

Variability in monsoon dynamics, warming, and snow cover drives agroecological transformation and community vulnerability in the eastern Himalaya

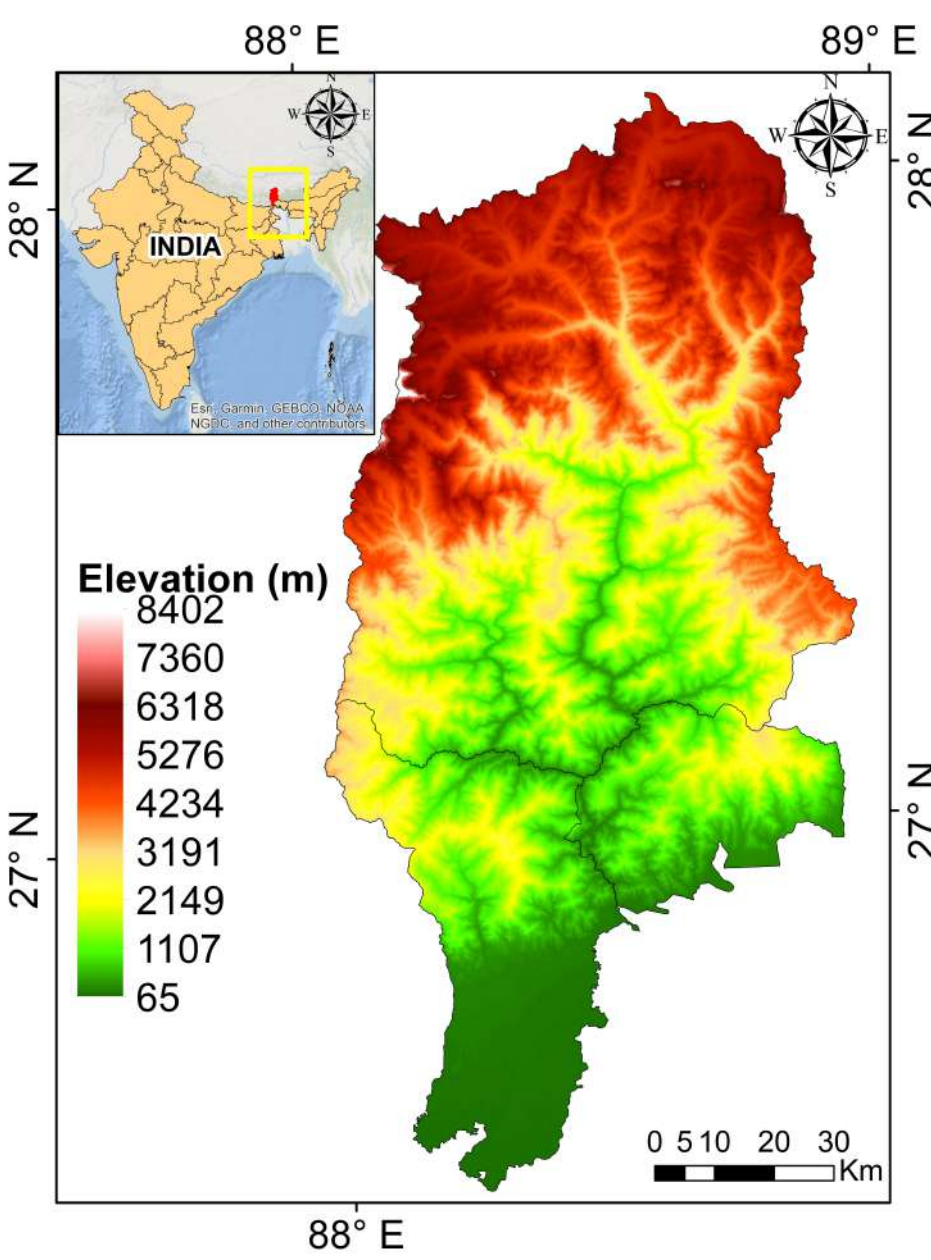
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Background and aim

- Climate change threatens high-altitude agroecosystems, food security and the resilience of mountain communities.
- In the eastern Himalaya, forest-dependent farmers report **crop productivity losses, pest and disease outbreaks** and increased human-animal conflict, yet very few studies cover these aspects.
- Aim:** to link long-term hydroclimatic change (warming, monsoon, snow cover) with farmers' perceived agroecological change and community vulnerability.

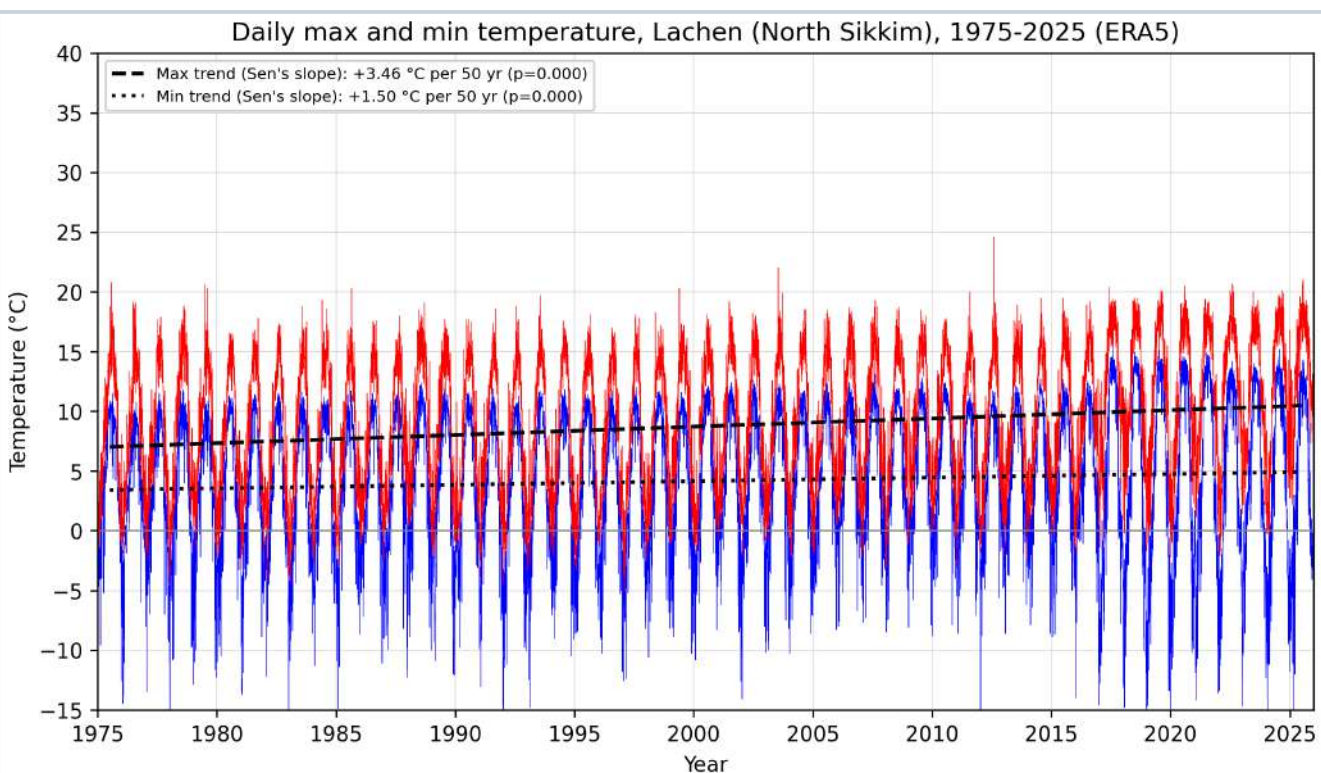
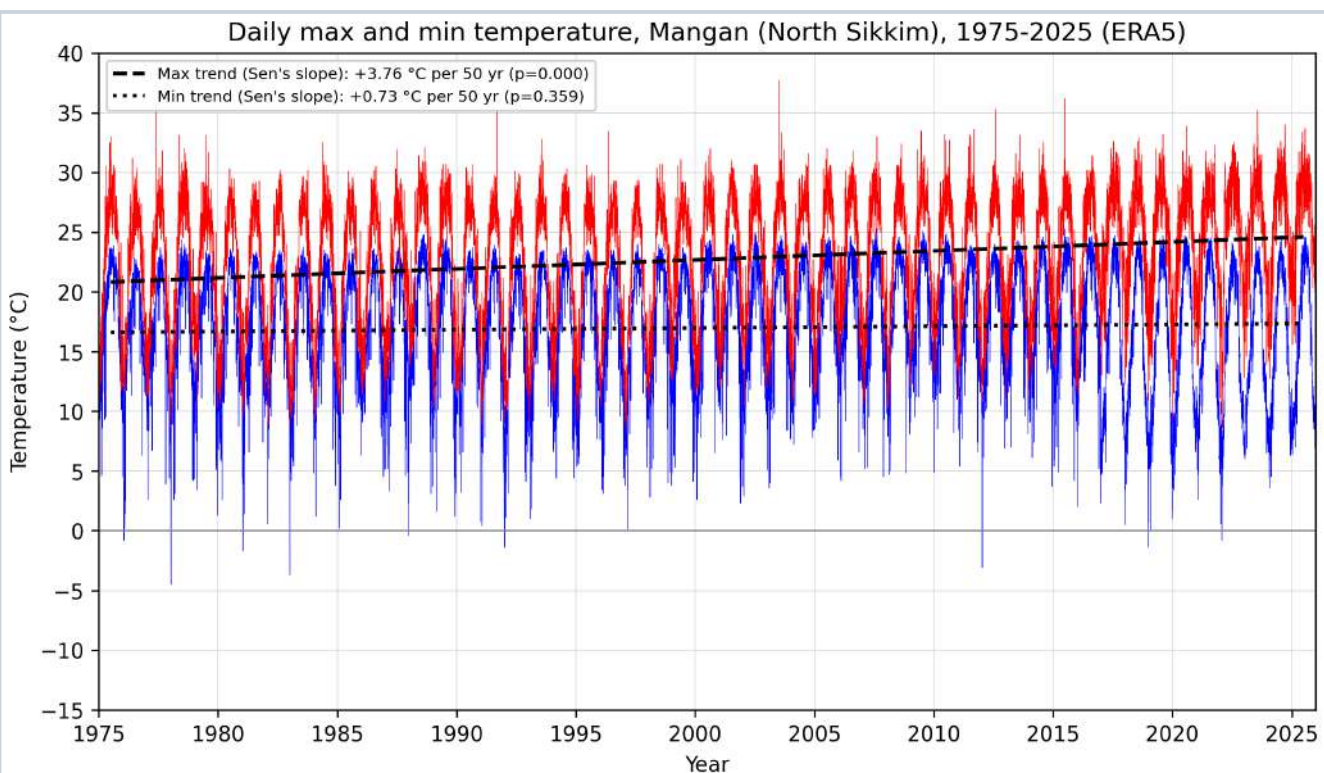
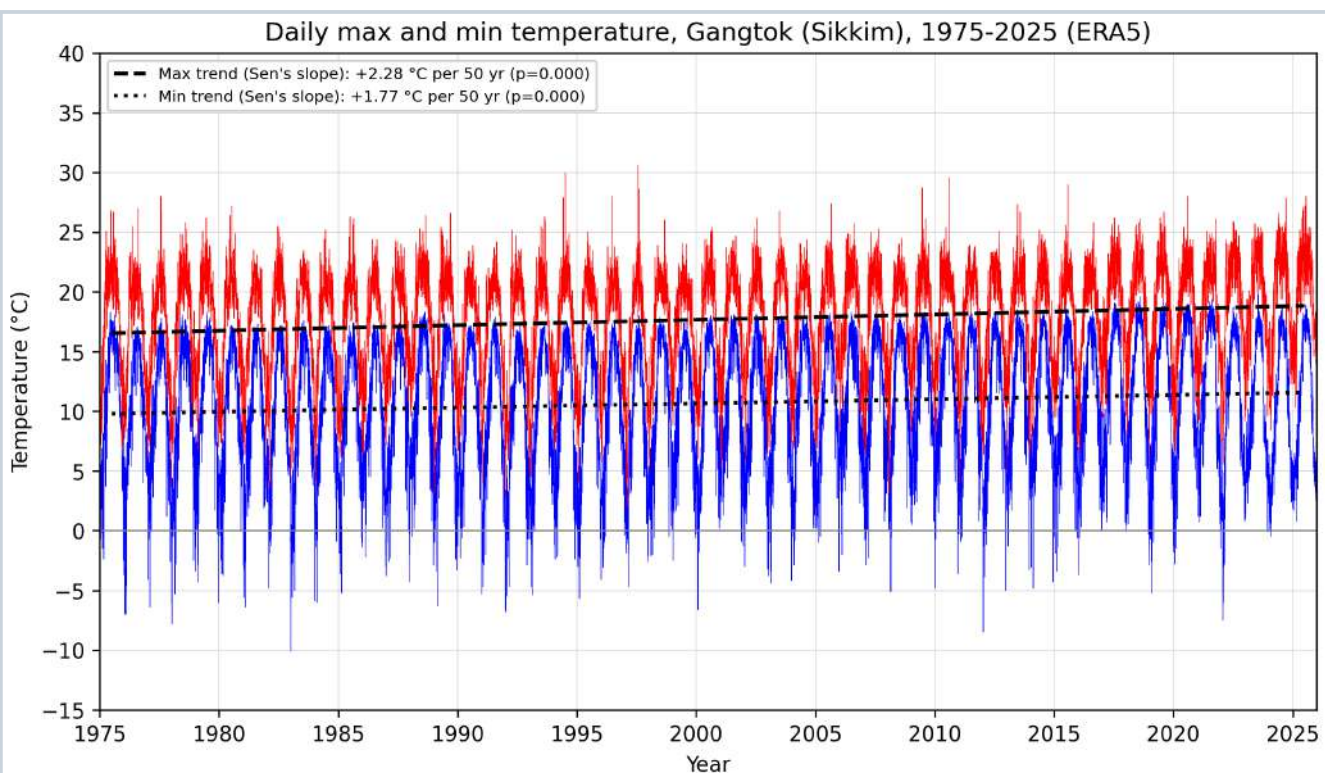
Study area



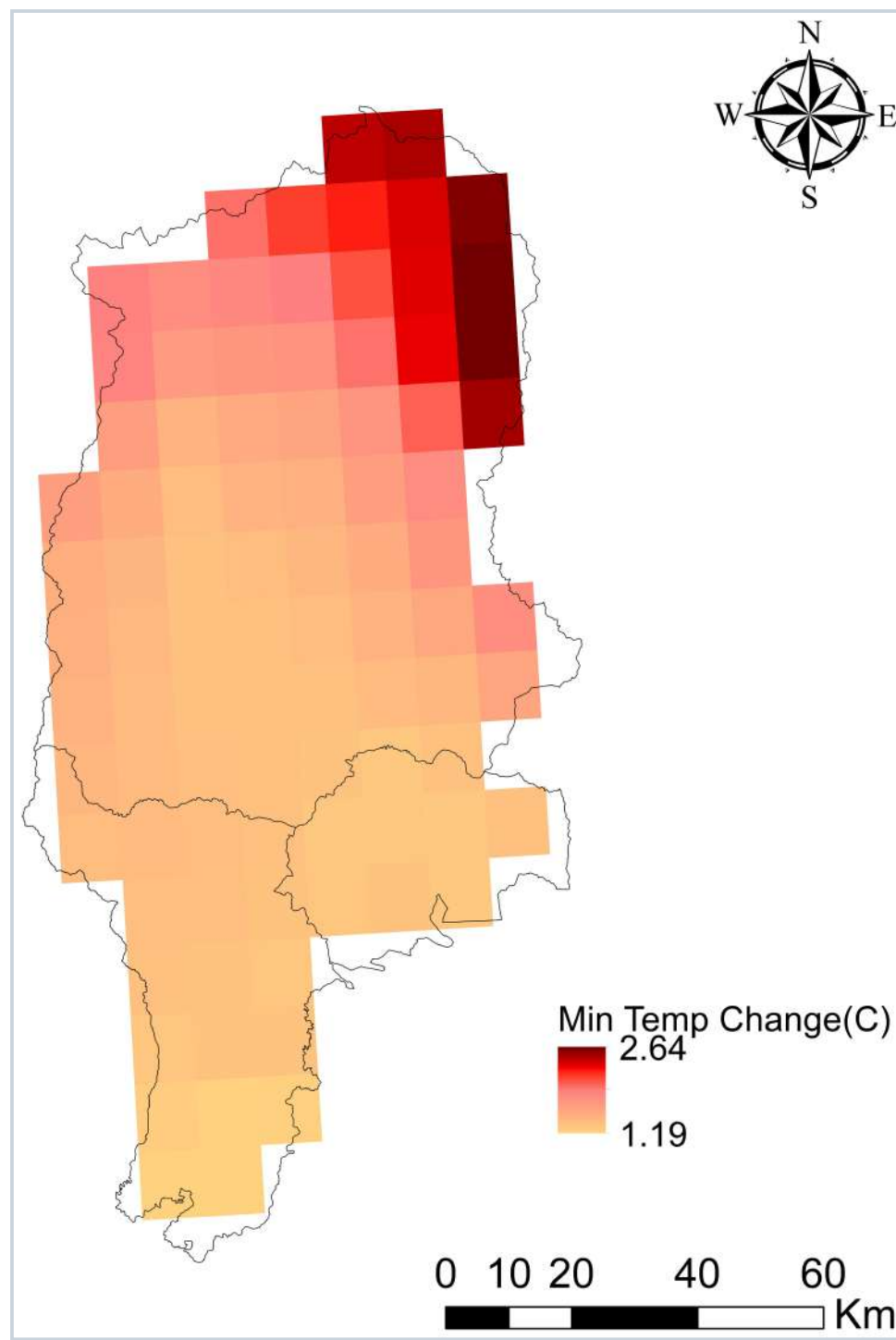
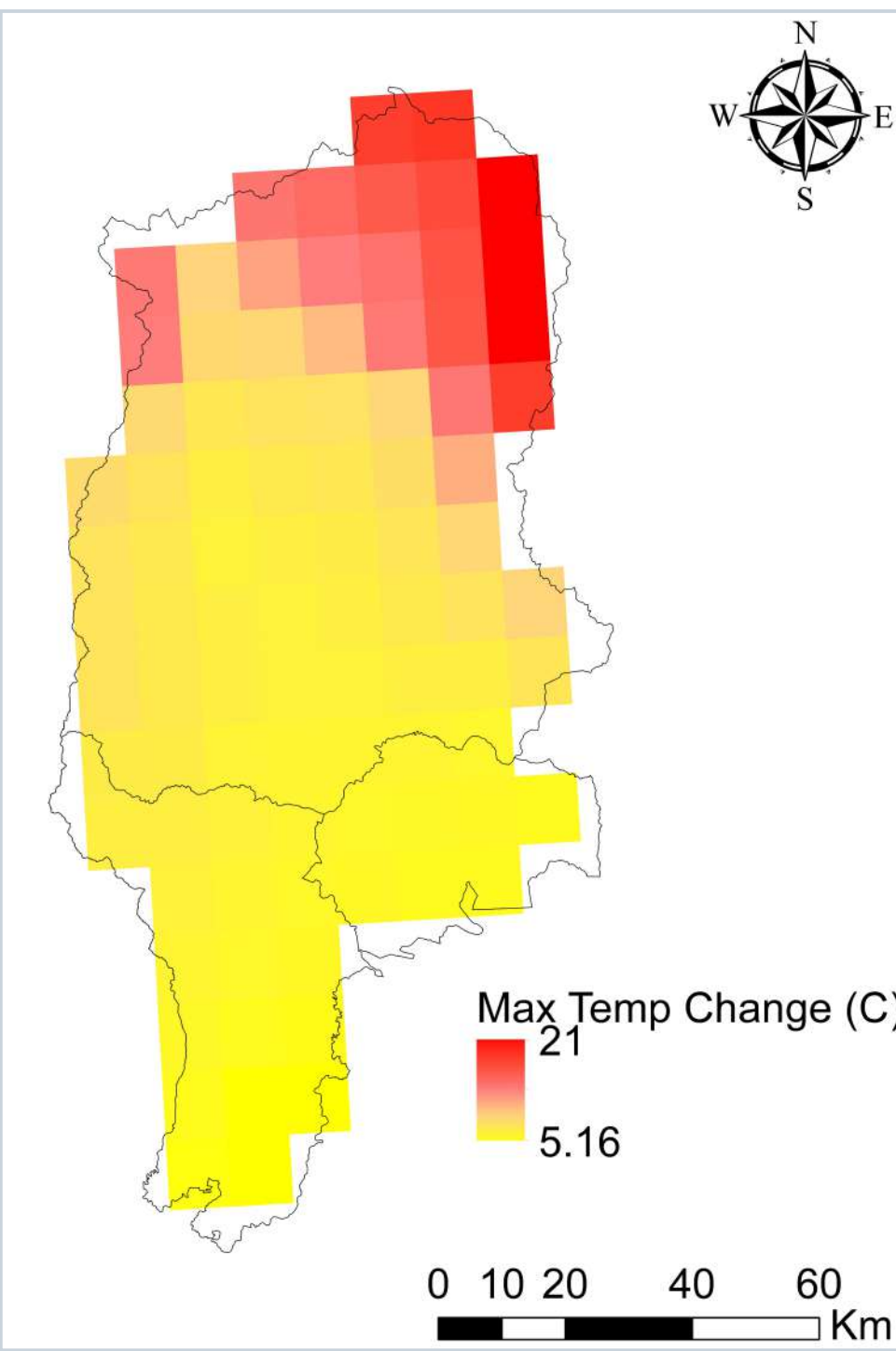
Data and methods

- Field survey:** 500 forest-adjacent croplands in the Sikkim and Darjeeling Himalaya (150–2500 m elevation).
- Climate:** ERA5 data (1975–2025); precipitation concentration index, Mann-Kendall test and Sen's slope estimator.
- Drivers:** Random Forest algorithm to identify controls on the spread of diseases, pests and weeds.

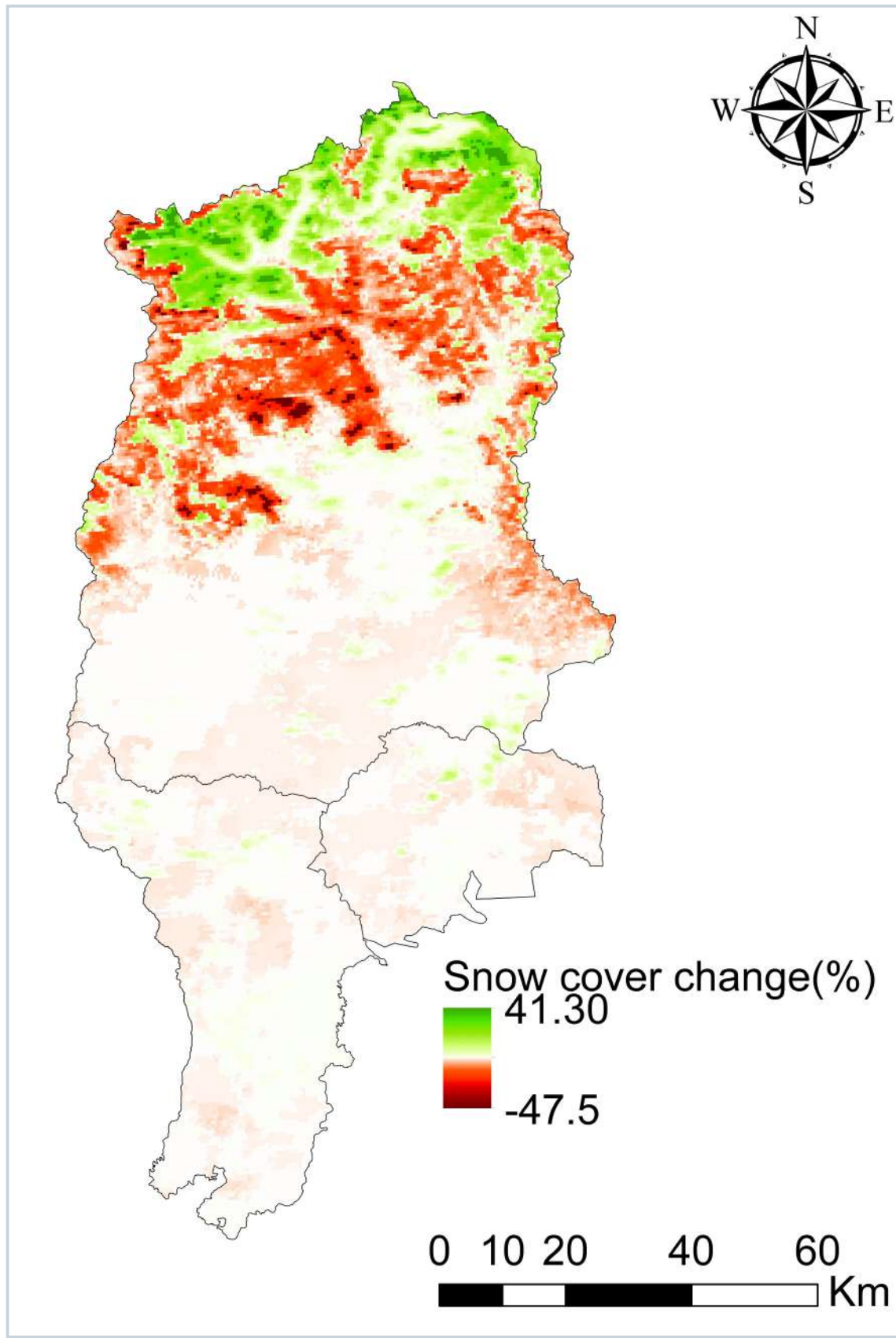
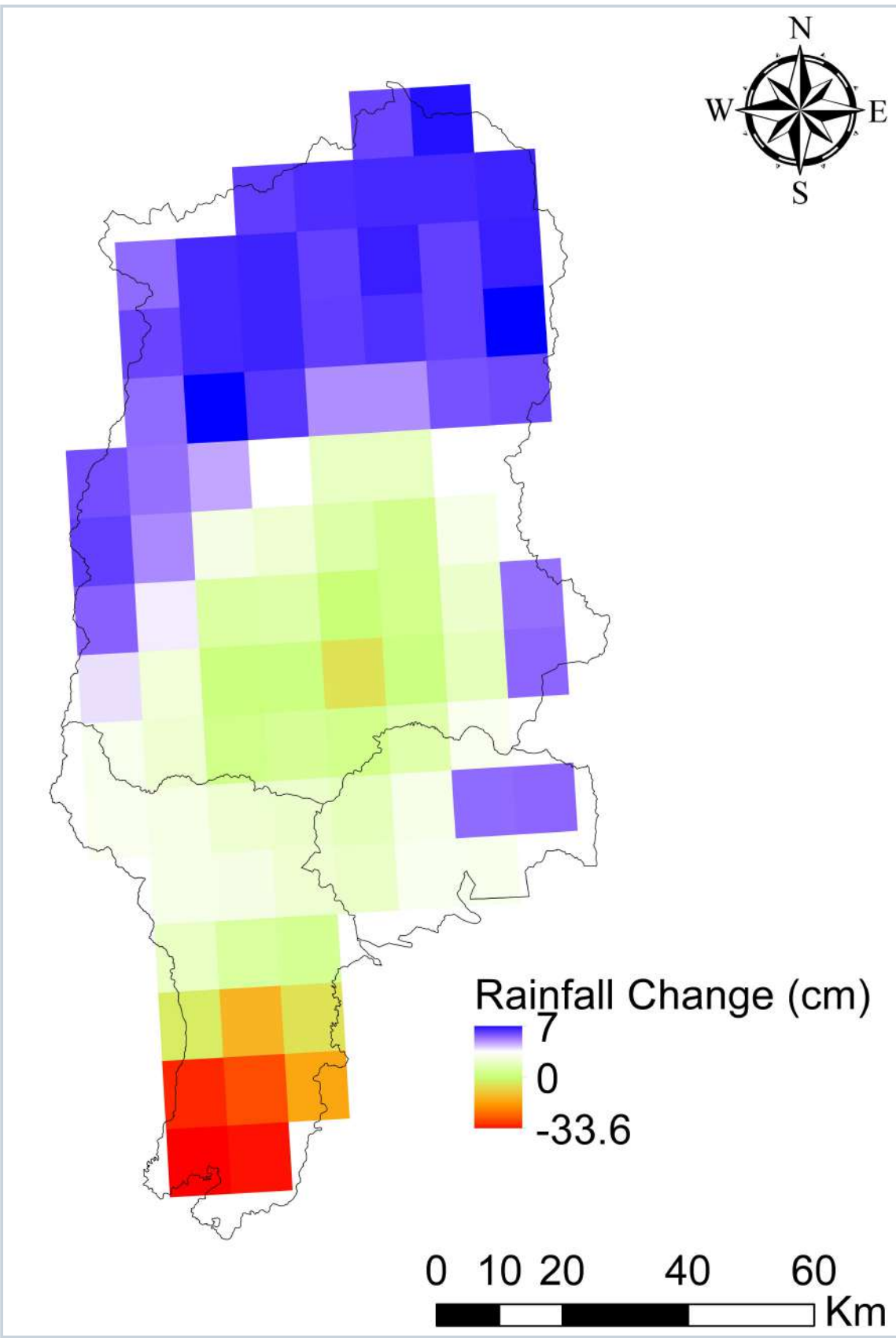
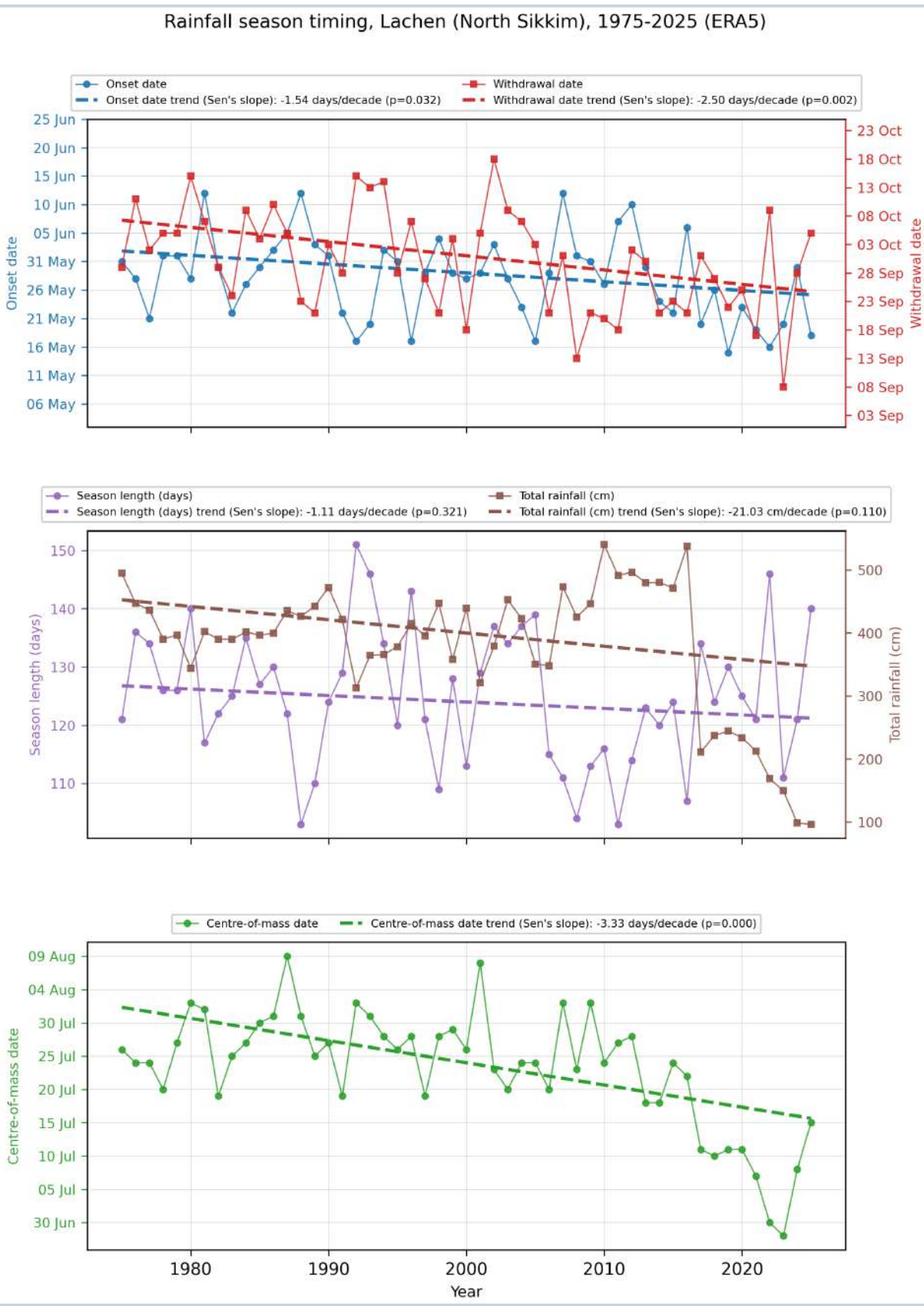
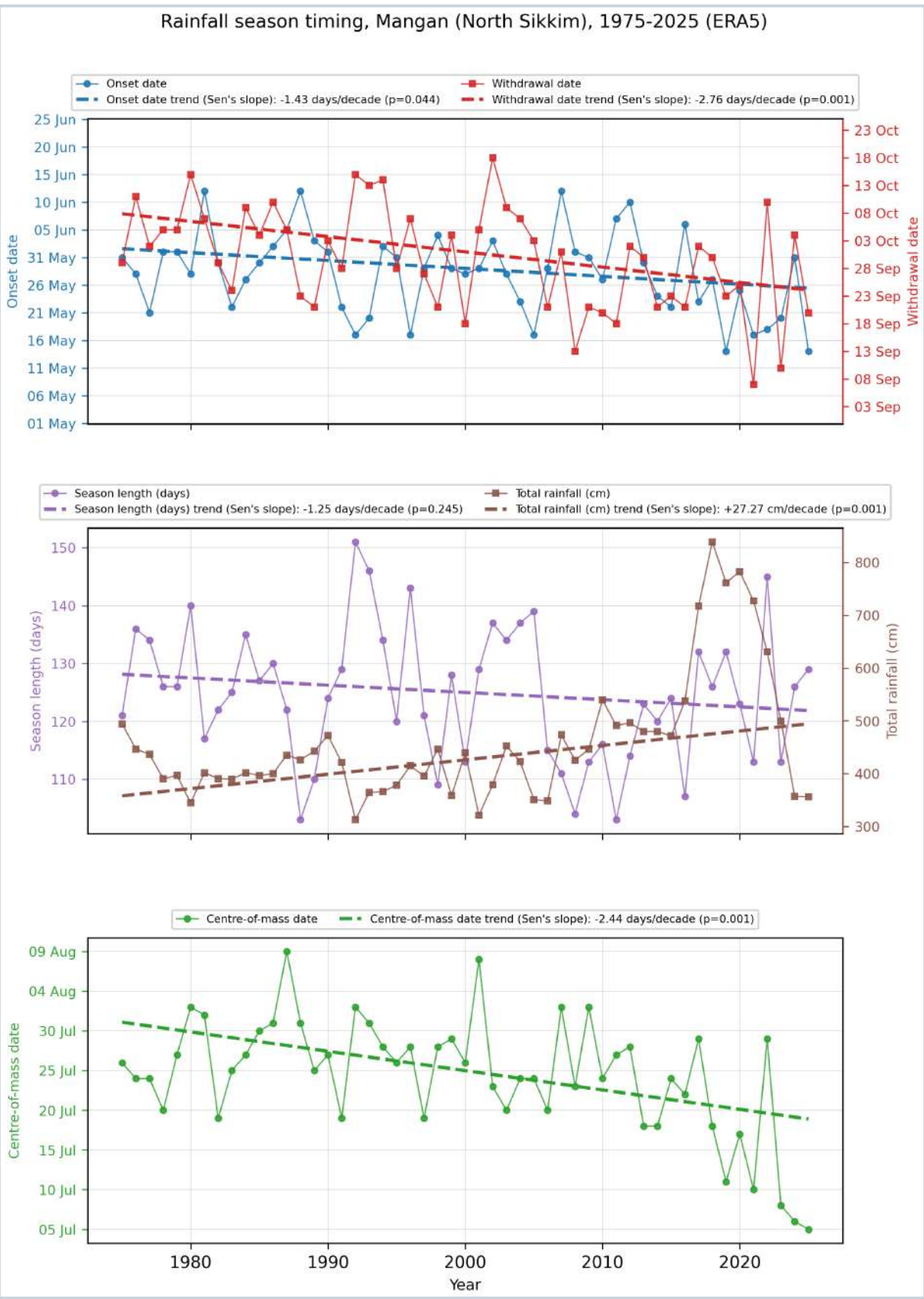
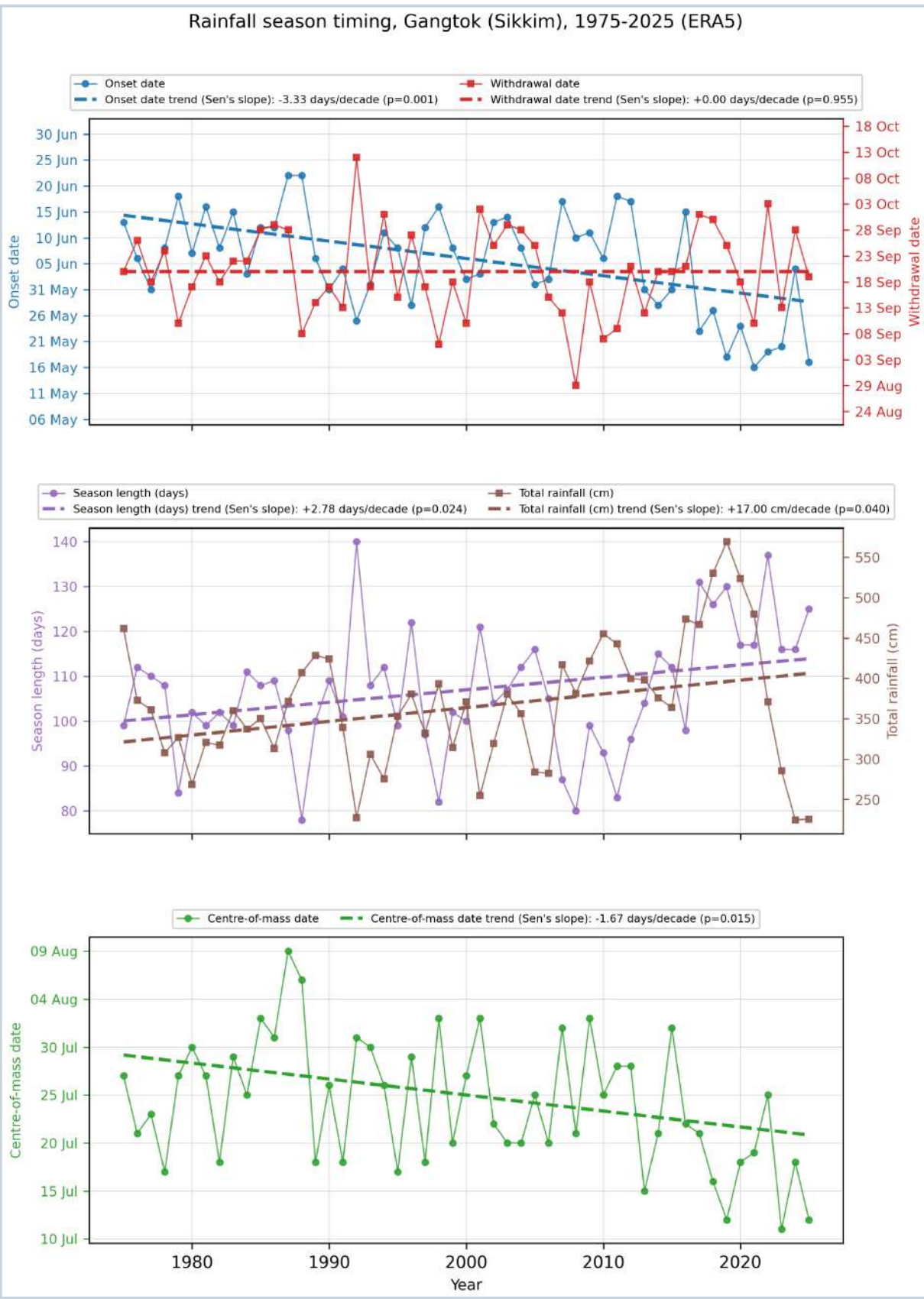
WARMING | Temperature trends at three stations and spatial change map



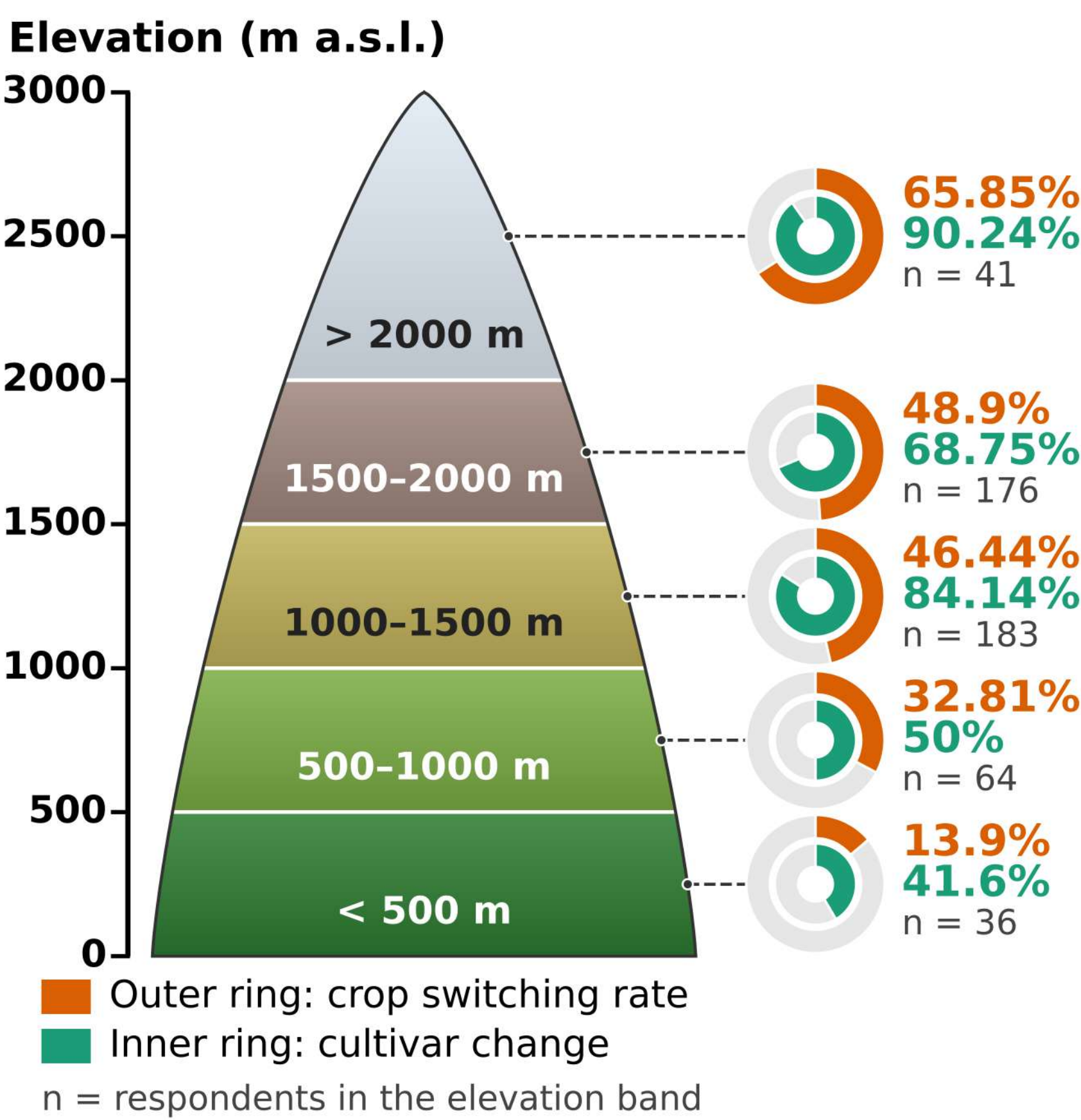
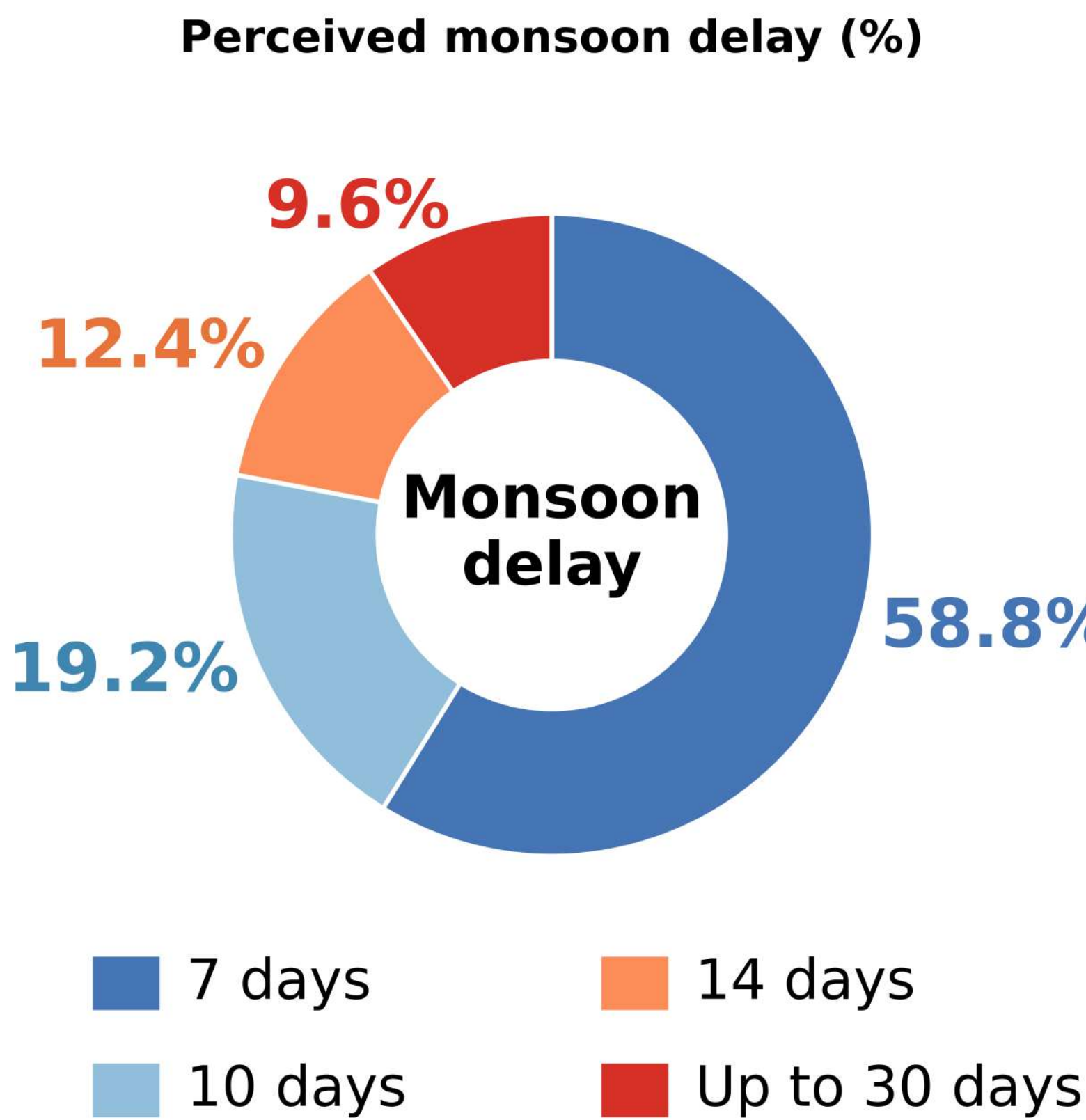
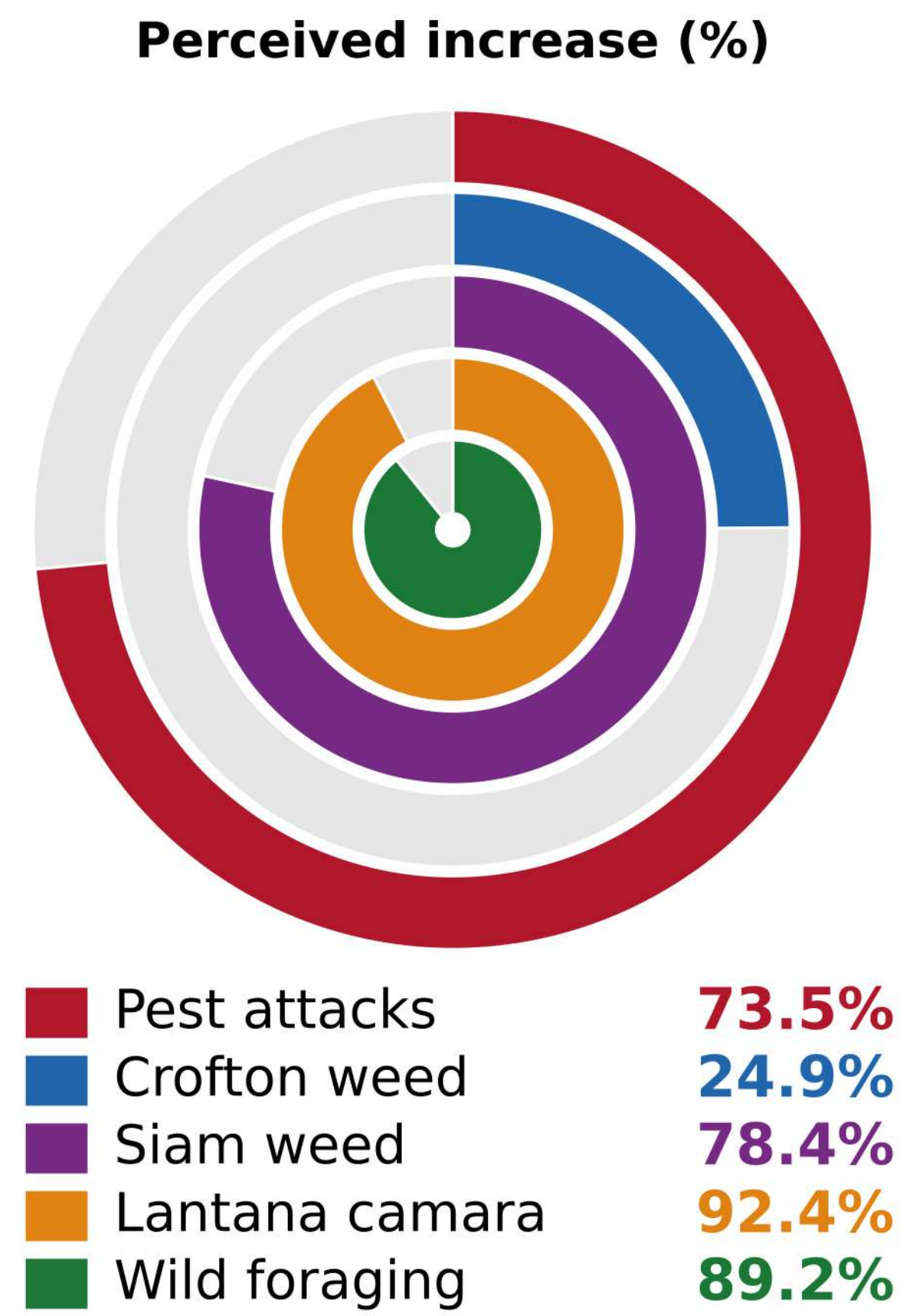
- Daily maximum (red) and minimum (blue) temperature, 1975–2025 (ERA5)** with Sen's slope trends. Maximum temperature rose significantly at all three stations; minimum temperature rose significantly at Gangtok and Lachen.
- Consistent elevation warming: **mean temperature rise of 0.8–1.9 °C**, with an upward trend in minimum temperatures. Maps show the spatial change in maximum and minimum temperature.



RAINFALL | Seasonal shift at three stations, rainfall change and snow cover change



FARMERS' PERCEIVED CHANGES | Ecology, monsoon delay and crop change by elevation



Water and coping

- Water:** more than 65% of respondents in South Sikkim, East Sikkim, Kalimpong and Darjeeling report **water scarcity**; in North and West Sikkim most farmers (>50%) perceive increased water.
- Coping:** drought-tolerant cultivars, altered sowing periods and, at times, a complete change of crop.
- Monsoon delay:** 7 days for most respondents, up to 30 days for some.

Key findings

- 89.2%** of 500 respondents observed increased wild foraging; shifts in crop combinations, delayed sowing periods, increased invasion of weeds and pests.
- Peak rainfall shifted from June–August to **July–September**: wetter wet season, drier dry period, intensified intra-annual variability.
- Snowfall frequency declined below 2500 m** — the main driver of disease, pest and weed spread (*Lantana camara*, *Ageratina adenophora*) in the Random Forest model; water security is also affected.

Conclusions and way forward

- Reactive coping — drought-tolerant cultivars, altered sowing periods, sometimes changing the crop — is **insufficient** to meet expected food production.
- Needed: **climate-informed agricultural planning**, re-delineation of agroecological zones, improved early warning for hydroclimatic variability, and integrated agriculture–forest policies to minimise human–wildlife conflict.