

Understanding the Changes in Winds and Precipitation over South Asia: Observations, Projections, and Limitations

Abstract

Beyond the global consensus on climate change, understanding its regional manifestations is essential for informed policy and effective decision-making. Yet the regions most vulnerable to climate impacts often lack robust and actionable climate information. South Asia exemplifies this challenge: home to over one-fifth of the global population, it faces multiple vulnerabilities arising from strong socioeconomic dependence on climate-sensitive sectors, complex land–ocean–atmosphere interactions, and limited model reliability at regional scales. Successive generations of climate models have produced inconsistent, at times contradictory, projections, underscoring the need for improved physical understanding and reliable detection of human-induced changes. Confidence in future projections depends on how well models reproduce historical changes, but reported changes in South Asian winds and precipitation remain uncertain due to observational gaps, limited agreement on underlying drivers, and the difficulty of separating forced signals from internal variability, and model uncertainty. With growing availability of long-term observations, large-ensemble (LE) simulations, and an increasingly distinguishable forced signal, it is now possible to evaluate model performance with greater confidence.

Leveraging these developments, this thesis examines how winds and precipitation over South Asia have changed in past, how they may evolve through the twenty-first century, and how reliably current models simulate these changes. Winds and precipitation represent distinct yet interconnected facets of the climate system: models explicitly simulate winds with higher fidelity, while precipitation, represented

through implicit sub-grid parameterizations, exposes structural and parameter uncertainties. Together, they provide an integrated perspective on the robust and fragile elements of model performance.

Historical analyses using multiple observations and large-ensemble (LE) simulations reveal a robust weakening of the continental subtropical westerlies (STWs), a key circulation feature whose role in South Asia's climate has been under-recognized, since the late twentieth century. This weakening originates from aerosol- and land-use land-cover (LULC)-driven surface cooling over northwestern South Asia, which reduces the zonal pressure gradient against a greenhouse-gas- (GHG-) warmed Arabian Peninsula, producing a differential warming pattern that deflects and slows the continental winds. In contrast to winds, the observed changes in precipitation—drying over the Indo-Gangetic Plain and increased precipitation in north-western and peninsular regions—are not simulated neither by CMIP nor LE models, reflecting persistent deficiencies in parameterizations governing convection, cloud microphysics, and aerosol–cloud interactions.

Future projections indicate a transition in the forcing regime. As aerosol emissions decline, their earlier cooling effect no longer masks GHG warming, allowing GHGs and LULC changes to emerge as the dominant drivers of circulation. These forcings strengthen near-surface winds over large parts of South Asia and increase the wind-energy potential, extending favourable regions beyond the present onshore resourceful regions. However, the realizable wind-energy potential remains constrained by uncertainties in irrigation representation and by socio-economic factors such as urbanization, land-use competition, and rising electricity demand.

In contrast, precipitation projections remain highly uncertain. Perturbed-parameter ensemble analyses and targeted numerical experiments demonstrate that small variations in parameter choices that govern convective and cloud-related processes can reverse the sign of regional precipitation change—even under identical SST forcing, indicating that conventional SST-based attribution assumptions may not hold regionally. These sensitivities arise from the competing effects of convective

heating and SST-forced response, which modulate precipitation most strongly along the margins of deep convection and in nearby secondary convective regions, where drying signals to warming commonly emerge. These regions include the Maritime Continent, Africa, and South America, which are equally vulnerable to climate-change-related uncertainties. This parameter-driven uncertainty exceeds internal variability and partly explains the divergent and often self-contradictory precipitation projections reported across successive model generations, even though global-mean precipitation responses to warming remain comparatively robust.

Together, the findings show that wind changes can be more robustly attributed and projected, whereas precipitation response remains uncertain because precipitation depends on parameterized convection and sub-grid processes that models cannot implicitly simulate, unlike winds, which are simulated by solving momentum equations. The thesis highlights the need for improved representation of sub-grid processes, strengthened regional customization, expanded use of coordinated LEs, greater integration of AI/ML approaches to refine uncertain parameterizations as immediate priorities, alongside longer-term progress toward kilometre-scale modelling to enhance the credibility of regional climate information for South Asia.