Investigating rain rate estimates from non-conventional satellites to supplement H SAF products at global scale

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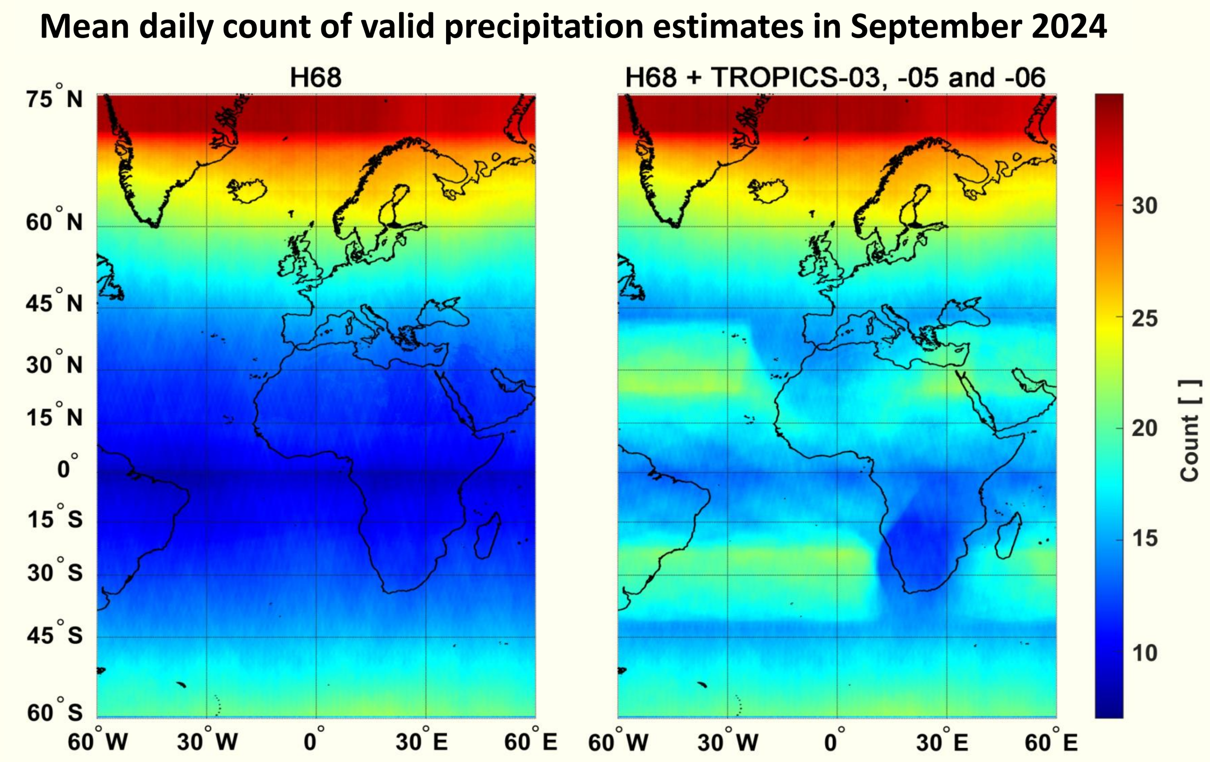
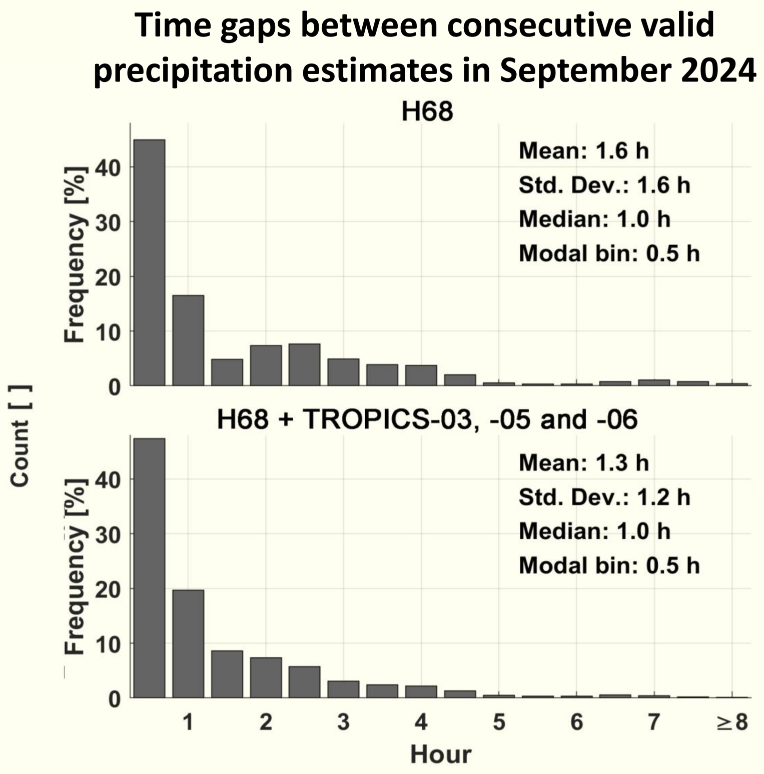
Daniele Casella[1], Domenico Cimini[2], Francesco Di Paola[2,*], Marco Petracca[1], Paolo Sanò[1]
1) National Research Council (CNR) of Italy, Institute of Atmospheric Sciences and Climate (ISAC) — 2) CNR, Institute of Methodologies for Environmental Analysis (IMAA) — * francesco.dipaola@cnr.it

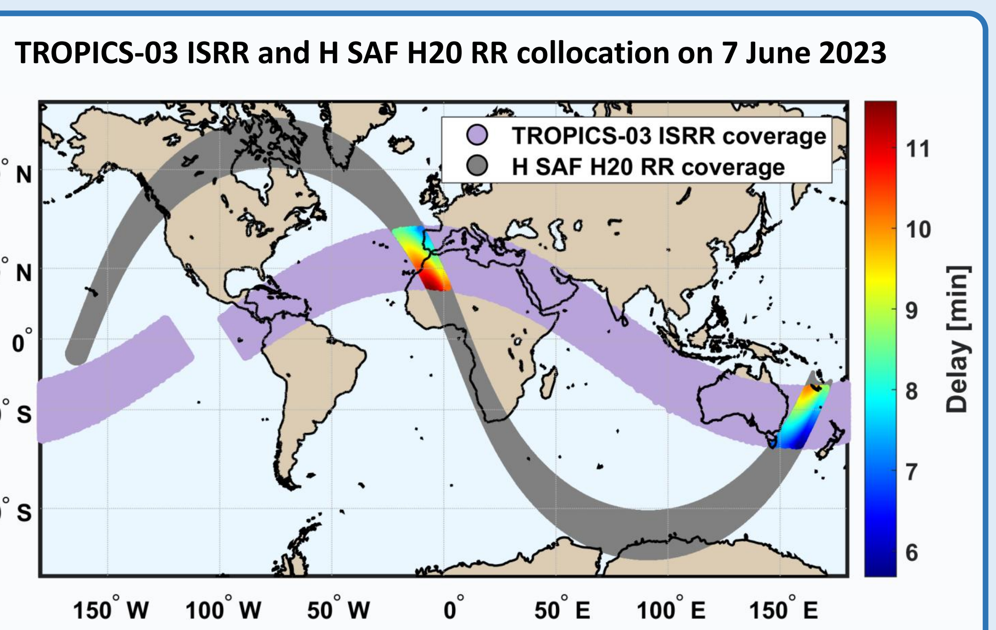
Passive microwave (PMW) observations are the backbone of H SAF precipitation products, but the corresponding radiometers fly on Low Earth Orbit (LEO) satellites, mostly on polar orbits, leading to non-uniform sampling, especially at low latitudes, where the largest revisit gaps occur. Small satellite PMW constellations, such as NASA's TROPICS mission (*Time Resolved Observations of Precipitation structure and storm Intensity with a Constellation of SmallSats*), a constellation of CubeSats carrying the 12-channel cross-track TROPICS Millimeter wave Sounder (TMS), can help mitigate these sampling gaps by increasing the availability of instantaneous rain rate (RR) retrievals. However, before TROPICS estimates can complement existing H SAF precipitation products, their consistency with operational H SAF references must be assessed and, where needed, improved. This study therefore evaluates the agreement between NASA TROPICS Level-2B Instantaneous Surface Rain Rate (ISRR) and H SAF H20 RR, used here as the reference, and explores an adjustment to reduce systematic differences. This adjustment should not be interpreted as a ground truth calibration, but as a consistency adjustment within the selected H SAF framework. Although TROPICS has concluded, it remains a valuable test case for assessing how PMW estimates from CubeSats could complement H SAF products and support future constellations such as Tomorrow.io.



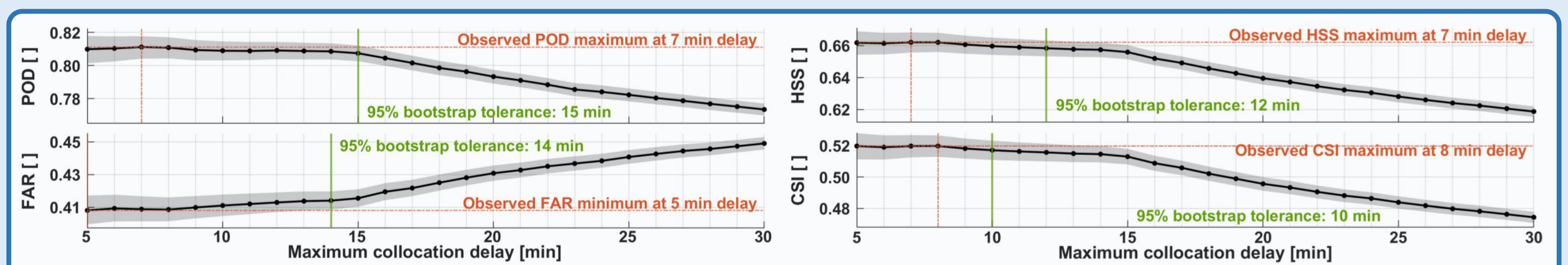


Potential sampling benefit from adding TROPICS – H68 is the H SAF Level 3 PMW precipitation product, provided every **30 minutes on a 0.25° × 0.25° grid** over the extended H SAF area, 60°S–75°N and 60°W–60°E. **Adding TROPICS-03, -05, and -06 ISRR mainly reduces low latitude observation gaps, increasing the domain mean daily count** of valid instantaneous estimates from 14.9 to 18.1. The fraction of 30-minute gaps rises from 44.9% to 47.4%, while the mean gap decreases from 1.6 h to 1.3 h.

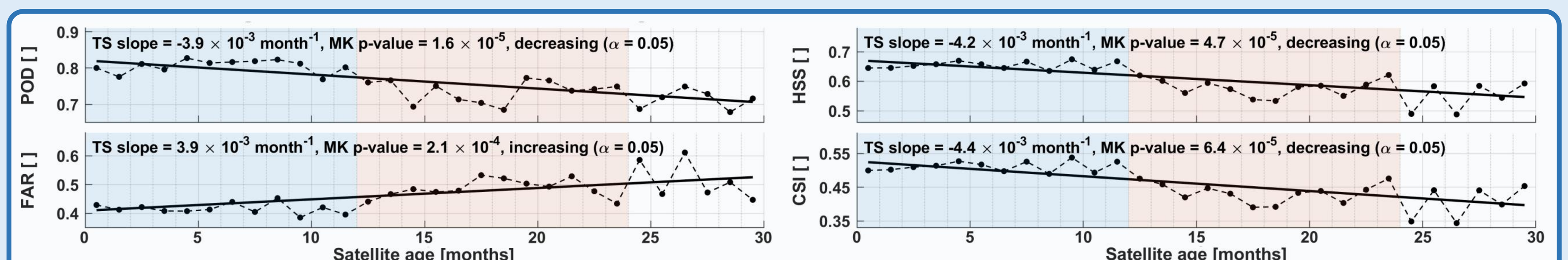
Match-up dataset construction and split



Spatial collocation – **H20 RR** was averaged over each **TROPICS G band footprint** to derive a reference value at ISRR scale, matching the coarser spatial sampling of the ISRR product. Footprints were modelled as **ellipses with scan dependent axes**, from 14.4 × 17.9 km at nadir to 34.1 × 125.6 km at the scanline edge.



Maximum collocation delay – A 5–30 min sensitivity test with **~10^4 block bootstrap replicates** indicated **10–15 min from categorical metrics**, while **continuous metrics indicated 17–30 min** (not shown). A **maximum delay of 15 min** was selected to balance skill and sample size.



Data split – Categorical metrics, consistent with the continuous metrics (not shown), indicated **decreasing agreement between TROPICS ISRR and H20 RR with satellite age**. **Months 1–12** were therefore used **for calibration** as the most reliable period, while **months 13–24** were kept as an independent **test dataset** to assess the calibration results.

TROPICS satellites used:
-01, -03, -05, and -06

Spatial collocation:
H20 RR averaged within TROPICS footprints

Temporal collocation:
maximum delay 15 min

Calibration datasets:
TRP-01: Aug 21–Jul 22
TRP-03/05/06: Jun 23–May 24
5.4×10^7 training samples
1.8×10^7 validation samples

Test dataset:
TRP-01: Aug 22–Jul 23
TRP-03/05: Jun 24–May 25
TRP-06: Jun 24–Mar 25
4.7×10^7 indipendent samples

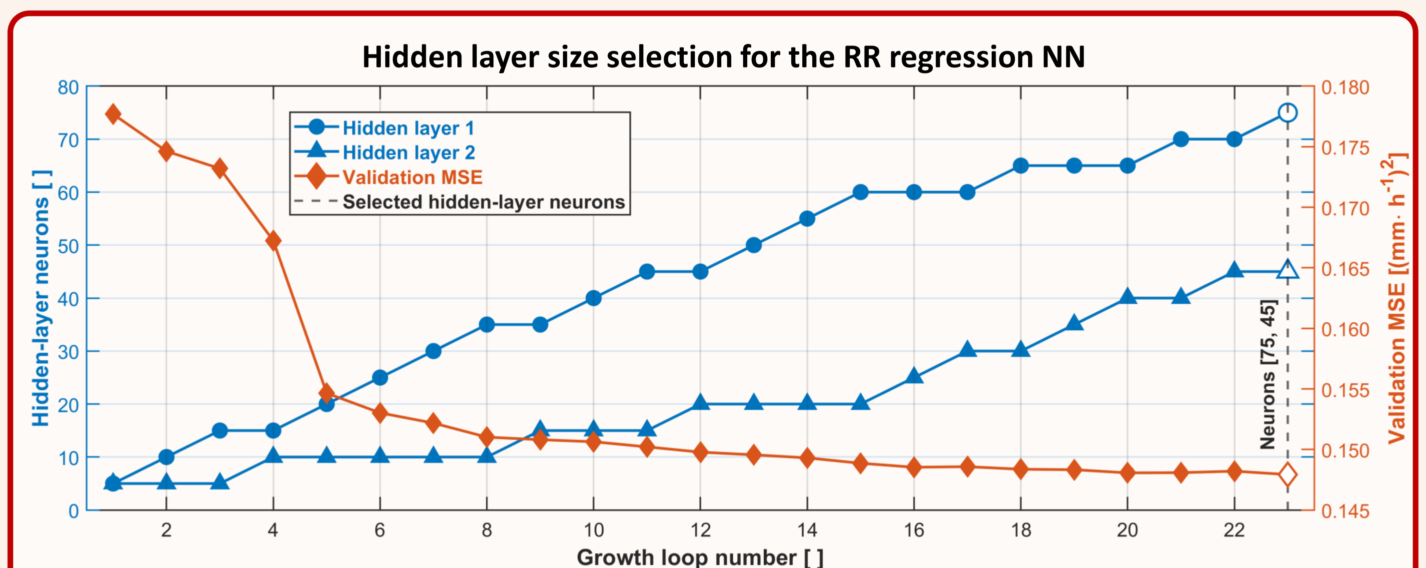
Calibration neural networks

Configuration steps: hidden layer growth → feature ranking → sequential pruning → batch size tuning → learning rate tuning

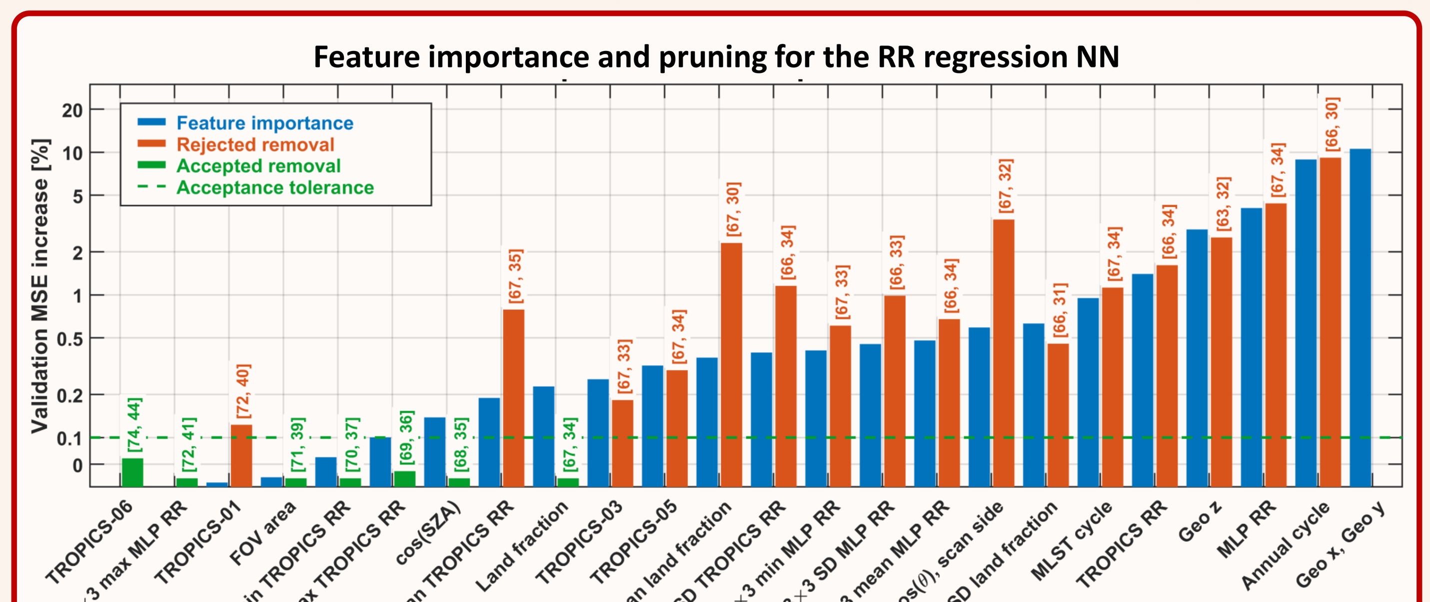
Two feedforward NNs were defined, each with two ReLU hidden layers and one output.

1) Rain/no rain NN
Output: **P(RR > 0.25 mm·h⁻¹)**
Loss: **Binary Cross Entropy (BCE)**
Inputs retained : **27**
Hidden neurons: **[300, 238]**
Batch size: **11,787**
Initial learning rate: **2.5×10^{-4}**

2) RR regression NN
Output: **RR**
Loss: **Mean Squared Error (MSE)**
Inputs retained: **21**
Hidden neurons: **[67, 34]**
Batch size: **61,032**
Initial learning rate: **1.25×10^{-4}**



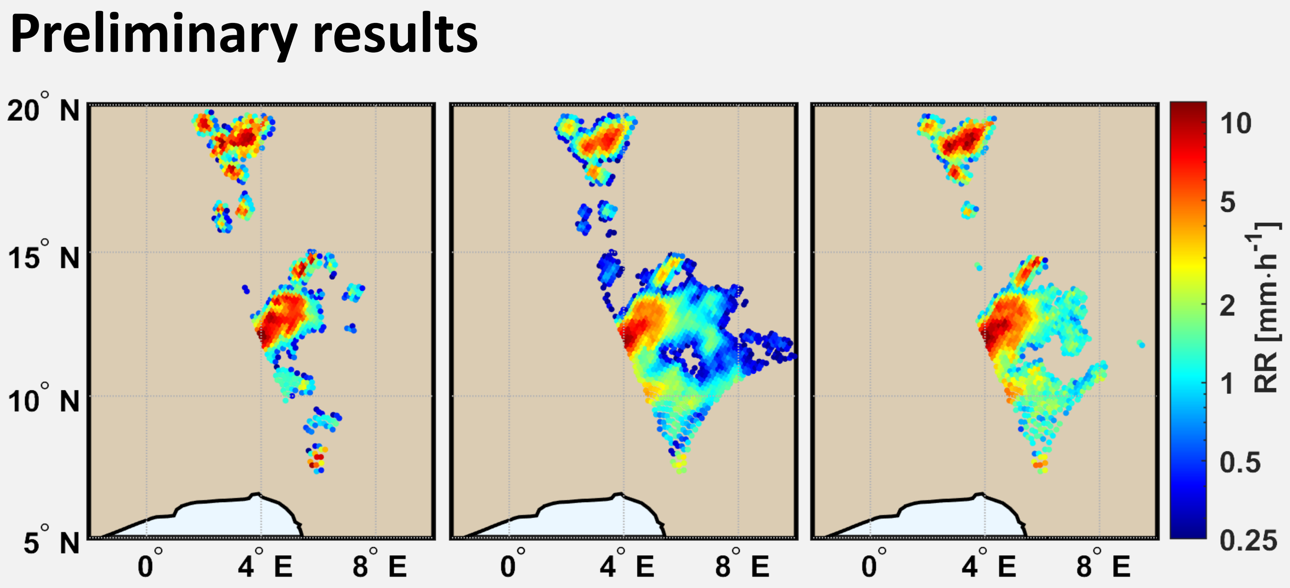
NN configurations were defined through iterative growth. At each loop, an NN specific **increment of 5 or 10 neurons was tested** on the first and second hidden layer over **five random seeds**. The candidate with the lowest validation loss was selected as the configuration. The search stopped after 3 consecutive loops without at **least 0.1% improvement**.



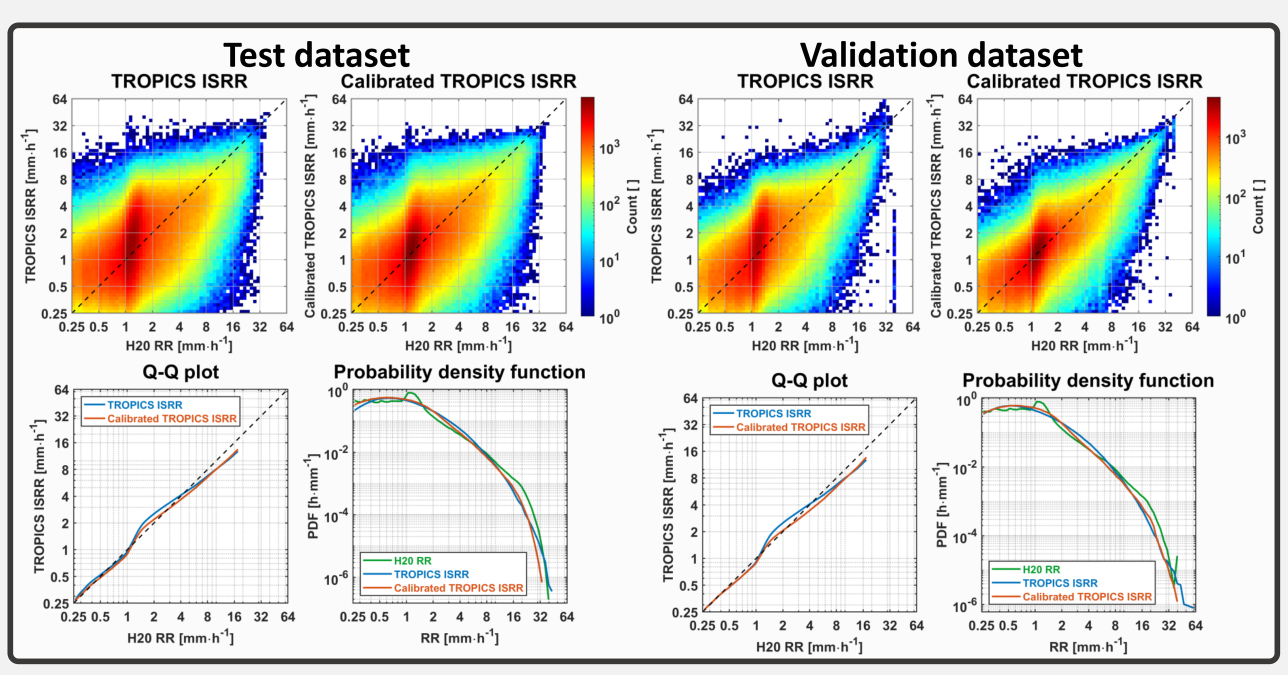
Feature importance was estimated from the validation loss increase after single feature removal. **Sequential pruning** then tested cumulative removals from least to most important, with **hidden layer sizes readjusted** and a 0.1% tolerance.

Batch size was optimized through an **adaptive sensitivity analysis** over five seeds, first around the current value and then near the lowest median validation objective. The **initial learning rate was tuned** by progressive halving, retaining only steps improving the validation objective by at least 0.1%.

Preliminary results



Example of RR fields from H20 RR (left), TROPICS-06 ISRR (center), and calibrated TROPICS-06 ISRR (right) on 19 Aug 2024 at 14:45 UTC over the northern Gulf of Guinea



	μ [mm/h]	σ [mm/h]	MBE [mm/h]	RMSE [mm/h]	CC	KGE	POD	FAR	HSS	CSI
Overall	2.03 (1.95)	2.60 (2.57)	0.03→-0.13 (-0.01→-0.19)	**2.22→2.12 (1.94→1.65)**	**0.57→0.61 (0.67→0.77)**	**0.52→0.57 (0.63→0.72)**	0.73→0.60 (0.81→0.73)	**0.48→0.32 (0.42→0.18)**	**0.58→0.62 (0.66→0.76)**	**0.43→0.47 (0.51→0.63)**
Land	2.61 (2.68)	2.52 (2.56)	**-0.68→-0.34 (-0.76→-0.39)**	**2.24→2.14 (2.14→1.82)**	**0.53→0.57 (0.63→0.72)**	**0.42→0.53 (0.50→0.68)**	0.66→0.52 (0.69→0.60)	**0.58→0.39 (0.54→0.22)**	**0.49→0.54 (0.53→0.67)**	**0.35→0.39 (0.38→0.51)**
Sea	1.88 (1.80)	2.60 (2.54)	**0.22→-0.07 (0.16→-0.14)**	**2.22→2.12 (1.88→1.60)**	**0.59→0.61 (0.70→0.78)**	**0.52→0.58 (0.63→0.73)**	0.77→0.64 (0.86→0.78)	**0.45→0.29 (0.38→0.16)**	**0.61→0.65 (0.70→0.80)**	**0.47→0.50 (0.56→0.68)**
Inner FOV	2.18 (2.05)	2.85 (2.75)	**-0.20→-0.19** (-0.16→-0.19)	**2.36→2.28 (2.02→1.78)**	**0.58→0.62 (0.68→0.77)**	**0.51→0.57 (0.62→0.72)**	0.75→0.62 (0.83→0.77)	**0.47→0.29 (0.41→0.17)**	**0.60→0.65 (0.67→0.79)**	**0.45→0.50 (0.53→0.66)**
Mid FOV	2.08 (2.01)	2.68 (2.62)	0.04→-0.12 (0.05→-0.17)	**2.25→2.16 (1.95→1.69)**	**0.59→0.62 (0.69→0.77)**	**0.54→0.59 (0.65→0.72)**	0.75→0.62 (0.83→0.75)	**0.47→0.31 (0.40→0.17)**	**0.59→0.64 (0.67→0.78)**	**0.45→0.49 (0.53→0.65)**
Outer FOV	1.81 (1.79)	2.18 (2.30)	**0.26→-0.07** (0.09→-0.20)	**2.04→1.89 (1.83→1.47)**	**0.55→0.57 (0.65→0.78)**	**0.51→0.55 (0.61→0.72)**	0.71→0.56 (0.77→0.68)	**0.51→0.36 (0.44→0.19)**	**0.54→0.58 (0.62→0.72)**	**0.41→0.43 (0.48→0.59)**

Independent test results are reported for TROPICS ISRR before → after calibration, with validation scores in parentheses. H20 RR mean (μ), standard deviation (σ) and continuous scores refer to common hit-only samples (RR ≥ 0.25 mm·h⁻¹), while categorical scores use the full datasets. Before calibration, TROPICS ISRR already shows encouraging performance: across test subsets, |MBE| is 1.5–26% of the H20 RR mean and RMSE is 83–94% of H20 RR σ, below the reference variability. Validation performance is better than test performance, consistent with decreasing agreement with satellite age shown above. Calibration reduces RMSE to 80–87% on test and 63–71% on validation, increases CC, KGE, HSS and CSI, and reduces FAR. The largest |MBE| remains over land but decreases after calibration. The lower POD reflects the trade-off accepted to reduce FAR and improve HSS and CSI. Density scatterplots, Q-Q plots and PDFs confirm closer agreement between calibrated TROPICS ISRR and H20 RR, especially on validation.

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