# High-resolution WRF Simulations over East Africa: Model Setup & Evaluation

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# Weather Research & Forecasting (WRF) Model

- *"Community Model"*: free and shared resource developed in late 1990s by National Center of Atmospheric Research (NCAR) and National Oceanic Atmospheric Administration (NOAA) with other institutions

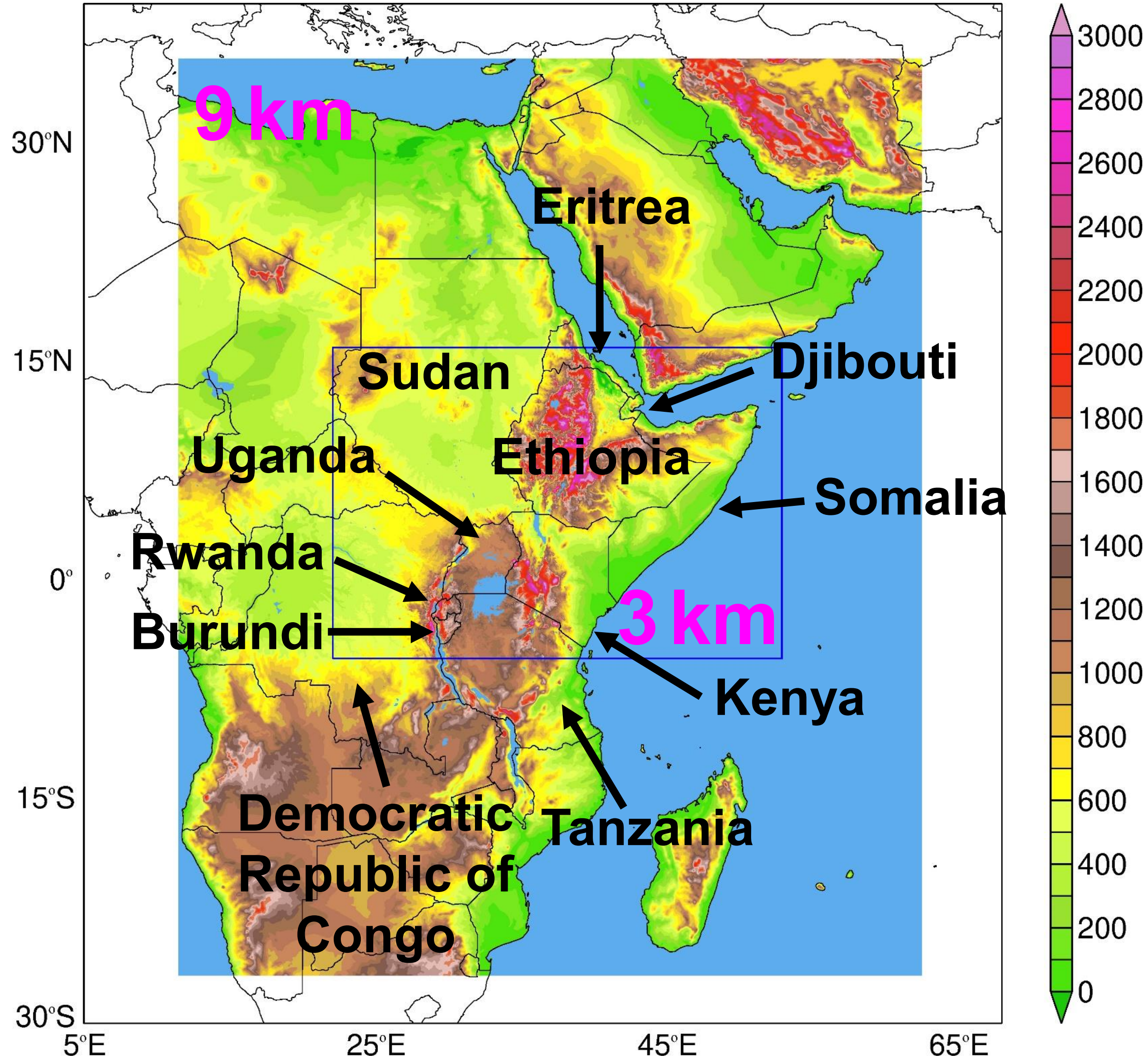
- WRF Version 1.0 released in December 2000; current release is Version 4.7.1 in June 2025

- WRF is suitable for use in a wide range of applications including:
  - Idealized (e.g. convection, surface fire, sea breeze) & real-case simulations;
  - Polar climate research (PolarWRF);
  - Coupled-model (e.g. ocean-atmosphere) applications;
  - Chemistry-related applications (WRF-CHEM);
  - Hydrometeorological and Hydrological applications (WRF-HYDRO);
  - Solar energy applications (WRF-SOLAR);
  - Planetary atmospheres research (PlanetWRF).

- WRF used by academic atmospheric scientists, forecast teams at operational centers, application scientists. Important to **calibrate model for target region**: different physics options optimized for different environments.

Download WRF: https://github.com/wrf-model/WRF/releases
WRF Users' Guide: https://www2.mmm.ucar.edu/wrf/users/docs/user_guide_v4/contents.html

# WRF-Africa Experimental Setup



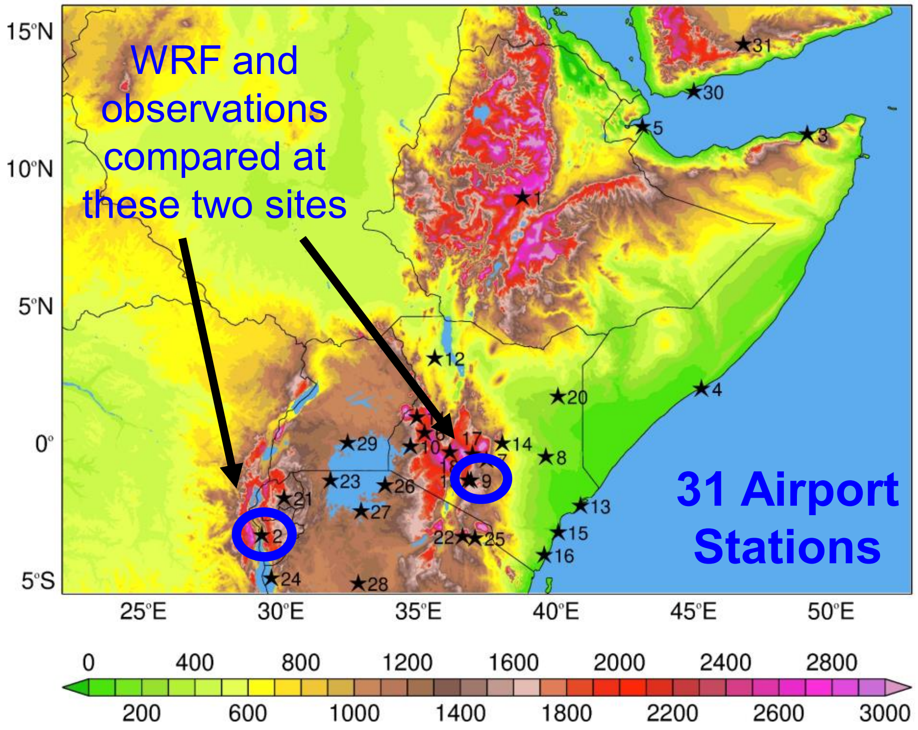

| Configuration | Specifications |
|---|---|
| **Model Version** | WRF Version 4.3.3 |
| **Vertical Resolution** | 37 levels concentrated in boundary layer and upper troposphere, with model top at 30 hPa |
| **Forcing Data** | 6-hourly ERA-5 reanalysis data |
| **Execution Mode** | WRF run for 1 month + 1 week spin-up before at a time for full year 2024 |
| **Cloud Microphysics** | WRF double-moment 7-class scheme (WDM7) |
| **PBL** | Yonsei University (YSU) with topographic correction |
| **Radiation** | Rapid Radiative Transfer Model for Global Circulation Models (RRTMG) for both SW & LW |
| **Cumulus** | Betts-Miller-Janjic (BMJ) adapted for convective tropics and coupled with precipitation convective cloud scheme **(switched off in 3 km grid)** |
| **Land Surface Model** | Noah LSM |
| **Interior Nudging (9 km grid only)** | Water vapour mixing ratio in mid-troposphere and winds and temperature in lower stratosphere on $\tau$ = 1 h excluding boundary layer towards ERA-5 values |

# WRF-Africa: Fields Stored & File Sizes

- Fonseca et al. (2015, GMD) and Koh and Fonseca (2016, QJRMS) **optimized WRF model for convective tropics** by calibrating tunable parameters in cumulus scheme and adding a precipitating convective cloud scheme to account for subgrid-scale cloud-radiation feedbacks. This version is used for downscaling of ERA-5 data over East Africa;
- WRF simulations performed on Stampede3 cluster: 1 month + 1 week spin-up take around **3.5 days** with **1440 CPUs**. **Raw model output** stored **hourly**, taking ~560 MB for 9 km grid and ~980 MB for 3 km grid → **~1.1 TB per month**;
- Raw output is post-processed to extract relevant surface fields and 3D on selected pressure levels. **Post-processed hourly files** have a size of ~262 MB for 9 km grid and ~457 MB for 3 km grid → **~522 GB per month**;
- **Total output** (raw + post-processed) takes **~1.6 TB per month** or **~20 TB per year**. Currently running model for previous years → multi-year WRF product ideally suited for training of ML models in data sparse region.

| Variable Type | List of Variables |
|---|---|
| 2D fields | Precipitable water, cloud top temperature, IVT, SLP, air temperature and dewpoint temperature, PBL depth, soil temperature & moisture, precipitation, surface radiation & heat fluxes, SSTs, etc. |
| 3D fields on 14 pressure levels (1000, 975, 950, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100 hPa) | Geopotential, Temperature, Water Vapour Mixing Ratio, 3D Wind components, Potential Vorticity, Absolute Vorticity |
| 3D fields on 37 model levels | Winds, temperature, cloud & moisture fields, radar reflectivity, etc. |

# Model Evaluation Datasets & Metrics




1. Addis Ababa Bole International Airport
2. Melchior Ndadaye International Airport
3. Bosaso International Airport
4. Aden Adde International Airport
5. Djibouti-Ambouli International Airport
6. Eldoret International Airport
7. Embu Airport
8. Garissa Airport
9. Jomo Kenyatta International Airport
10. Kisumu International Airport
11. Kitale Airport
12. Lodwar Airport
13. Manda Airport
14. Tharaka Nithi Meru Airport
15. Malindi Airport
16. Moi International Airport
17. Nyeri Airport
18. Nakuru Airport
19. Wilson Airport
20. Wajir Airport
21. Kigali Airport
22. Arusha Airport
23. Bukoba Airport
24. Kigoma Airport
25. Kilimanjaro International Airport
26. Musoma Airport
27. Mwanza International Airport
28. Tabora Airport
29. Entebbe International Airport
30. Aden International Airport
31. Ataq Airport

| Evaluation Dataset | Specifications |
|---|---|
| **Weather Station Data** | Hourly observations at 31 airport stations; daily statistics at 70 stations available at NOAA Global Surface Summary of the Day (NOAA GSOD) dataset |
| **IMERG GPM Precipitation** | Satellite-derived precipitation estimates (0.1° × 0.1°; 30-min) from 1998 to present from Integrated Multi-Satellite Retrievals (IMERG) for the Global Precipitation Mission (GPM) |
| **ERA-5 Reanalysis** | Hourly products at 0.25° × 0.25° from January 1940 to present |

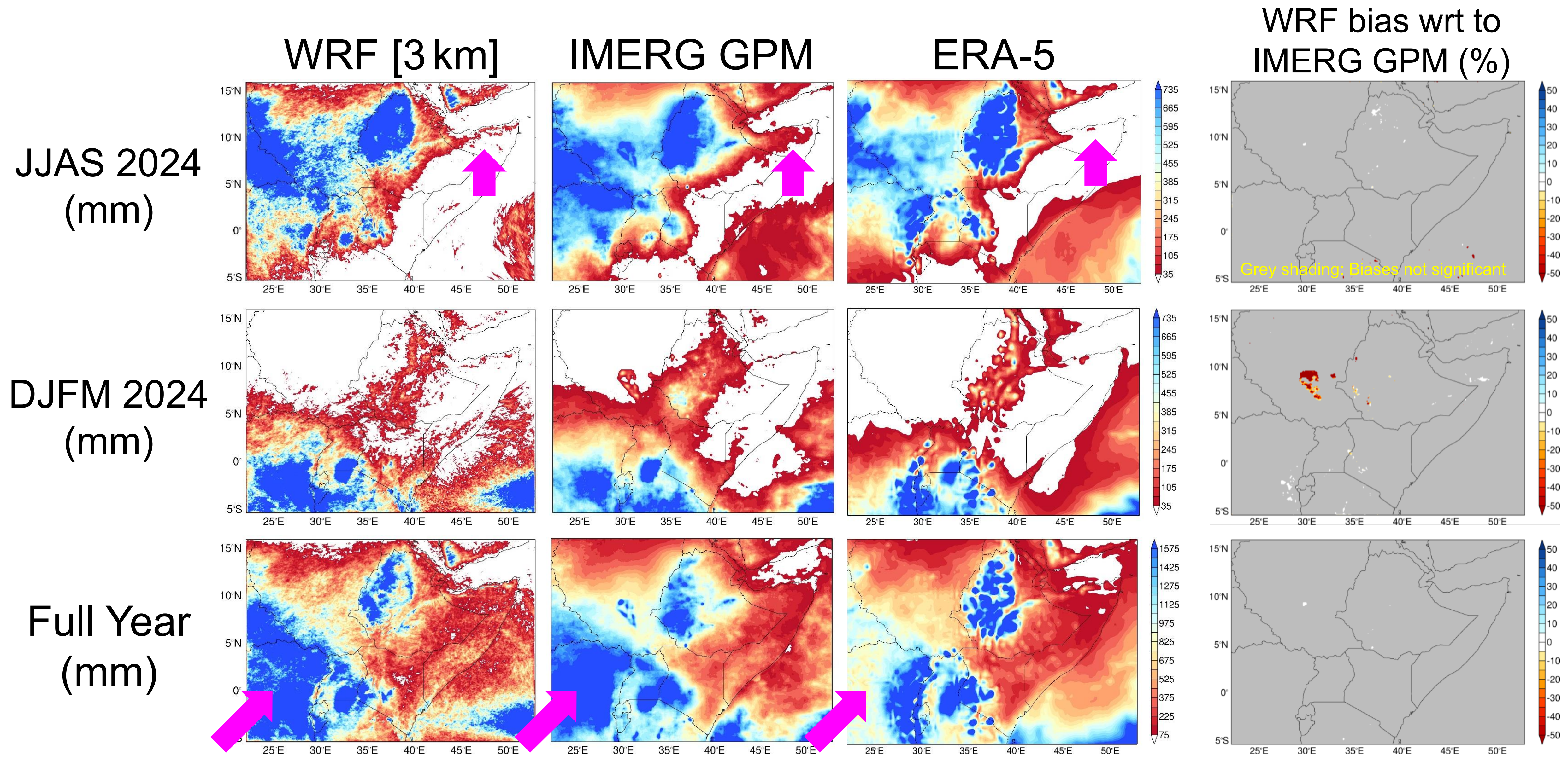
**Verification Diagnostics** **(Koh et al., 2012, JGR)**

$D = F - O$ Model bias: mean discrepancy ($\overline{D}$) between forecasts ($F$) and observations ($O$)

$\mu = \frac{\langle D \rangle}{\sigma_D}$ Normalized bias ($\mu$): ratio of bias to standard deviation of discrepancy between $F$ and $O$

If $|\mu| < 0.5$, contribution of bias to RMSE is small and biases considered not significant

# Evaluation of Model’s Precipitation



# Comparison of WRF 3 km Precipitation with IFS 4.4 km

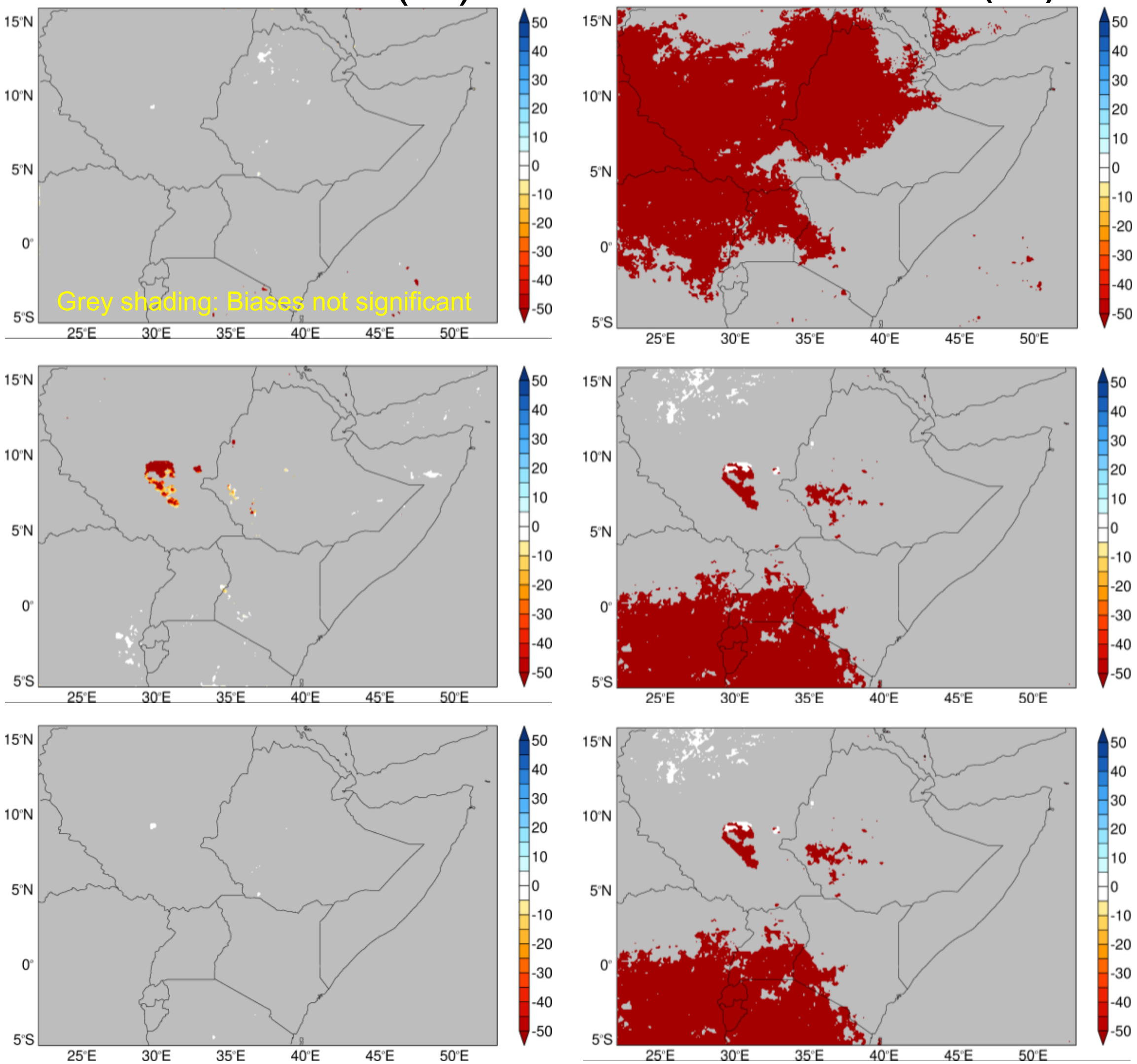
WRF bias wrt to IMERG GPM (%)

IFS bias wrt to IMERG GPM (%)

JJAS 2024

DJFM 2024

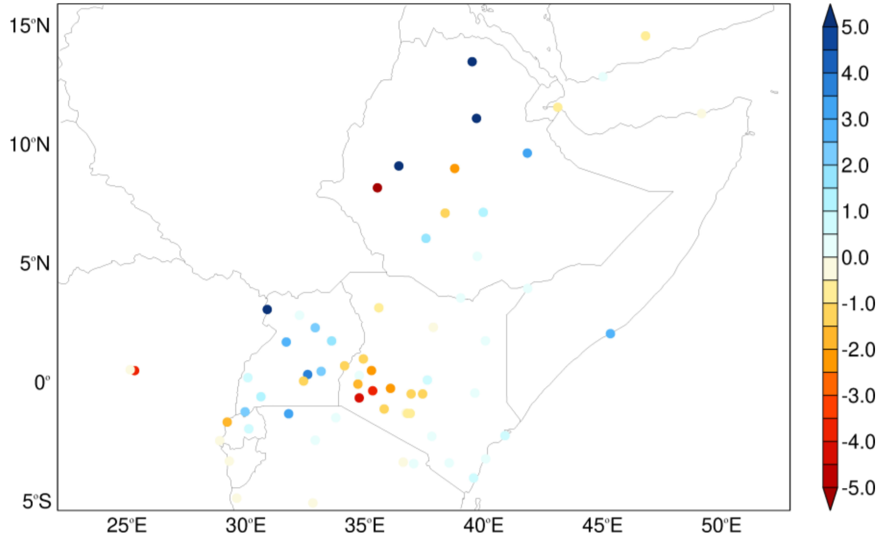
Full Year



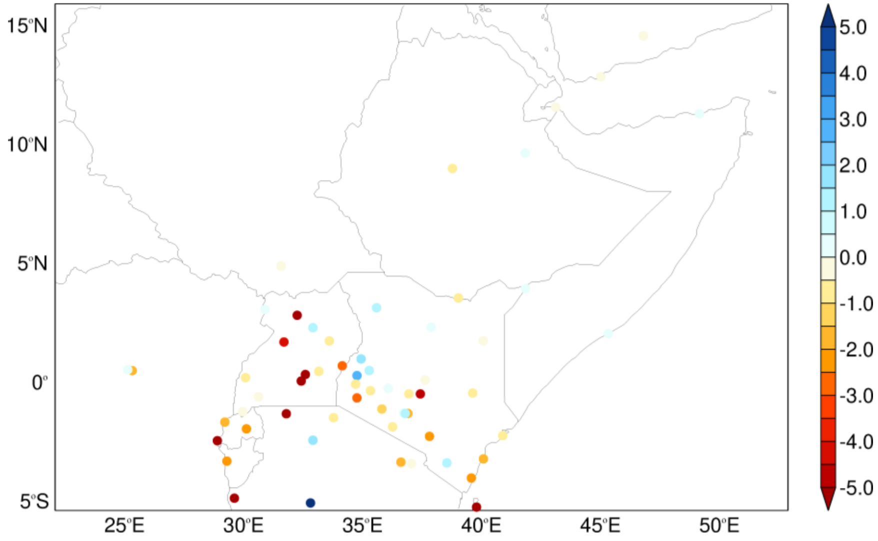

- Integrated Forecast System (IFS) Cycle 48r1 4.4 km atmosphere (137 vertical levels) and 5 km ocean (69 vertical levels) model run for 2020-2024 at ECMWF (ERA-5 is generated with older IFS Cycle 41r2);
- Daily accumulated IFS 4.4 km data extracted and skill scores with respect to IMERG GPM computed as done for WRF 3 km;
- **WRF 3 km has superior performance to IFS 4.4 km over East Africa** for individual months, seasons, and full year for rainfall → IFS 4.4 km has tendency to overestimate observed precipitation in the region;
- Calibrated numerical model run uncoupled can give more skillful predictions compared to state-of-the-art model run by ECMWF → **added value of model optimization**.

# Evaluation Against Daily Station Data (WRF biases)

### JJAS 2024; Precipitation (mm day$^{-1}$)

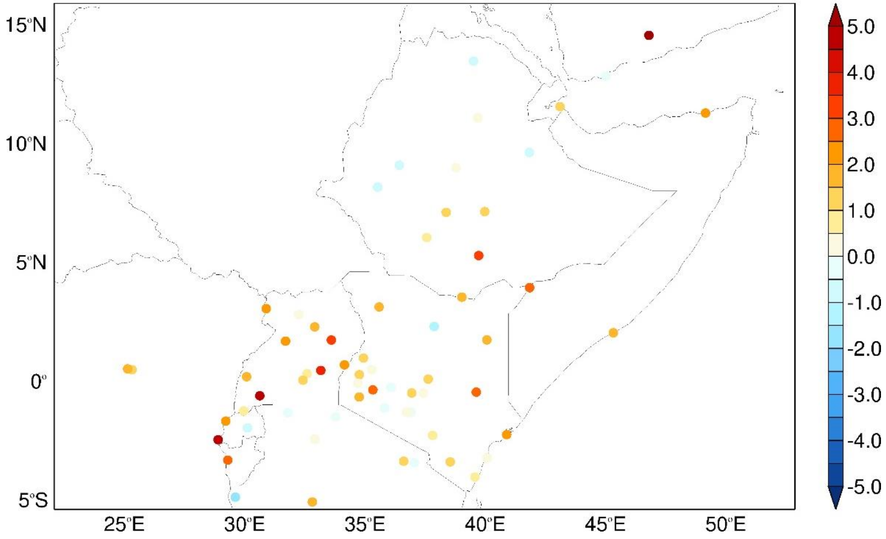



### DJFM 2024; Precipitation (mm day$^{-1}$)

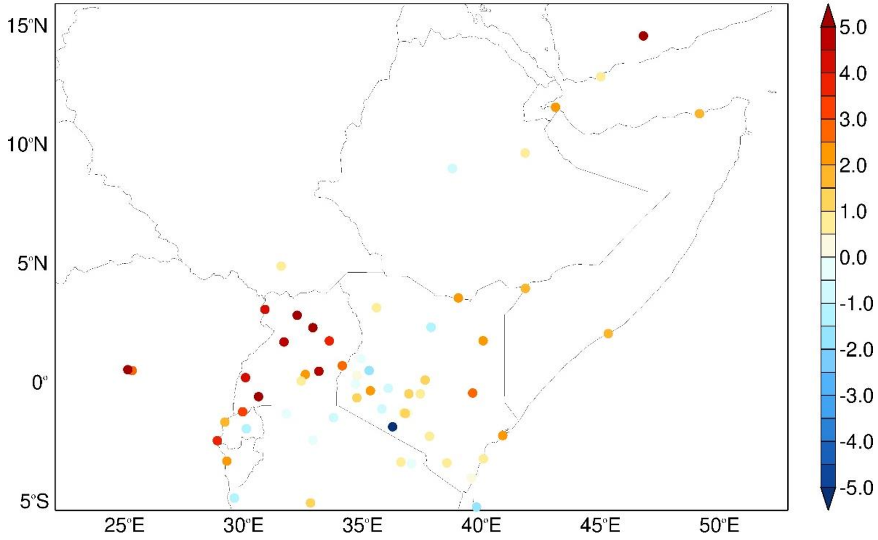



- Evaluation against station data (closest WRF grid-point selected);
- Precipitation biases generally within 3 mm day$^{-1}$ for both warm and cold seasons;
- Precipitation overestimated over the Ethiopian Highlands and underestimated over equatorial Africa.

### JJAS 2024; Daily-mean Temperature (°C)



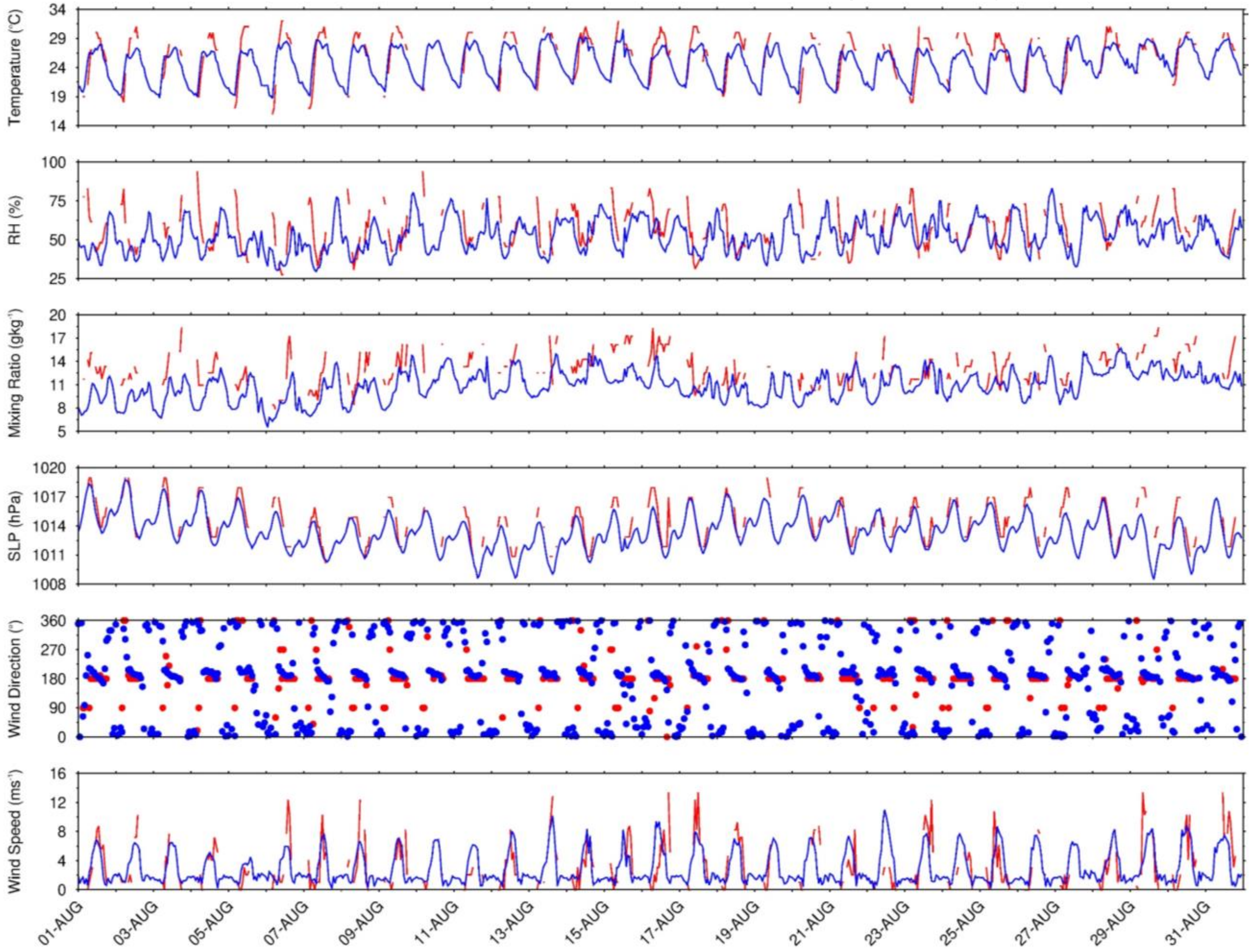

### DJFM 2024; Daily-mean Temperature (°C)



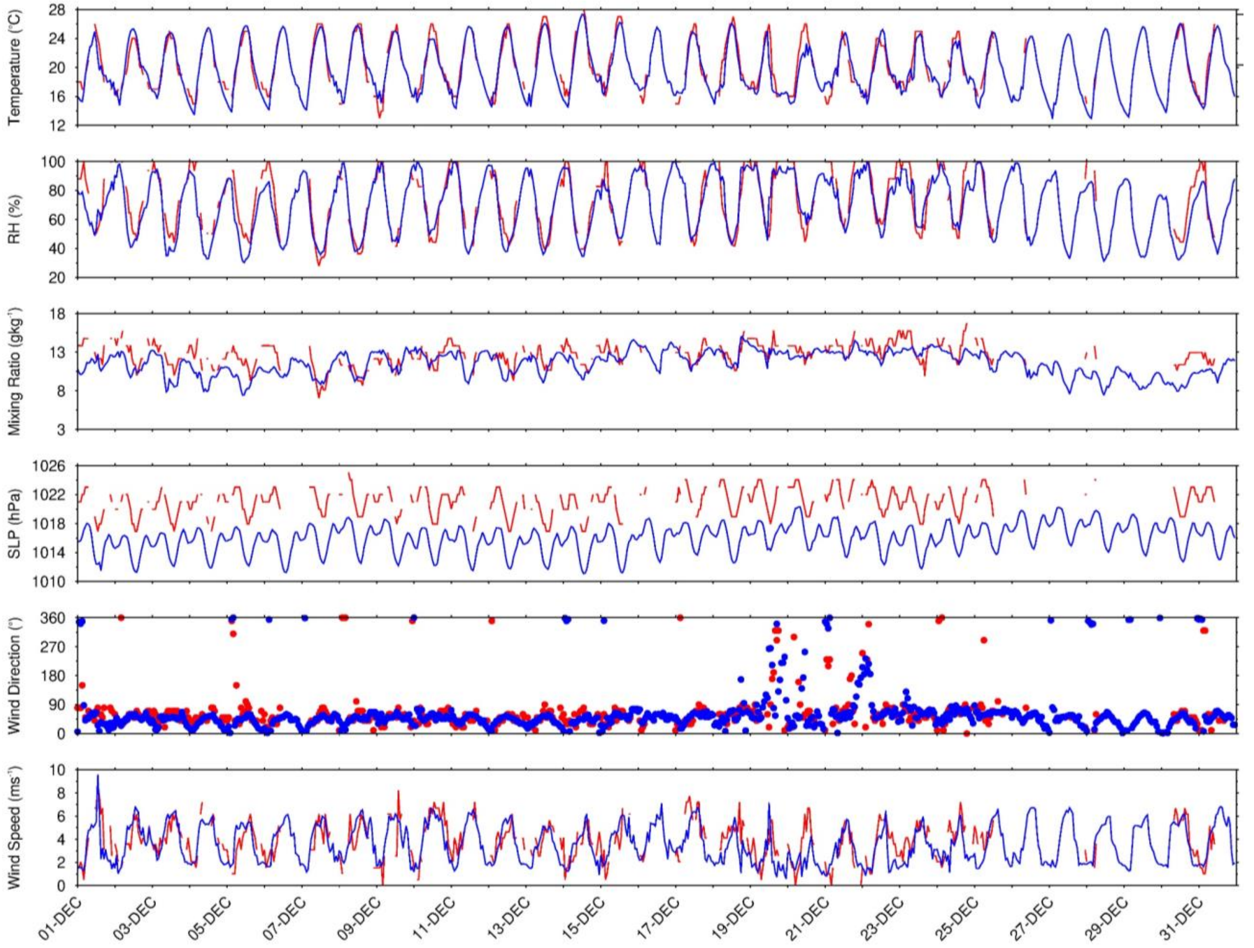

- Model-predicted daily-mean air temperature generally within 2°C of that observed;
- Drier conditions and weaker wind speeds (typically by 0.5-1.5 m s$^{-1}$) over equatorial Africa in line with warmer temperatures.

# Evaluation Against Hourly Airport Data

WRF (blue) & METAR (red) hourly data at Bujumbura International Airport (3.324°S, 29.319°E) for August 2024




WRF (blue) & METAR (red) hourly data at Jomo Kenyatta International Airport (1.319°S, 36.926°E) for December 2024




- WRF simulates well diurnal cycle and day-to-day variability;
- Semi-diurnal tide signal in surface pressure captured by WRF.
- Shift in SLP due to incorrect representation of topography;
- Cooler air advection from 19-21 December captured by WRF.

# Conclusions & Ongoing Work

- WRF model set up in 9 km – 3 km configuration over East Africa and run for full year of 2024;
- Evaluation against satellite-derived precipitation estimates showed good agreement, with **WRF 3 km** product **outperforming ERA-5 27 km** dataset mostly over high terrain and in deep tropics;
- WRF predictions in close agreement with hourly observations at 31 airport stations in the region, with model capturing diurnal cycle and effects of mid-latitude cold/dry air intrusions;
- **Precipitation biases generally within 3 mm day$^{-1}$** when compared to in-situ measurements, tendency for overestimation over high-terrain. For other fields WRF data also in close agreement with observations: e.g. modelled and observed air temperature generally within 2°C, 10-m wind speed within 1.5 m s$^{-1}$, and 2-m mixing ratio within 1.5 g kg$^{-1}$;
- Currently running model for previous years → WRF product ideally suited for training of ML models in data sparse region.

# Relevant Publications

Fonseca, R., Koh, T.-Y., & Teo, C.-K. (2019) Multi-scale interactions in a high-resolution tropical-belt experiment and observations. *Climate Dynamics.* https://doi.org/10.1007/s00382-018-4332-y

Fonseca, R., Zhang, Y., & Yong, K.-T. (2015) Improved simulation of precipitation in the tropics using a modified BMJ scheme in the WRF model. *Geoscientific Model Development*, 8, 2915-2928. https://doi.org/10.5194/gmd-8-2915-2015

Koh, T.-Y., S. Wang, & B. C. Bhatt (2012) A diagnostic suite to assess NWP performance. *Journal of Geophysical Research*, 117, D13109. https://doi.org/10.1029/2011JD017103

Koh, T.-Y., & Fonseca, R. (2016) Subgrid-scale cloud-radiation feedback for the Betts-Miller-Janjic convection scheme. *Quarterly Journal of the Royal Meteorological Society*, 142, 989-1006. https://doi.org/10.1002/qj.2702