47th EWGLAM and 32nd SRNWP workshop
22-25 September,
Norrkoping, Sweden

Implementation of the Regional Atmosphere Land 3 (RAL3) configuration within the next-generation Momentum framework and LFRic atmosphere

Met Office:

Sylvia I Bohnenstengel, Mike Bush, James Warner, Anke Finnenkoetter, Anne McCabe, Christine Johnson, James Kent, Huw Lewis

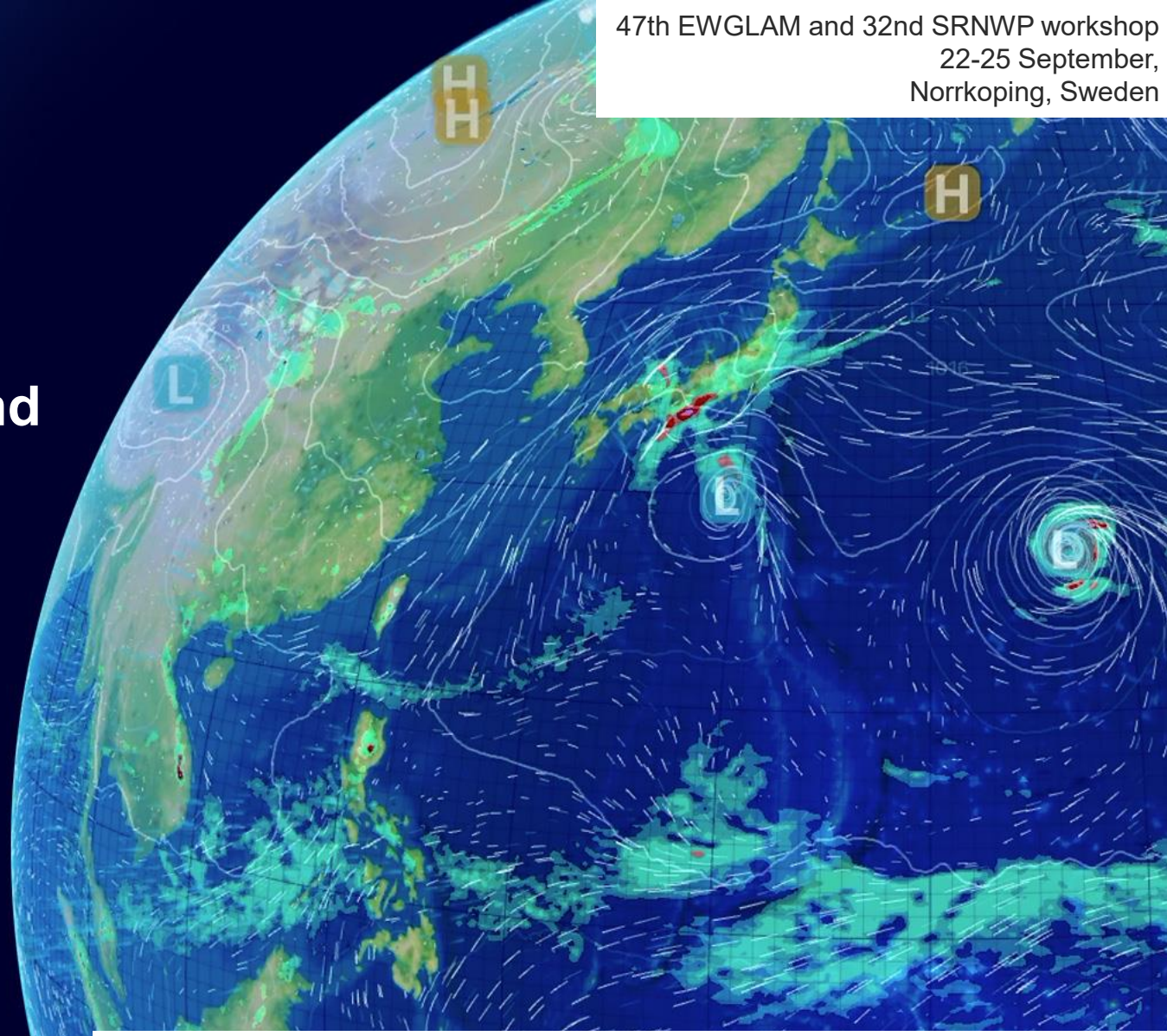
Arathy Menon, Bernard Claxton, Calum Scullion, Carol Halliwell, Chris Short Dasha Shchepanovska, David Flack, Huw Lewis, Ian Boutle, John Edwards, James Frost, Kirsty Hanley, Mark Weeks, Richard Jones, Sana Mahmood, Stuart Webster, Tom Bendall.

NIWA: Jorge Bornemann, Stuart Moore.

Bureau: Belinda Roux, Charmaine Franklin, David Lee, Vinod Kumar.

CCRS: I-Han Chen, Jerry Liu, Kalli Furtado, Pratiman Patel, Yi Wang.

NCRMWF: Saji Mohandas.



With grateful thanks to all scientists and scientific software engineers across the Met Office, Momentum Partnership and beyond whose work has contributed directly and indirectly to the outputs presented in this presentation.

Met Office

RAL3-LFRic project

The RAL3-LFRic project is an initiative within the Met Office's Next Generation Modelling System (NGMS) programme

Aim: transitioning the Regional Atmosphere and Land 3 (RAL3) configuration from the Unified Model (UM) to LFRic.

Focus: enhancing the scalability, flexibility, portability, and usability of regional atmospheric models, ensuring they are well-suited for future supercomputer architectures.

Met Office

Scientific software

- Atmosphere: LFRic
- Land Surface: Jules
- Ocean & Sea Ice: NEMO, SI3
- Biogeochemistry: MEDUSA, ERSEM
- Chemistry & Aerosol: UKCA
- Data Assimilation: JEDI
- Verification: METplus

developed by the Met Office and partners

Momentum®
Unified Earth Environment Prediction Framework

modular, scalable software ecosystem for building Earth system prediction systems

Technical software

- Infrastructure: LFRic
- Domain specific compiler: PSyclone
- Model coupler: OASIS
- Data assimilation: JEDI
- Workflow engine: Cylc
- Configuration management software: Rose

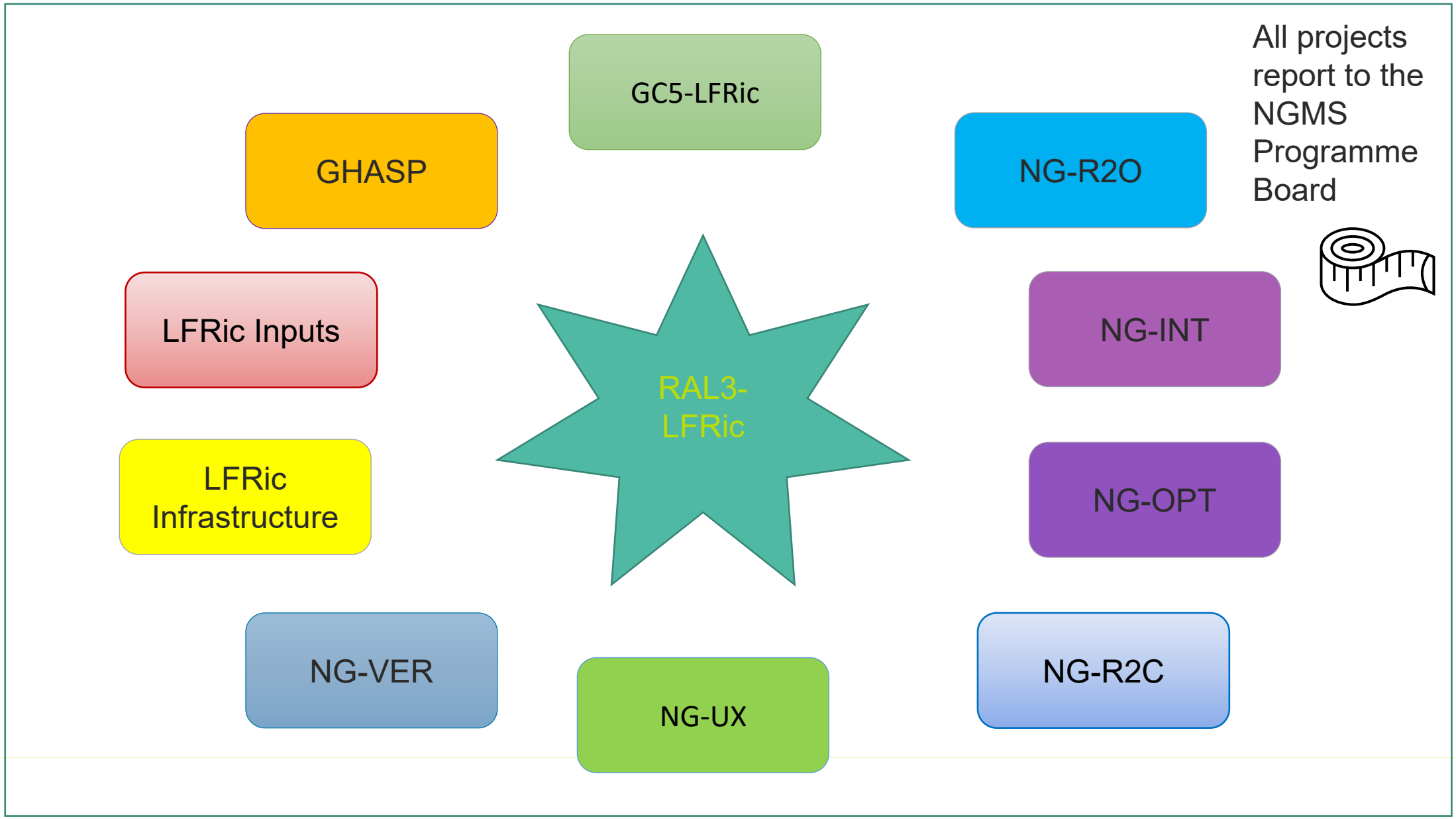
Science configuration

RAL3-LFRic

Regional **A**tmosphere **L**and (RAL3) research configuration as a well-tested and understood baseline for future developments.

combines the new next generation atmospheric model (LFRic) infrastructure with the latest science configuration developed for regional modelling applications known as Regional Atmosphere and Land 3 (RAL3).

Links to other NGMS Projects



Met Office

Project lead: Mike Bush

RAL3-LFRic project structure

Work Package	Focus	Purpose
WP1 Sylvia Bohnenstengel	Development of CSET (Convective - scale Evaluation Toolkit)	To support model evaluation through diagnostics and verification tools
WP2 Anne McCabe	Suite and workflow development	To build and maintain the infrastructure needed to run and test the RAL3-LFRic configuration
WP3 James Warner, Anke Finnenkoetter	Acceptance criteria, testing, and development strategy	To assess the scientific performance of the model and ensure it meets the defined acceptance criteria
WP4 Christine Johnson	Variable resolution meshes, lateral boundary condition (LBC) meshes, and solver optimisation	To enhance the model’s computational efficiency and stability through mesh and solver improvements

RAL3-LFRic domains across Momentum partnership

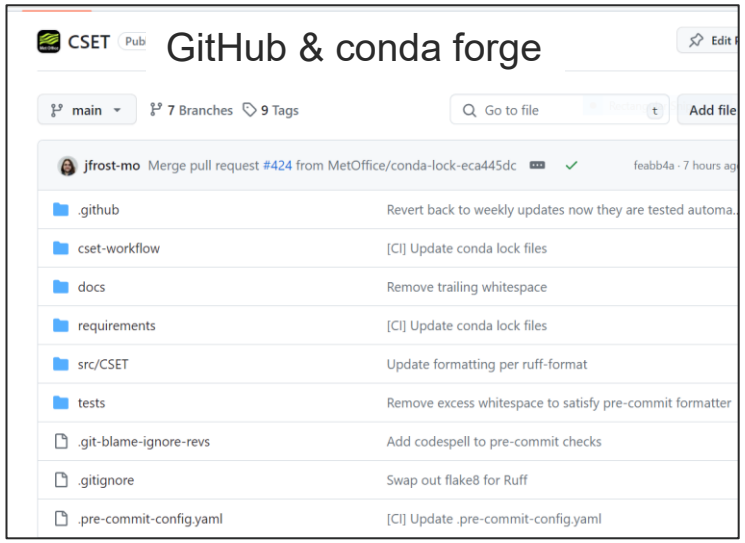
EXP	DOMAIN	GRID	CONFIG	DATES
A	UK KM-SCALE	1.5km	708.1	24 first of month and 48 targeted case studies.
B	UK KM-SCALE	1.5km	708.2	43 case studies.
C	UK KM-SCALE	1.5km	708.2.2	2 case studies.
D	UK Sub-KM	300m	708.1.1	12 case studies (WesCon summer 23)
E	UK Sub-KM	300m	708.2.1	6 case studies.
F	Melbourne	1.5km	708.1	4 case studies
G	Melbourne	1.5km	708.2	1 case study.
H	Darwin	1.5km	708.2	3 case studies.
I	New Zealand North Island	1.5km	708.2	6 case studies.
J	Auckland	1.5km	708.1	8 case studies.
K	New Zealand South Island	1.5km	708.2.2	4 case studies.
L	South East Asia	4.4km	708.1	34 case studies (random and targeted)
M	South Africa	4.4km	708.1	11 targeted case studies
N	West Africa	4.4km	708.1	16 case studies JJAS 2024.
O	East Africa	4.4km	708.3	4 case studies
P	Delhi KM-SCALE	1.5km	708.3	2 case studies
Q	Delhi Sub-KM	300m	708.2	4 case studies
R	UK Climate	1.5km	803.2	~3 years 2 months (26th August)
S	UK Ensemble	1.5km	708.2	42 case studies
T	UK Ensemble	1.5km	708.2.2	2 case studies.
U	UK Stretch Grid	1.5km	708.3.1	48 case studies.
V	Darwin Ensemble	1.5km	708.2	3 case studies.
W	Full Arctic	8.33km	708.1a	24 case studies.
X	Greenland	4.4km	708.1a	51 case studies.
Y	India	4.4km	828.1	4 case studies.
Z	Poland	4.4km	828.1	1 case study
AA	Singapore	1.5km	803.1	30 case studies (daily for one month)

- 22 domains
- 4 resolutions
- Case studies
- Climate runs
- Ensemble properties
- Stretched grid
- RAL3 base science configuration (Bush et al., 2024)
- LFRic driven by UM currently

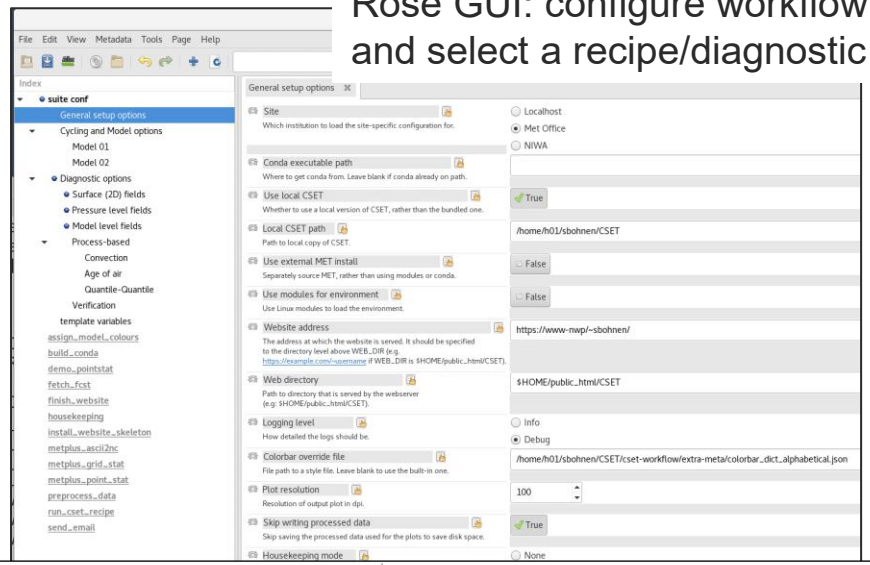
Bush, M et al. (2024) The third met Office unified model-JULES regional atmosphere and land configuration, RAL3. *Geoscientific Model Development Discussions*, pp.1-58.

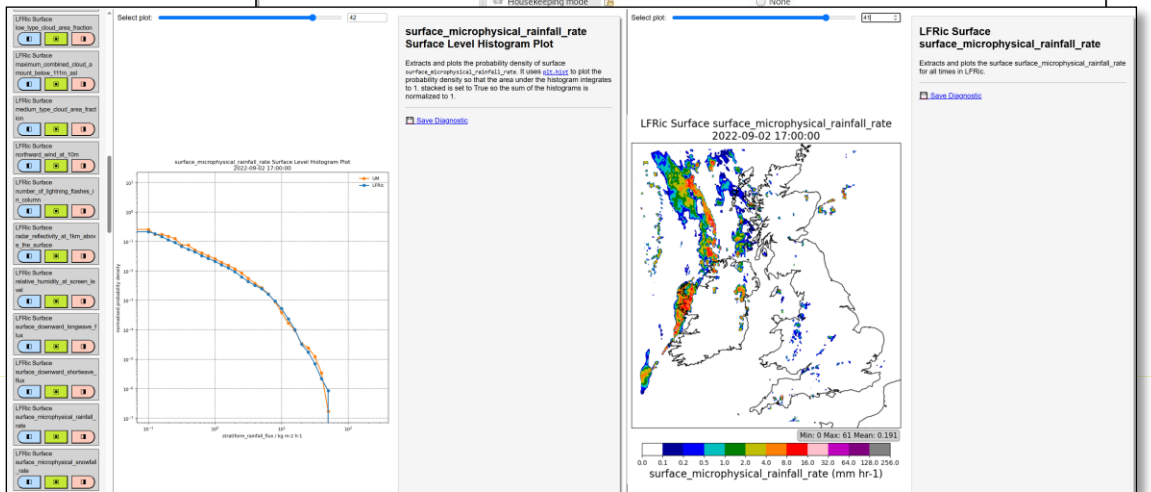
Convective- and Turbulent **S**cale **E**valuation **T**oolkit: CSET

Community tool for process-oriented evaluation supporting RAL development



Rose GUI: configure workflow and select a recipe/diagnostic





Website with

- Diagnostics visualisation
- Ensembles
- download data
- information about diagnostic

Library

- Operators
- Recipes
- METplus wrappers (linking to operational verification tools)
- metadata

to (pre-)process analysis of data and generate diagnostics and plots

Workflow (flow.cylc cylc8)

orchestrates

- build conda environment
- install CSET
- fetch data
- run and link of multiple recipes
- run METplus wrappers
- webpage
- cleans
- housekeeping

Met Office

What are the benefits of using CSET?

Development is supported by our three pillars

Technical

- Built on modern software
  - Python 3
  - Cylc 8
  - GitHub
  - Builds on Iris and METplus
- Easy to use and contribute
  - Clear documentation incl tutorials
  - Reproduceable
  - Portable
  - Open access
- QA and best practice
  - Automation for testing and docs
  - Scientific peer review

Science

- Align parametrisation, diagnostics development and evaluation research linked to Regional Atmosphere Land (RAL) suites
- Process based understanding, evaluation, and verification
- Flexible evaluation code
- Aligned with operational verification to support PS and RAL3-LFRic testing
- Ensembles and LFRic supported by default

Community

- Centralised and documented resource
- Common working practices
- Legacy for diagnostics and observations
- Community development

RAL3-LFRic benefits:

- Rapid subjective evaluation and identification of model issues
- Scaling up of evaluation

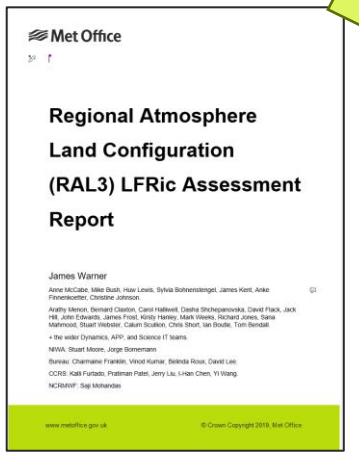
Find out more: https://metoffice.github.io/CSET

CSET enables standardised RAL3-LFRic evaluation across Momentum partnership

RMED Trac page lists all experiments, tickets, templates.
Guidance and workflow with examples provided.

	Experiment/trial	Dates	process/phenomena	Acceptance criteria	Lead scientists (running)	Lead scientists (evaluating)	Links	Status
A.	UK Kilometre-scale case studies		Convection, fog, extratropical cyclones, frontal ppn.	1A, 1C	Anne McCabe	Various, TBC	Link to template	Not started
B.	Melbourne trial		Frontal rainfall, extratropical cyclones.	1A	Dave Lee	Various, TBC	Link to template	Not started
C.	NZ domain testing		Complex terrain, frontal rainfall, extratropical cyclones.	1A	TBC	Stuart Moore	Link to template	Not started
D.	Tropical Africa		Convection.	1B	James Warner	James Warner	Link to template	Not started
E.	South-East Asia		Convection, tropical cyclones.	1B	Richard Jones	Richard Jones	Link to template	Not started
F.	Singapore case studies		Convection.	1B	Kalli Furtado	Kalli Furtado	Link to template	Not started
G.	India trial		Convection, lightning.	1B	Arathy	Arathy	Link to template	Not started
H.	Darwin ensemble trial		Convection, tropical cyclones.	1B, 4A, 4B, 4C	Dave Lee	Various, TBC	Link to template	Not started
I.	Sub-km scale case studies over the UK		Convection, fog, extratropical cyclones, frontal ppn.	1D	Kirsty Hanley	Kirsty Hanley	Link to template	Not started
J.	UK ensemble trial		Ensemble spread.	4A, 4C	Anne McCabe	Anne McCabe	Link to template	Not started
K.	UK climate trial		Convection, extratropical cyclones, frontal rainfall, extremes.	6A, 6B, 6C, 6D	Calum Scullion	Simon Tucker	Link to template	Not started
L.	UK coupled AO trial		Air sea interaction	7A	Sana Mahmood	Sana Mahmood	Link to template	Not started

- Standardised tickets and evaluation templates of analysis across trials
- Emphasis on process evaluation
- Ensuring full acceptance criteria coverage
- Efficient translation into RAL3-LFRic report


Met Office

Regional Atmosphere Land Configuration (RAL3) LFRic Assessment Report

James Warner

RAL3-LFRic assessment report summarises consolidated RAL3-LFRic performance across partnership.

Tickets: For verification and process-evaluation, capturing ongoing plots/work in documents.

#717 assigned model_evaluation

Opened 2 days ago
Last modified 19 hours ago

RAL3-LFRic Assessment: Processes Master Ticket

Reported by:	jameswarner	Owned by:	jameswarner
Priority:	normal	Milestone:	RAL3-LFRic
Component:	Not Allocated	Keywords:	
Cc:		Configuration:	Not defined
Model code status:	Not lodged		
Purpose:			
RA change:	no	RL change:	no

Description (last modified by jameswarner) Δ

This is the master ticket for process evaluation in the RAL3-LFRic Assessment.

Ticket	Summary	Status	Owner
#718	RAL3-LFRic Assessment: Processes [Convection]	new	
#719	RAL3-LFRic Assessment: Processes [Fog]	new	
#723	RAL3-LFRic Assessment: Processes [Land-Surface Interactions]	new	
#728	RAL3-LFRic Assessment: Processes [Air-Sea Interactions]	new	
#729	RAL3-LFRic Assessment: Processes [Sub-KM]	new	
#720	RAL3-LFRic Assessment: Processes [Tropical Cyclones]	assigned	richardjones
#721	RAL3-LFRic Assessment: Processes [Diurnal Cycle]	assigned	mikebush
#722	RAL3-LFRic Assessment: Processes [Extratropical Cyclones + Fronts]	assigned	richardjones
#724	RAL3-LFRic Assessment: Processes [Complex Terrain]	assigned	annemccabe
#725	RAL3-LFRic Assessment: Processes [Tropical Waves]	assigned	jameswarner
#726	RAL3-LFRic Assessment: Processes [Monsoon]	assigned	jameswarner
#727	RAL3-LFRic Assessment: Processes [Ensembles]	assigned	annemccabe

Templates: One per trial, high level findings for verification and process themes where applicable.

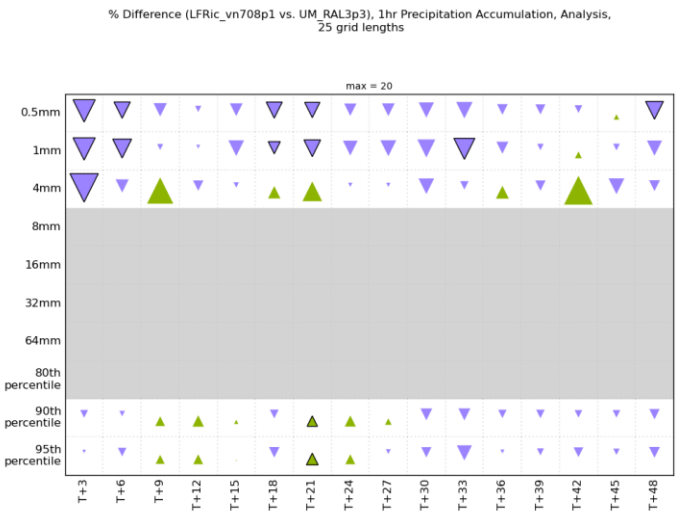
RAL3-LFRic Evaluation Template	
Contributor(s) + Organisation(s)	
Trial Details (*When initialised, forecast length, domain used, resolution, configuration used if deviating from vn0, suite-IDs).*	
Links to Evaluation Suites (*CSET links, RES links etc.)*	
Headline Summary (*Summary of key findings/verdict compared to RAL3-UM, ~100 words/2-3 sentences).*	
Verification *Please provide a headline summary for the following variables, if applicable. Please use both subjective evaluation using typical forecast charts using CSET (could you tell the models apart? This helps us identify qualitative biases that domain averages might not capture), and quantitative verification (RMSE, etc.) against observations using the RES where applicable. Please link any plots to the corresponding verification tickets/comment. **Please also put any general scorecards in ticket #709***	
Temperature [#710] *Surface, screen level, column profiles, upper air.*	*Qualitative:* *Quantitative:*

Selective results

Focus on precipitation

Verification: FSS Precipitation 25 grid length

ExpA UK 1p5km 708p1 vs GPM



ExpA UK 1p5km 708p1 vs Radar

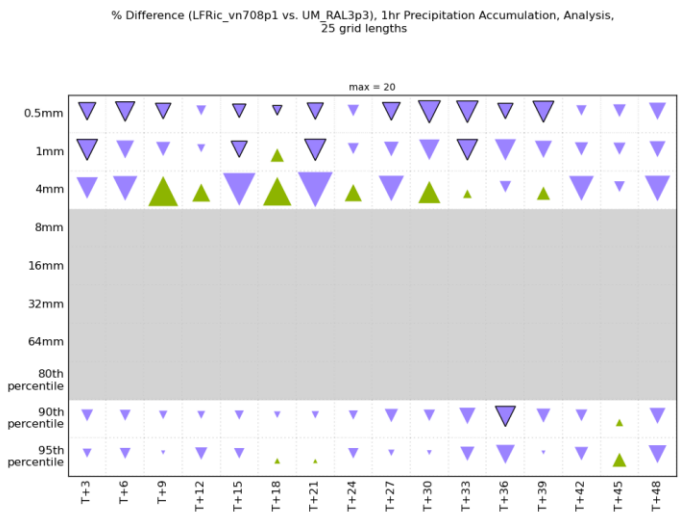


Figure information

Triangles with black outline are statistically significant

Green indicates improvements in LFRic relative to the UM, purple indicate degradations.

The relative size of the triangle indicates the relative change in skill.

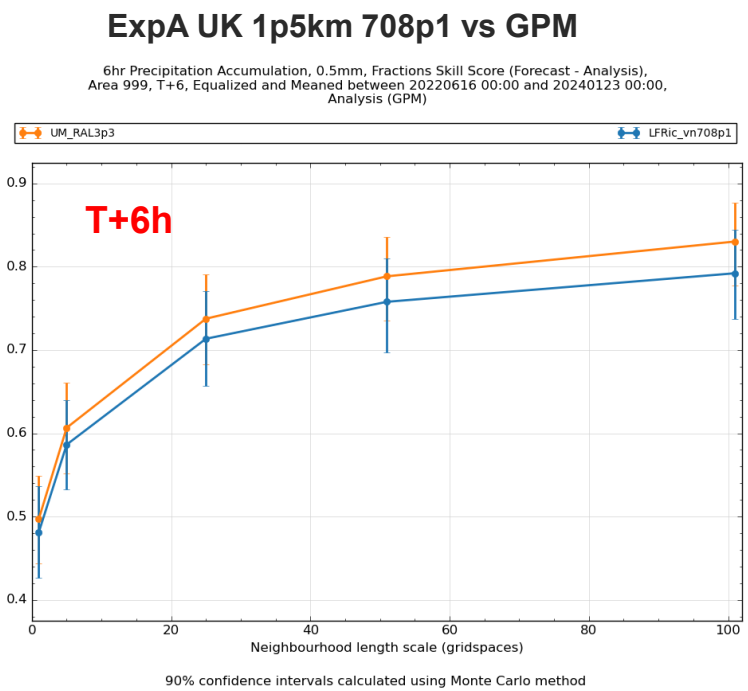
Broad degradation in LFRic relative to the UM against both GPM and radar.

Consistent across thresholds and neighbourhood sizes.

Change in skill is small

Results supported by other mid-latitude and tropical domains

Verification: FSS score curves for ExpA precipitation



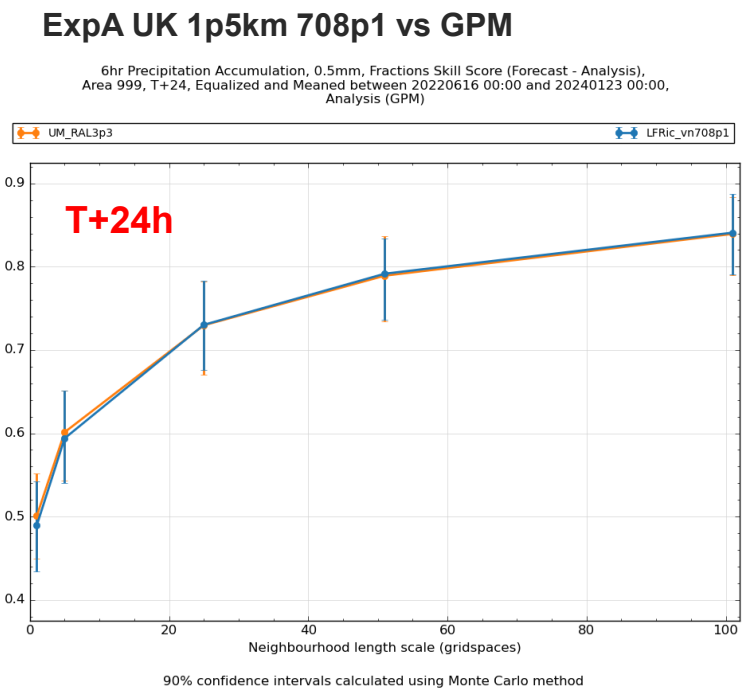


Figure information

Fractional skill score curves

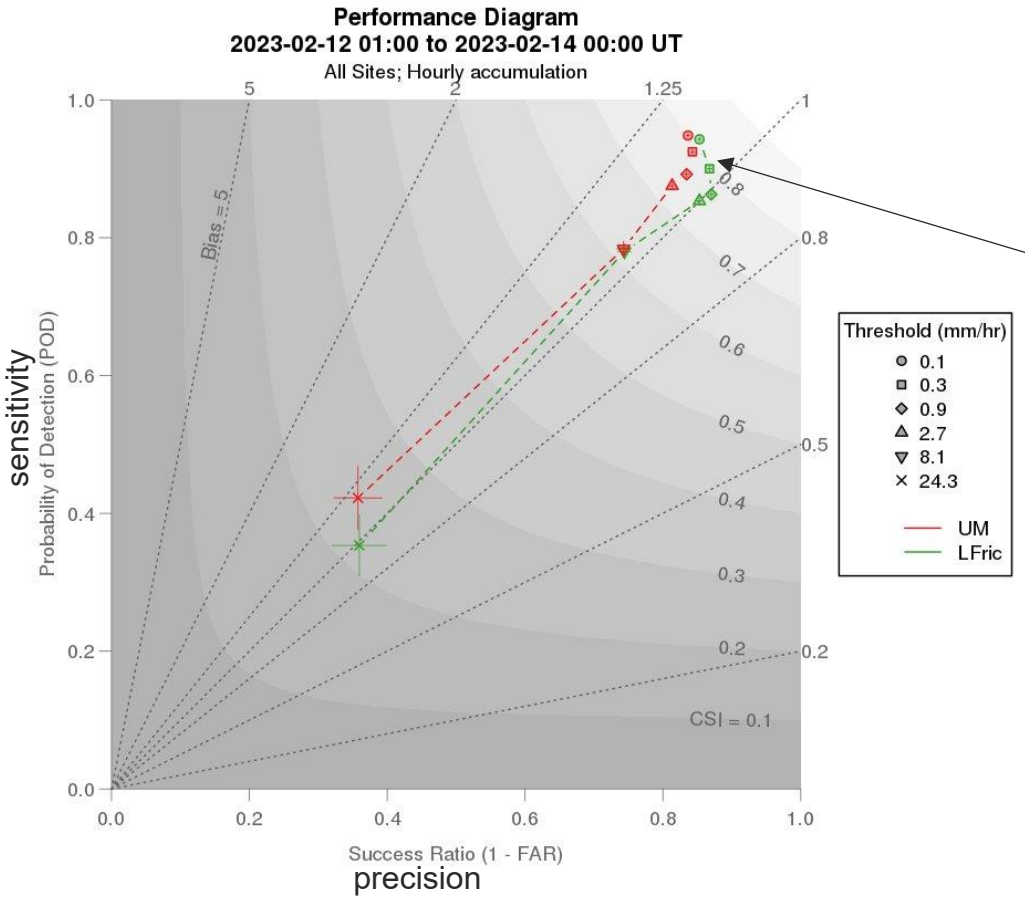
0.5 mm threshold

UM orange, Lfric blue

Absolute change in skill is small by T+24h (despite being statistically significant due to large sample).

Performance diagram ex tropical cyclone Gabrielle

ExpI NZ North Island domain



LFRic has slightly reduced positive categorical bias (less overforecasting)

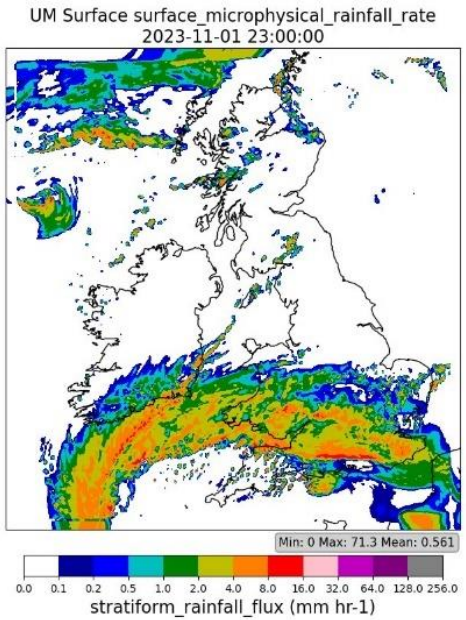
Lfric has slightly higher skill for lower thresholds (CSI)

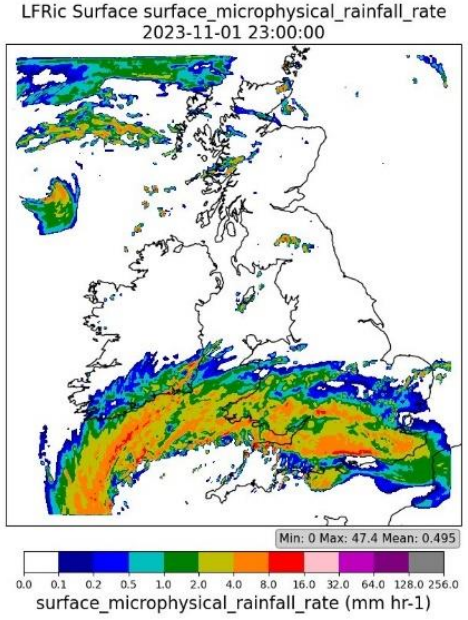
LFRic has a sensitivity ~ precision, however differences are small compared to UM at similar critical success indices measuring the performance.

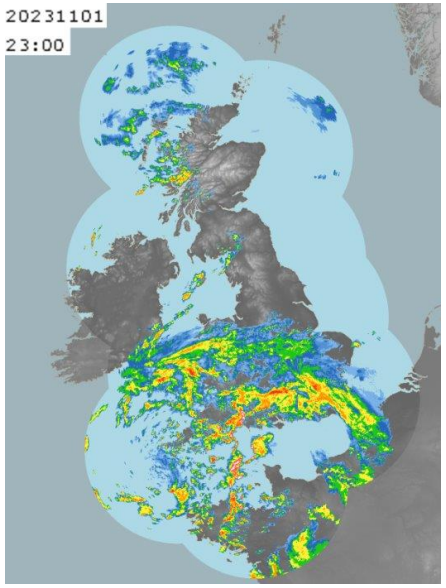
CSI: overall performance Bias: over vs underforecasting

Frontal precipitation

Case study 1st November 2023: warm frontal rainfall





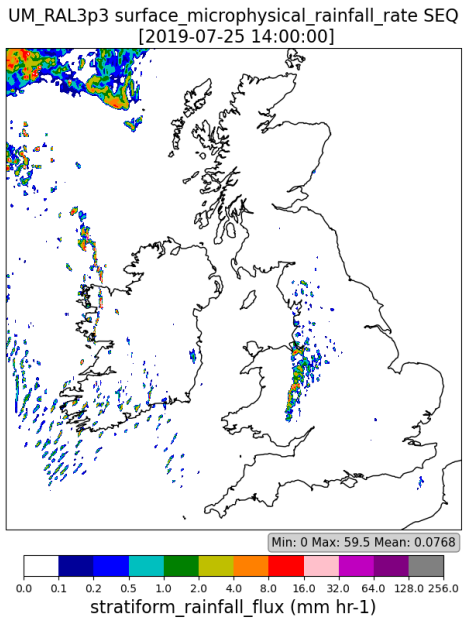


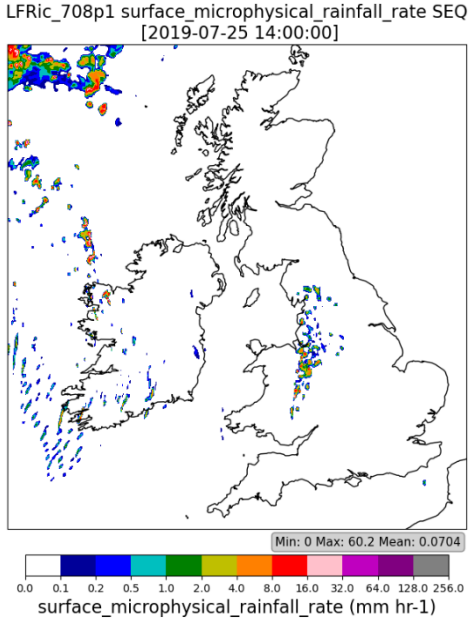
22 case studies across occluded, warm and cold frontal structures

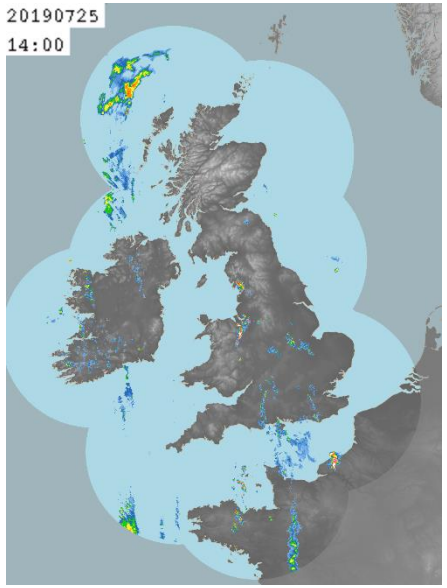
- **LFRic and UM similar rainfall structure and evolution within expected ensemble spread**
- lack of light rainfall (<0.5mm/hr)
- LFRic rainband slightly more fractured with sharper edges between individual convective cells.
- Differences tend to occur over orography, which could be linked to different orography ancils/smoother terrain in LFRic.
- both deficient compared to radar with moderate rainfall too broad

Convective precipitation

Case study 25th July 2019



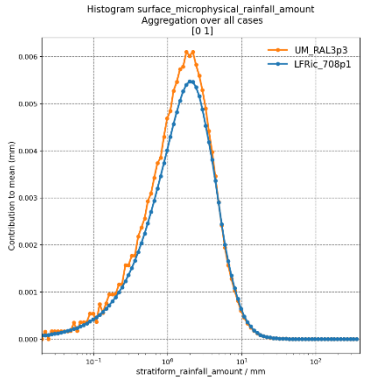




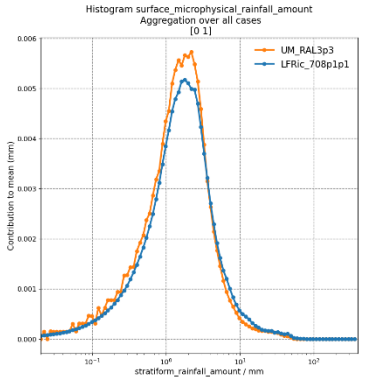
- **UM and LFRic: very similar rain distribution**
- UM tends to produce excessive showers (particularly sub-KM)
- LFRic reduces this bias and improves comparison to radar
- UM and LFRic produce showers in similar location (more than observed)
- LFRic still too large and more intense than observed, particularly post-frontal.
- LFRic intensities stronger.

Distribution of the fractional contribution to daily rainfall for each rainfall bin

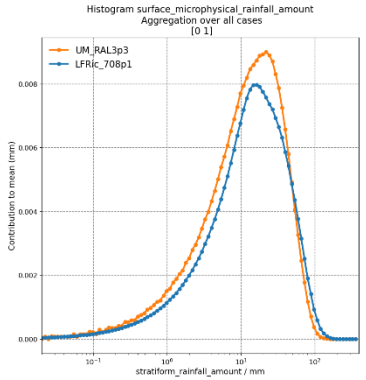
ExpA UK 1p5km 708p1



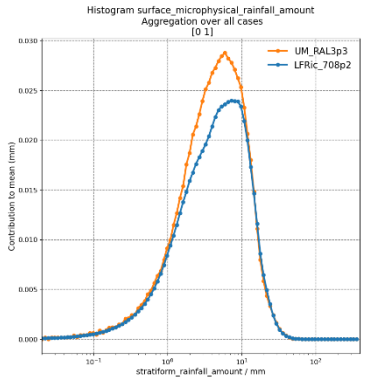
ExpD sub-KM 708p1p1



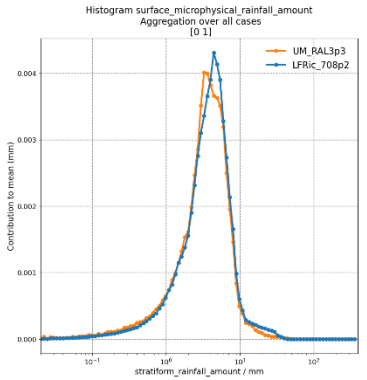
ExpN WAfrica 4p4km 708p1



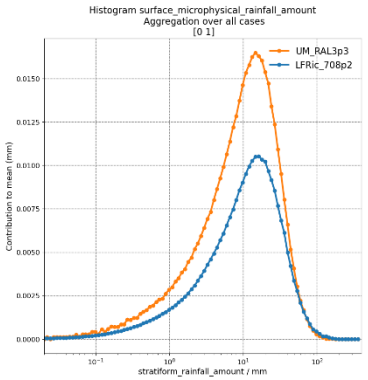
ExpI NZNorth 1p5km 708p2



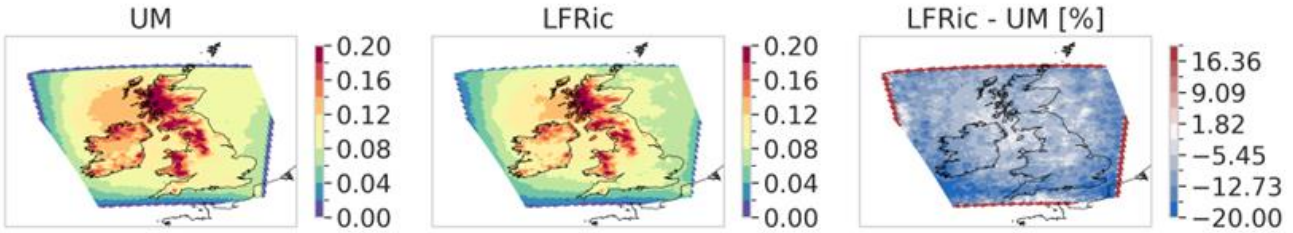
ExpQ Delhi Sub-KM 708p2



ExpH Darwin 1p5km 708p2

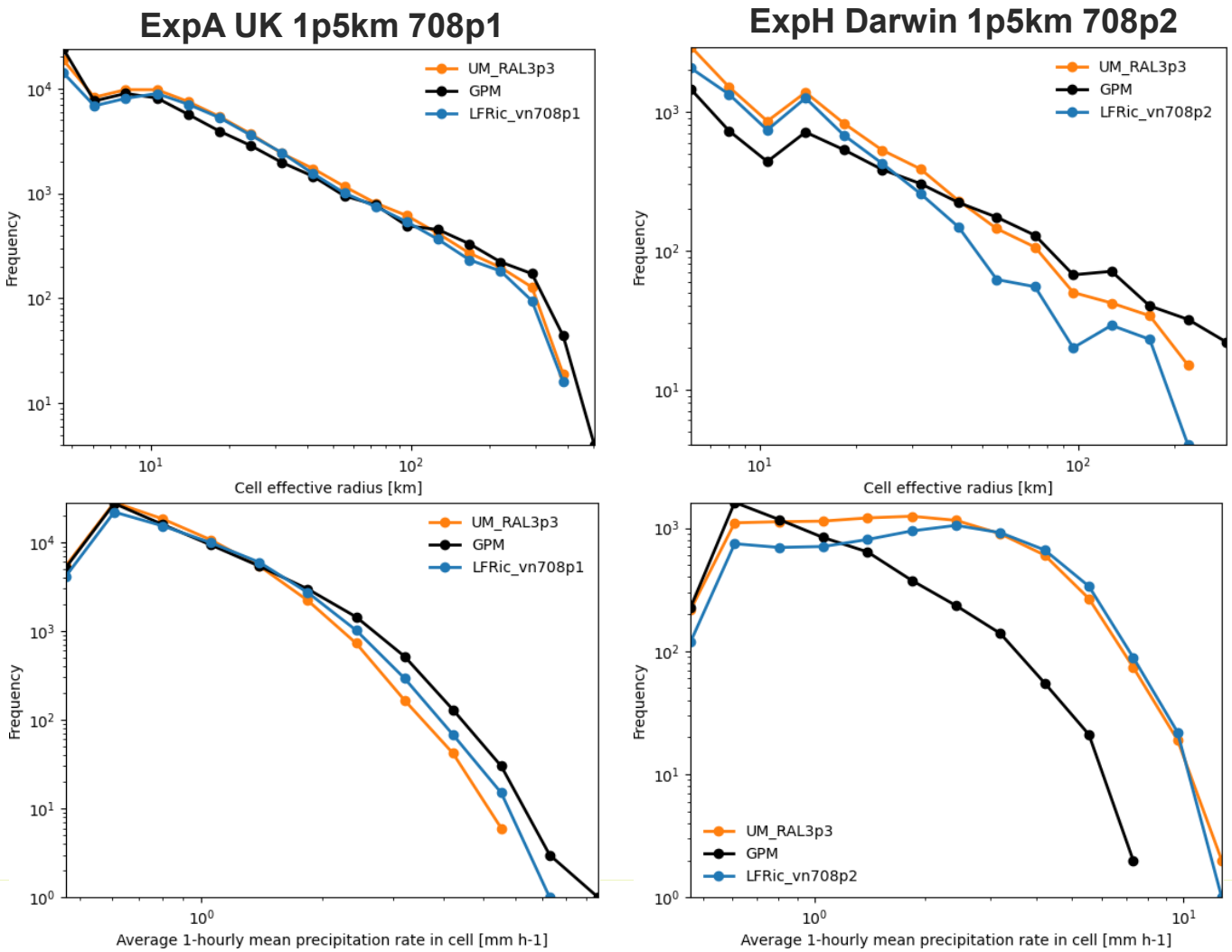


Regional climate runs: Rainfall rate [mm hr-1]
2000-01-01 – 2002-12-30



- Distribution shifts consistent with UK Climate runs, and other tropical domains such as the 4p4km India (ExpY).
- Slight increase in high rainfall amounts, notably at sub-KM UK, but also at 4p4km in the tropics (West Africa).
- Similar distributions (sub-KM Delhi) with smaller sample size (2 case studies) not showing same change in mid range
- Reduction in rainfall amount in LFRic due to lower medium rainfall amounts. Light rain reduction appears greater than increase in intense rain.

Cell statistics against GPM



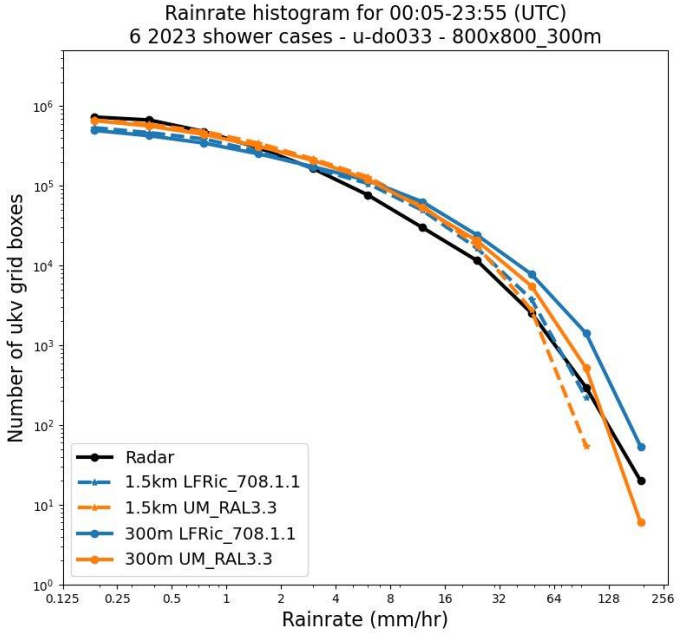
Consistent reduction in large cells in UK KM-Scale but also in tropical regions.

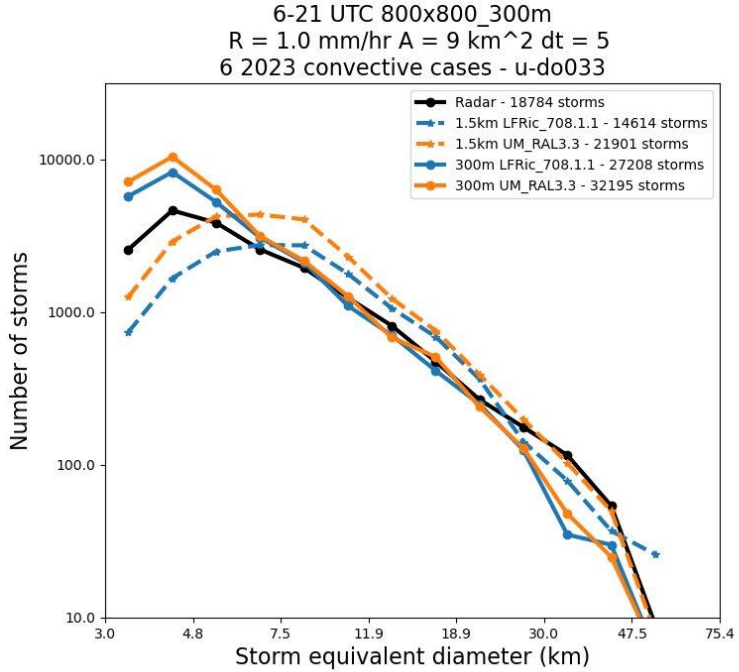
Cell intensities are higher in LFRic compared to the UM in UK KM-Scale simulations.

Darwin and West Africa indicate less light rainfall in cells, which performs worse against radar than UM.

Model resolution impact: sub-km precipitation

Relative shift in rain distribution similar between UM and LFRic moving from km-scale to sub-km-scale





Very slight reduction in light rainfall

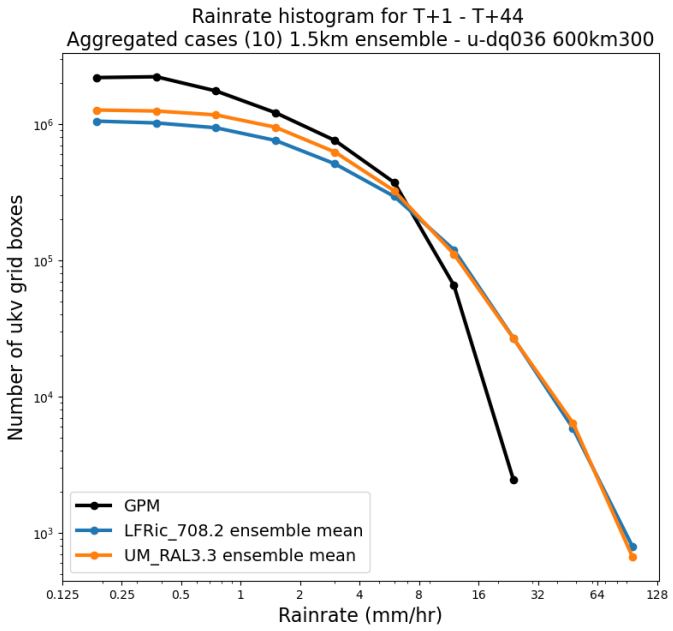
Increased frequency of intense rainfall in sub-km-scale for LFRic and UM

Increase in small cells from km to sub-km scale

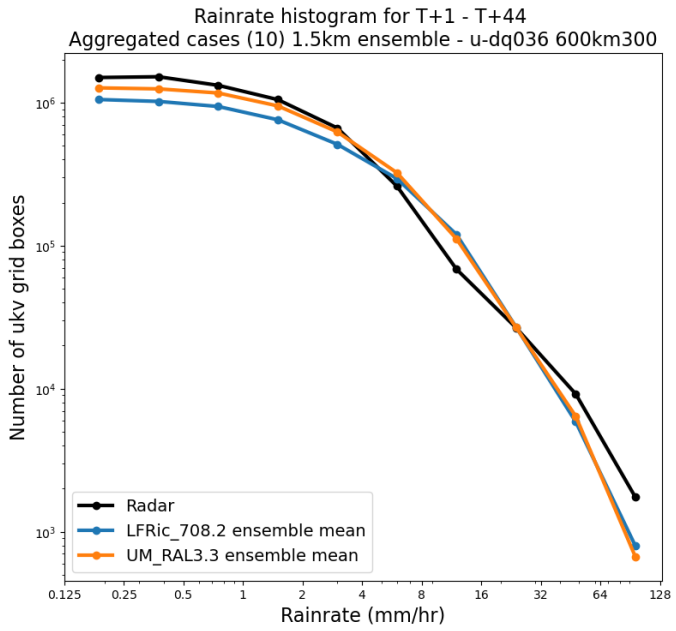
Reduction in medium and large cells from km to sub-km scale

Choice of observation matters

GPM



radar



Models overestimate intense rainfall vs GPM

Models underestimate intense rainfall against radar

Prioritisation in RAL4 of having distinct rainfall verification datasets (GPM, radar, AWS).

High-level performance summary

General overview

- HiRA verification shows no significant and consistent degradation of surface variables (screen level temperature, wind, visibility) or cloud (fraction, base height).

Rainfall:

- Slight reduction in total rainfall(5-10%): reduction in light rain greater than increase through intense rain, PDF shift towards less light rainfall, showers more intense, sharper gradients across cells & reduction in cell size
- a broad degradation of FSS against GPM and radar in nearly all domains.
- **Hypothesis: Transport scheme in LFRic is slightly less diffusive than UM → RAL4 testing**

Convection

- is more fragmented,
- cold pools and density currents in general are slower to propagate and less coherent.
- Wave propagation away from convection more prominent at upper levels in LFRic.

Cloud:

- There is less cloud (predominantly medium and high cloud) across all domains,
- often leads to a warmer screen temperature and amplified diurnal cycle.

Wind

- Wind speeds at 10m are stronger than the UM. Slight degradation in some tropical domain performance.

MSLP

- There is a mean sea level pressure positive bias relative to the UM in all KM-Scale domains, with some spin-up artifacts during the first few hours.

Ensemble:

- spread skill relationships, sub-KM, stretched grid within expected tolerance of a model science upgrade.

Spin-up

- artifacts present in cloud (spin-down), slower spin-up of rainfall.

sylvia.bohnenstengel@metoffice.gov.uk

Met Office

additional material

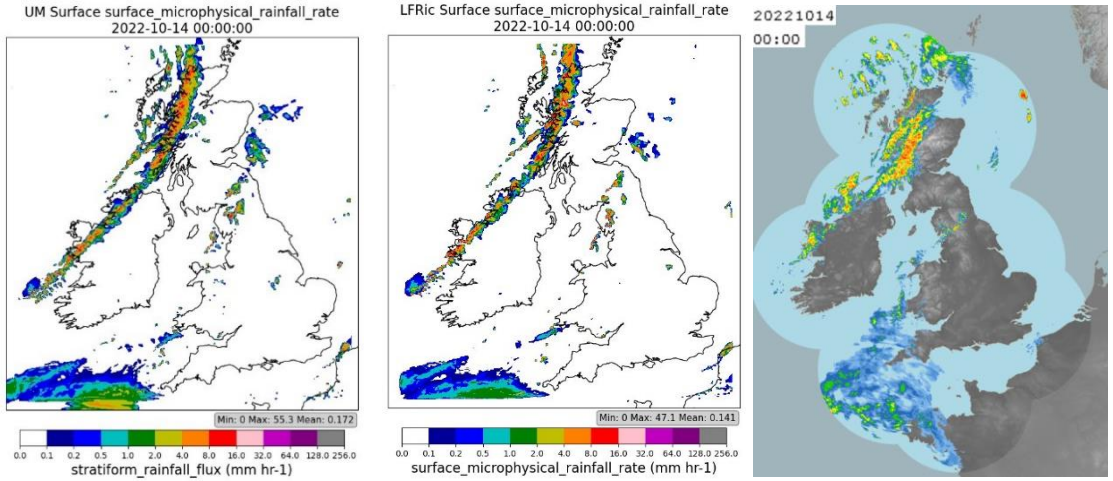
RAL3-LFRic science configuration

Microphysics	Double-moment microphysics CASIM (Field et al, 2023)
Cloud	Bimodal cloud scheme (Van Weverberg et al., 2021a,b) – unifying midlatitudes and tropics
BL	Revised blending between 3D Smagorinsky and 1D BL schemes above diagnosed BL
Radiation	SOCRATES radiative transfer scheme (Edwards and Slingo, 1996; Manners et al., 2018) with a configuration based on GA3.1 (Walters et al., 2011) achieving higher consistency with CASIM
Orography Land surface	Review of regional land settings more consistent with GAL Include turbulent form drag from flow over complex terrain
Advection	**LFRic uses** Flux-Form Semi-Lagrangian (FFSL) scheme **UM uses** semi-implicit semi-Lagrangian (SISL) scheme
Dynamical Core	LFRic uses GungHo dynamical core. FFSL implemented within a finite-volume framework on an unstructured mesh. UM use a structured latitude-longitude or rotated pole grid.

RAL3 science configuration: Bush, M et al. (2024) The third met Office unified model-JULES regional atmosphere and land configuration, RAL3. *Geoscientific Model Development Discussions*, pp.1-58.

Frontal precipitation

Case study 14th October 2022: occluded front structure similar between LFRic and UM (deficient compared to radar).



22 case studies across occluded, warm and cold frontal structures

- **LFRic and UM similar rainfall structure and evolution within expected ensemble spread**
- lack of light rainfall (<0.5mm/hr)
- LFRic rainband slightly more fractured with sharper edges between individual convective cells.
- Differences tend to occur over orography, which could be linked to different orography ancillaries/smoother terrain in LFRic.

Met Office

Transport

MoL (Method of Lines)

$$\frac{\partial \rho_i}{\partial t} + \frac{1}{\Delta x_i}\left(\mathcal{F}_{i+1/2} - \mathcal{F}_{i-1/2}\right) = 0,$$

Change in density is equal to the fluxes in and out.

CFL-limited

FFSL (Flux-Form Semi-Lagrangian)

$$\rho_i^{n+1} = \rho_i^n - \frac{1}{\Delta x_i}\int_{t^n}^{t^{n+1}} \mathcal{F}_{i+1/2} - \mathcal{F}_{i-1/2}\, dt.$$

Total change in density is equal to the total fluxes over the timestep.

No CFL limit

Efficient
Conservative
Consistent
Reversible
Flux-limited
Monotonic
Accurate
Stable

Met Office

https://pypi.org/project/geovista-slam/

SLAM (Structured Limited Area Model)

- GeoVista utility to transform ugrid limited area model data into structured lat/lon representation
- Data is changed to a rows and columns structure, no regridding
- Rotated pole domains: Coordinates are converted from real lat/lon into rotated pole space
- Can be used to structure individual cubed sphere panels (not tested yet…)

```
temperature_at_screen_level / (K)   (time: 3; -- : 419904)
    Dimension coordinates:
        time                            x       -
    Mesh coordinates:
        latitude                        -       x
        longitude                       -       x
```

slam

```
temperature_at_screen_level / (K)   (time: 3; grid_latitude: 648; grid_longitude: 648)
    Dimension coordinates:
        time                            x               -               -
        grid_latitude                   -               x               -
        grid_longitude                  -               -               x
```

Met Office

LAM = Limited Area Model

UM Grid vs LFRic Grid

UM LAM grids and LFRic LAM grids look the same on the surface

- rotated pole
- no poles or irregular cubed sphere features in regional modelling
- grid boxes arranged to form rows and columns

Underlying data structure is very different!

UM	**LFRic**
structured	unstructured (UGRID)
actual rows and columns matrix	one big long array with all the data dumped in

Met Office

Slide on assessment criteria

Criteria	Requirements
1.	Subjective analysis
3.	Objective verification
4.	Ensembles
5.	DA
6.	Climate
8.	Stability
10.	Runtimes