

Decoding the Descent: Raindrop Evaporation and Its Impact on Isotope based Climate Model Fidelity

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Introduction

- Rainwater isotope conservative behaviour has led to integration within isotope-enabled General Circulation Models (GCMs), which simulate rain and vapour isotopes and are benchmarked against proxy records to constrain past atmospheric circulation.
- However, these models have significant isotope biases over Indian proxy locations. About 70% of this bias arises from inadequate representation of raindrop evaporation within models (Nimya et al., 2022).
- As raindrops fall through an unsaturated sub-cloud layer, partial evaporation alters isotopic composition
- Its importance, the raindrop evaporation fraction remains poorly constrained due to limited observations.

Methods and Materials

- Daily vapour and rain samples collected at IITM Pune during JJAS months of 2019.
- Stable isotopes of oxygen ($\delta^{18}\text{O}$) and hydrogen (δD) were measured using a laser-based Liquid Water Isotope Analyser (LWIA-45P).
- One-dimensional Below Cloud Interaction Model (BCIM) is used to quantify raindrop evaporation.
- The model consists of a single vertical column that extends from the ground to the height where a single hydrometeor is introduced.

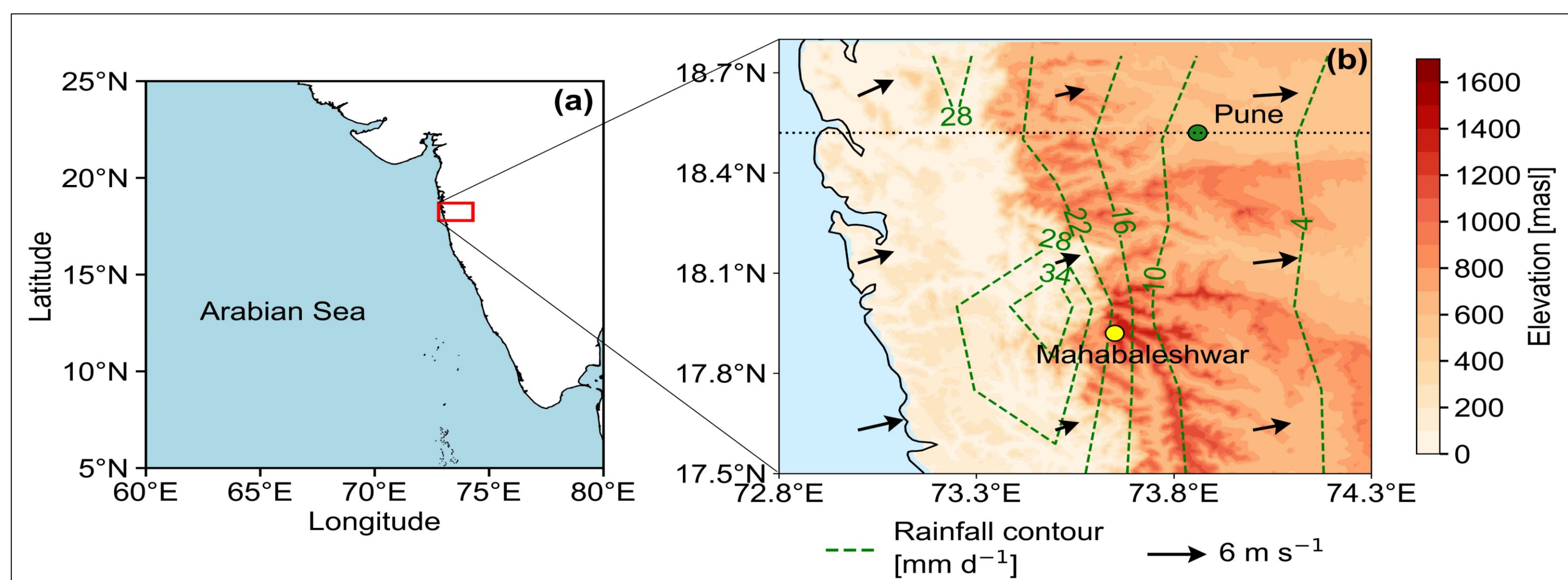
Microphysics of a falling hydrometeor

- Stable isotopes are measure as
$$\delta = \left(\frac{R_{\text{sample}} - R_{\text{VSMOW}}}{R_{\text{VSMOW}}} \right) \times 1000$$

R - ratio of the heavier isotope to the lighter isotope ($^2\text{H}/^1\text{H}$ or $^{18}\text{O}/^{16}\text{O}$)
- The change in mass of a falling hydrometeor is calculated as (Pruppacher and Klett, 2010)
$$\frac{dm}{dt} = \frac{2\pi D f_v D}{R_w^*} \left(h \frac{e_{\text{sat}}(T_\infty)}{T_\infty} - \frac{e_{\text{sat}}(T_d)}{T_d} \right),$$

Where f_v is ventilation coefficient, D is diffusivity of vapour, $R_w^* = R/M_w$ specific gas constant for water vapour, h is ambient relative humidity, T is ambient temperature, T_d is hydrometeor temperature, $e_{\text{sat}}(T_\infty)$ is saturation vapour pressure in the ambient air. T_1 , and $e_{\text{sat}}(T_d)$ saturation vapour pressure above the hydrometeor surface $e_{\text{sat}}.T_d$.
- Calculation of the isotopic composition along the fall trajectory of a hydrometeor (Pfahl et al. 2012)
$$\frac{dm'}{dt} = \frac{2\pi D f_v D}{R_w^*} \left(\frac{f_v' D'}{f_v D} \right)^n \left(h \cdot \frac{e'_{\text{sat}}(T_\infty)}{T_\infty} - \frac{e'_{\text{sat}}(T_d)}{T_d} \right)$$

Study area



Acknowledgement

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Assessing raindrop evaporation over northern Western Ghats from stable isotope signature of rain and vapour

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Input parameters used for the BCIM model

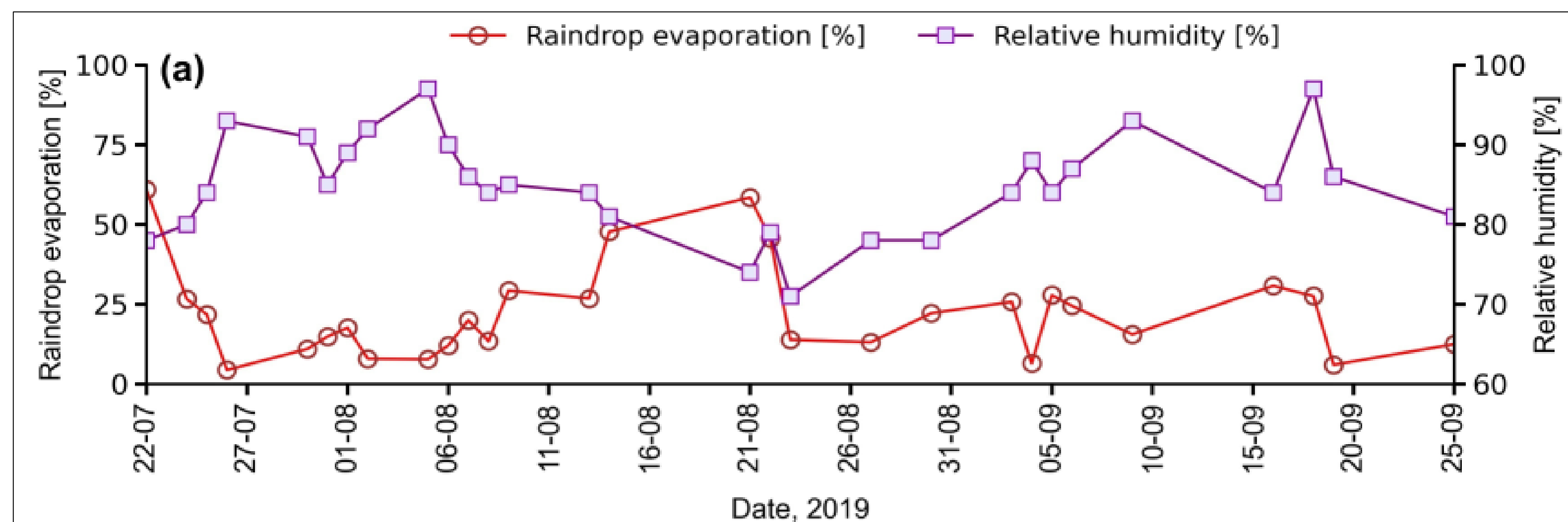
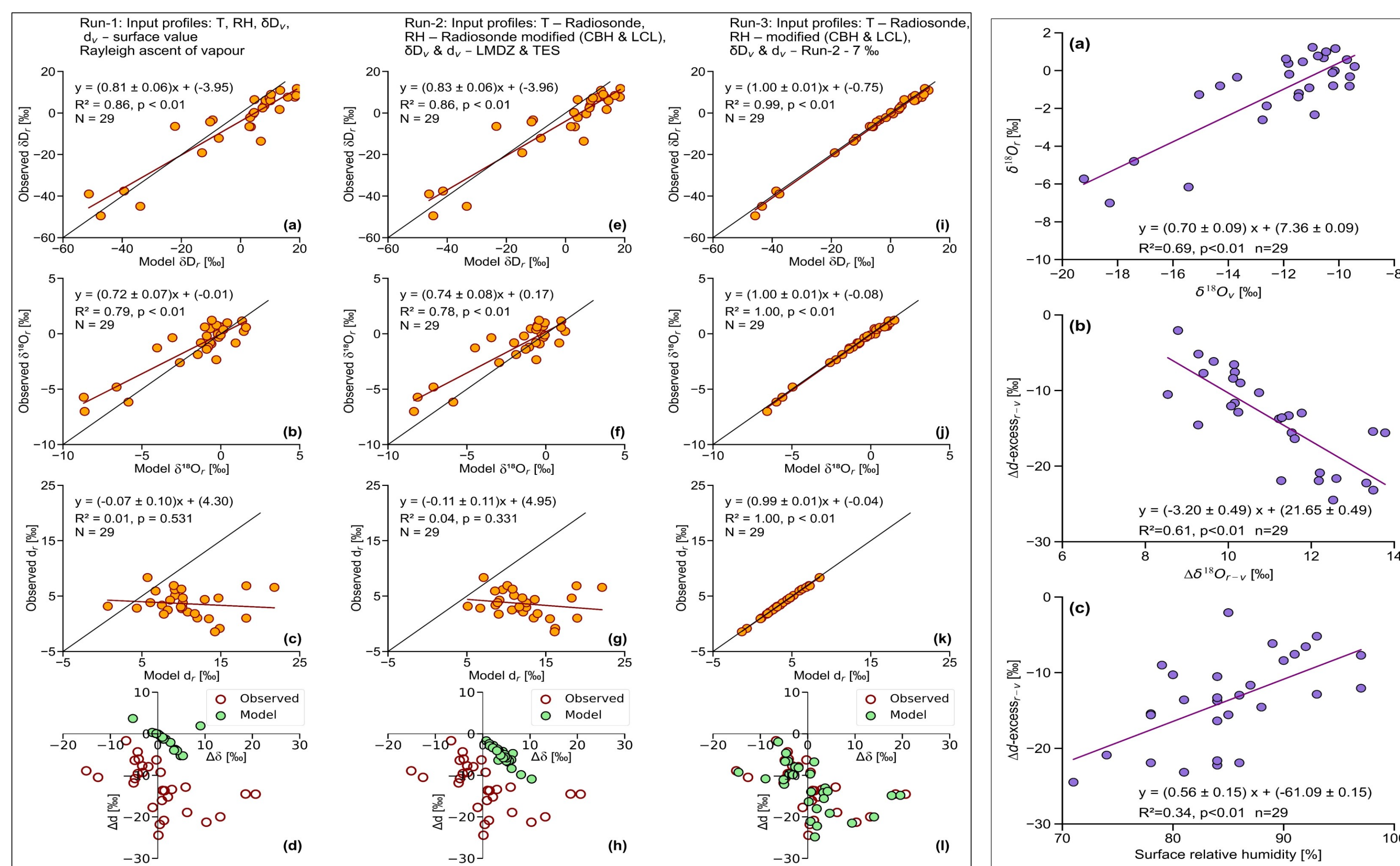
Table 1. Input parameters for the three BCIM runs.

Sl. No	BCIM input	Parameters for Run-1	Parameters for Run-2	Parameters for Run-3
1	Drop size	Marshall–Palmer equation using hourly rainfall data obtained from IMD	Same as Run-1	Same as Run-1
2	RH profile	Rayleigh ascent ~ 15 % increase per km and 100 % above CBH to drop introduction height	Radiosonde values normalized to surface observation and changed to 100 % above CBH to drop introduction height	Same as Run-2
3	Temperature profile	Rayleigh ascent Lapse rate ~ 5.6 °C km ⁻¹	Radiosonde normalized to ground value	Same as Run-2
4	D _v profile	Rayleigh ascent ~ 7 ‰ decrease per km	TES normalized to measured surface value	D _v values reduced slightly (within ±4 ‰), keeping the shapes like Run-2
5	d _v profile	Rayleigh ascent ~ 0.1 ‰ increase per km	LMDZ D _v and ¹⁸ O values used to get d _v normalized to the measured ground value	d _v decreased from Run-2 average of 17 ‰ to an average ~ 10 ‰
6	Raindrop formation height (CLWC peak)	ERA5 CLWC peak	Same as Run-1	Same as Run-1
7	Cloud Base Height (LCL)	LCL from radiosonde profiles using skew-T log P diagram	Same as Run-1	Same as Run-1

Results and Discussion

Observed versus model values for rain δD_r , $\delta^{18}\text{O}_r$, and d_r for various runs

Rain-vapour isotope exchange



Conclusion

- Rayleigh-based approach overestimates rain isotope values, incorporating radiosonde derived temperature–humidity profiles and improved vapour isotope inputs from satellite and model data enhances model accuracy.
- We find that 3–50% (mean ~23%) of rainfall evaporates before reaching the surface.
- Considerable cooling of the boundary layer, leading to localized downdrafts and changes in atmospheric stability.
- Sensitivity analysis indicates that a 10% increase in evaporation can reduce surface rainfall to similar proportion (Nimya et al, 2026).
- These results highlight the need to better parameterize raindrop evaporation to improve isotope simulations and rainfall predictions.