

An update on Dust Forecasting and Data Assimilation at the Met Office

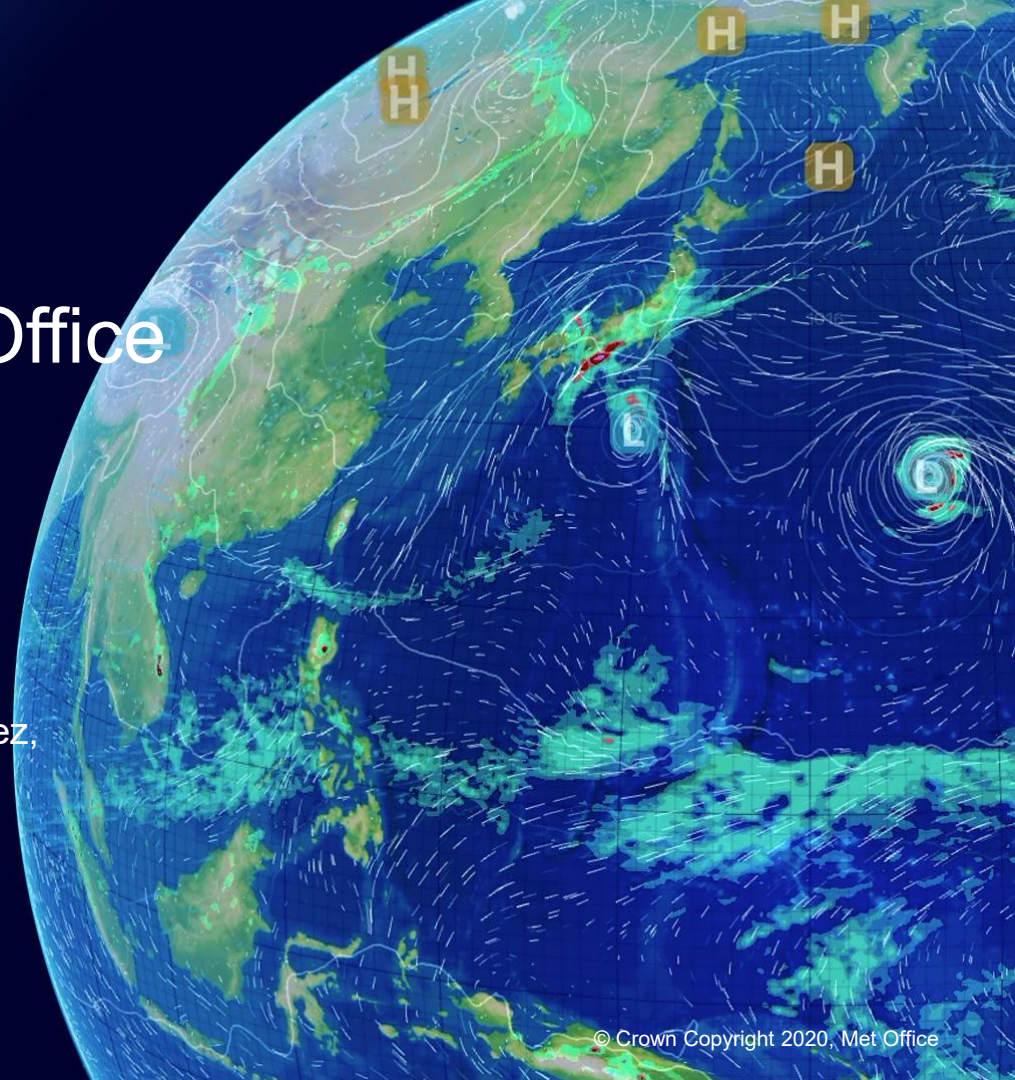
Heather Lawrence

Melissa Brooks

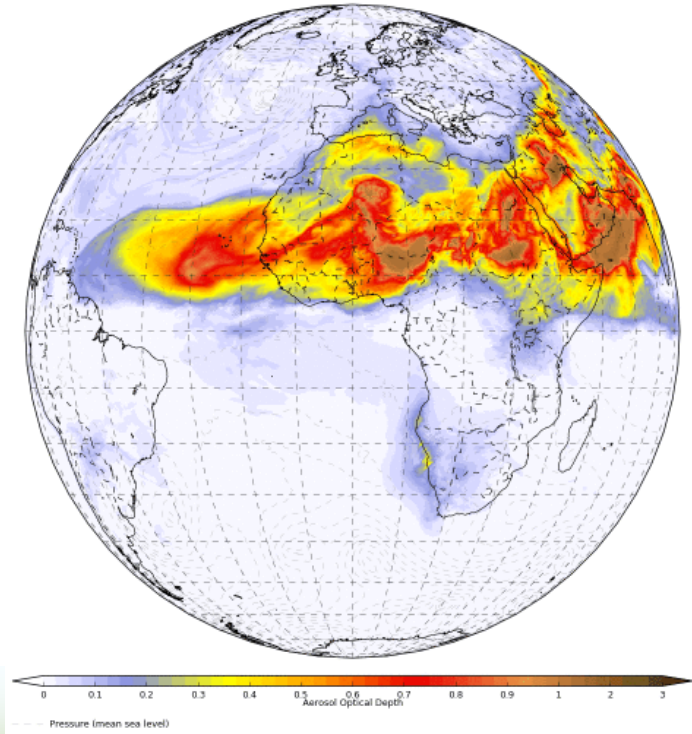
Anthony Jones

With help from:

Marek Wlasak, Mike Cooke, Cristina Charlton-Perez,
Samantha Pullen, Mary Forsythe, Bob Tubbs,
Patrycja Siwek

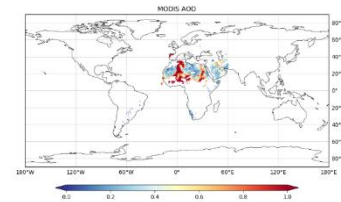


Dust AOD at 550.0 nm
Met Office Oper. Global from 2022/05/16 12Z
Mon 2022/05/16 12Z T+0

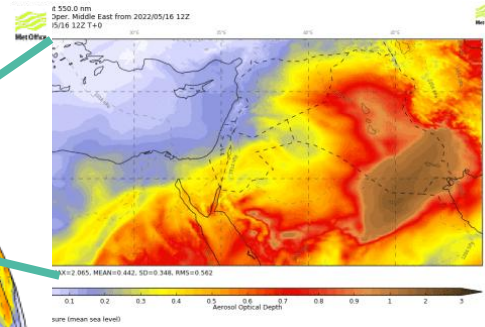
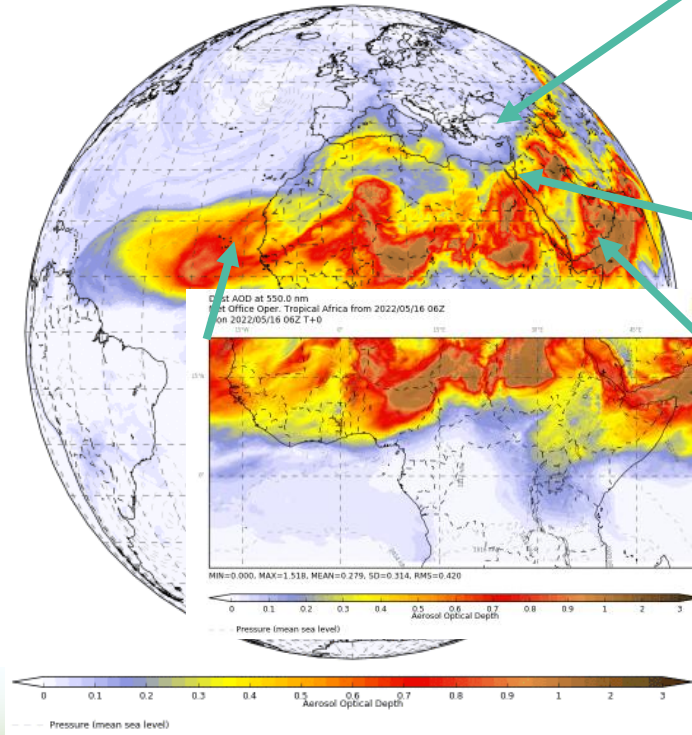


A Global to Regional scale system

- Our global model has ~10km resolution
- Wind/temperature/humidity etc. obs assimilated.
- Limited Dust observations assimilated
 - 4D-VAR (Aqua, Terra MODIS and S-NPP, NOAA-20 Deep Blue VIIRS AOD)



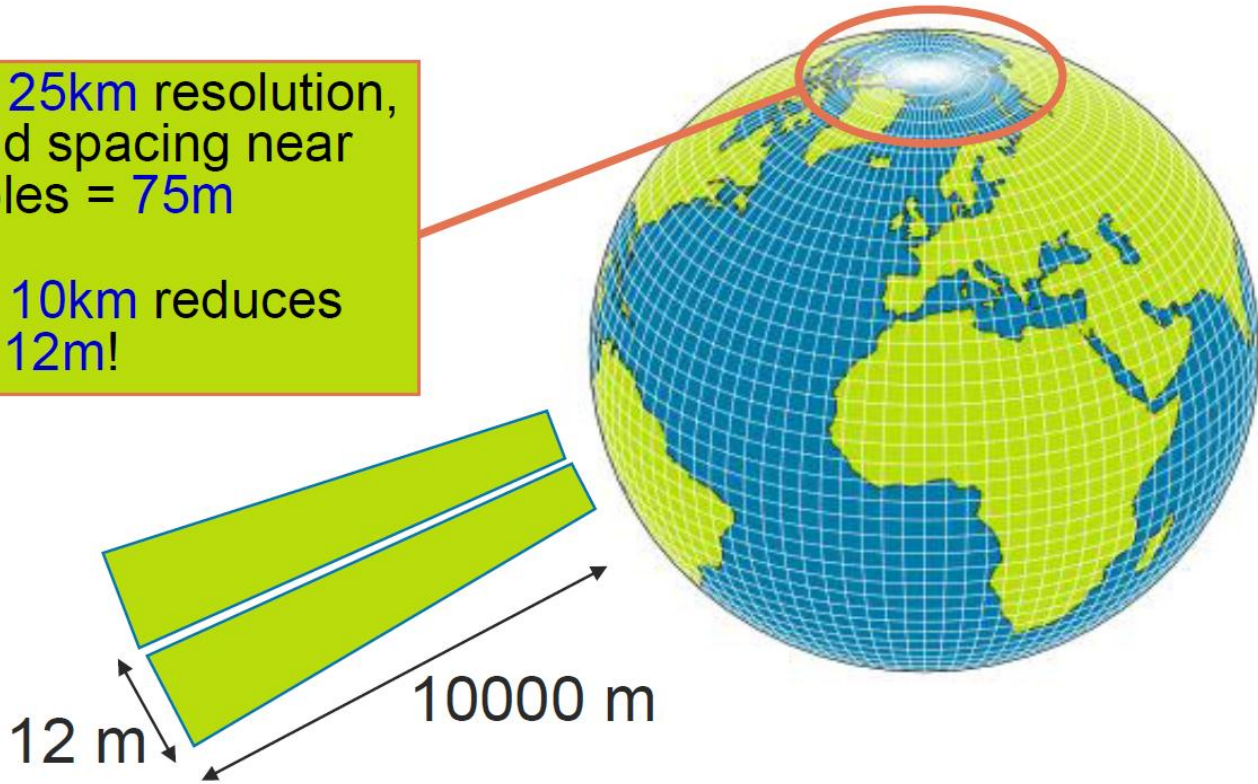
Dust AOD at 550.0 nm
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A Global to Regional scale system

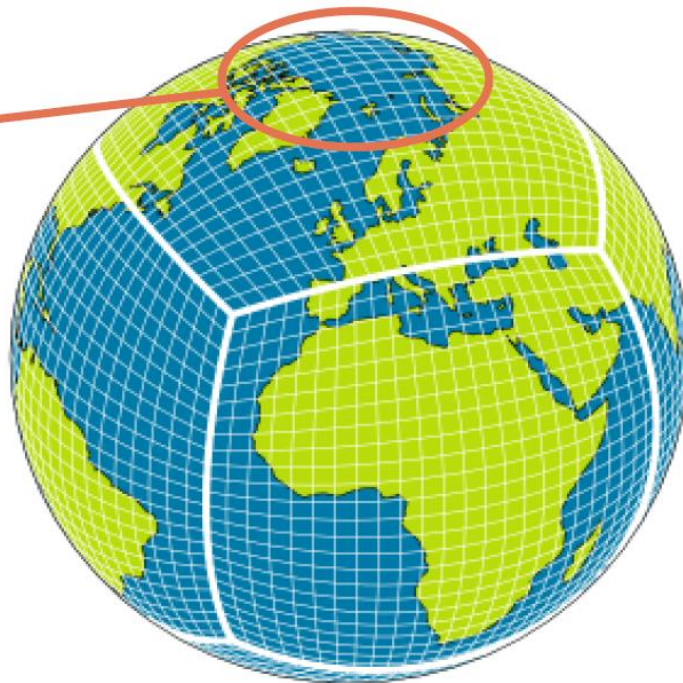
- Initialises regional 4km and 1.5km models (in obs sparse regions)
- These add detail to the global start
- Customer requirements: UK and arid regions
 - Aerosols: Dust only, at high res

- At 25km resolution, grid spacing near poles = 75m
- At 10km reduces to 12m!



This is the UM's scalability limit

- A new grid is essential or any resolution increase
- Migration to a cubed-sphere
- LFRic is our new forecast model



LFRic sits within a modelling framework called Momentum – The Unified Earth Environment Prediction Framework

Developing in partnership with the Met Office, BoM Australia/CSIRO, MoES/NCMWRP India, NEA/MSS/CCRS Singapore, NIWA New Zealand

From idealised tests in 2018, LFRic is now 'standard' model and part of GC model development process (Global Coupled model used in NWP and climate modelling.)

Global Coupled (GC) 6 model is defined and frozen:

- GC5 (doi:10.5194/egusphere-2026-2425)
- + LFRic dynamical core + essential changes like GLOMAP mode aerosols

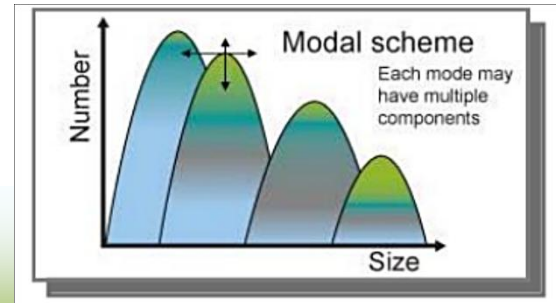
CLASSIC Dust:

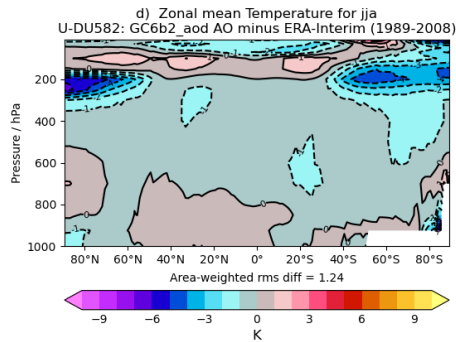
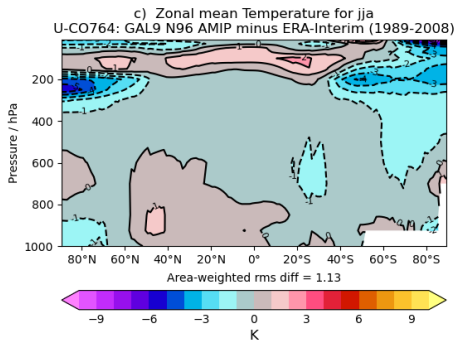
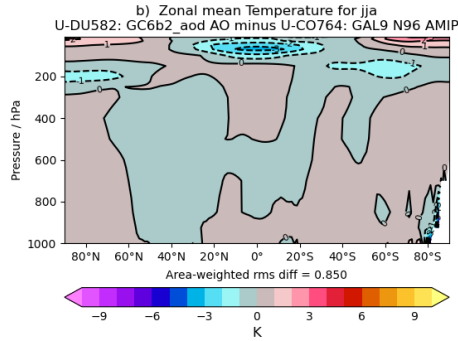
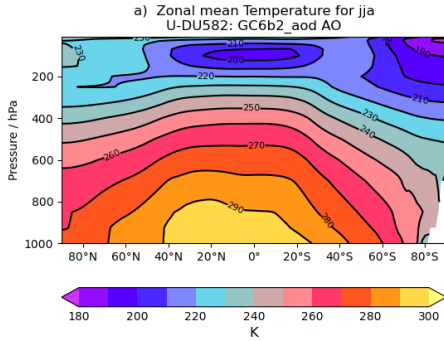
- Mass based, 'binned' by size into 2 dust bins.

Bin	d_{min}	d_{max}
1	0.2	4.0
2	4.0	20.0

GLOMAP MODE:

- Number and mass give a PSD:



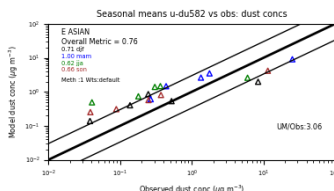
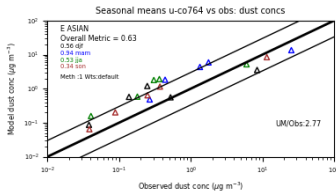
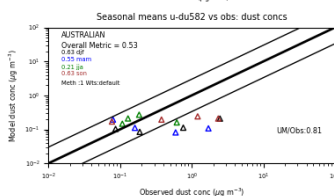
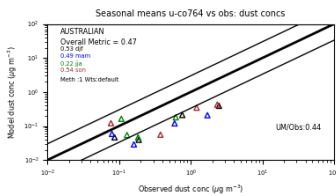
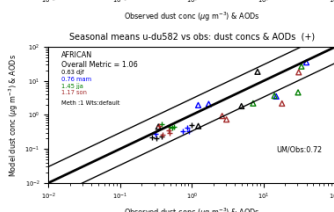
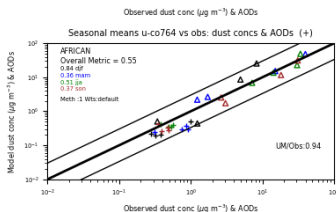
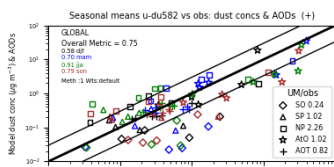
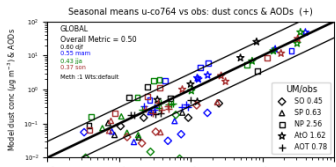


In a 20 year ‘AMIP’ climate model run – GC6 is very similar to GC5. e.g.

- Temperature structure
- Radiative fluxes
- Winds etc.

GC5

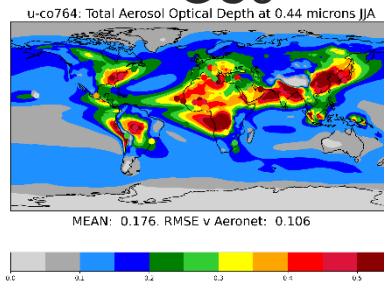
GC6.beta2



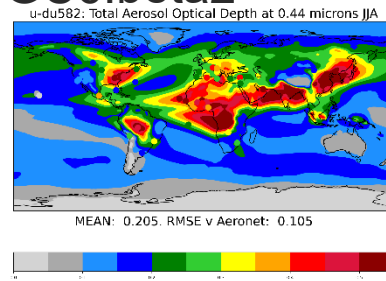
In a 20 year 'AMIP' climate model run – GC6 is very similar to GC5. e.g.

- Dust comparison vs Obs
- And AOD maps:

GC5



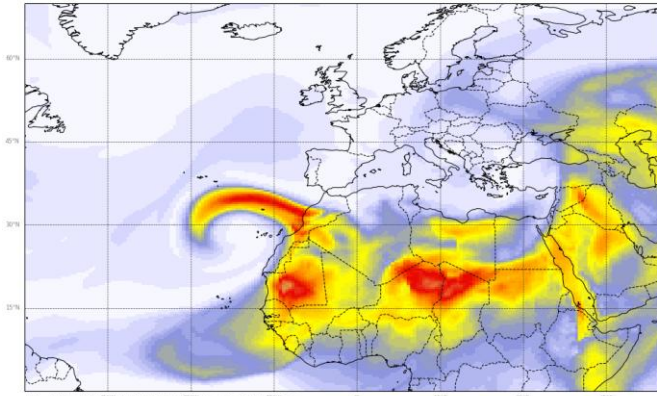
GC6.beta2



LFRic – a new model

GC5

Dust AOD at 550.0 nm
GAL9 (u-dt826) from 2025/03/26 12Z
2025/03/29 12Z to 2025/03/30 12Z, T+72 to 96

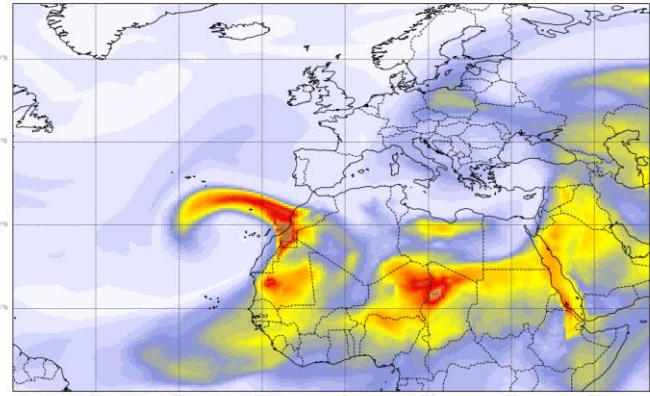


MIN=0.003, MAX=0.955, MEAN=0.148, SD=0.156, RMS=0.215

Aerosol Optical Depth

GC6.beta2

Dust AOD at 550.0 nm
GC6 beta3 (u-dy260) from 2025/03/26 12Z
2025/03/29 12Z to 2025/03/30 12Z, T+72 to 96



MIN=0.012, MAX=1.455, MEAN=0.144, SD=0.138, RMS=0.199

Aerosol Optical Depth

On individual forecasts – AODs appear very similar

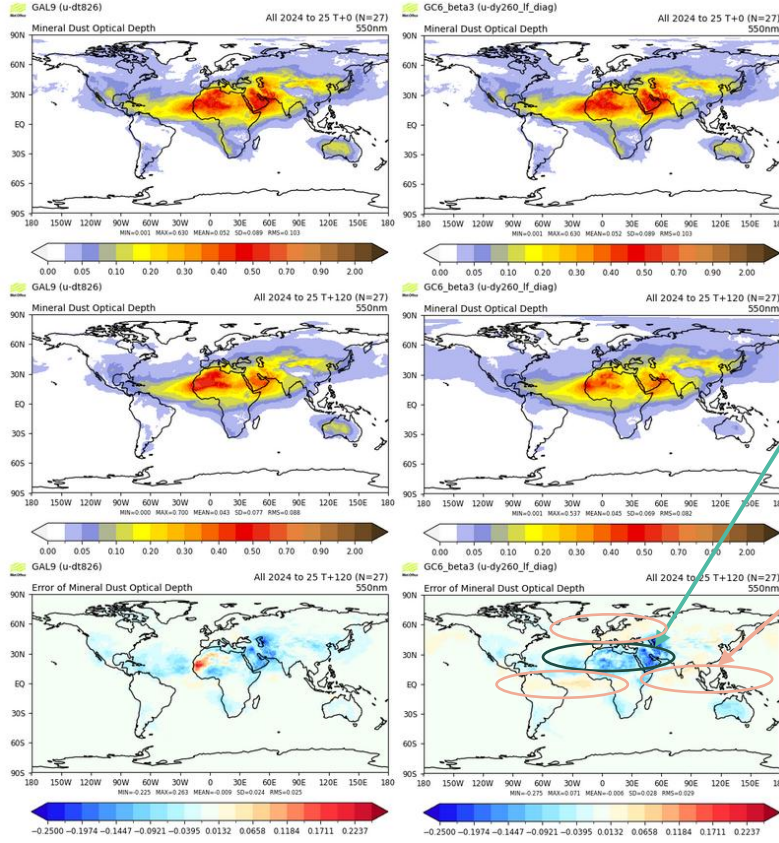
GC5

GC6.beta2

Analysis

Mean T+120

Bias T+120

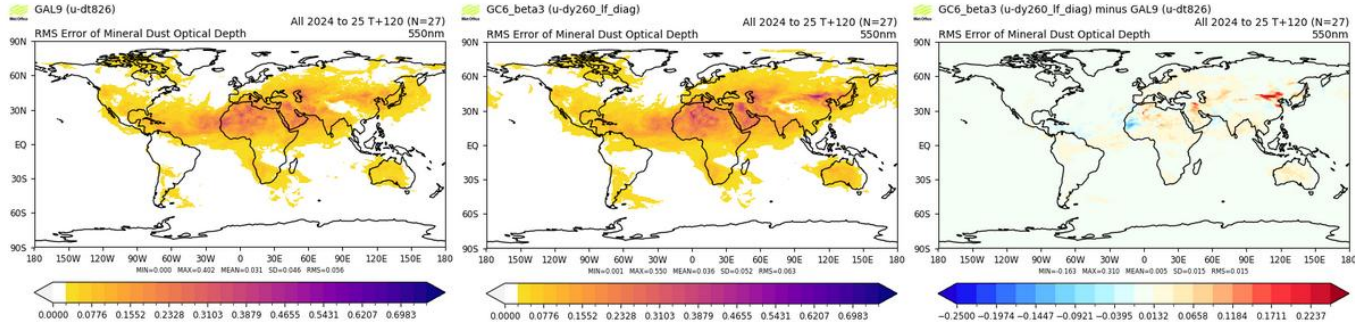


Mean bias over NWP case studies:

- During the forecast we're emitting a little less dust
 - (reducing +ve bias in West Africa)
- But more it is being transported out of 'dust zones'.

GC5

GC6.beta2

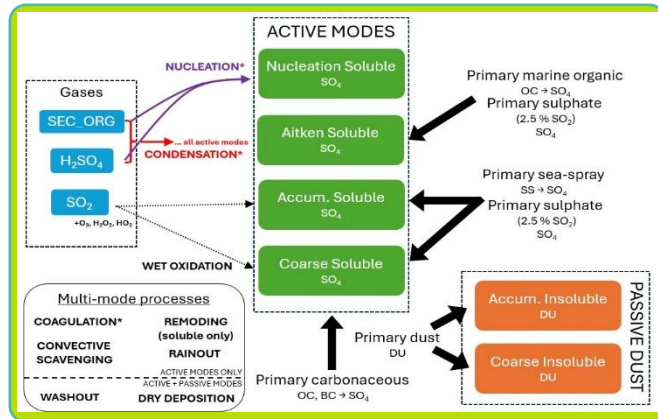


RMS Errors increased overall (mean 0.036 vs 0.031).

- On balance, minor tuning needed as we move towards implementation as the system builds.
- GC6 timeline is 2027,Q3 to 2028 Q2.

- Aerosol complexity in Met Office operational suites dependent on model resolution and user-end applications
- *A consistent and scalable representation of aerosol that works on both weather and climate timescales is now important to Meteorological centres with weather and climate interests such as the UK Met Office*
- Global NWP uses prognostic dust with all other aerosol diagnostic from monthly climatologies
- For regional NWP, we introduce and evaluate a new scheme – **SOL/INSOL**

UKCA aerosol scheme name	UKCA aerosol setup #	Prognostic / Diagnostic	Number of aerosol lognormal modes	Aerosol Species SO ₄ = sulphate BC = black carbon OC = organic carbon SS = sea-salt NO ₃ = fine nitrate NH ₃ = Ammonia NN = coarse nitrate DU = dust	Target model	Replaces
GLOMAP-clim	2	Diagnostic	5 (4 sol, 1 ins)	SO ₄ , BC, OC, SS	Global NWP, seasonal, decadal	CLASSIC-clim
GA7 default (retd)	2	Prognostic	5 (4 sol, 1 ins) + CLASSIC dust	SO ₄ , BC, OC, SS	-	-
Dust only	6	Prognostic	2 (2 ins)	DU	Global NWP	CLASSIC 2-bin dust
NG-GA default	8	Prognostic	7 (4 sol, 3 ins)	SO ₄ , BC, OC, SS, DU	Global coupled	GA7 default
SOL/INSOL	11	Prognostic	6 (4 sol, 2 ins)	SO ₄ (sol), DU (insol)	Regional NWP	MURK
Gold standard	12	Prognostic	8 (4 sol, 4 ins)	SO ₄ , BC, OC, DU, SS, NO ₃ , NH ₄ , NN	ESM, Air Quality	GA7 default

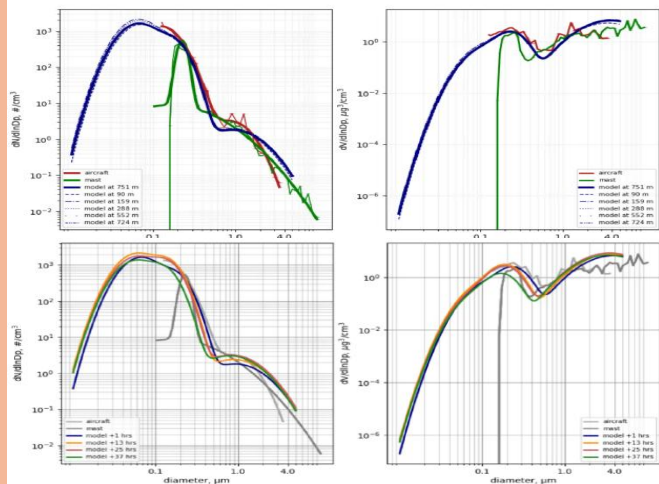


- SOL/INSOL is a simple version of the UKCA chemistry and aerosol model used in the UK's Unified Model (UM)
- 4 soluble modes in the nucleation, Aitken, accumulation and coarse sizes, and dust in 2 insoluble modes in the accumulation and coarse sizes
- Aerosol single-scattering albedo is prescribed from 4D climatologies – either on radiation wavebands or broadband
- The model can be 1- or 2-way coupled with cloud microphysics (CASIM), with 2-way permitting evaluation of the aerosol “**regeneration**” effect where hydrometeor evaporation reintroduces aerosol to the atmosphere

- Aerosol initialised to CAMS (ECMWF) forecasts produces a reasonable size distribution (below) compared to MOSSA aircraft and mast observations
- $PM_{2.5}$ concentrations for CAMS initial conditions agree well with AURN observations for **31 case studies** – slight negative bias with height but $R^2=0.86$
- Summary: aerosol mass concentrations stable in UKV; CAMs initialisation from T+24H forecast a good starting point preceding full DA

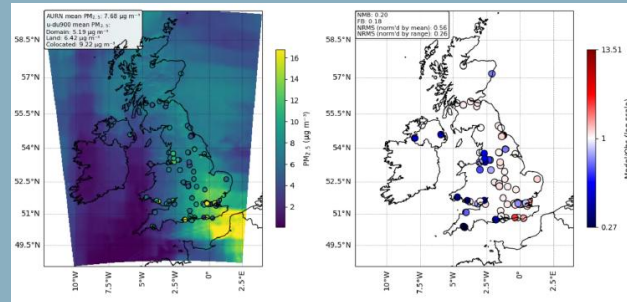
Initial conditions

Aerosol size distributions vs MOSSA aircraft

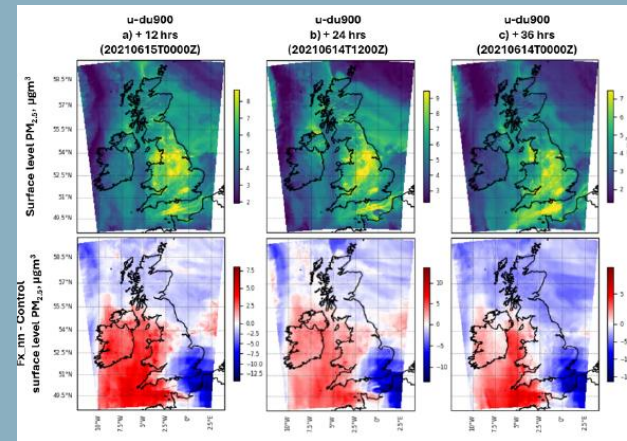


PM_{2.5} vs AURN observations case study (15/06/21)

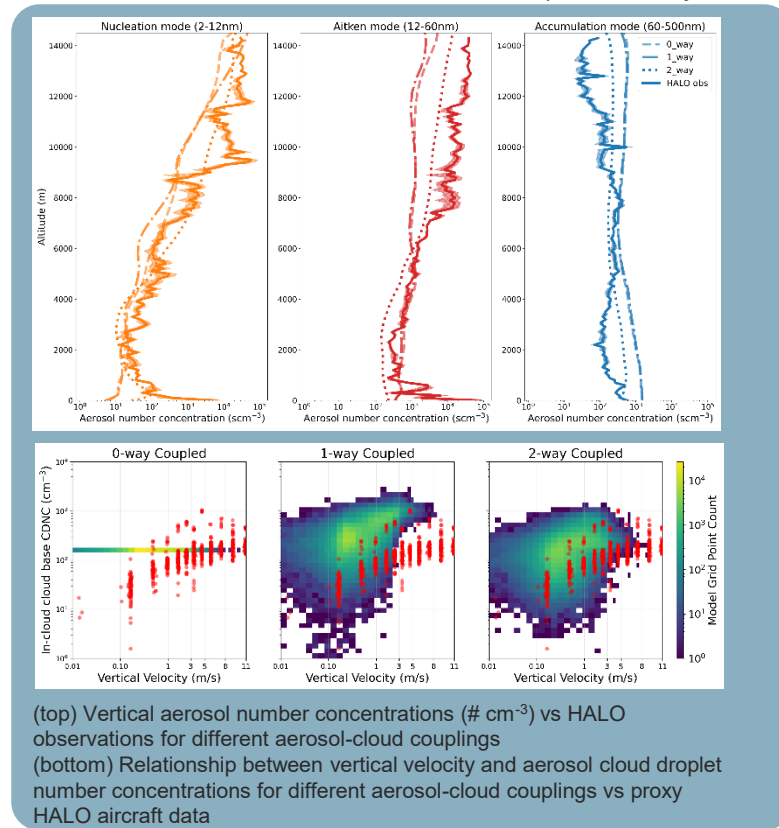
Initial conditions



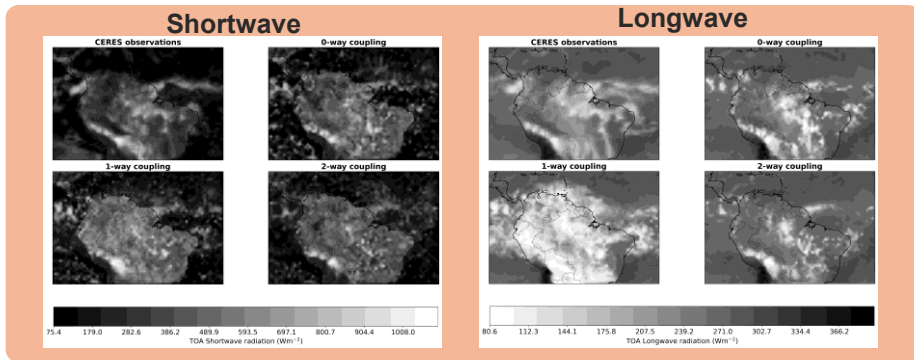
Forecasts



- Case study (15th Jan 2023) selected from CAFÉ ATTO flight/surface campaign selected for model intercomparison project to evaluate aerosol cloud interactions
- CAMS initialised aerosol with number concentrations close to HALO observations for 3 size modes up to ~6km altitude (right)
- Simulations show high sensitivity of cloud/radiative response to aerosol-cloud coupling. With 2-way coupling (aerosol reemission from hydrometeor- evaporation), shortwave and longwave fluxes close to CERES (below)
- With 1-way coupling (no reemission), aerosol anomalously transported to high altitudes producing too much ice cloud without tuning
- Summary: aerosol regeneration effect important for decent representation of aerosol-cloud interactions (ACI) in CAFÉ-ATTO case study



(top) Vertical aerosol number concentrations ($\# \text{ cm}^{-3}$) vs HALO observations for different aerosol-cloud couplings
 (bottom) Relationship between vertical velocity and aerosol cloud droplet number concentrations for different aerosol-cloud couplings vs proxy HALO aircraft data



JEDI

JEDI is a collaborative development between JCSDA partners to develop a unified data assimilation system:

- From toy models to Earth system coupled models
- Unified observation (forward) operators (UFO)
- For research and operations (including O2R2O)
- Share as much as possible without imposing one approach (one system, multiple methodologies/configurations)

Motivation

Changes in HPC landscape

Fully exploit future generations of supercomputers
Scalability, efficient I/O
Memory and novel parallelism in era of large (1000s) ensemble DA

Technical

Increased modularity (more object-oriented capabilities)
Expanded range of platforms (traditional HPC, cloud, laptop, etc)

More complex science

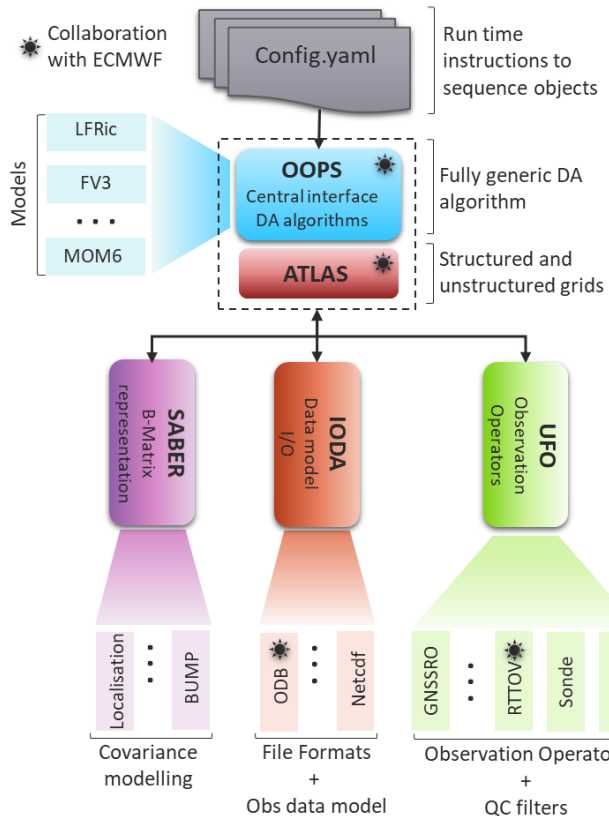
Flow-dependent QC, ensembles
Strongly-coupled earth system DA, etc.

Future Applications

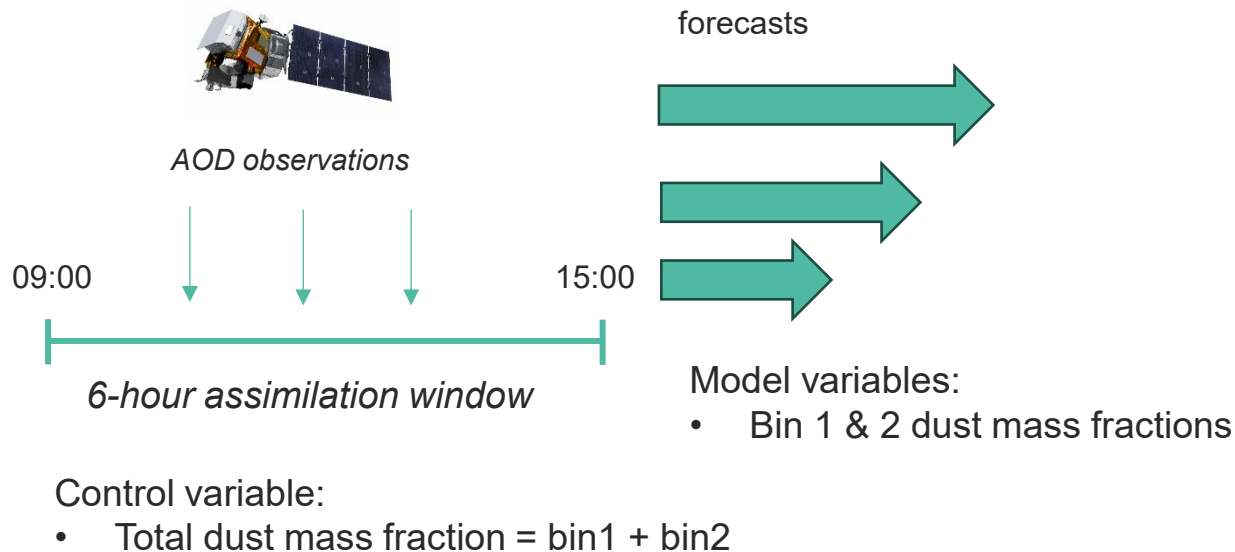
Nowcasting, cloud analysis, city-scale DA, composition DA, multi-models, etc.

Human

Current OPS/VAR too complex for wide-spread use
Need to encourage wider collaboration (academic users, those working on other models)



Model vs. Control variables for Dust



Model vs. Control variables for Dust

Minimise cost function:

$$J(x) = \frac{1}{2} (x_b - x)^T B^{-1} (x_b - x) + \frac{1}{2} \sum_k (y - G(x))^T R^{-1} (y - G(x))$$

Total mass fraction $M = m_1 + m_2$

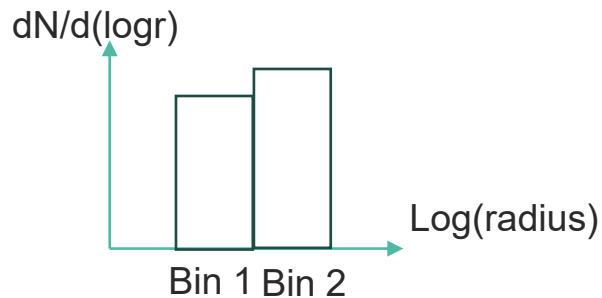
*AOD calculation
and FC model
from bin1, bin2
variables*

Increments in total bin mass are split into the bins using their background fractions:

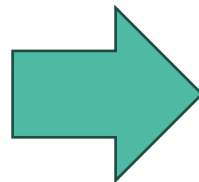
$$\delta m_i = \frac{m_i}{m_1 + m_2} \delta M$$

Dust model change

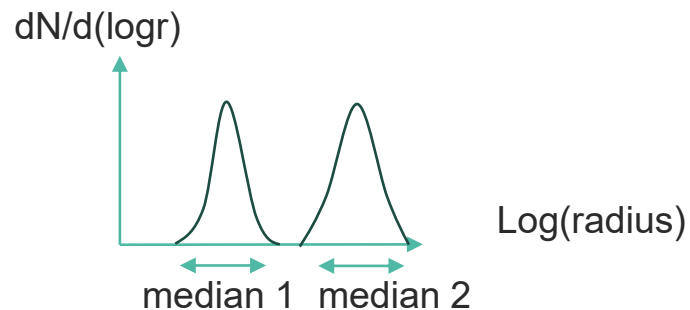
UM CLASSIC model: 2 size bins, 2 variables



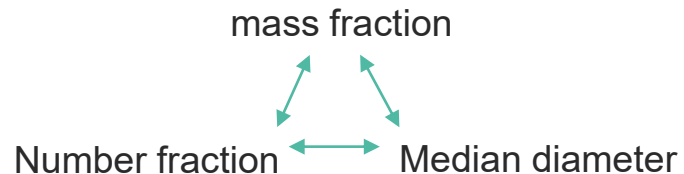
- 2 bin mass fractions



LFRic GLOMAP/UKCA model: 2 modes, 4 variables



- Modal mass & number fractions



What should we use as the control variable for the LFRic GLOMAP/UKCA dust model?

First approach

Use all 4 model variables as separate control variables

$$J(x) = \frac{1}{2} (x_b - x)^T B^{-1} (x_b - x) + \frac{1}{2} \sum_k (y - G(x))^T R^{-1} (y - G(x))$$

4 separate control variables

4 separate control variables

$$x = \begin{bmatrix} \text{accumulation mode mass fraction,} \\ \text{coarse mode mass fraction,} \\ \text{accumulation mode number fraction,} \\ \text{coarse mode number fraction} \end{bmatrix}$$

Apply transforms to B

Progress so far: New AOD forward operator

$$AOD = \sum_{nmodes=2} \sum_{nlev} \frac{1}{g} m_{mode} * k_{ext}(m_{mode}, n_{mode}) * \Delta P$$

Mass fraction for mode1 or mode2

Depends on dust size

k_{ext} calculation

1. Determine median diameter from number and mass fraction

$$D_{vm,r}(i, j, k) = \left[\frac{6}{\pi e^{4.5 \ln^2 \sigma_r}} \times \frac{k_B}{R_a} \times \frac{1}{n_{mode}(i, j, k)} \frac{m_{mode}(i, j, k)}{\rho_x} \right]^{1/3} e^{3 \ln^2 \sigma_r}$$

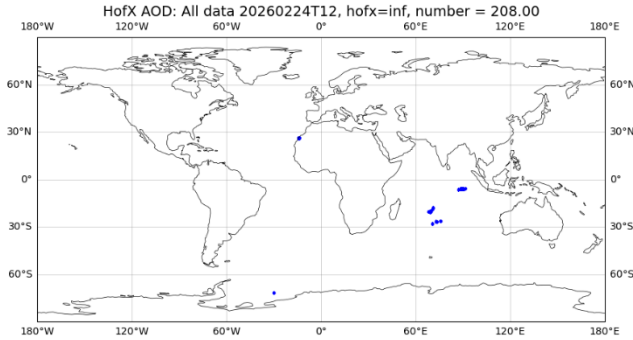
2. $k_{ext} = f(D_{vm,r}(i, j, k))$

- Lookup tables/Best fit

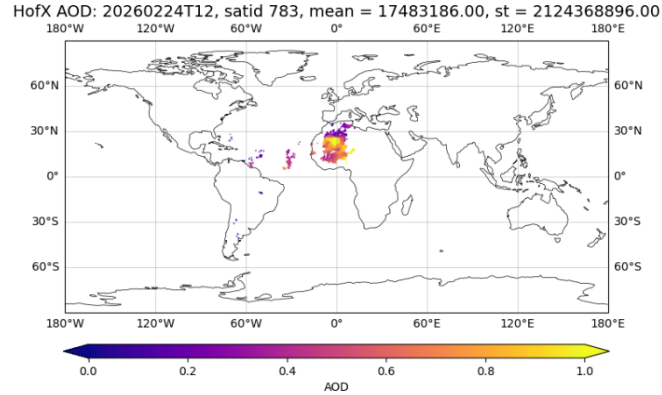
Progress so far: New AOD forward operator

But...

Some infinite AOD values



+ some crazy large AOD values



$$D_{vm,r}(i, j, k) = \left[\frac{6}{\pi e^{4.5 \ln^2 \sigma_r}} \times \frac{k_B}{R_a} \times \frac{1}{n_{mode}(i, j, k)} \times \frac{m_{mode}(i, j, k)}{\rho_x} \right]^{1/3} e^{3 \ln^2 \sigma_r}$$

If n is too small the diameter could blow up

Adding bounds to the median diameters resolved the issue...

Apply transforms for B

Eventually we want to redo B, *but for now B is still total bin mass*

$$J(x) = \frac{1}{2} (x_b - x)^T B^{-1} (x_b - x) + \frac{1}{2} \sum_k (y - G(x))^T R^{-1} (y - G(x))$$

B is written as a combination of the correlation part C and variance part Σ^2

$$B = \Sigma C \Sigma$$

We can apply a series of transforms to B using the TL and adjoints

$$B = T V K \Sigma C \Sigma K^T V^T T^T$$

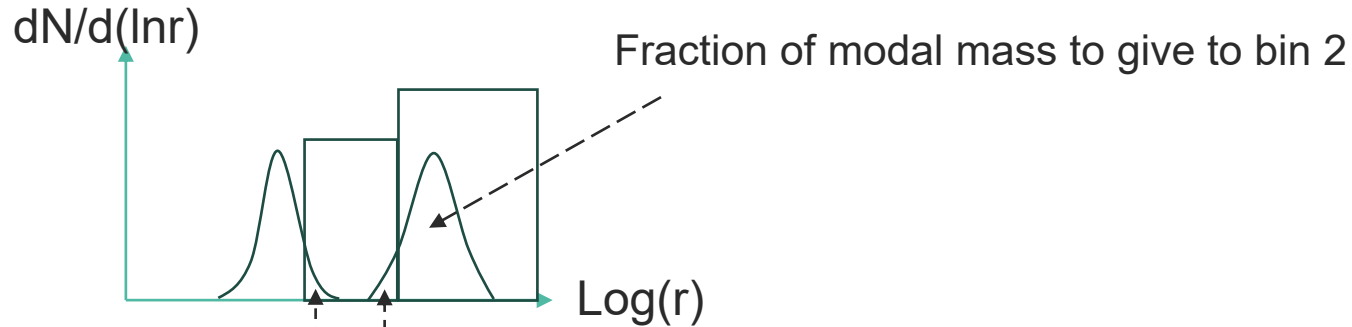
Transform B from total bin mass to the 4 separate modal variables.

Transforms for B : LFRIC to UM

1. Transform from total to separate bin mass fractions

Transforms from Anthony Jones

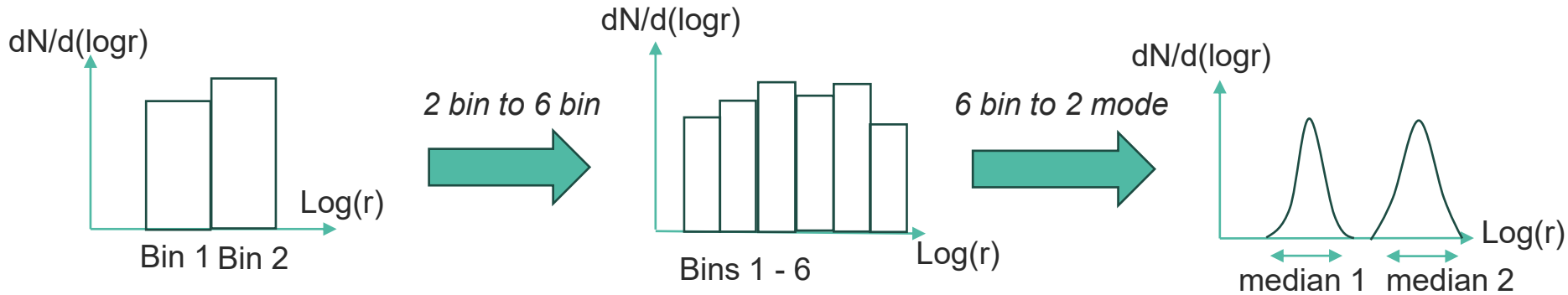
$$m_i = \frac{m_i}{m_1 + m_2} M$$



$$Bin\ Mass = \frac{1}{2} \times \sum_{r=1}^2 \left[\operatorname{erf} \left(\frac{\ln(D_{\max, \text{BIN}_i} / D_{vm,r}(i, j, k))}{\sqrt{2} \ln \sigma_r} \right) - \operatorname{erf} \left(\frac{\ln(D_{\min, \text{BIN}_i} / D_{vm,r}(i, j, k))}{\sqrt{2} \ln \sigma_r} \right) \right] m_r(i, j, k)$$

Transforms for B : UM to LFRIC

2. Transform bin mass fractions to modal mass and number fractions



Mass mode1 $m_{acc} = 0.19 \text{ mass}_{bin1}$

Mass mode2 $m_{cor} = 1.12 \text{ mass}_{bin1} + 1.20 \text{ mass}_{bin2}$

Number mode1 $n_{acc} = 3.875e^{-11} \text{ mass}_{bin1}$


Number mode2 $n_{cor} = 4.253e^{-12} \text{ mass}_{bin1} + 2.26e^{-13} \text{ mass}_{bin2}$

*Transforms taken
from CLASSIC/UM
code*

New control variables: summary

- Aim to in the first instance use all 4 GLOMAP dust variables as control variables, transforming around B (for now) and eventually move to using an ensemble
- Advantages:
 - This could make things easier with future datasets that are sensitive to only one mode (such as IASI-Mapir)
- Possible pitfalls?
 - Currently under-observed with only AOD assimilated which may make it difficult to have 4 separate control variables
 - The transforms rely on good overlap between the GLOMAP and CLASSIC models which may not always be the case

Alternative approach

$$J(x) = \frac{1}{2} (x_b - x)^T B^{-1} (x_b - x) + \frac{1}{2} \sum_k (y - G(x))^T R^{-1} (y - G(x))$$


- Use total modal mass as control variable = mode1 + mode2
- Fix modal diameters at background values (with upper/lower bounds)
- Assume

$$B_{modal\ mass} = B_{bin\ mass}$$

→ This could be tried as an alternative option for comparison

Summary

- LFRic model migration is complete in GC6 – dust/aerosols use GLOMAP-MODE. This produces very similar forecasts.
- Development work is ongoing for JADA/LFRic with the aim to complete this around December 2026 - September 2027
- The use of new control variables for LFRic is being considered

Future Work

- SOL/INSOL – a simple aerosol configuration of GLOMAP mode to move beyond just dust
- Replace transforms in JADA with real background error covariances, possibly in the ensemble
- Assess and introduce NOAA-21 Deep Blue AOD product once available
- Evaluate new datasets if and when we can and once JADA is completed: 3MI, SLSTR AOD, EarthCARE, IASI Mapir...