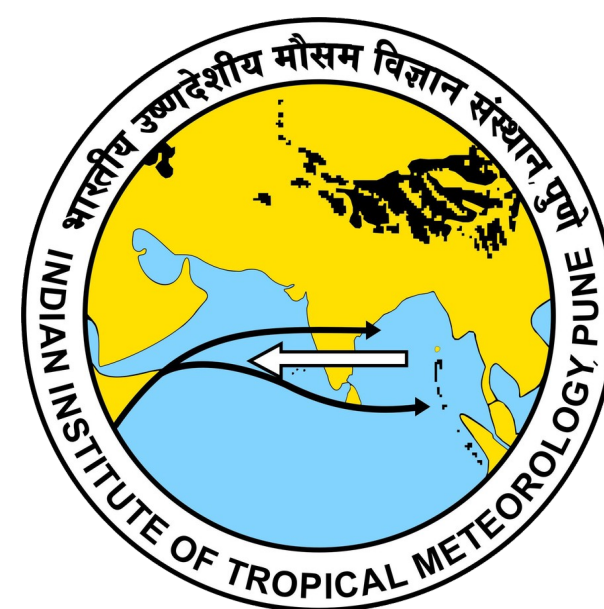


Depth-Dependent Soil Moisture Variability Across Homogeneous Climatic Regions of India

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Main result: with depth, soil moisture varies more slowly and has a longer memory in all six regions, but the amount differs among regions (GLDAS); the stations show a similar pattern.

Introduction and Data

How do the variability and memory of soil moisture vary with depth across the homogeneous climatic regions of India?

The **surface layer** exchanges water with the air and reacts within days, whereas the **deeper layers** store water for plants and keep the memory of rain (Seneviratne et al., 2010).

Station data come from the India Meteorological Department (IMD) AGRO network, with 199 point locations and 15-minute readings (daily means are used) from March 2021 to December 2024 at depths of 10, 30, 70 and 100 cm.

Model data come from the Global Land Data Assimilation System (GLDAS) Noah (Rodell et al., 2004), on a daily 0.25° x 0.25° grid from 2001 to 2021, for the layers 0-10, 10-40, 40-100 and 100-200 cm.

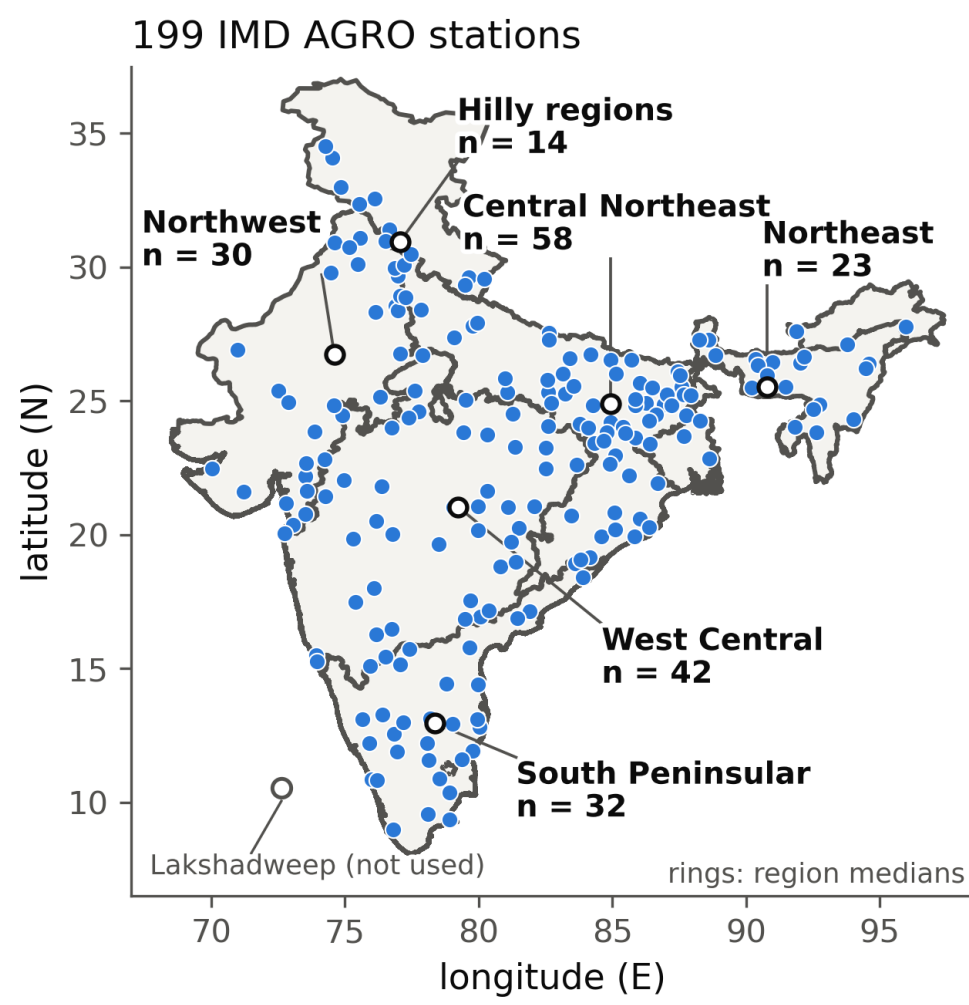


Fig. 1 Locations of the 199 IMD AGRO stations and outlines of the six regions (n: number of stations)

Methodology

Station readings were quality controlled, which removed 28 to 32% of the readings (mostly exact 0 and 100). Anomalies are the daily values minus a smooth seasonal cycle, represented by the mean and three annual harmonics (Fig. 2).

The **fast share** is the fraction of the variance of the anomalies at periods shorter than 15 days. Memory is measured by the **e-folding time**, which is the lag (in days) at which the autocorrelation of the anomalies falls below 1/e (about 0.37). It is computed for the monsoon season (June to September) on the regional mean series of each depth, and the 95% intervals are obtained by resampling the 21 years for GLDAS and the stations for the station data. If the autocorrelation stays above 1/e up to the longest lag (90 days for stations, 120 days for GLDAS), the memory is longer than that lag.

The **robustness** of the difference in e-folding time between the deepest and the top GLDAS layer is tested by recomputing it in four ways (Fig. 5): with the main calculation (three harmonics), with two and four harmonics, and with each year's own mean anomaly subtracted (year-to-year differences removed).

GLDAS is evaluated against the stations in 2021 by the correlation of the raw values and of the anomalies (35-day mean removed) and by the mean difference (Fig. 6). The **Bowen ratio**, which relates the heating of the air to evaporation, is shown by region and season for GLDAS, together with the GLDAS soil temperature by depth (Fig. 7).

Key Findings

Table 1 Results by region

Region	GLDAS, top to deepest layer	Gain	Gain, year-to-year removed	Stations, 10 to 100 cm	Bowen ratio, Mar-May / Jun-Sep
Northwest	10 to 34	+24	+13	28 to >90	5.7 / 0.8
Central Northeast	15 to 33	+18	+10	>90 to >90	2.1 / 0.3
Northeast	5 to 23	+18	+12	7 to 14	0.7 / 0.2
West Central	9 to 17	+8	+5	16 to 81	5.7 / 0.4
South Peninsular	9 to 79	+70	+14	9 to >90	2.2 / 0.5
Hilly regions	17 to >120	>+103	+16	14 to >90	1.2 / 1.2

E-folding time in days, June to September; >: longer than the window (90 days stations, 120 days GLDAS). Gain: deepest (100-200 cm) minus top (0-10 cm) layer, GLDAS; year-to-year removed: each year's own mean anomaly subtracted (Fig. 5). Bowen ratio: GLDAS (Fig. 7).

Discussion

Table 1 shows that the increase of memory with depth differs in size but not in sign, ranging from +8 days in West Central to more than +103 days in the Hilly regions.

Fig. 2 shows that the seasonal cycle is smaller and later in the deepest layer in five of six regions (GLDAS). Its maximum comes about 2 to 4 weeks after that of the top layer (dots), whereas in the Northeast the layers differ little.

Fig. 3 shows that the fast share decreases about sixfold with depth for soil moisture and by more than two orders of magnitude for soil temperature (GLDAS).

Fig. 4 shows that memory is longer in the deepest than in the top layer in every region (GLDAS). In June to September the e-folding time is 5 to 17 days at 0-10 cm and 17 to 79 days at 100-200 cm, except in the Hilly regions, where it is longer than 120 days. In the Northwest the 70 and 150 cm layers are not distinguishable. At the stations, the e-folding time is longer at 100 cm than at 10 cm in five of six regions, whereas in the Central Northeast it was not reached within 90 days at any depth.

Fig. 5 shows that the deepest layer has the longer e-folding time in every region under all four variants. When each year's own mean anomaly is subtracted, the increase is smaller (5 to 16 days), which suggests that part of the longer deep-layer memory reflects conditions stored from one year to the next.

Fig. 6 shows that GLDAS reproduces the seasonal evolution ($r = 0.62$ to 0.76) but not the short-term anomalies ($r = 0.17$ to 0.38), and that it is drier than the stations by 2 to 8 percentage points.

Fig. 7 shows that the Bowen ratio is above 1 where heating of the air predominates and below 1 where evaporation predominates. For soil temperature, the fast share decreases from about 0.3 to almost zero and the e-folding time (June to September) increases from about 15 to 130 days with depth (means of the six regions).

Limitations

Memory is derived mainly from GLDAS, which reproduces short-term variability only weakly. The station records are short (1.0 to 3.7 years) and affected by offsets and sensor faults, so the station memory is uncertain. A change in the GLDAS forcing in 2000 restricts the analysis to 2001 to 2021.

Next Steps

Future work will add further datasets, estimate memory from longer station records after correcting offsets and sensor faults and extend the autocorrelation window beyond 120 days to resolve the memory of the deep layers.

Results

Seasonal cycle of soil moisture by GLDAS layer (mean and three annual harmonics, 2001 to 2021)

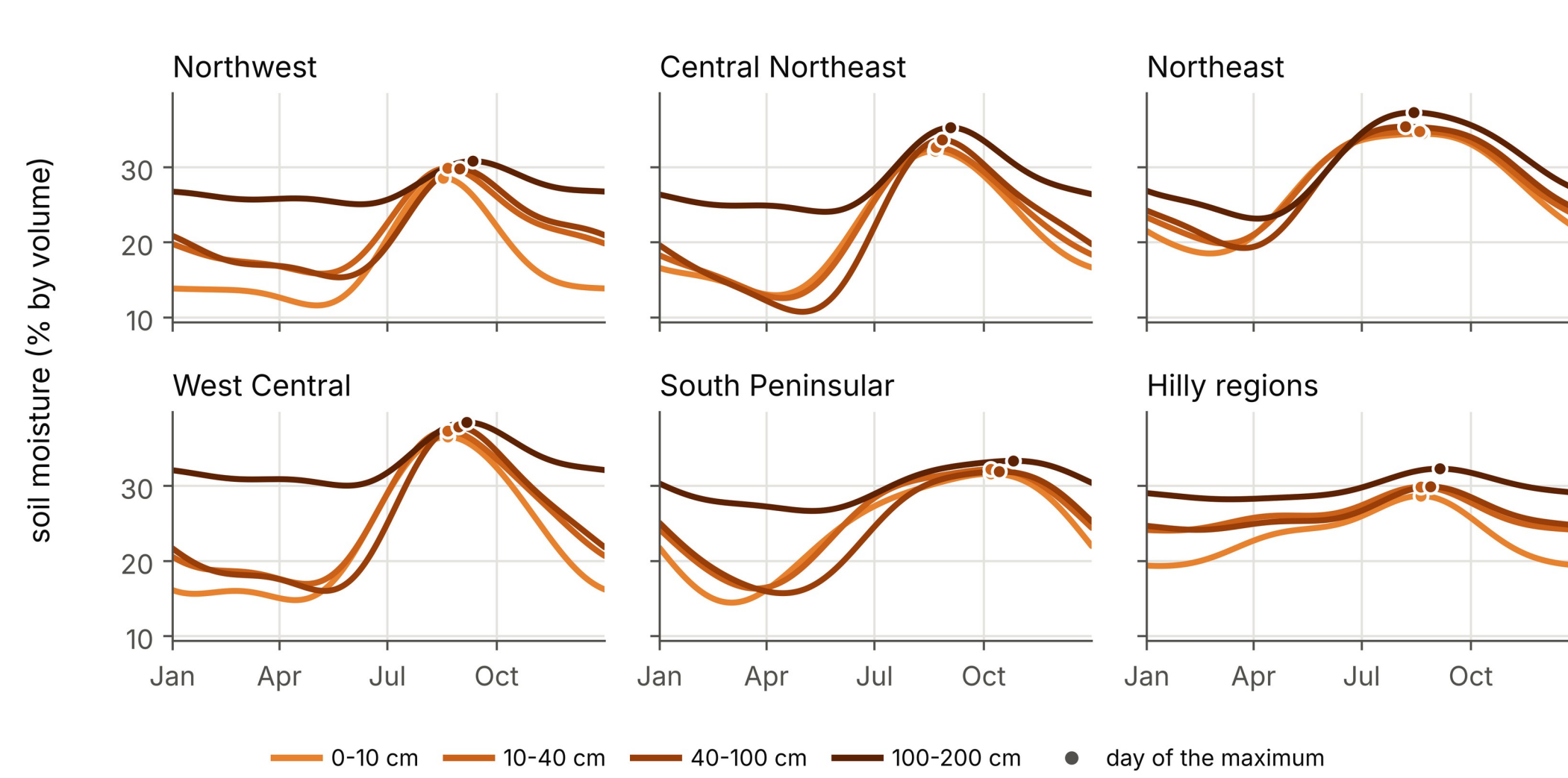


Fig. 2 Seasonal cycle of soil moisture by GLDAS layer and region (mean and three annual harmonics, 2001-2021: the cycle removed to obtain anomalies). Dots: day of the maximum

E-folding time of soil moisture anomalies, June to September

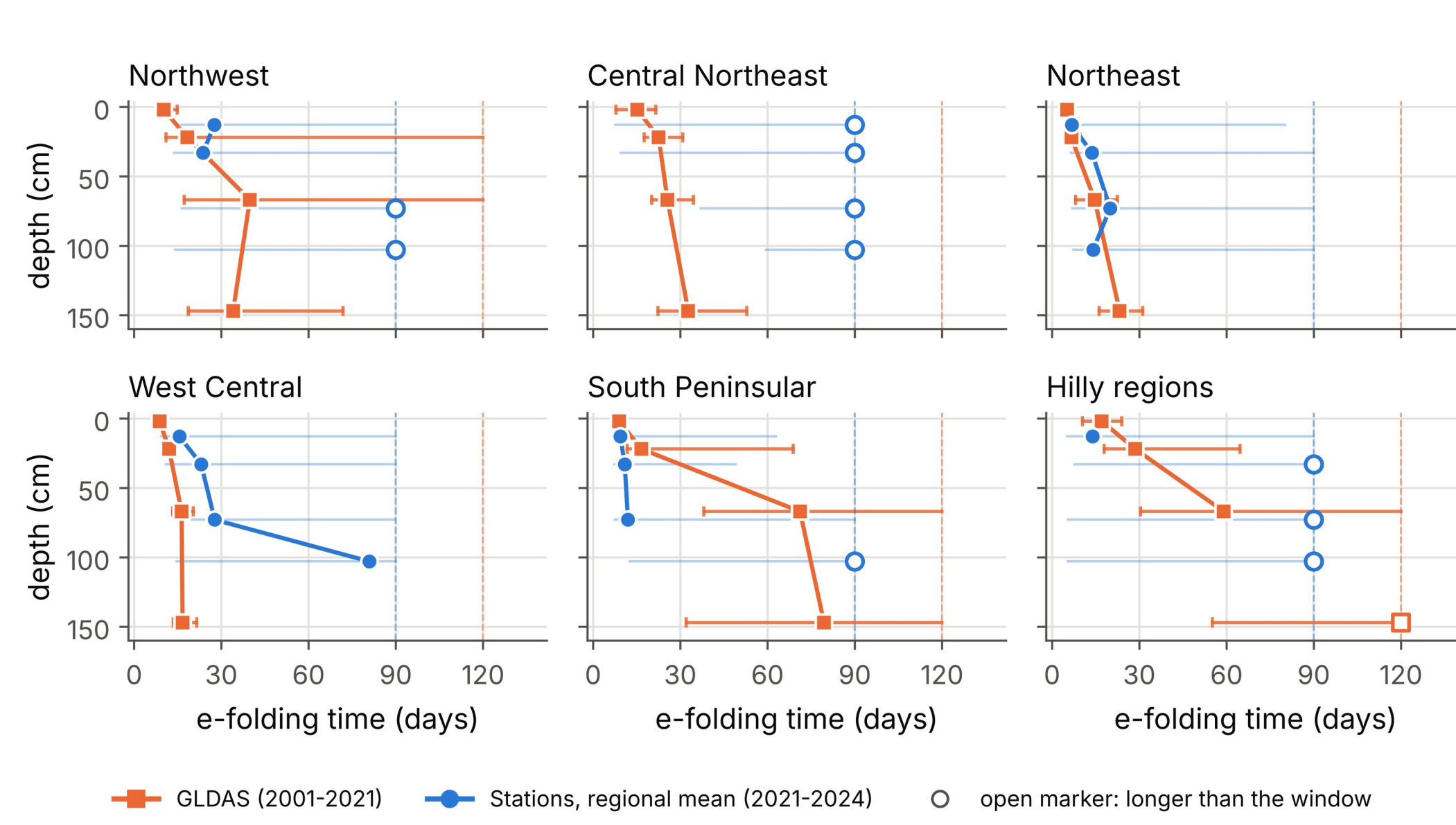


Fig. 4 E-folding time of soil moisture anomalies (June to September) by depth and region. Bars: 95% intervals (GLDAS: resampling the 21 years; stations: resampling the stations). Open markers: no e-folding time within the longest lag (90 days stations, 120 days GLDAS)

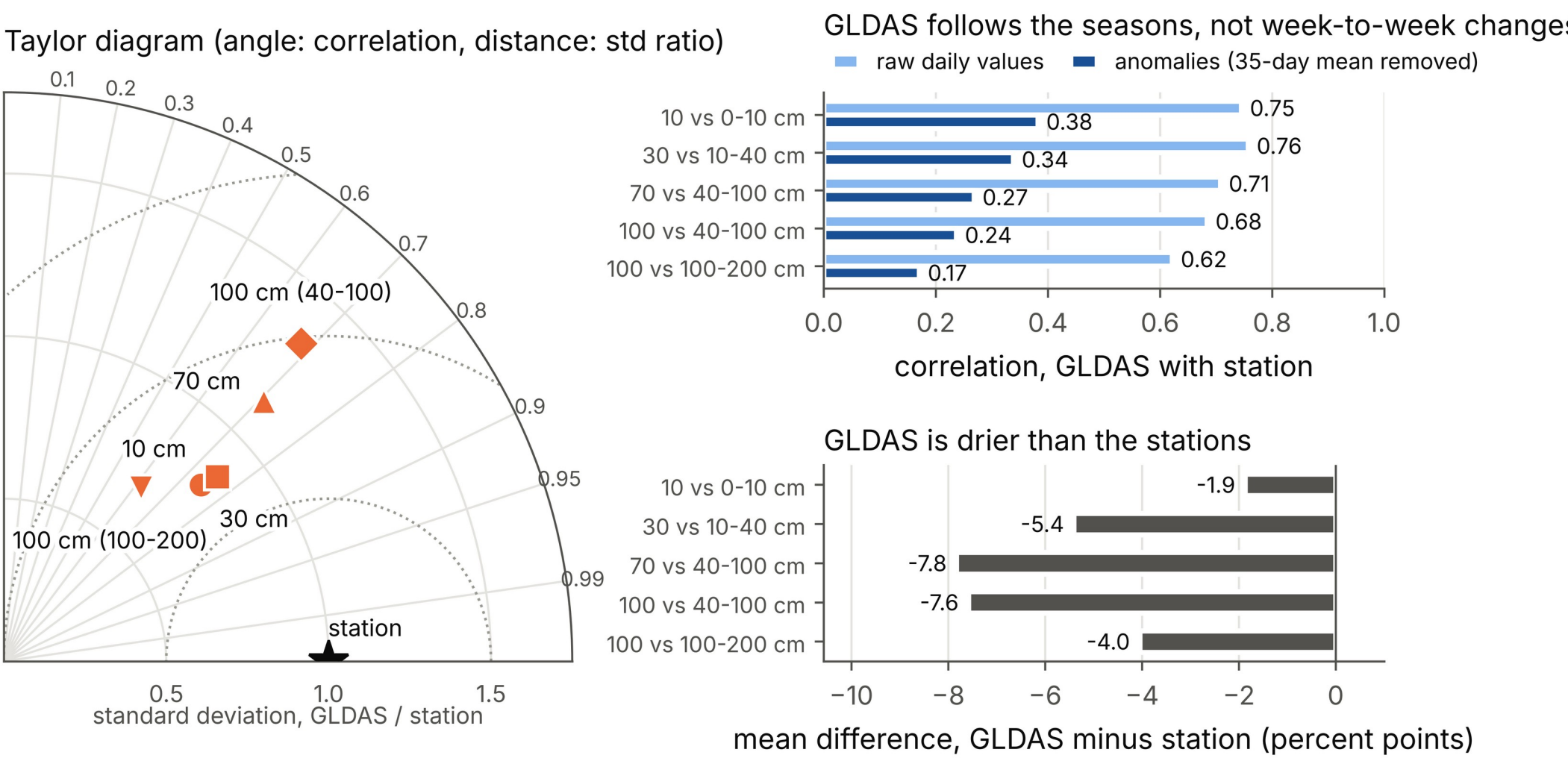


Fig. 6 GLDAS versus station soil moisture in 2021 (medians over about 170 stations): Taylor diagram, correlation and mean difference. Labels: station depth versus GLDAS layer

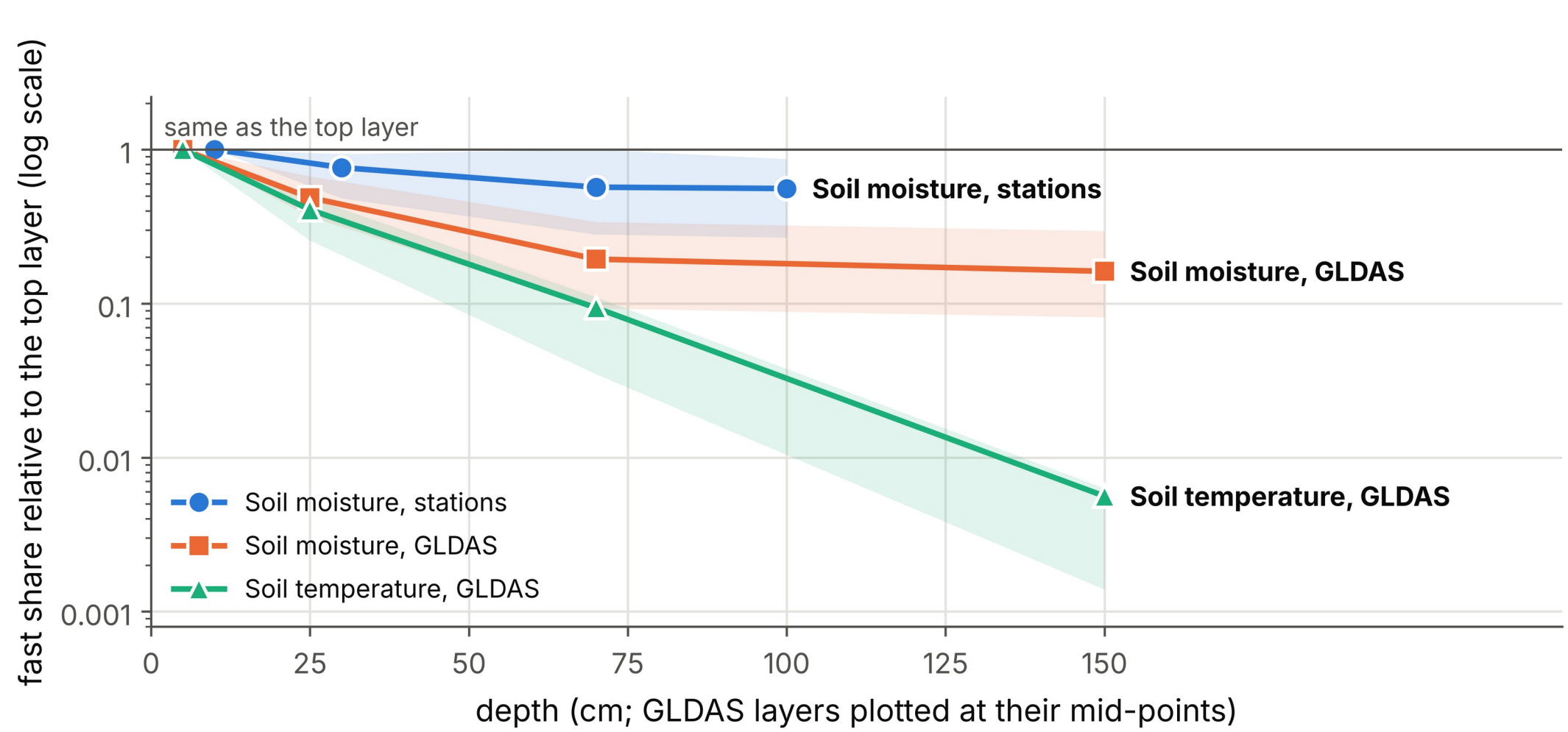


Fig. 3 Fast share of variance (periods shorter than 15 days) relative to the top layer, as a function of depth (median of the six regions; shading: range among regions)

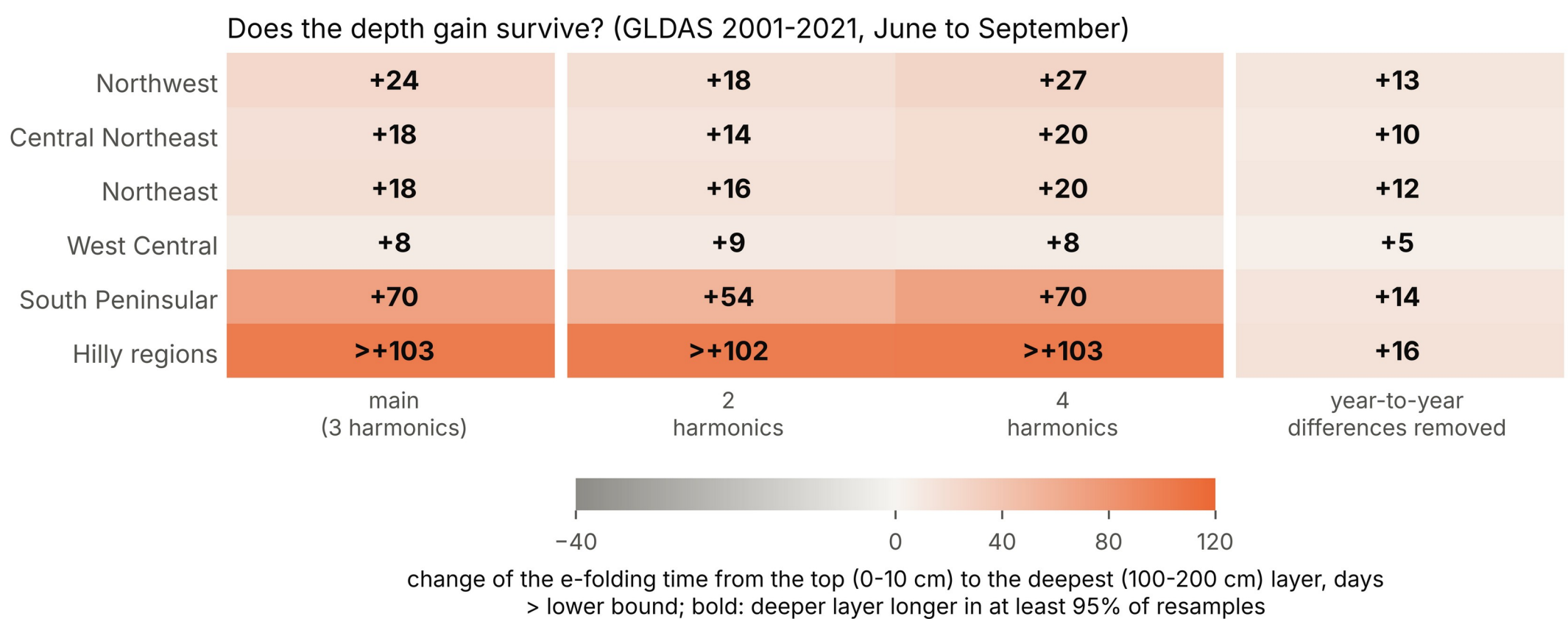


Fig. 5 Change in the e-folding time (days) from the top (0-10 cm) to the deepest (100-200 cm) GLDAS layer, June to September, under four variants of the calculation. >: lower bound. Bold: the deeper layer has the longer e-folding time in at least 95% of the resamples of the years

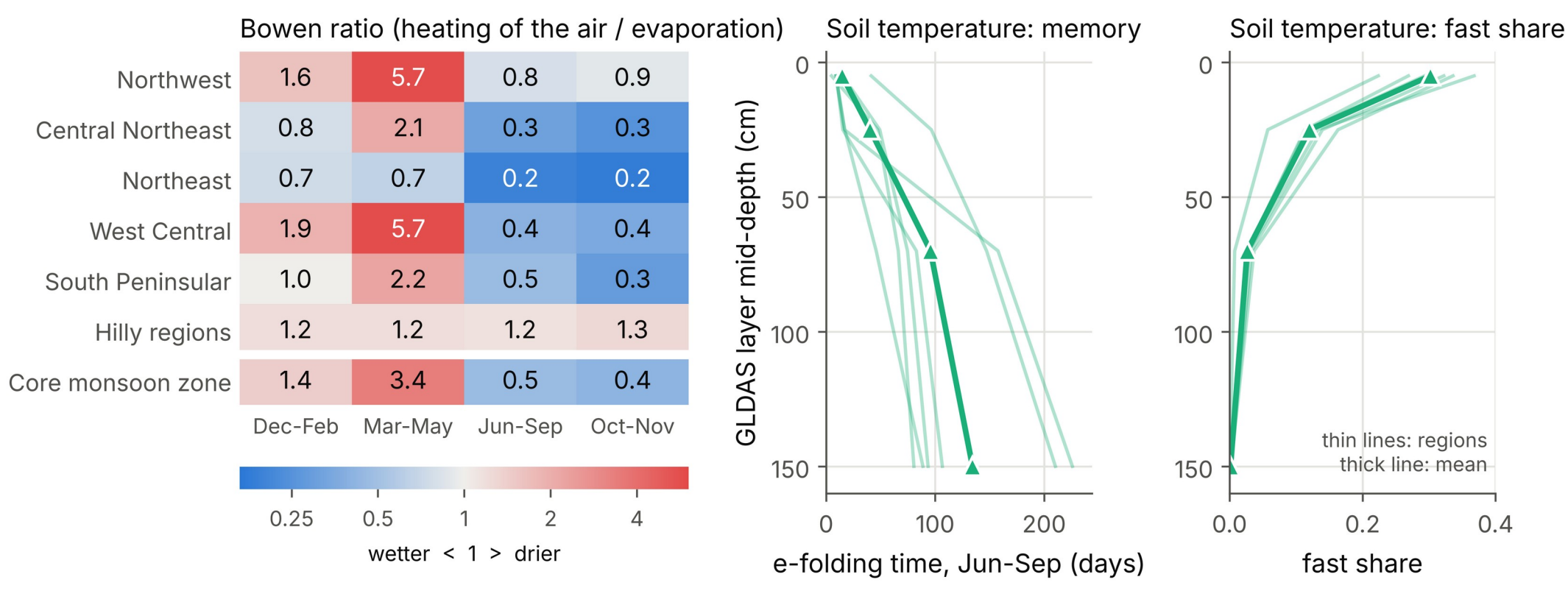


Fig. 7 Bowen ratio by region and season (including the core monsoon zone, 17.0 to 30.1°N, 71.5 to 88.7°E; Goswami et al., 2023), and GLDAS soil temperature: e-folding time (June to September) and fast share by depth

Conclusions

The share of fast variability decreases with depth. The fraction of the variance at periods shorter than 15 days is smaller at the deepest level than at the top level in all six regions, in the stations and in GLDAS.

Memory increases with depth in all six regions, by different amounts. In the monsoon, the e-folding time of soil moisture anomalies is longer in the deepest GLDAS layer (100-200 cm) than in the top layer (0-10 cm). The difference remains under all four variants of the calculation (Fig. 5), including when year-to-year differences are removed, although it then shrinks to 5 to 16 days. At the stations, the e-folding time at 100 cm exceeds that at 10 cm in five of six regions, but the records (1.0 to 3.7 years, median 2.3 years) are too short and uncertain for absolute values.

The Bowen ratio (GLDAS) differs by region and season. Before the monsoon (March to May), it exceeds 5 in the Northwest and West Central regions, which indicates predominant heating of the air. In the monsoon it is below 1 in all regions except the Hilly region, which indicates predominant evaporation.

Acknowledgement and References

Acknowledgements. Station data: India Meteorological Department (IMD) AGRO network. Model data: GLDAS, NASA GES DISC.

References. Goswami, M. M., et al. (2023). Understanding the soil water dynamics during excess and deficit rainfall conditions over the core monsoon zone of India. *Environ. Res. Lett.*, 18, 114011.

Rodell, M., et al. (2004). The Global Land Data Assimilation System. *Bull. Amer. Meteor. Soc.*, 85, 381-394. Seneviratne, S. I., et al. (2010). Investigating soil moisture-climate interactions in a changing climate: a review. *Earth-Sci. Rev.*, 99, 125-161.