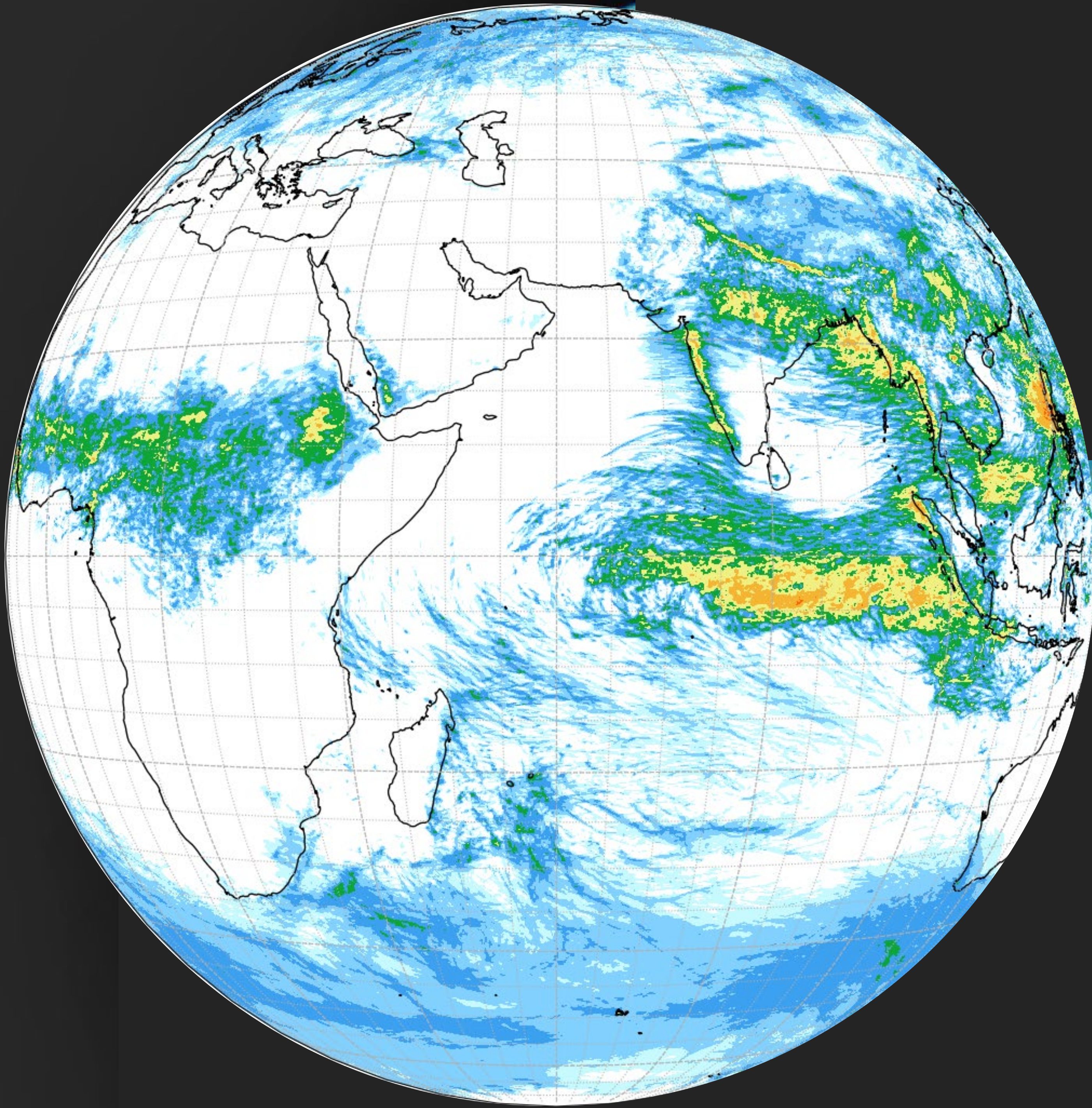
Met Office

Challenges in the evaluation of the K-Scale model hierarchy.

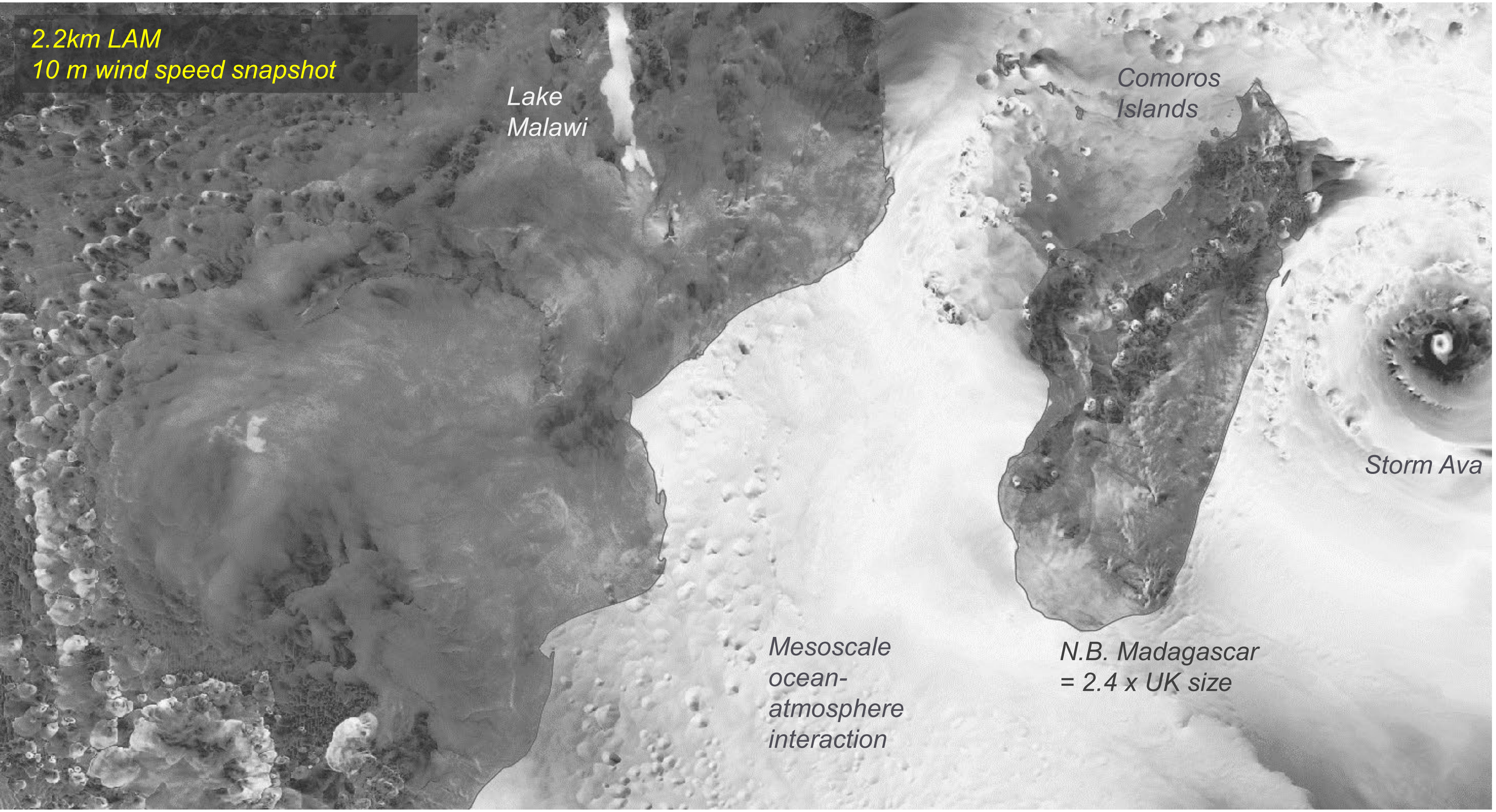
Claudio Sanchez, Richard, Jones Huw Lewis, James Warner, Dasha Shchepanovska, Samantha Smith and Alison Stirling.

Workshop on Diagnostics for Global Weather Prediction. ECMWF, Reading, UK. 12 September 2024.



What is K-Scale?

K-Scale: 1-10km grid-spacing, where convection is partially resolved



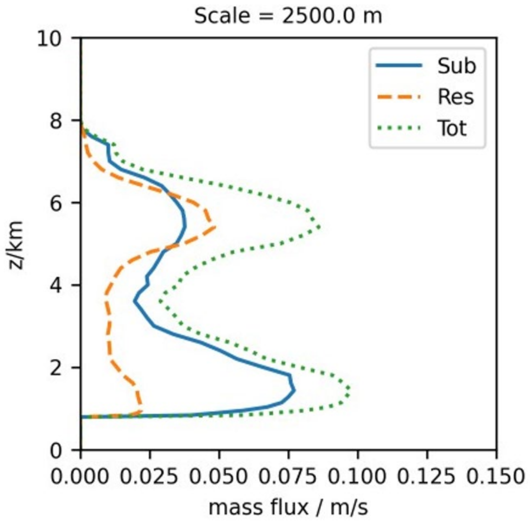
Routinely run as Limited Area models (LAM).

- Better at capturing extreme precipitation.
- Improved diurnal cycle.
- Improved intensification of tropical cyclones.
- Improved representation of orographic and coastal processes.

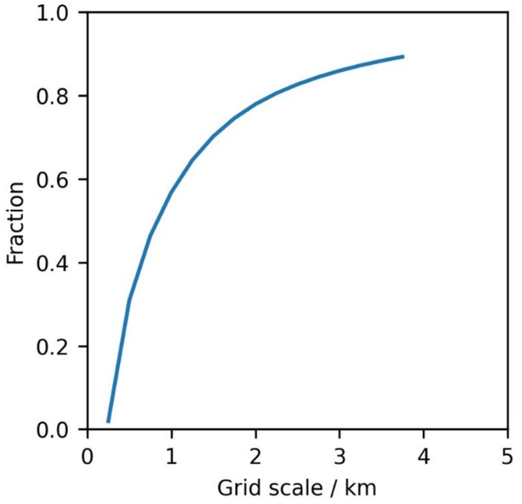
Global models starting to run in global models, unknown representation of large-scale processes. Traditionally dominated by the global parent model in LAMs.

“Partially resolved” convection

Ongoing work led by Samantha Smith and Alison Stirling (MetOffice) separates mass fluxes into resolved and subgrid for a cold-air outbreak case.



[Left] Vertical profile of a domain average Mass flux on a 2.5km model.

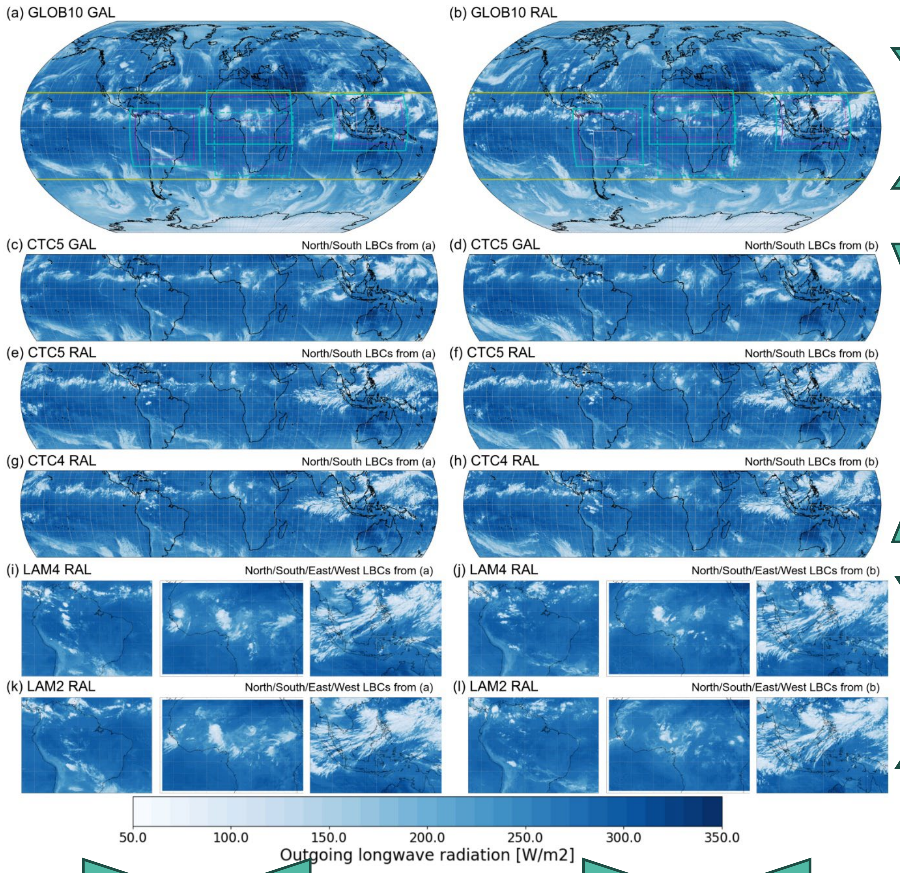


[Left] Fraction of the mass flux that would still be sub-grid as a function of model grid scale.

- At 2km resolution, 80% of mass flux is sub-grid on this case. Need for a scale aware convection scheme.
- MetUM has none at the moment, LAMs at K-Scales run without a convection parametrization.
- These LAMs provide value across several regions, e.g. North Atlantic (Milan et al., 2020. QJRMS). Africa (Woodhams et al., 2018. MWR) or South-East Asia (Ferret et al. 2021. Weather and Forecasting).
- However, precipitation is too strong in these LAMs, “over-doing weak convective events”
- Impacts un “unresolved subgrid convection” at global scales?

What is the K-Scale hierarchy?

How do we evaluate the benefits of km-scale pseudo global models vs LAMs driven by traditional global models with convective parametrization? The K-Scale hierarchy could give us some answers!



GLOB10: Global models at 10km, 0.09°x 0.14° lat-lon

CTCs: Cyclic Tropical Channels. Longitudinally global with North and South boundaries (driven by the global model).

At 5km 0.05°x 0.07° lat-lon.
and 4.4km, 0.04°x 0.04° lat-lon

LAMs: Continental Scale LAMs (driven by the global model) over S. America, Africa and South-East Asia (SEA).

At 4.4km, 0.04°x 0.04° lat-lon and and 2.2km 0.04°x 0.04° lat-lon

CTCs and LAMs driven by **GLOB10-GAL** (inc. convection param.)

CTCs and LAMs driven by **GLOB10-RAL** (no convection param.)

What are GAL9 and RAL3?

***"global" O(>10km)* and *"regional" O(<10km)* science configurations**

GAL9: Convection parameterised

Convection

RAL3: **No convection scheme**

GAL9: PC2 - *prognostic*; ,
Wilson et al 2008

Large-scale cloud

RAL3: Bimodal cloud - *diagnostic*; KVW 2021

GAL9: Wilson & Ballard. 1999

Microphysics

RAL3: CASIM 2-moment; Field 2022

e.g. Walters et al., 2019. GMD

e.g. Bush et al., 2023. GMD

Vertical model grid:

Global: L70 with 80km lid

CTCs & LAMs: L90 with 40km lid

Evaluation of the hierarchy

Met Office

The K-Scale hierarchy is run following the **DYAMOND protocol** (Stevens et al., 2019. Progress in Earth and Planetary Science):

- 40 day runs in summer (1st Aug 2016) and winter (20th Jan 2020).
- … initialized from UM global analysis and daily updating SST with OSTIA.

Evaluation over the three regions (S. America, Africa and SEA).

Exploring differences in the representation of convection and upscale feedbacks between global, CTCs and LAMs across different resolutions and science configurations.

- Precipitation: diurnal cycle and PDFs.
- Kinetic Energy power spectra.
- African Easterly Jet + MCS properties.

Computational Costs

Met Office

Experiment	Grid points	N. Proc [NX*NY* 2 OMP]	Node-hr / sim. day*	Relative cost	Data write IO / day+	Diagnostic data / day#
GLOB10	344 M	2560	105	= 1.00	383 Gb	11.9 Gb
CTC5	649 M	2560	200	1.90	559 Gb	17.3 Gb
CTC4	**1.34 G**	2560	365	3.48	1150 Gb	33.7 Gb
LAM4 (S. Amer.)	149 M	864	71	0.68	36.8 Gb	4.4 Gb
LAM2 (S .Amer.)	594 M	3072	320	3.05	262 Gb	14.7 Gb

Running on MetOffice's Cray XC40 'broadwell' CPUs.

Room for improvements
- Input-Output (IO)
- Parallelisation
- Data-compression.

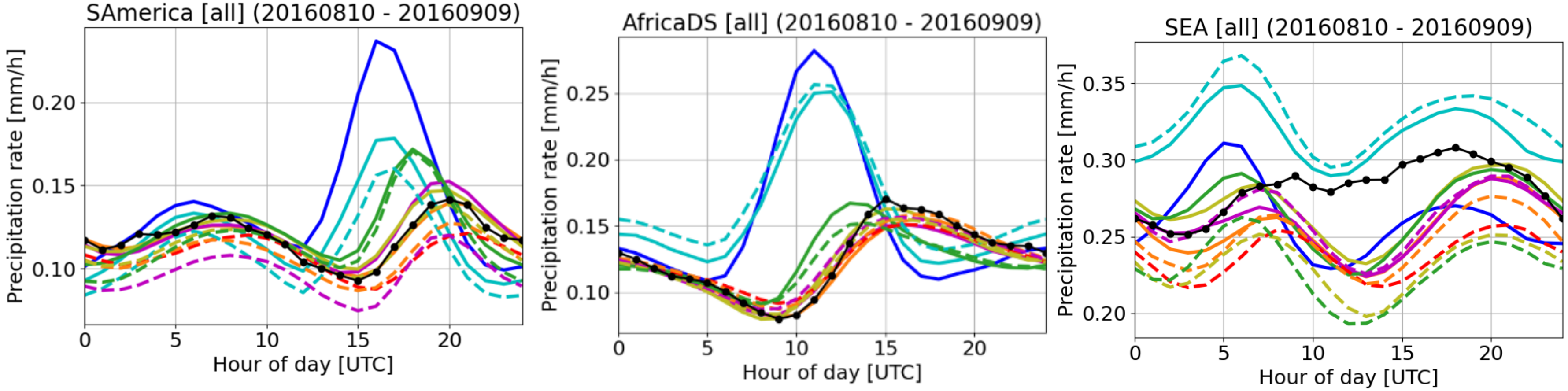
- Cost relative to a 10km operational global model (GLOB10GAL):
  - CTC5 about x2
  - CTC4 and LAM2(s) both x3.5
- Large IO to produce "dumps" (initial condition files containing all prognostics), diagnostics are <10%

Met Office

Diurnal Cycle of Precipitation

DYAMOND summer only (eq. results for winter).

S. America | Africa | SEA



[Left] Lat-Lon average of Diurnal cycle of precipitation and daily avg. for the 40 days period. Different regions (panels) and different members of the K-Scale hierarchy (colours).

Legend:

GPM-IMERG
GLOB10-GAL9
GLOB10-RAL3
CTC5-GAL9
CTC5-RAL3
CTC4-RAL3
LAM4-RAL3
LAM2-RAL3

— CTCs and LAMs driven by **GLOB10-GAL9**
- - CTCs and LAMs driven by **GLOB10-RAL3**

- D.C. of **GLOB10** and **CTC5 with GAL** starts too early in land-bound regions (S. America and Africa). **RAL** improves it.
- **LAM2** triggers convection earlier than **LAM4**.
- SEA region is complicated! E.g. land-sea breezes on several islands with very different orography and orientation to background flow.

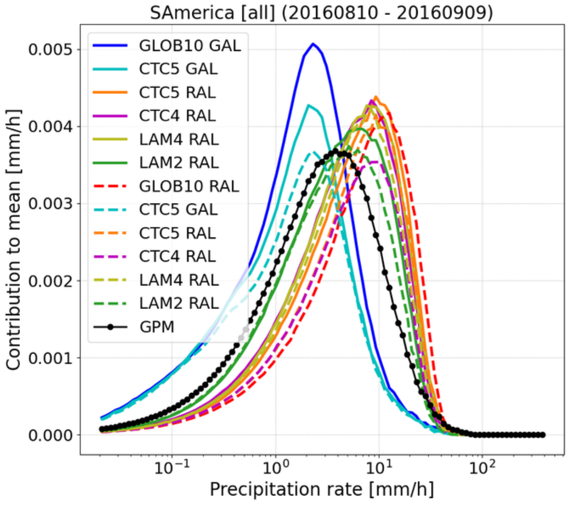
Jones et al. 2024, in preparation for BAMS.

Met Office

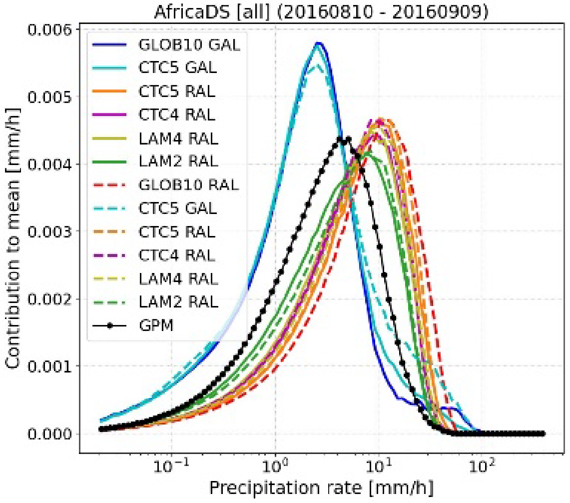
Frequency distribution of precipitation

DYAMOND summer only (eq. results for winter).

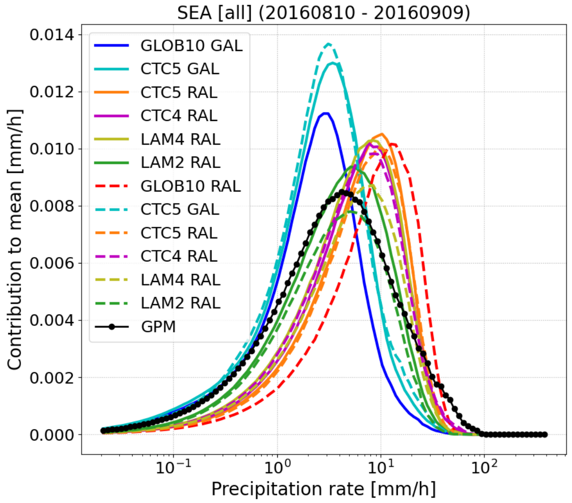
S. America



Africa



SEA



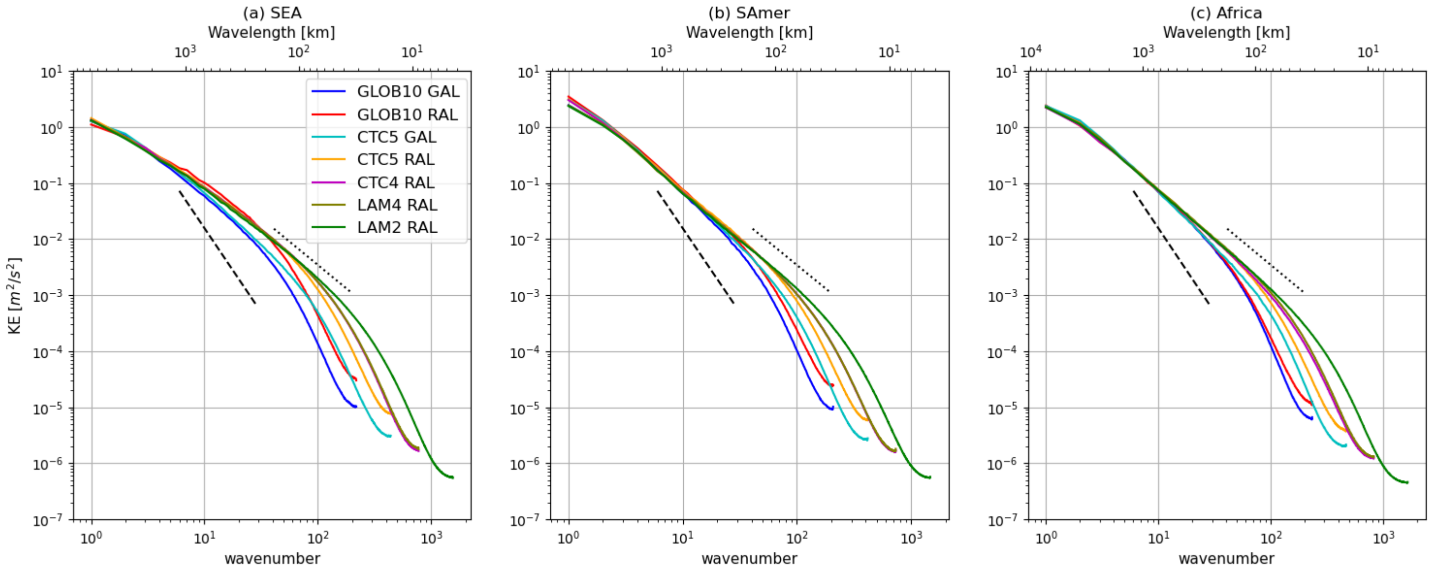
[Left] PDF of domain averaged precipitation for different members of the K-Scale hierarchy (colours). Panels show different regions

- **GAL** produces too much light precipitation (< 1mm/hr) and too little heavy precipitation (>100 mm/hr).
- **RAL** reverses the bias, too much heavy precipitation.
- **LAM2** reduces the peak of rainfall towards GPM-IMERG from the **CTC(s)-RAL** and **LAM4**.
- **RAL** produces more fragmented precipitation than **GAL** in precipitation histograms (not shown).

Jones et al. 2024, in preparation for BAMS.

Upscale: KE spectra

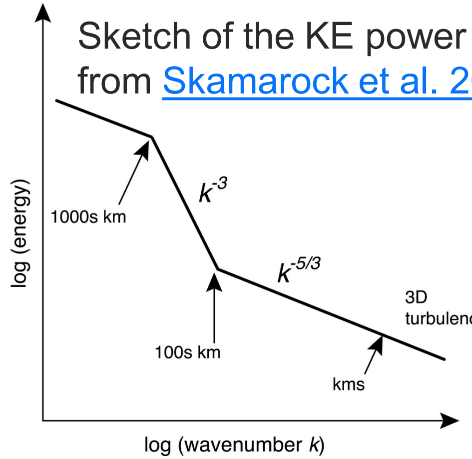
A model 's ability to reproduce the Kinetic Energy (KE) power spectra indicates whether it is faithful to the dynamics of the atmosphere (Skamarock, 2004. MWR).

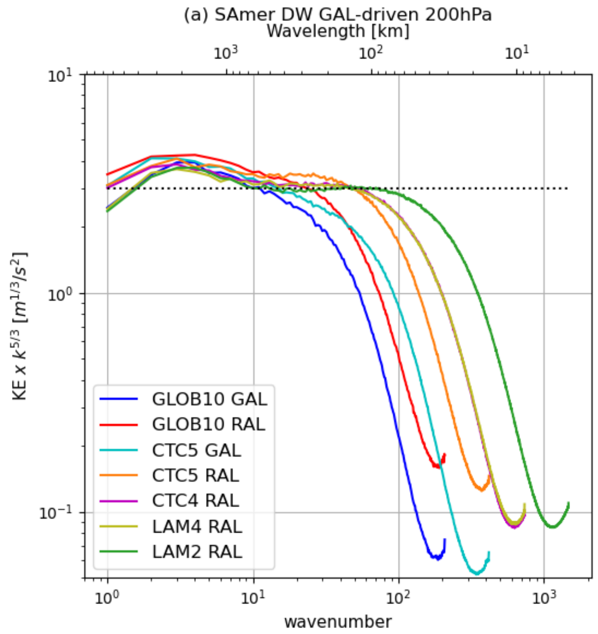


[Top] KE power spectra for 10S-10N at 200hPa (winter case). CTC and LAMs driven by GLOB10-GAL S.America region with a 1-D DCT (lat. avg.)

- **GLOB10** and **CTC5** with **GAL** miss the -5/3 slope at the mesoscale, whereas simulations with RAL capture it (even GLOB10!). See scaled plot (right).
- Same effective resolution across member, rather small (15-20 Δx!).
- Small differences between regions.

Sketch of the KE power spectra, from Skamarock et al. 2014.



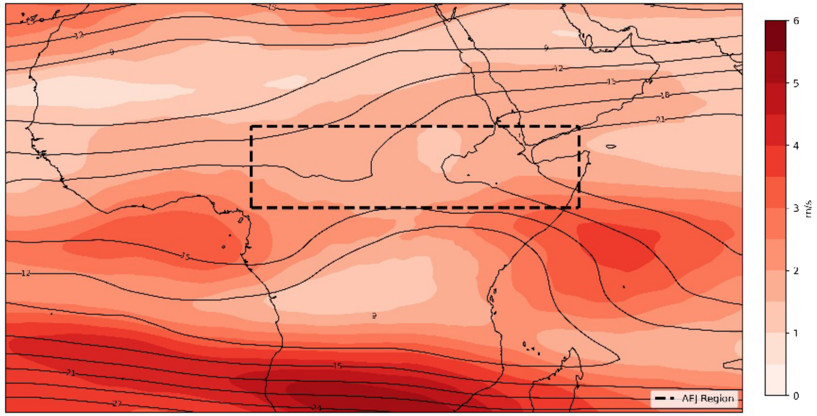


[Top] Scaled to $k^{-5/3}$ for S. America.

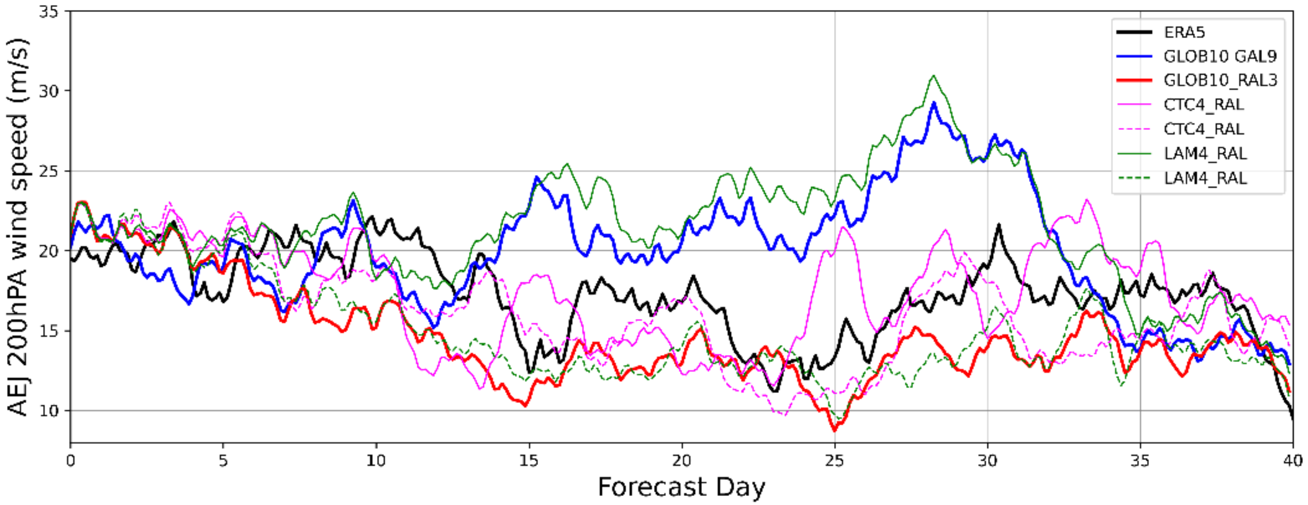
Jones et al. 2024, in preparation for BAMS.

Upscale: Africa Easterly Jet

Representation of the tropical easterly jet over Africa during DYAMOND summer



[Top]: mean (contours) and standard deviation (colours) of the 200hPa horizontal wind speed 1980-2020 climatology for DYAMONND summer period (1st Aug to 10th Sept).



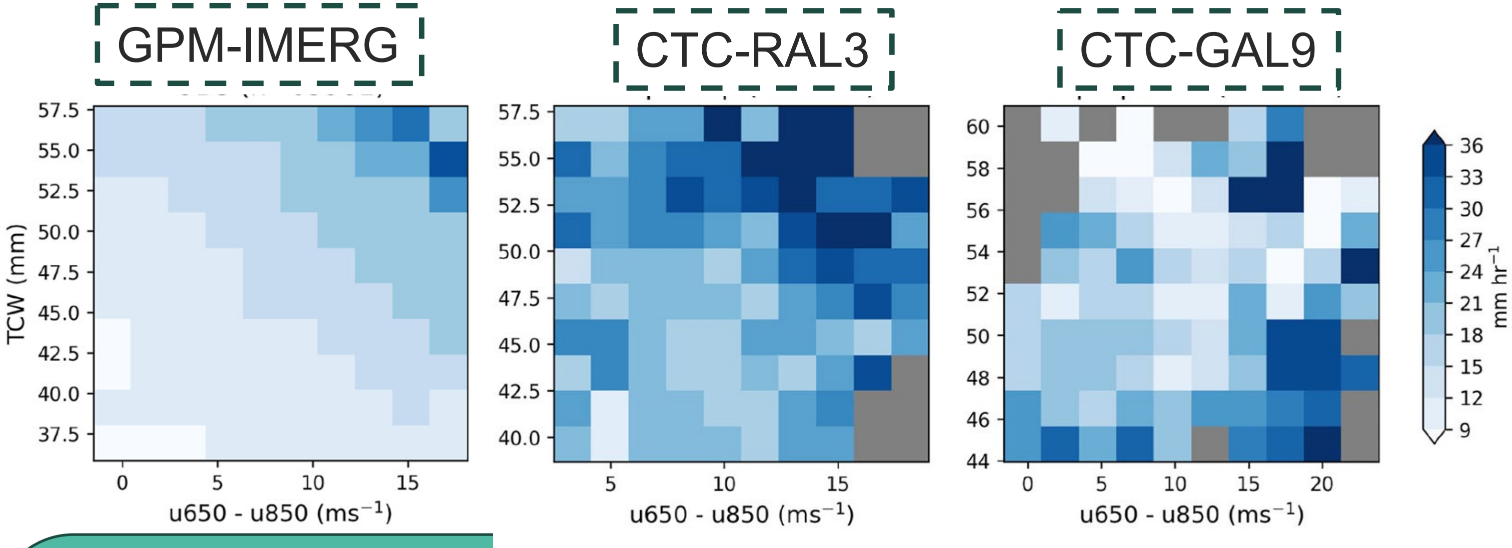
[Top]: Timeseries of wind speed over at 200hPa the dashed black box in the right plot for the DYAMOND summer.

- Jet speeds up above 20 m/s in **GLOB10-GAL** and **LAM4 driven by GLOB10-GAL**.
- **GLOB10-RAL** and **CTC4-RAL3** (driven by both global models) and **LAM4 driven by GLOB10-RAL3** slow the jet, closer to ERA5.
- Ongoing work by J. Warner shows that **GAL** produce weaker updrafts and reduced diabatic heating. This strengthens the temperature gradient at upper levels, and subsequently increases jet speed through thermal wind balance.

Jones et al. 2024, in preparation for BAMS. Warner et al. 2024/25 in preparation.

Better Representation of MCS

Understanding dynamical drivers/control, e.g. West African Mesoscale Convective Systems (MCS) role of wind shear.



[Left]: Maximum MCS rainfall at 16-21 UTC, binned by Total Column Water (TCW) and wind shear. Note, GPM covers a multi-year sampling period, CTCs only 40 days.

- MCS rainfall max. in very most and strong wind shear environments.
- This is well captured by **CTC-RAL**, but with higher precipitation.
- **CTC-GAL** shows no relation to TCW.
- **CTC-RAL** updraft entrainment decreases with shear leading to a realistic increase of extreme rainfall.
- **RAL3** showing better skill than simulations with older regional configurations (not shown).

Courtesy of Ben Maybee, further info at [Maybee et al., 2024, GRL.]

Twin experiments

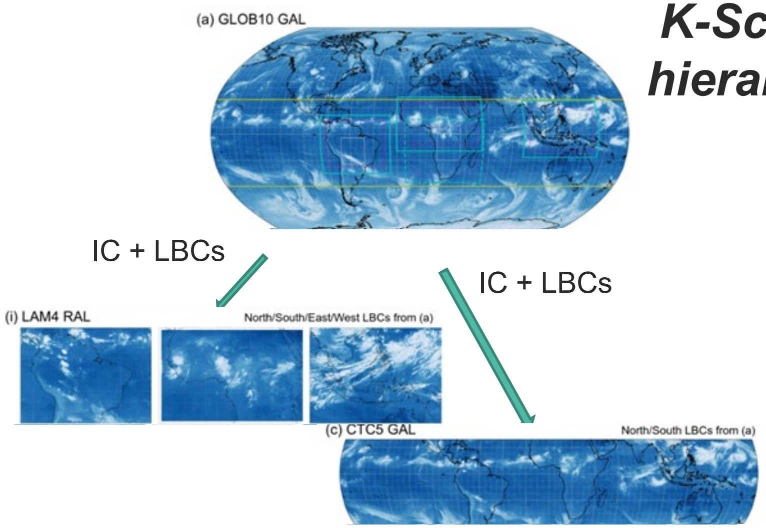
An additional hierarchy (driven by GAL9 only) is run for the DYAMOND winter. GLOB10-RAL3 is also run (without nested CTC and LAM).

Follows “twin experiment” methodology of Judt, 2018. JAS. It applies a small gaussian perturbation at θ initial field on the global analysis.

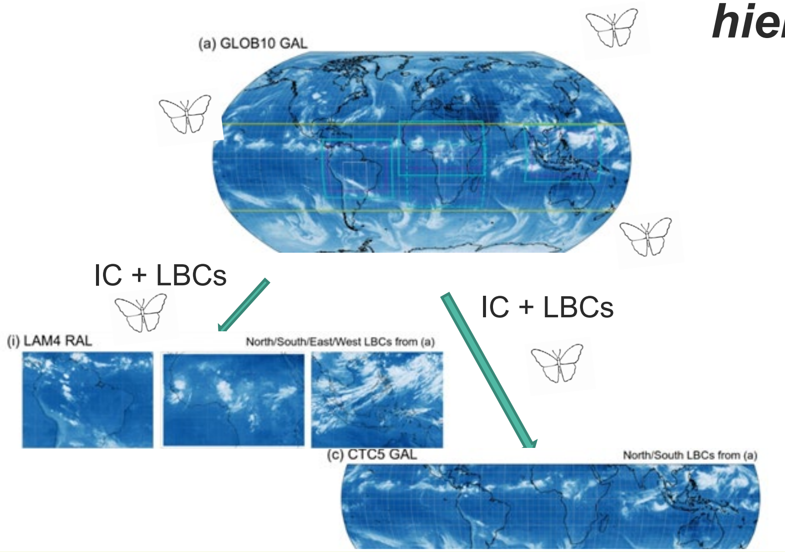
Aim to explore the intrinsic predictability across configurations and resolutions within the K-Scale hierarchy.

Using the power spectra of the Difference in the Kinetic Energy (**DKE**) between the original hierarchy and the twin hierarchy. is analysed to explore the **intrinsic predictability**.

K-Scale hierarchy

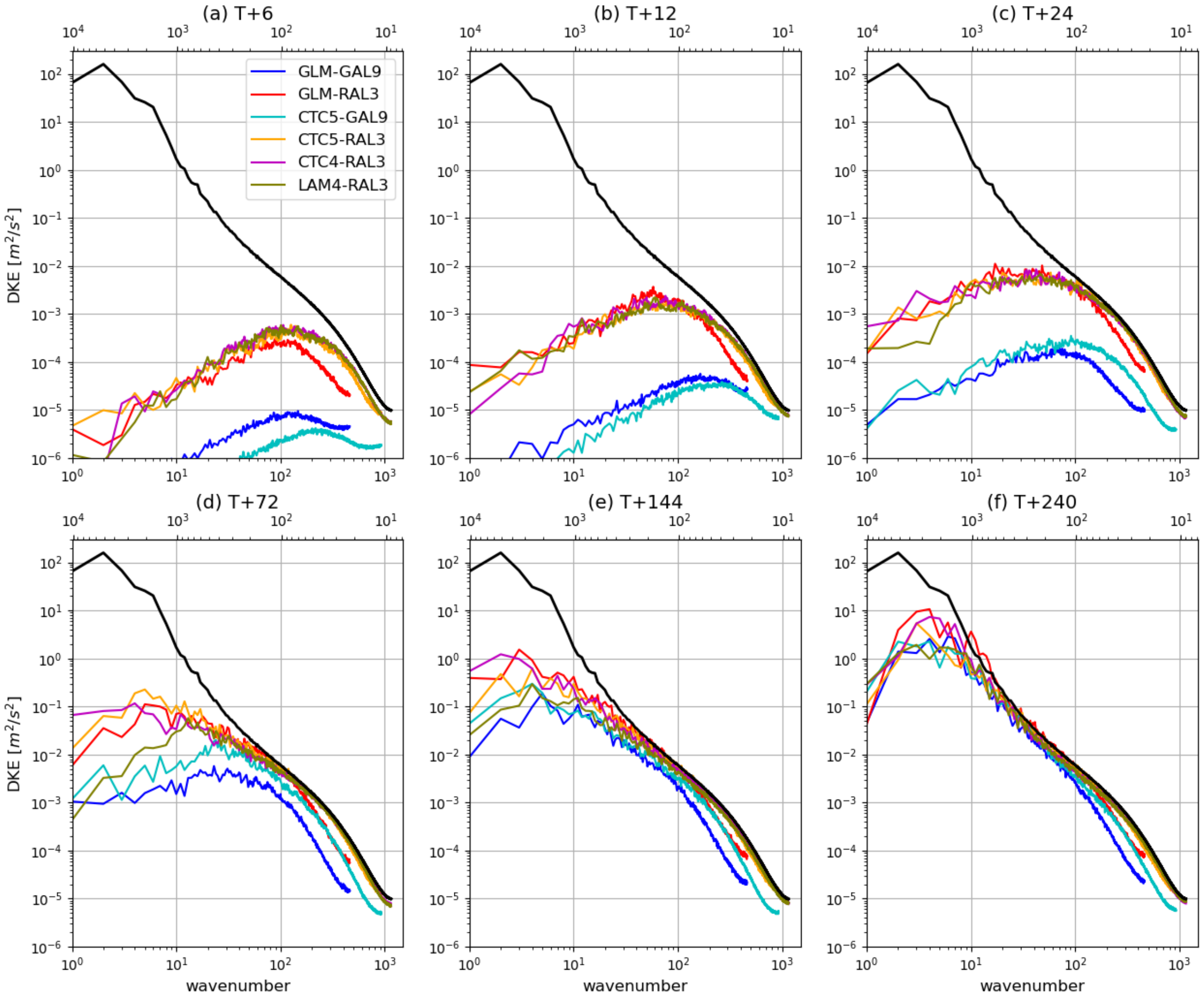


K-Scale TWIN hierarchy



Twin experiments (2)

The DKE differences across members of the K-Scale hierarchy at different lead times using the DCT of [Dennis, 2002 MWR.]



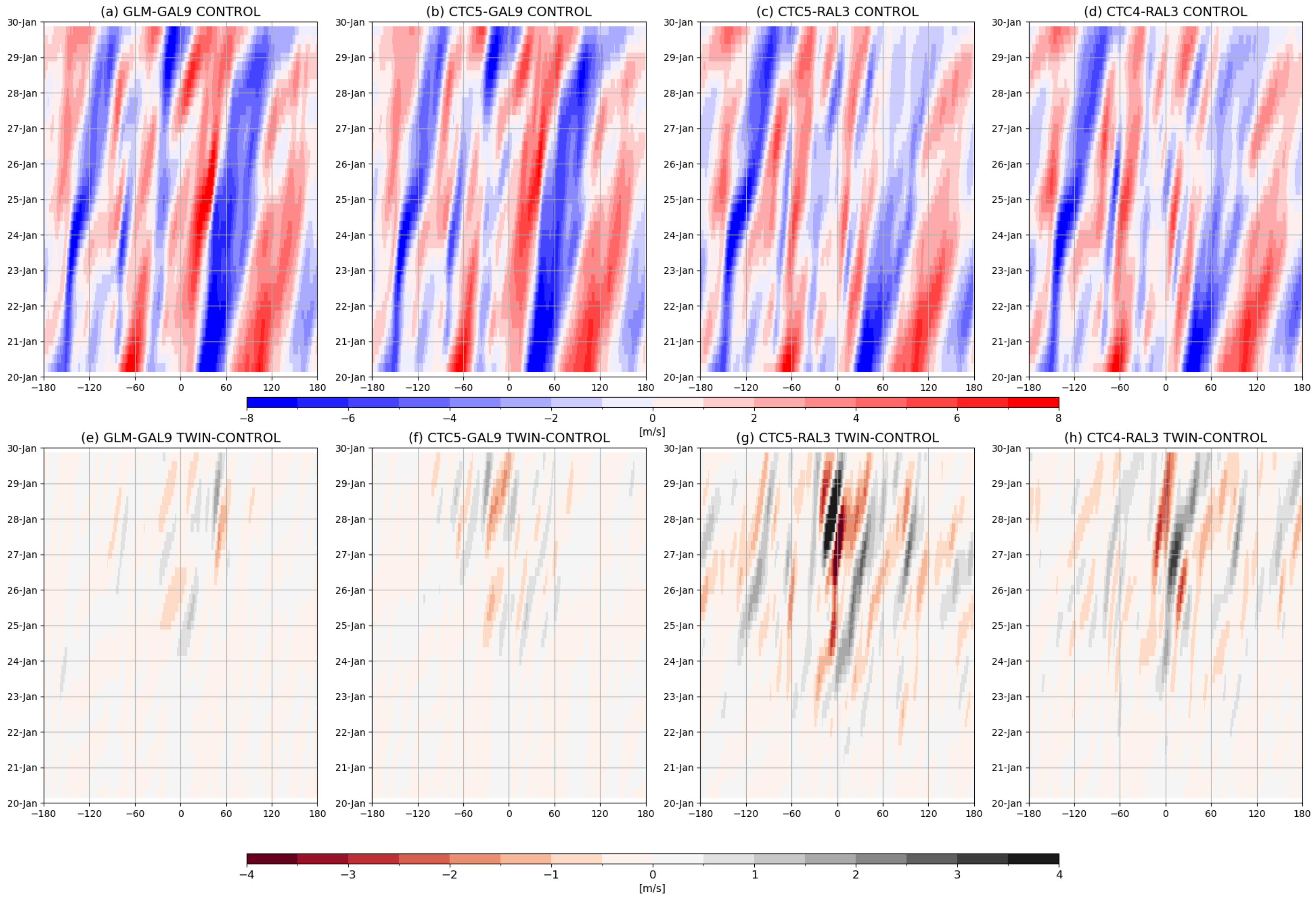
[Left] DKE power spectra over Africa. Horizontal wind field, over 925, 850, 700, 500, 250 and 200hPa. Black line shows saturation.

- **DKE** in simulations with **RAL** reaches saturation on the first day on wavelengths below 100km (a-c), **GAL** simulations take longer.
- Amplitude of DKE larger in RAL than GAL (e.g. CTC5-GAL vs CTC5-RAL), but they both peak at the same scales.
- Implications for ensemble spread in EPS? Is **GAL** too diffusive? Is the **RAL** “resolved convection” over doing differences?

Twin experiments, CCKW

Kelvin waves, obtained following [Yang et al 2021, Weather and forecasting] for real-time forecasts.
Only applied to global and CTC (wave identification tool not available for LAMs).

GLM10-GAL | **CTC5-GAL** | **CTC5-RAL** | **CTC4-RAL**



[Top]: Kelvin waves at 200hPa (a-d) u amplitude for Kelvin. (e-h) Differences between twin experiments.

- Amplitude of negative phases weaker in **RAL** simulations (e.g.one init. at 0-60E)
- Larger differences in **RAL** twins than **GAL**, starting 2 days earlier.
- Differences grow earlier than [Judt, 2020, JAS.] (MPAS at 3km, diff from day 10). Diff model and wave identification methodology.

Met Office

Conclusions

- The **K-Scale hierarchy** is developed to explore the **benefits of running at global K-Scale resolutions** to the convectional LAMs driven by global with convection parametrized.
- We find a **higher sensitivity** to a **science configuration with convection parametrization** (**GAL**) or **without** (**RAL**) than **horizontal resolution** in the following areas
  - Diurnal cycle of precipitation and the distribution of precipitation.
  - KE power spectra
- Only simulations with **RAL** simulations **capture** the **$k^{-5/3}$ slope** in the KE power spectra
- The representation convection in **RAL** global and pseudo-global simulations **slows the African Easterly Jet**, in agreement with ERA5.
- A twin experiment is developed to explore the intrinsic predictability across the members of the K-Scale hierarchy.
  - The DKE in **RAL** simulations has **a larger amplitude** but grows at the same rate in time **than GAL** across scales.
  - **GAL** takes several days to **saturate at small scales**.

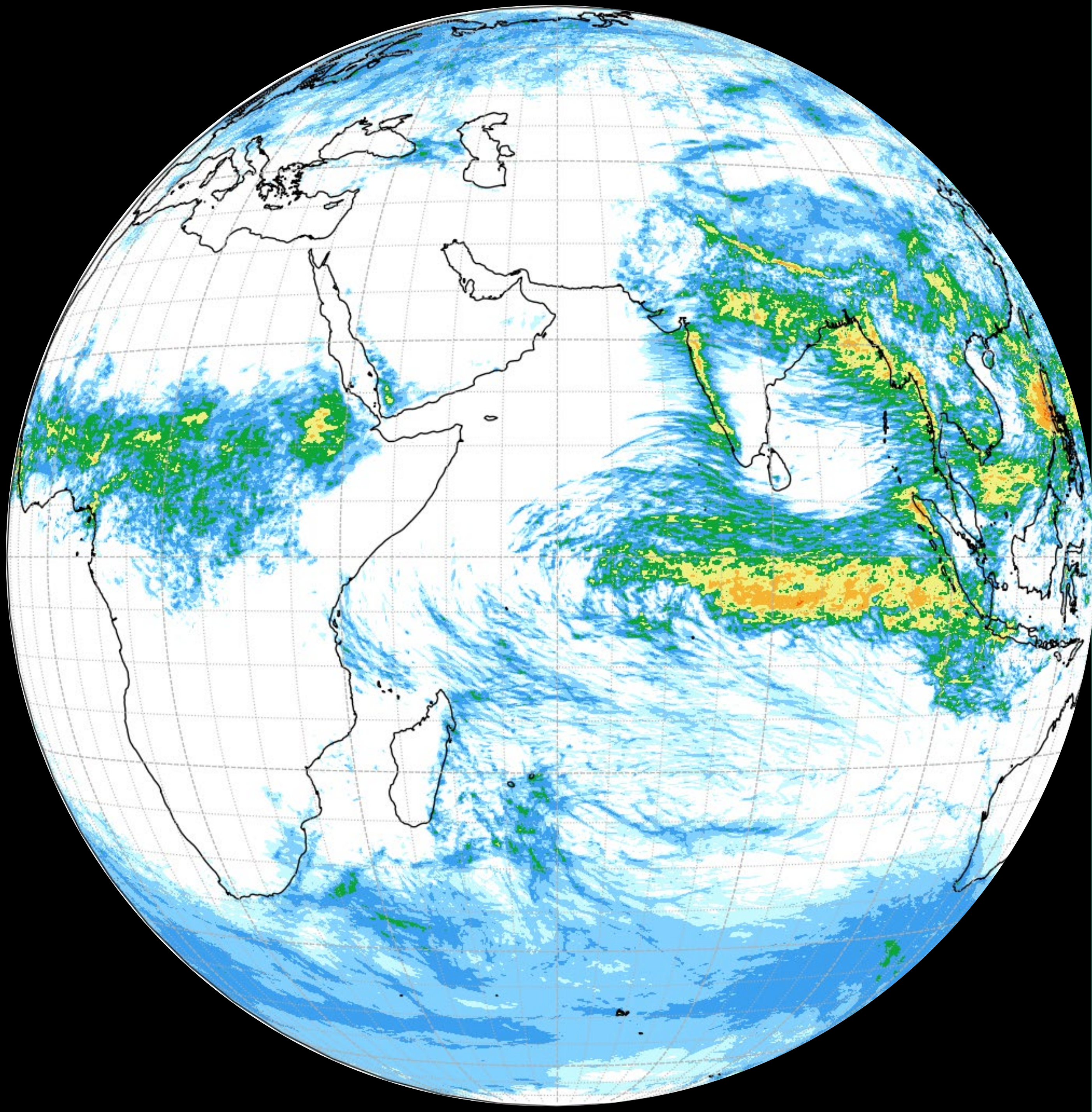
Met Office

Future work

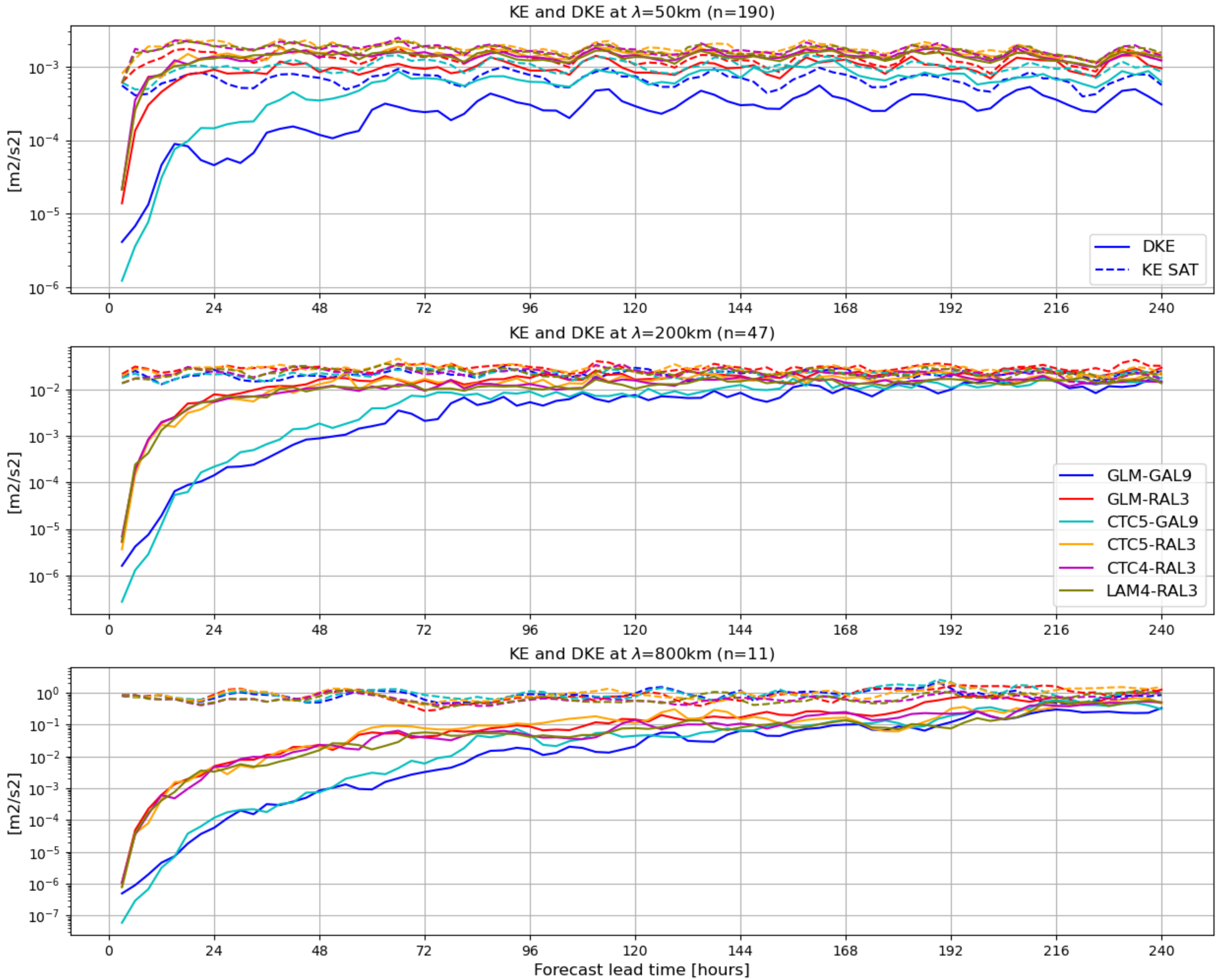
- Investigate **the role of diabatic process** triggered by convection in the deceleration of the **African Easterly Jet**, e.g. using the Semi-Geotropic inversion tool to find balanced response from convection.
- Run and analyse a **K-Scale ensemble hierarchy** (3-5 members only!). Check that **DKE still grows faster** in RAL simulations than GAL when initialized by the ensemble of DA. Implications for global ensemble prediction at K-Scales.
- Explore **differences in more processes**:
  - More on Convectively Coupled Equatorial Waves (**CCEW**).
  - Madden-Julian Oscillation (**MJO**).
- Preparation of the UK/MetOffice **contribution to DYAMOND 3**. One year simulation from Feb 2020 to Feb 2021.
- **Development** of a **scale aware convection scheme** and investigate the subgrid convection at K-Scales.

Met Office

Thank you for your attention!



Twin experiments (3)



[Left] Timeseries of the amplitude of DKE power spectra at different wavelengths (top) 50km (middle) 200km and (bottom) 800km. Dashed lines show saturation for each model.