Tropical Wave Diagnostics and Their Applications to Numerical Weather Models

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ECMWF Workshop on Diagnostics for Global Weather Prediction

September 11th, 2024

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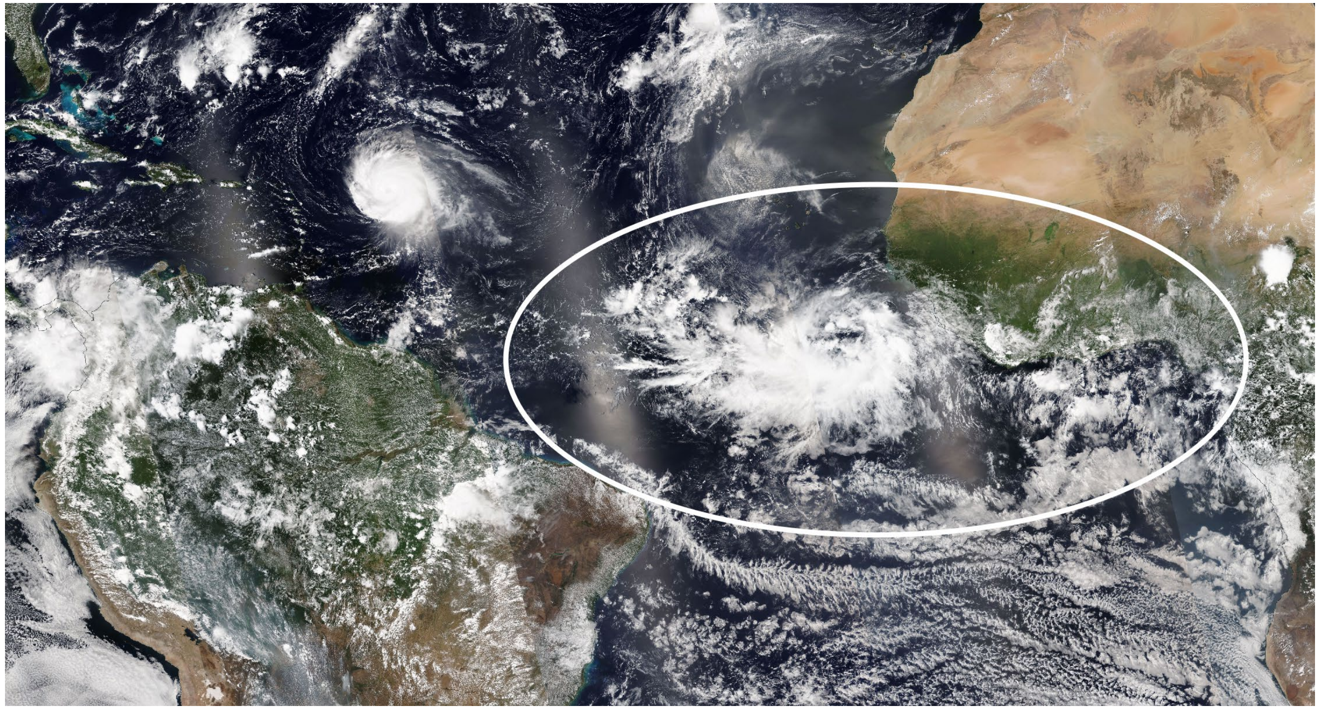
Waves in the Tropics

Weather in the tropics is dominated by tropical waves



- Easterly waves, taking the form of **African easterly waves (AEWs)** in the Atlantic, drive rainfall in the Sahel and can lead to tropical cyclones
- Equatorial waves, such as **Kelvin waves** and **equatorial Rossby waves**, help drive precipitation and interact with other phenomena

*But to study these, we first have to figure out how to **identify** and potentially even **change** these waves in reanalysis and model data!*

Objectives of This Talk

1. Introduce some of the tools and datasets that exist for **African easterly wave identification,** including their use within numerical model simulations

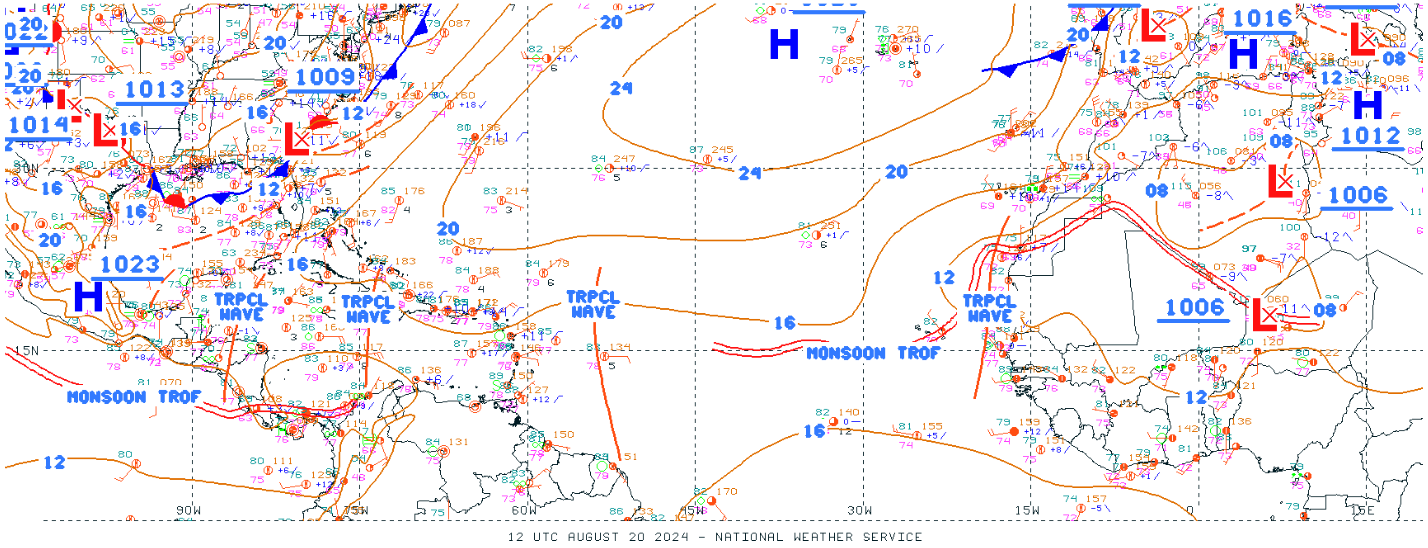
2. Show that **equatorial wave strength (namely, Kelvin waves) can be modified at model initialization**, and demonstrate potential modeling applications

My focus will be mostly on Africa and the Atlantic, but these principles have global implications

African Easterly Wave Tracking

Why Objectively Identify AEWs?

- **Skilled hand-analysis is still done operationally (NHC)**
- While useful, **this data can be subjective**
- We need **automated and consistent** methods to track a large number of AEWs, especially those in numerical simulations



TAFB Unified Surface Analysis on 12Z August 20th, 2024**: the "gold standard"**

Tracking African Easterly Waves

- Many AEW trackers use curvature vorticity (CV)
- But not the only way to do it, others have tried different methods
- Modern trackers are build upon many decades of work *(Berry et al. 2007; Bain et al. 2014; Brammer and Thorncroft 2015; Belanger et al. 2016, etc.)*

I'll review a few, but for time cannot be comprehensive:

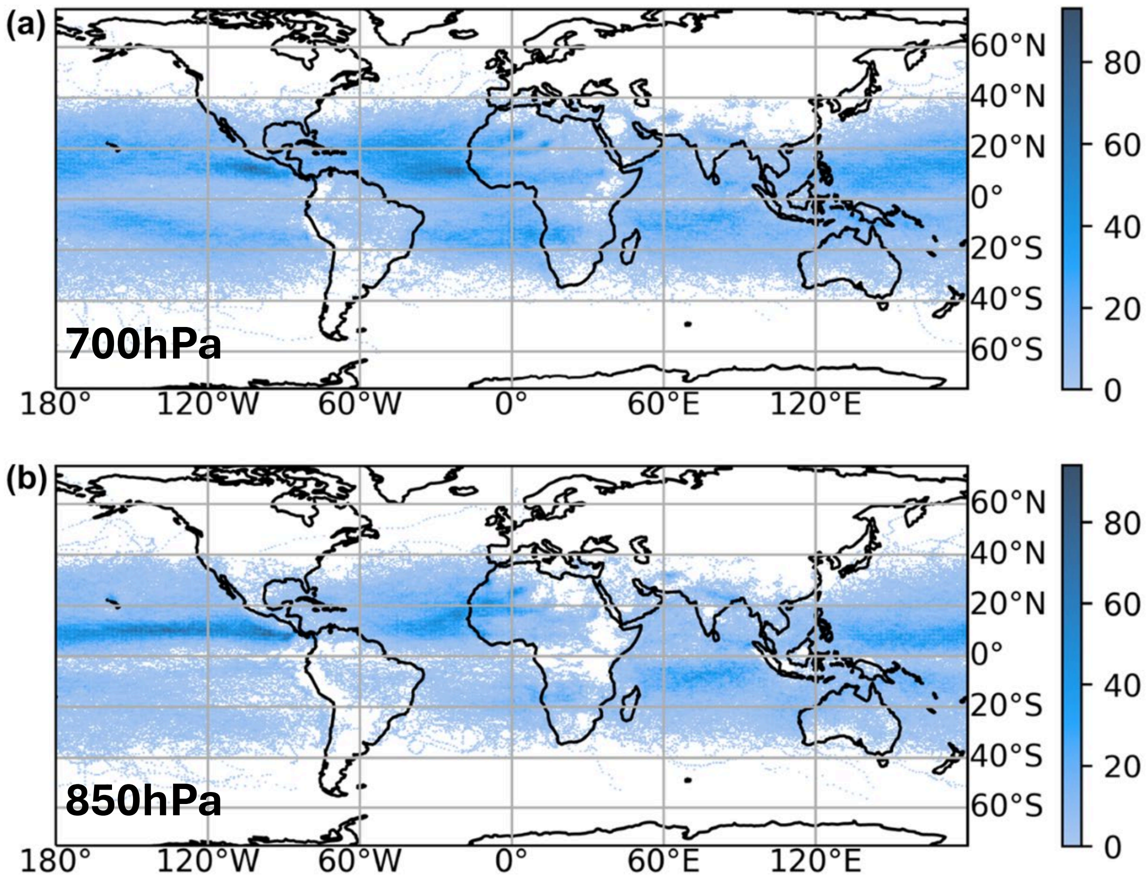
- Hollis et al. (2024) } AEW centers using CV
- Lawton et al. (2022) } AEW centers using CV
- Fischer et al. (2024) } AEW troughs using CV; identify PV features
- Downs et al. (*TBD*) } Artificial intelligence (AI)

Each type of tracker has it's own unique advantages!

Hollis et al. (2024) TEW Database

- Tropical easterly waves (TEWs) tracked globally using 700hPa and 850hPa curvature vorticity (CV)
- TRACK algorithm *(Hodges 1995)*

Fig. 2 from Hollis et al. (2024) showing TEW density



Highlights

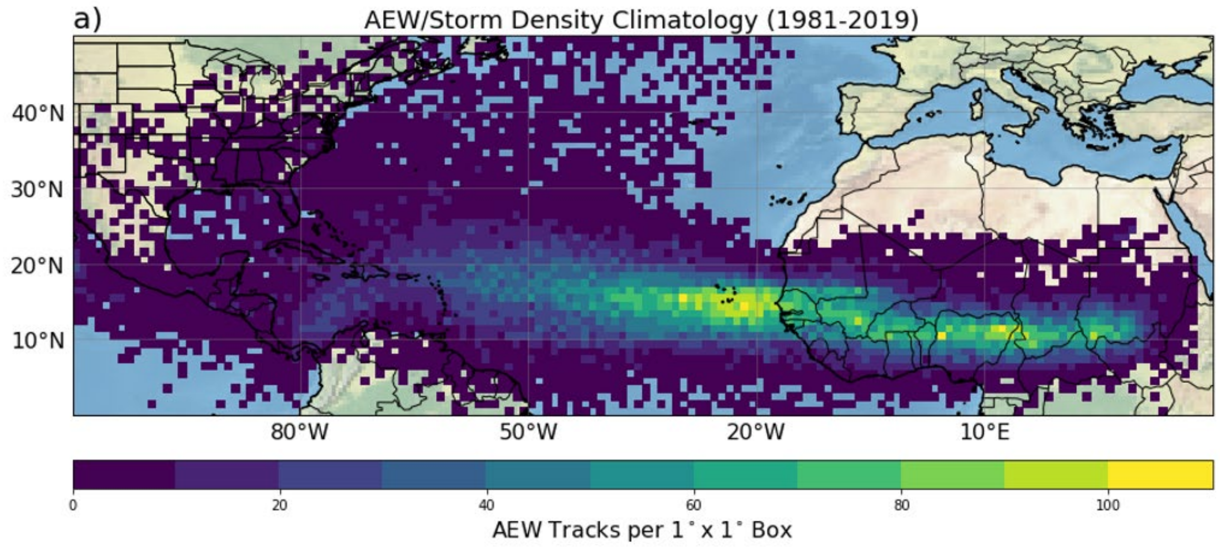
- **Run on MERRA-2, 1981-2021**
- A long-spanning **global** dataset
- No public tracking algorithm, but TRACK could constrained using their methods

Useful for those needing global TEW tracks!

Lawton et al. (2022) AEW Tracker (QTrack)

- Track AEWs using 700hPa CV
- When AEWs over land, meridional averaging used; when over ocean, extrapolation method used

Fig. 1a from Lawton et al. (2022) showing AEW density



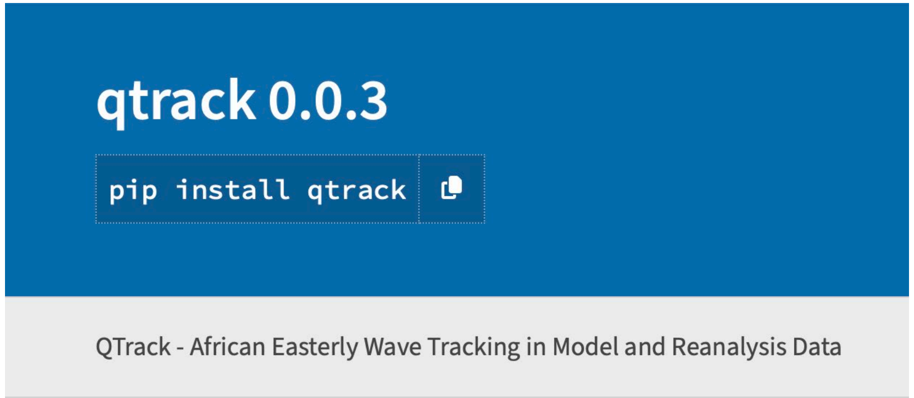
Highlights

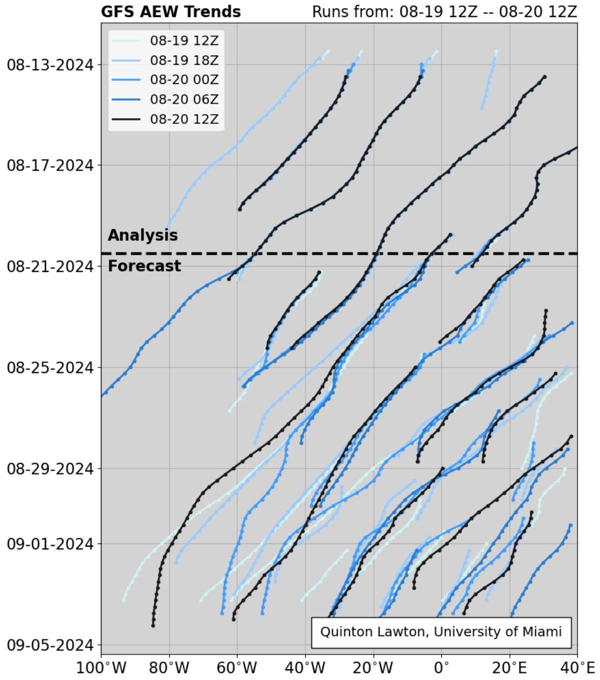
- **Run on ERA5 and MERRA-2 (1980 – 2023)**
- Successfully used in model simulations, including IFS, MPAS-A systems
- Tracker implemented as python module *qtrack*
- Arguably most successful near African coastline and over the continent

Useful for those wanting to identify AEW centers in numerical models, and those with focus over African continent and Atlantic

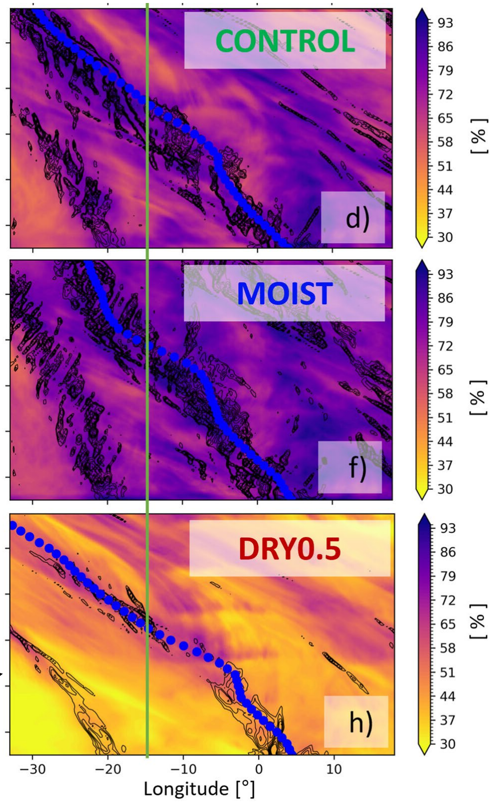
QTrack Module and Numerical Models

- This AEW tracker has been applied to many numerical simulations (GFS, IFS, MPAS-A, etc.)
- Newly released python package **QTrack** with (customizable) tracker
- Github with examples: https://github.com/qlawton/QTrack
- Install with *pip install qtrack*





AEW Tracks in GFS
qlawton.rsmas.miami.edu

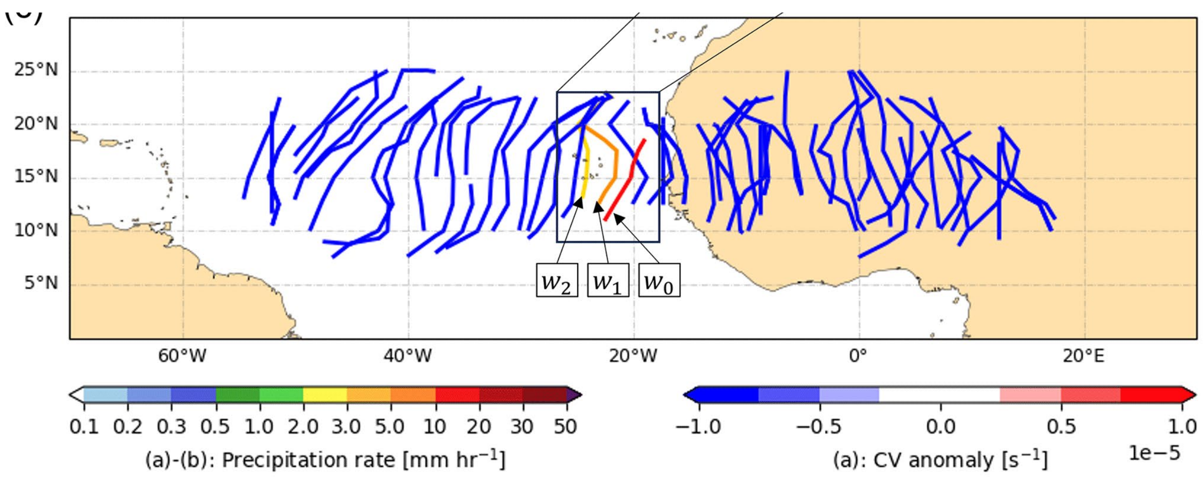


AEW tracks (blue scatters) used for MPAS-A experiments by Núñez Ocasio et al. (2024)

Used in NASA CPEX-CV campaign (Nowottnick et al. 2024; *BAMS*)

Fischer et al. (2024) PV Tracker

Fig. 1c from Fischer et al. (2024) showing example (single) AEW track



- Identify wave **troughs** by finding regions of zero CV advection)
- Troughs connected using overlap approach
- 3D features of potential vorticity (PV) then identified and tracked

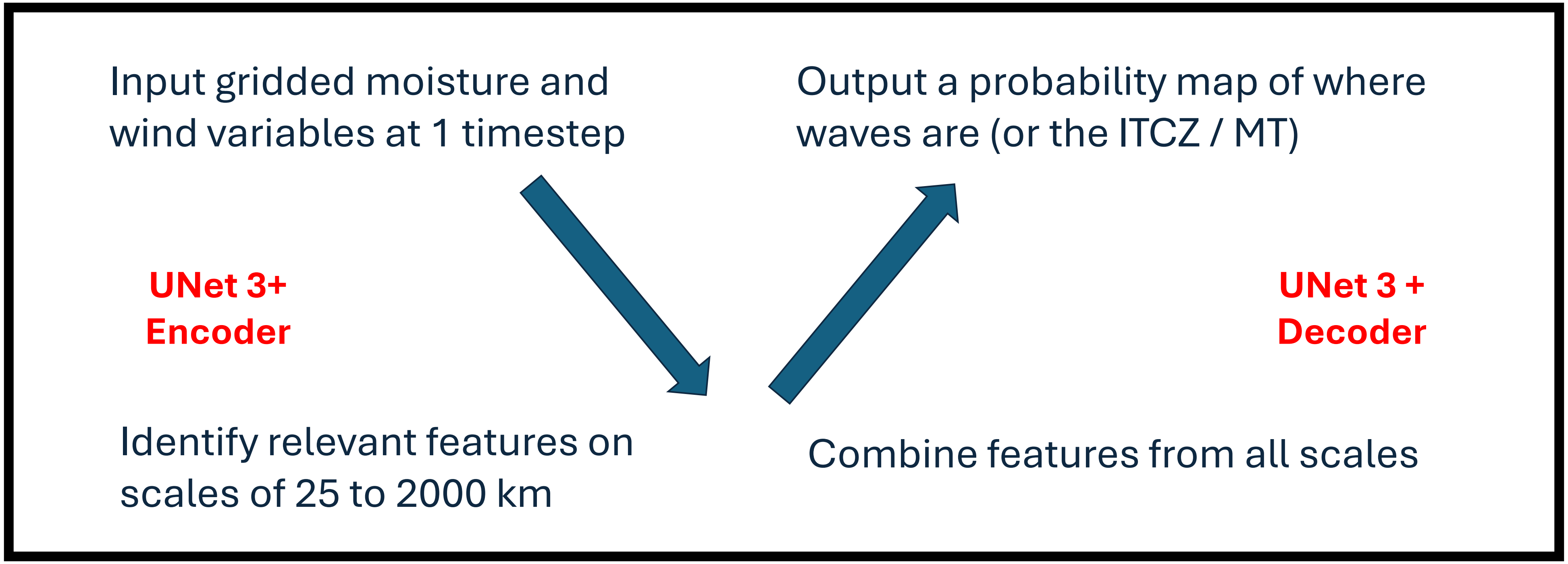
Highlights

- **Run on ERA5, 1940 – 2022**
- Includes PV feature identification and quantification
- Tracks online, method included in *enstools-feature* framework

Useful for those interested in 3D PV features in AEWs!

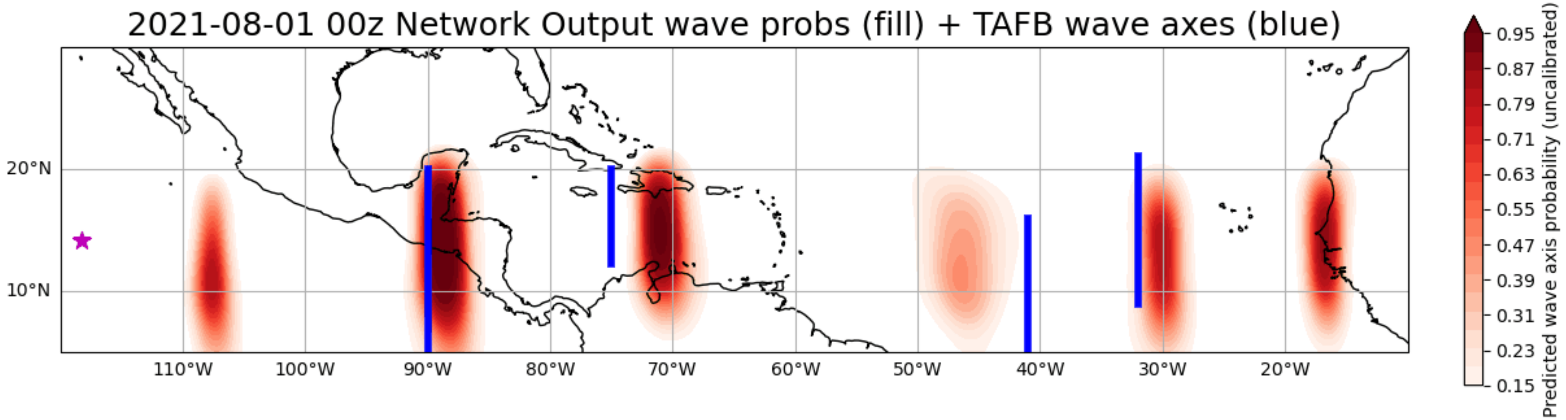
Tracking AEWs using AI

- Uses input fields consisting of ERA5 wind & moisture, GridSat-B1 IR
- Read-in wave troughs via NHC's Tropical Weather Discussions
- Train neural network to optimally identify TAFB's transcribed wave troughs
- Output probability map of wave location



Downs et al. (*in prep*) Example

- Labels are not always aligned with NHC's, especially at low probabilities
- But rarely see AI-analyzed label with no matching NHC label

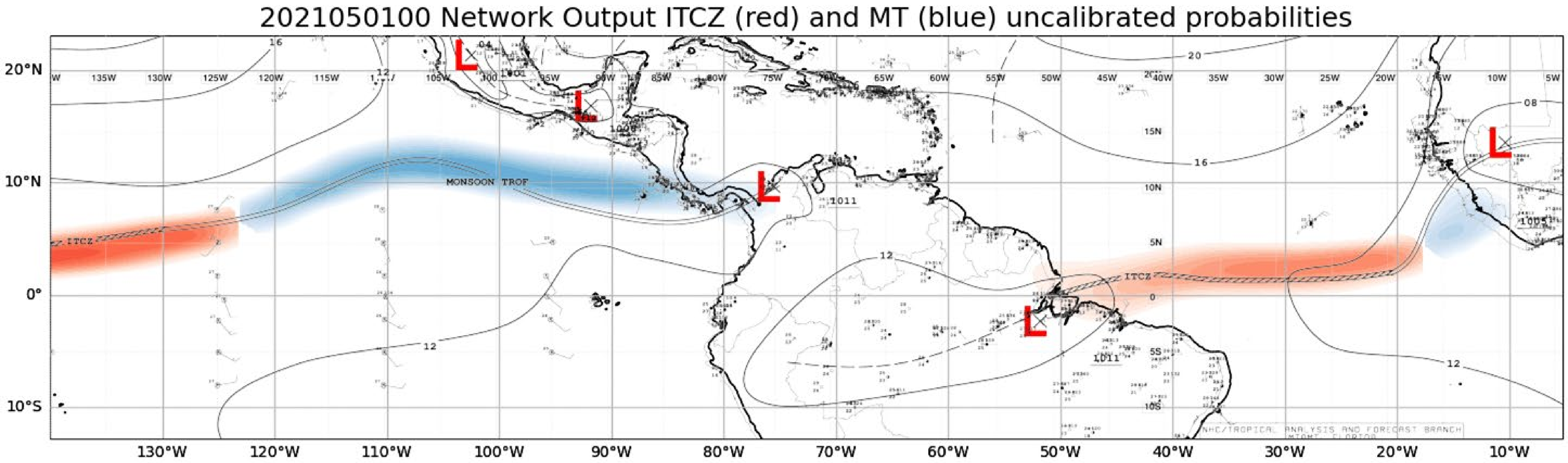


Highlights

- **Trained on ERA5, GridSat, and NHC output; data for 1981 – 2023**
- Arguably more successful at capturing Caribbean and weak AEWs
- Only run to longitude 0E; **less useful for continent/east of 10°W**

Useful for those who are interested in AEWs in the Caribbean and weaker waves that transit the ocean!

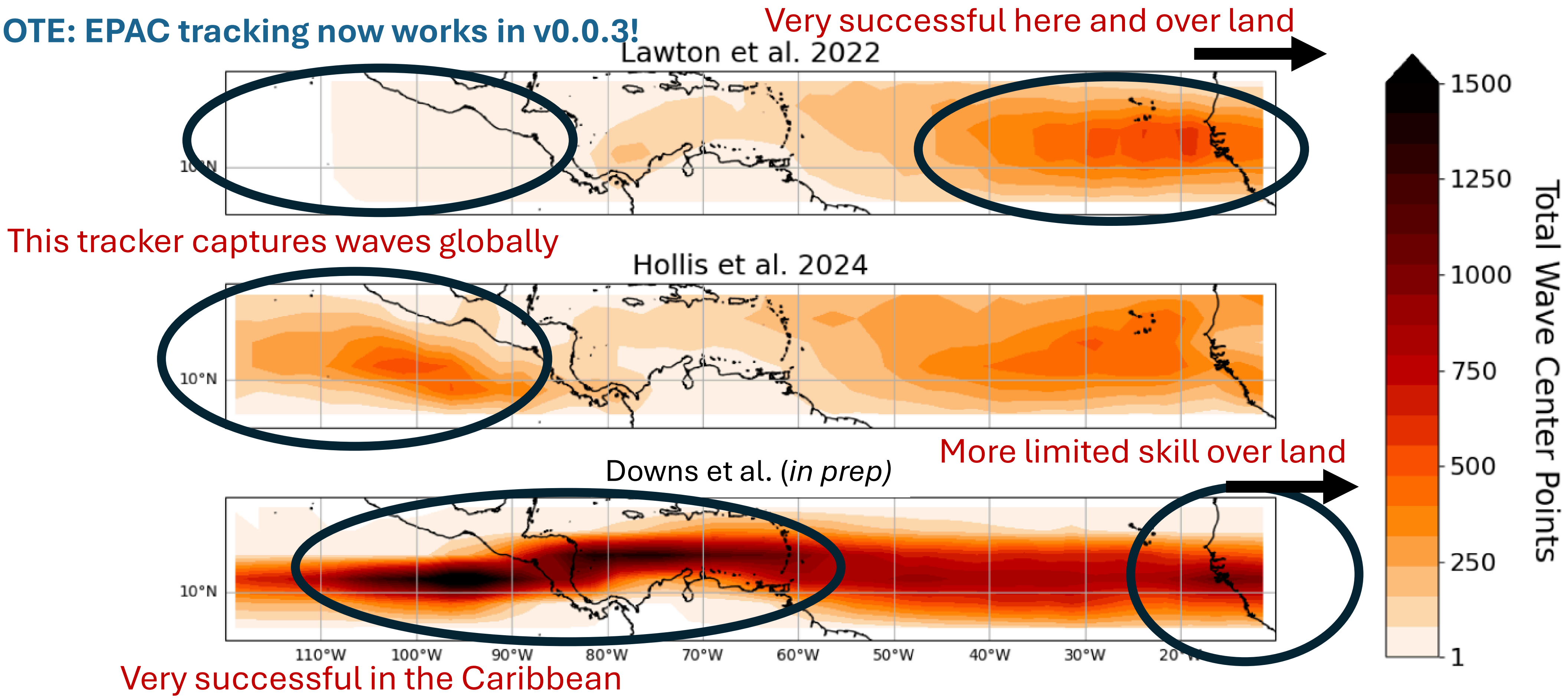
Also ongoing work to track ITCZ



Surface analysis maps from TAFB

Comparing Three AEW Trackers

NOTE: EPAC tracking now works in v0.0.3!



Can only compare Downs et al. (in prep) qualitatively; figure **overstates number of waves** due to narrow banding and polygons

Summary of AEW Trackers

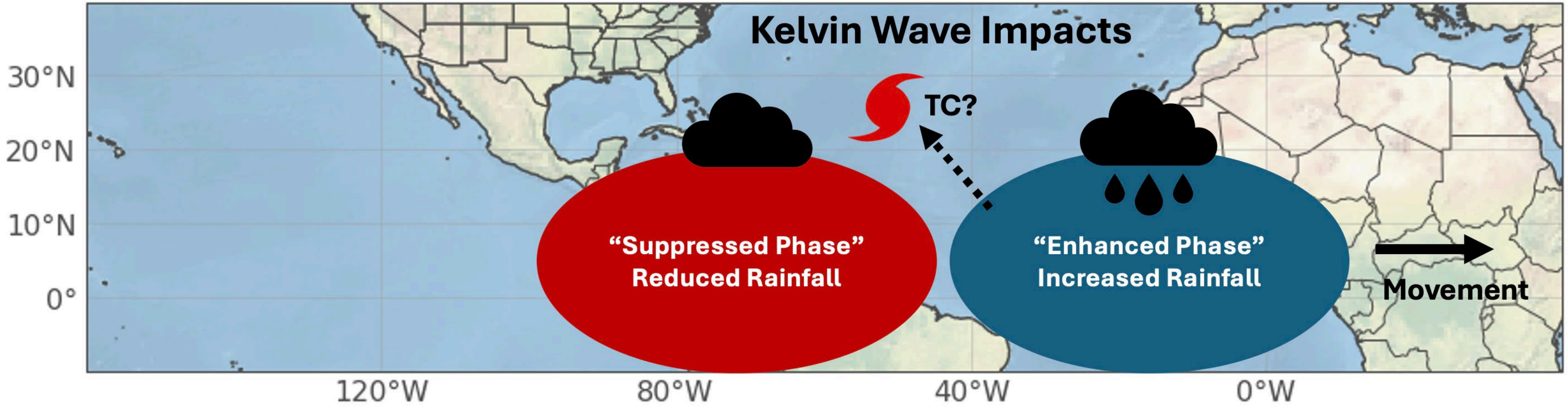
- **Using any of these is likely to work generally fine,** but you should evaluate your needs and use case
- **Historical tracks publicly available for all four**; implementable algorithm public for *Lawton et al. (2022)* and *Fischer et al. (2024)*

Tracker	Biggest Advantage	Code and Model Applications
Hollis et al. (2024)	Global tracks, run on two levels	Would need to adapt TRACK using constraints listed in paper
Lawton et al. (2022)	Very skillful over African continent and E. Atlantic	Python module *qtrack* available; has been applied to models before
Fischer et al. (2024)	Identification of PV features	Method available in *enstools-feature*
Downs et al. *(in prep)*	Caribbean and weaker AEWs	Will be public in future upon publication

Modifying Kelvin Waves in Simulations

Equatorial Wave Identification

- **I won't delve into the methods of equatorial wave identification**
- Recommend the Knippertz et al. (2022) article on the subject!
- Will focus on some work we've done to modify convectively-coupled Kelvin waves (CCKWs) in MPAS-A experiments (Lawton et al. 2024)



Why Modify a CCKW?

- **CCKWs have well-established impacts on other weather phenomena**
  - Easterly waves
    (i.e., Lawton et al. 2022)
  - Tropical cyclogenesis
    (i.e., Schreck 2015; Lawton & Majumdar 2023)
  - Rainfall, sometimes extreme
    (i.e., Mounier et al. 2007; Latos et al. 2021)
- **Operational modeling systems still struggle to simulate CCKWs**
  (i.e., Yang et al. 2021; Gehne et al. 2022; Lawton et al. 2024)

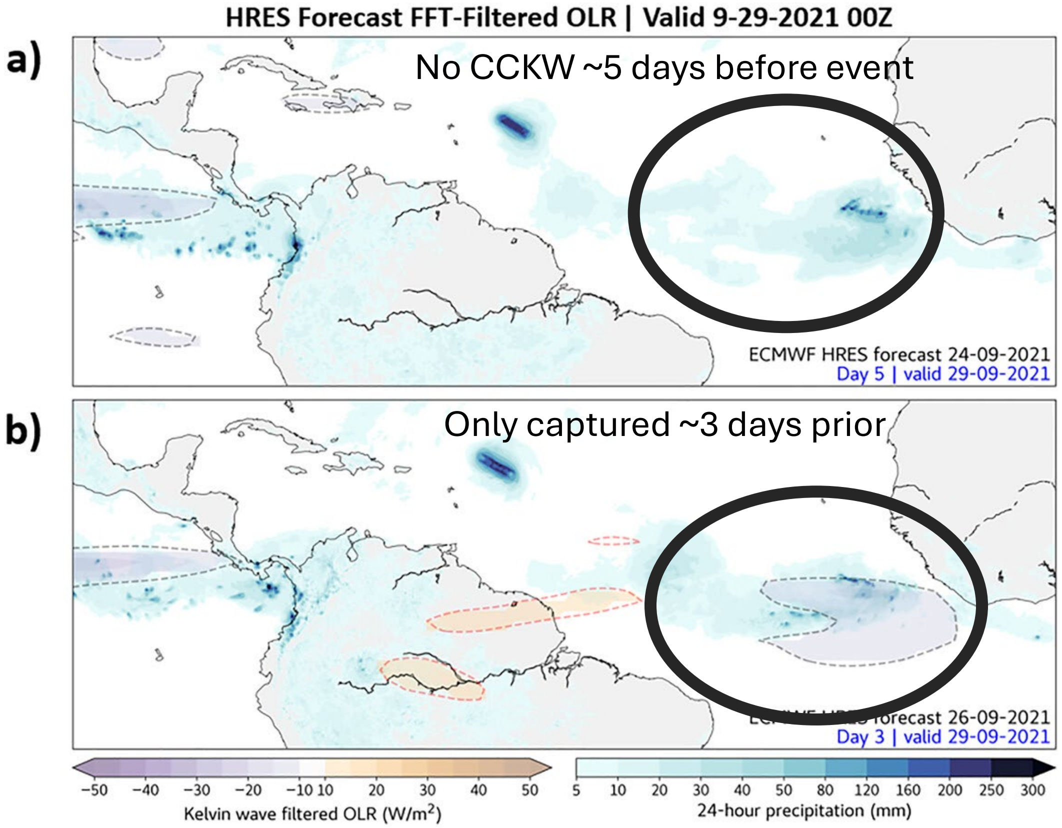
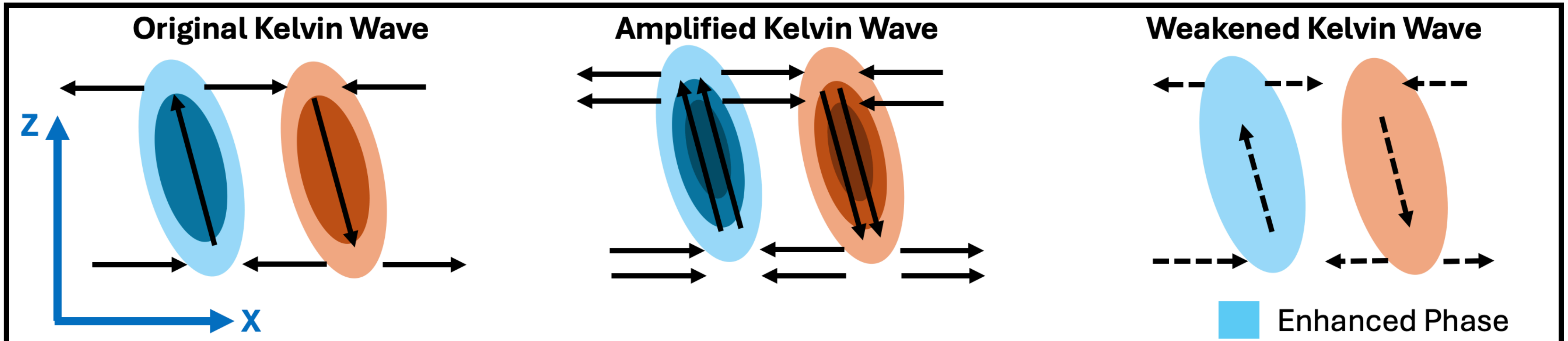


Fig. 16 from Lawton et al. (2024)

Modifying CCKW strength in numerical model simulations could help **attribute their impacts on other weather features** and **assess the influence of CCKWs on downstream forecasts**

Modifying CCKWs in 30km MPAS-A experiments (Lawton et al. 2024)

1. FFT-filter IFS data in one month period surrounding initialization time to find **“Kelvin wave signals”**
2. Limit this filtered data to a 20°S to 20°N latitude range
3. **Add or subtract this data (at all model levels)** to original IFS fields at initialization time
4. Run MPAS-A experiment with adjusted IFS initialization that has initial CCKW modified



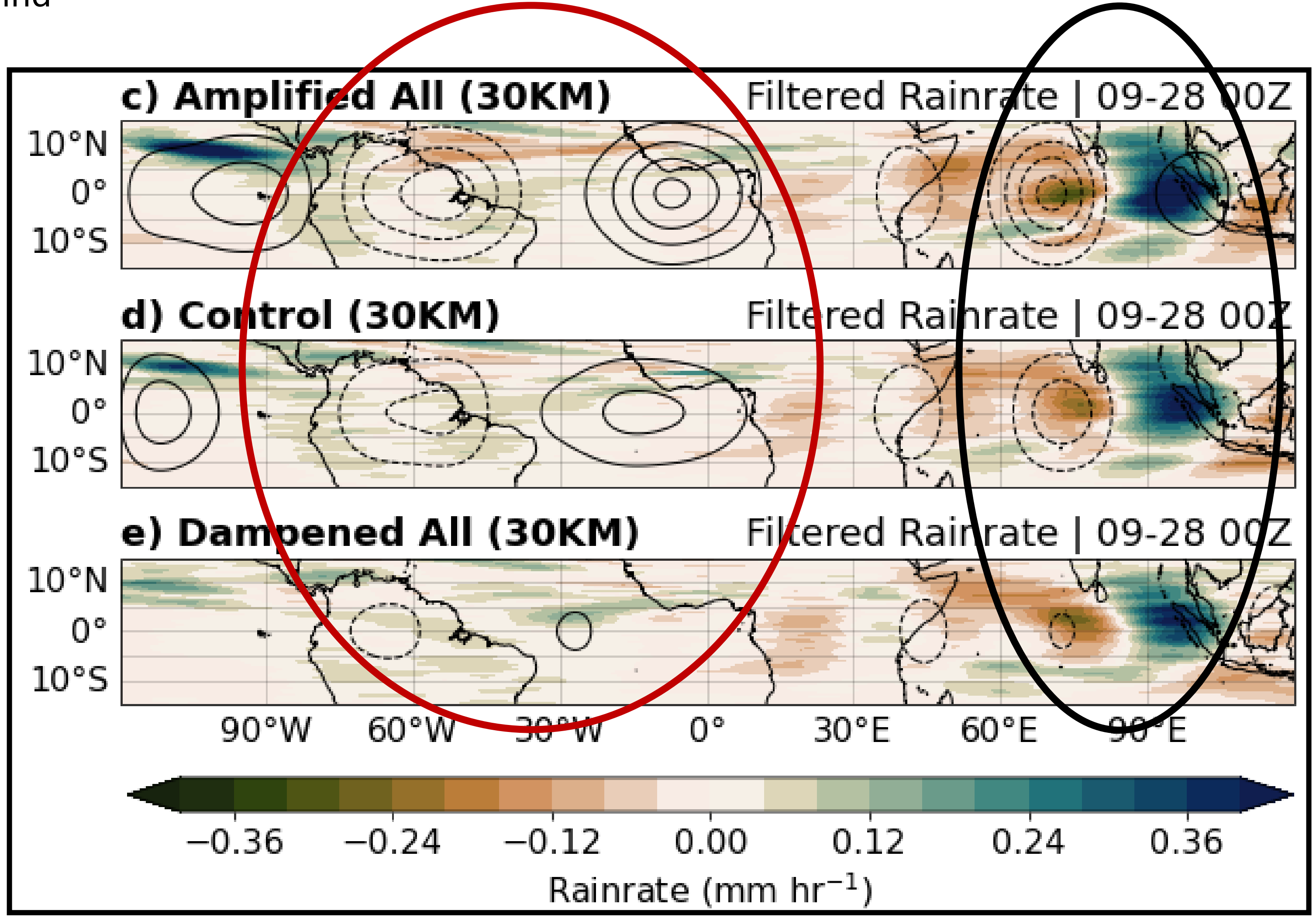
Modifying Kelvin Waves in Simulations

Example in MPAS-A Experiments

Shading: FFT-Filtered (Kelvin band) rain rates
Contours: PCF-Filtered (Kelvin band) 200hPa zonal wind
Snapshot taken 4-days into run (9-28-2021 00Z)

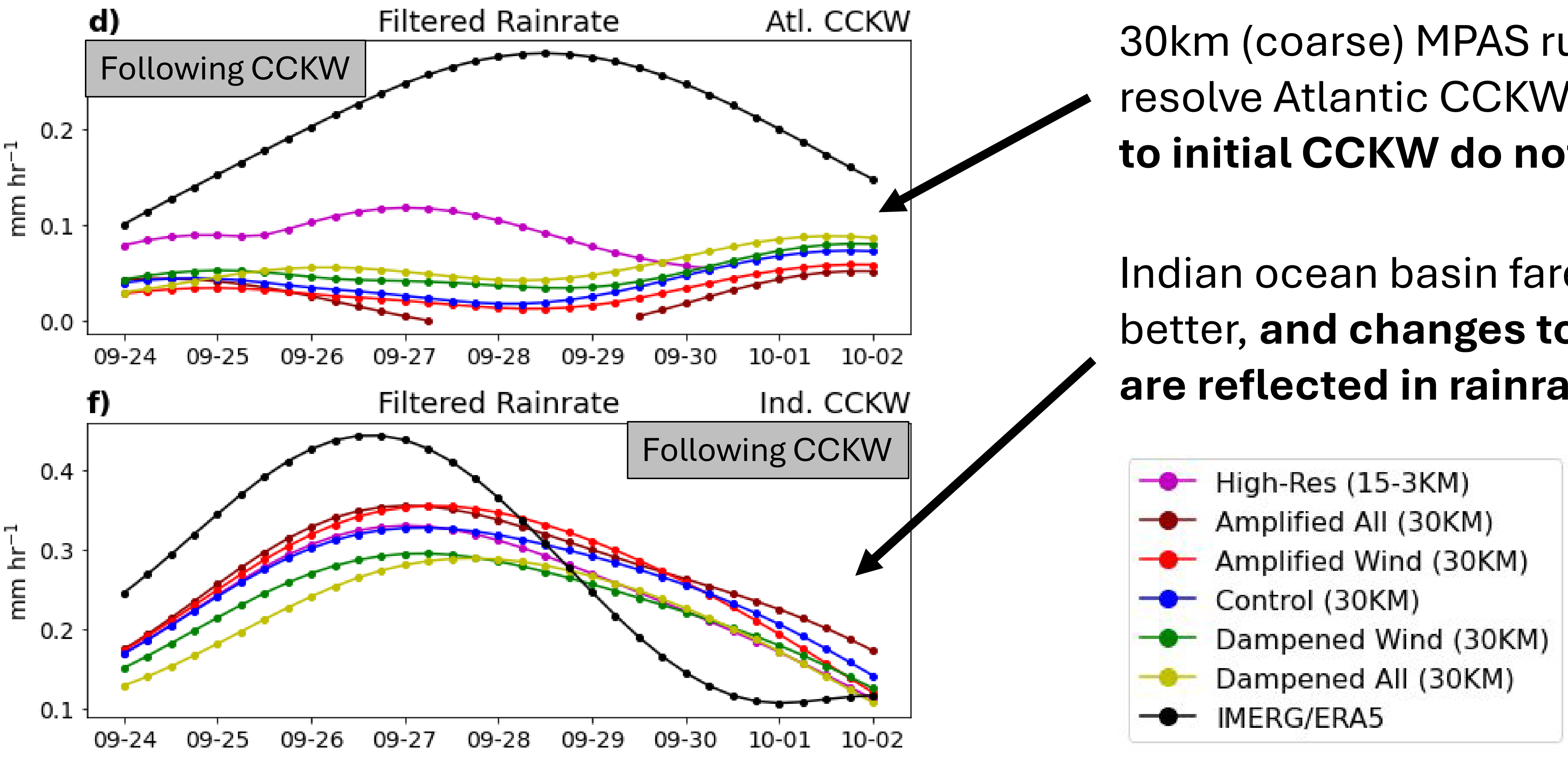
Takeaways from modified simulations

- Modification method changed the FFT-filtered rainrate and upper-level winds of the Indian Ocean CCKW
- Only upper-level winds appear changed across simulations for Atlantic CCKW



Lawton et al. (2024)

Insights



30km (coarse) MPAS runs fail to resolve Atlantic CCKW; **changes to initial CCKW do not help.**

Indian ocean basin fares much better, **and changes to CCKW are reflected in rainrate**

Summary and Implications

AEW/TEW Tracking

- **Several trackers exist, and should be picked based on your use case**
- Lawton et al. (2022) and Fischer et al. (2024) both have their methods published in public packages, lending them to use in numerical modeling
- New work by Downs et al. (*in prep*) could improve Caribbean AEW tracks
- **A future study directly comparing trackers could be illuminating**

Wave Modification

- Lawton et al. (2024) introduced a method to modify CCKWs in simulations
- Modifying waves may be useful for model evaluation and attribution work
- **This method could possibly be applied to other filtered wave types**

Resources and Datasets

- **Hollis et al. (2024)**: https://doi.org/10.1007/s00382-023-07025-w
  - Historical Tracks: https://doi.org/10.5281/zenodo.10076724

- **Lawton et al. (2022)**: https://doi.org/10.1175/MWR-D-21-0321.1
  - Qtrack GitHub: https://github.com/qlawton/QTrack
  - Historical Tracks: https://zenodo.org/records/13350860

- **Fischer et al. (2024):** https://gmd.copernicus.org/articles/17/4213/2024/
  - Historical Tracks: https://doi.org/10.5281/zenodo.8403744
  - *enstools-feature:* https://doi.org/10.5281/zenodo.10062273

- **Downs et al. (*in prep*):** *currently in review*
  - Historical tracks to be public soon!