The performance of the CoMorph A convection scheme in global simulations with the Met Office Unified Model

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CoMorph:

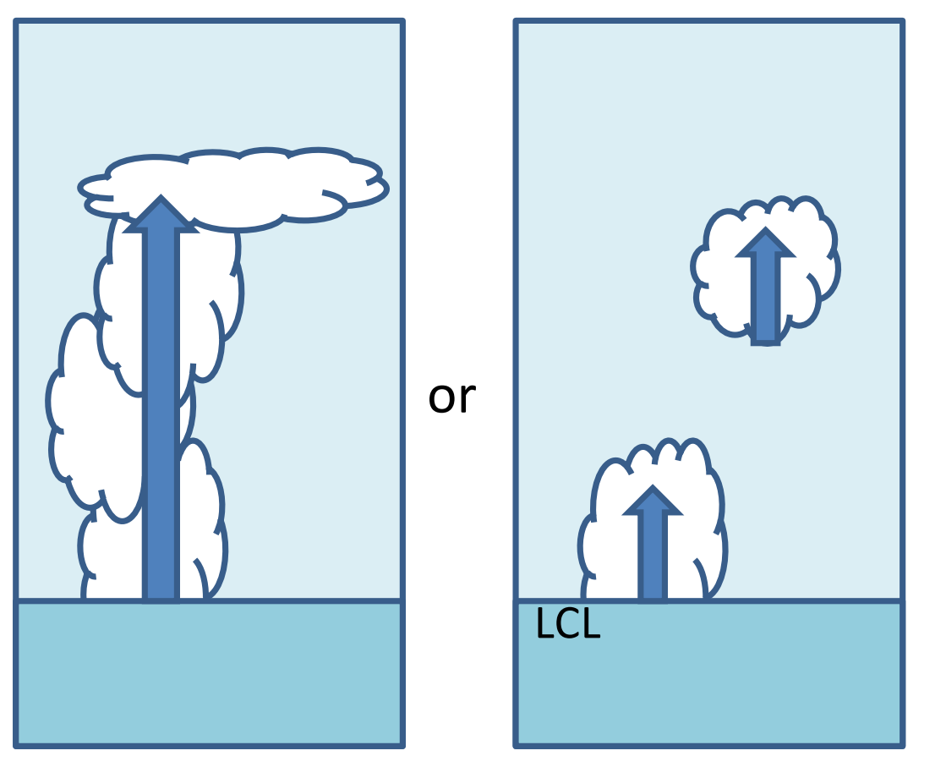
A new parameterisation scheme for moist convection in the Met Office Unified Model.

Still a diagnostic mass-flux convection scheme, but with a total redesign, and flexible code structure to allow various assumptions to be relaxed…

Design goals:
- Remove ad-hoc structural assumptions which have hampered progress in the past.
- Allow representation of new physical processes which were previously neglected.

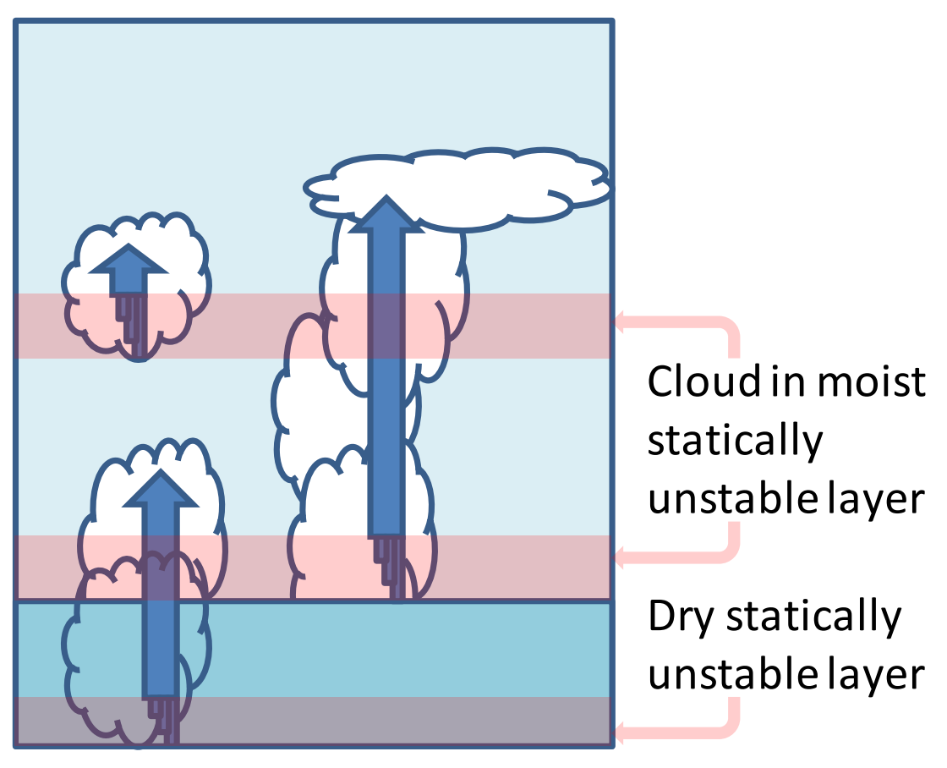
"Traditional" approach:

- Complex empirical trigger functions.
- A-priori diagnosis of a unique "cloud-base" height.
- Plume can only start from surface or other prescribed height.
- Separate schemes for "deep", "shallow" and "mid-level" convection (must be pre-diagnosed which one to trigger).



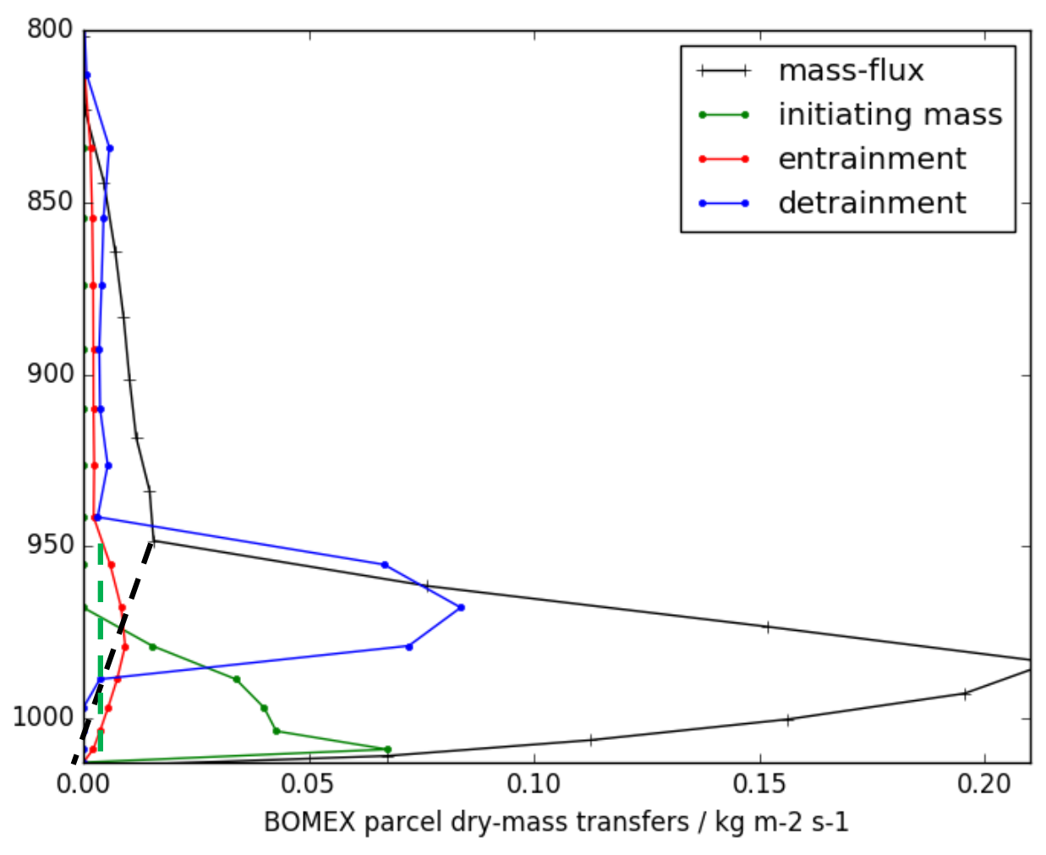
CoMorph – Back to Basics:

- Convecting parcels launch from any height where there is local vertical instability.
- Plumes from different unstable layers integrated independently.
- Single parcel ascent / descent code for all plumes.
- Updraft radius / entrainment rate depend on the turbulent mixing-length in the parcel's source-layer.



Diagnostic bulk vertical mass transport budget

$$\frac{\partial M}{\partial z} = g + e - d$$



Initiating mass-source from each height depends on local vertical instability: (dry-static instability in clear-air, moist-static instability in large-scale cloud)

$$g = \frac{1}{4}\rho\sqrt{-N^2}$$

Entrainment rate inversely proportional to radius of convective thermal: (radius is proportional to turbulence length-scale from the boundary-layer scheme, with enhancement by the previous precip-rate to represent organisation of convection)

$$e = M\frac{0.2}{R}$$

$$R_{init} = \alpha\frac{K_m}{\sqrt{\langle w'^2\rangle}}$$

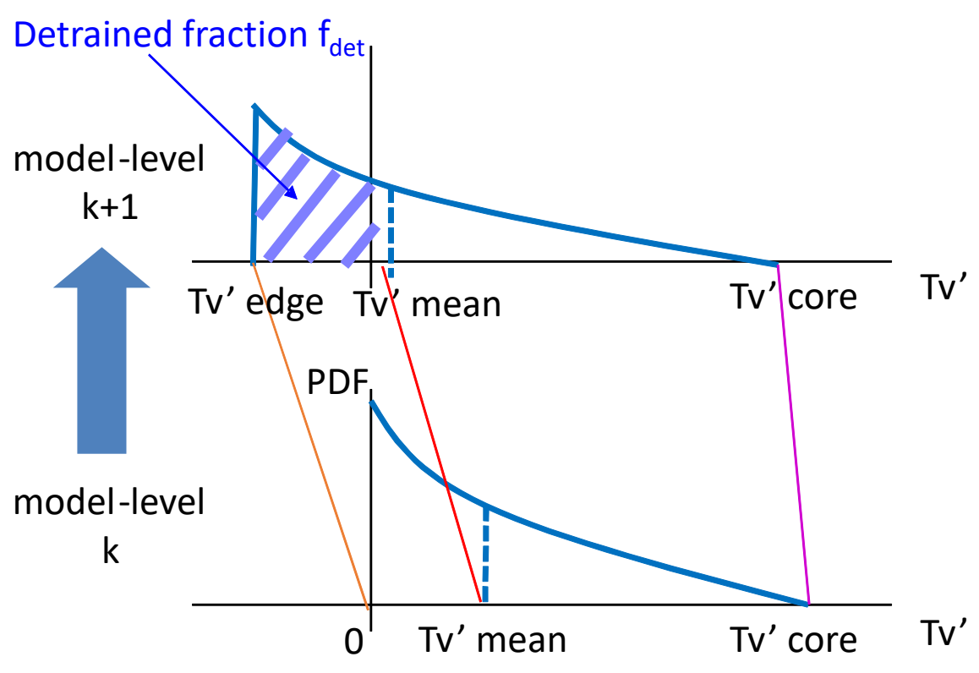
$$\alpha = \alpha_0 + \frac{pr}{pr_{max}}(\alpha_{max} - \alpha_0)$$

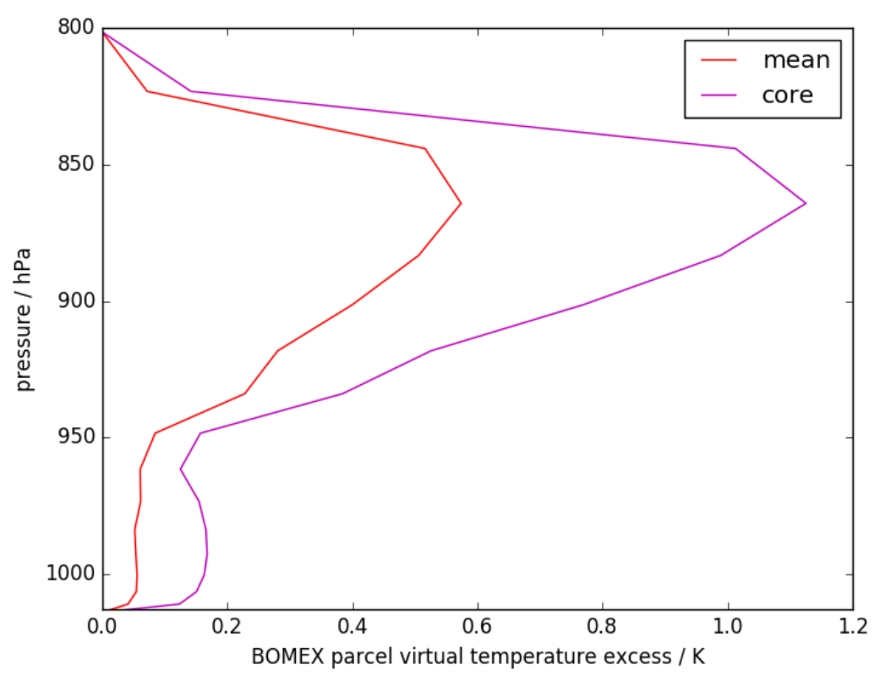
Detrainment rate based on sorting an assumed-PDF of buoyancy within the bulk plume, with implicit numerical method w.r.t. the environment / detrainment threshold…

$$d = \frac{M}{dz}\int_{T_{v\,edge}}^{T_{v\,env}} PDF(T_v)\,dT_v$$

Implicit Assumed-PDF-based detrainment

- Buoyancy, T, q, u, v, etc assumed to have a power-law PDF *within the bulk plume*.
- Separate parcel ascent calculations are done for the in-plume mean properties, and for a less dilute parcel "core", to constrain the PDF.
- At each level-step, detrain the fraction of the PDF which becomes non-buoyant (due to entrainment, changes in environment Tv, etc)





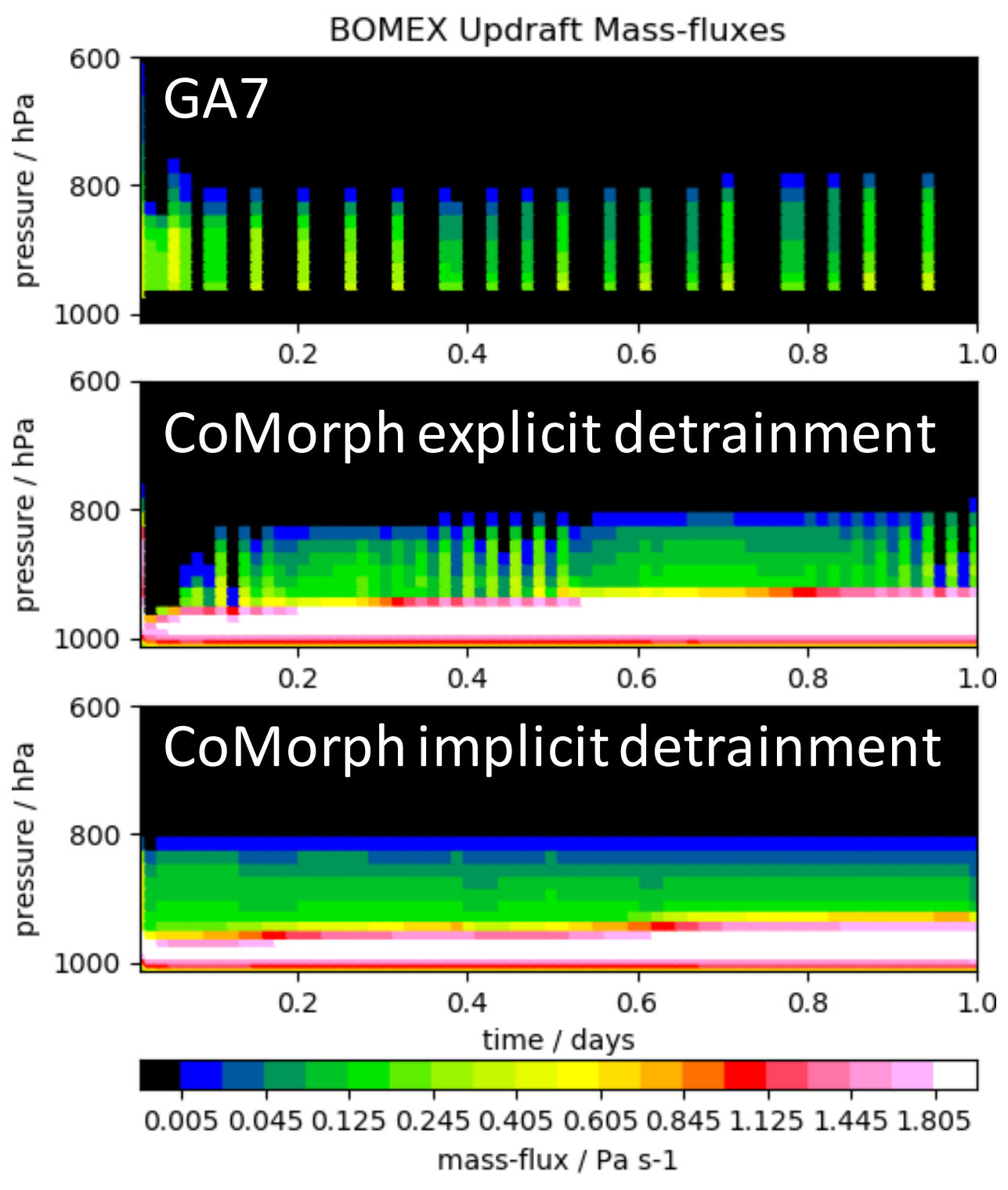
$T_v' = T_{v\,parcel} - T_{v\,env}$

But how to define $T_{v\,env}$ when it is changing due to the convective increment?

For smooth behaviour with Δt ~ 10 minutes, need implicit-in-time discretization, accounting for the convective heating:

$$\theta_{v\,env}^{det} = \theta_v^* + \alpha\frac{M_k}{\rho}(1 - f_{det})\Delta t\frac{\partial\theta_v}{\partial z}$$

Need to iterate to solve for consistent f_{det} and $T_{v\,env}$.



In CoMorph, there is no "cloud-base closure"; cloud-base mass-flux is an emergent property (depends on the small fraction of the sub-cloud layer mass-flux which is not detrained at the boundary-layer-top inversion, before the parcel reaches saturation).

Traditional cloud-base closure approach does not work as intended; instantaneous closure produces too much heating at cloud-base, so the inversion is too strong for convection to trigger at all next timestep. Time-mean mass-flux is modulated by the fraction of timesteps on which convection is able to trigger.

CoMorph implicit detrainment calculation allows us to simulate this equilibrium (w.r.t. strength of the boundary-layer-top inversion) without intermittent behaviour.

Note: CoMorph simulates large overturning mass-fluxes within the boundary-layer which would "double-count" the non-local fluxes already modelled by the UM boundary-layer scheme. To avoid this, CoMorph's increments are vertically homogenised within the surface mixed-layer.

The CoMorph A UM science configuration

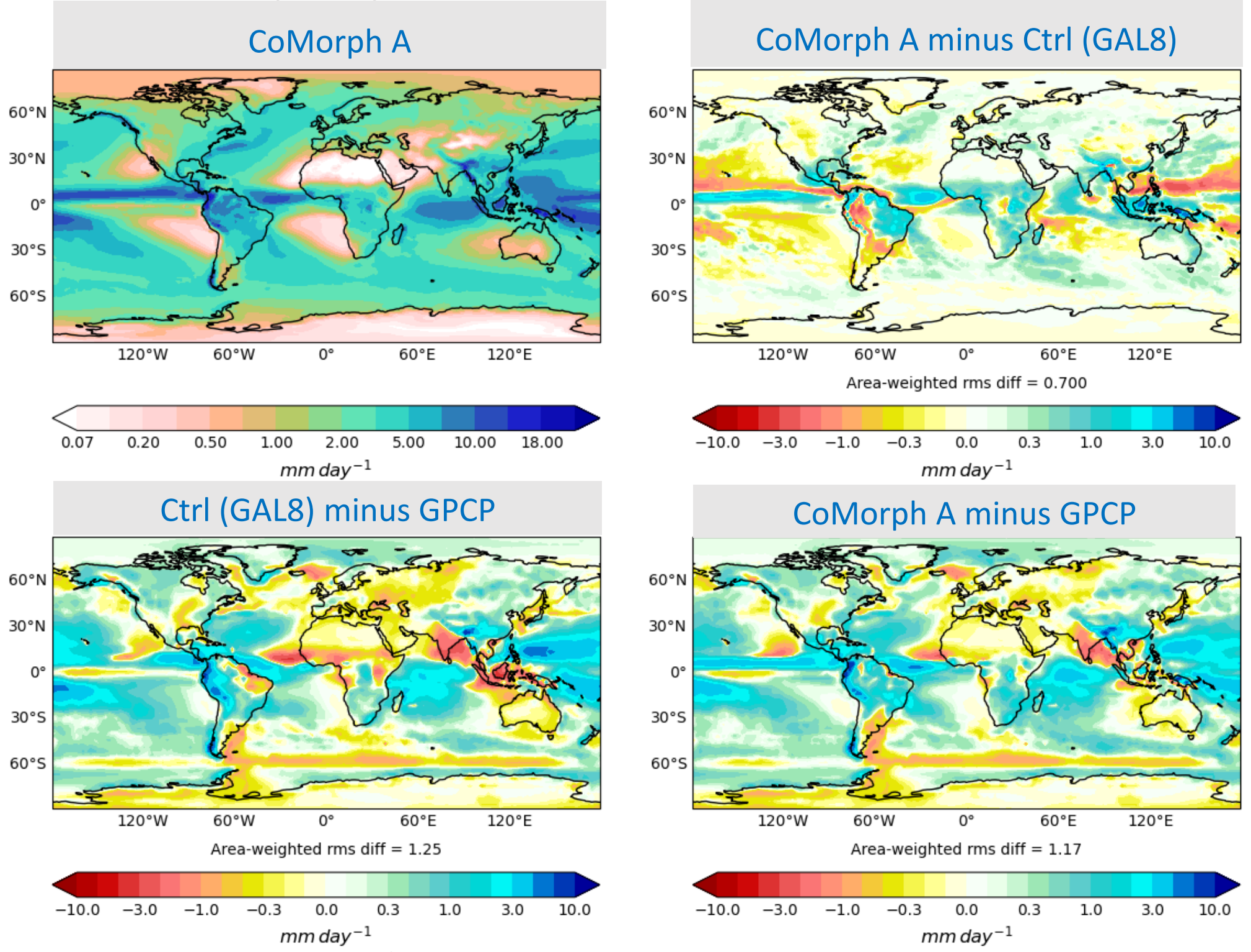
CoMorph A is a package of changes to the UM physics, which includes:

- All moist convection is simulated in a unified way using the CoMorph convection scheme.
- Sub-grid stratiform cloud is prognosed using the PC2 cloud-scheme (Wilson *et al.* 2008), using the bimodal scheme (van Weverberg *et al*. 2021) to initiate condensation, a revised homogeneous forcing calculation (Morcrette 2021), and various improvements to the numerical methods.
- The large-scale microphysics scheme (based on Wilson & Ballard 1999) uses additional prognostic variables for graupel and the sub-grid area fraction occupied by rain and graupel. Fall / evaporation / melting of both large-scale and convective precipitation is handled by this scheme (comorph increments the rain and graupel prognostics instead of producing precipitation at the surface).
- Several minor changes to the (Lock *et al.* 2000) boundary-layer scheme, including revised vertical interpolation of the local Richardson number.
- For advection of the thermodynamic and moisture fields, linear upwind corrections are applied at stagnation points in the flow, to improve conservation / avoid "grid-point storms".
- Additional vertical transport of heat and moisture is applied using the Leonard terms (Hanley *et al.* 2019).
- Various minor bug-fixes / improvements to moisture conservation.
- Various parameter changes to retune the TOA radiation.

Global Climate Simulations

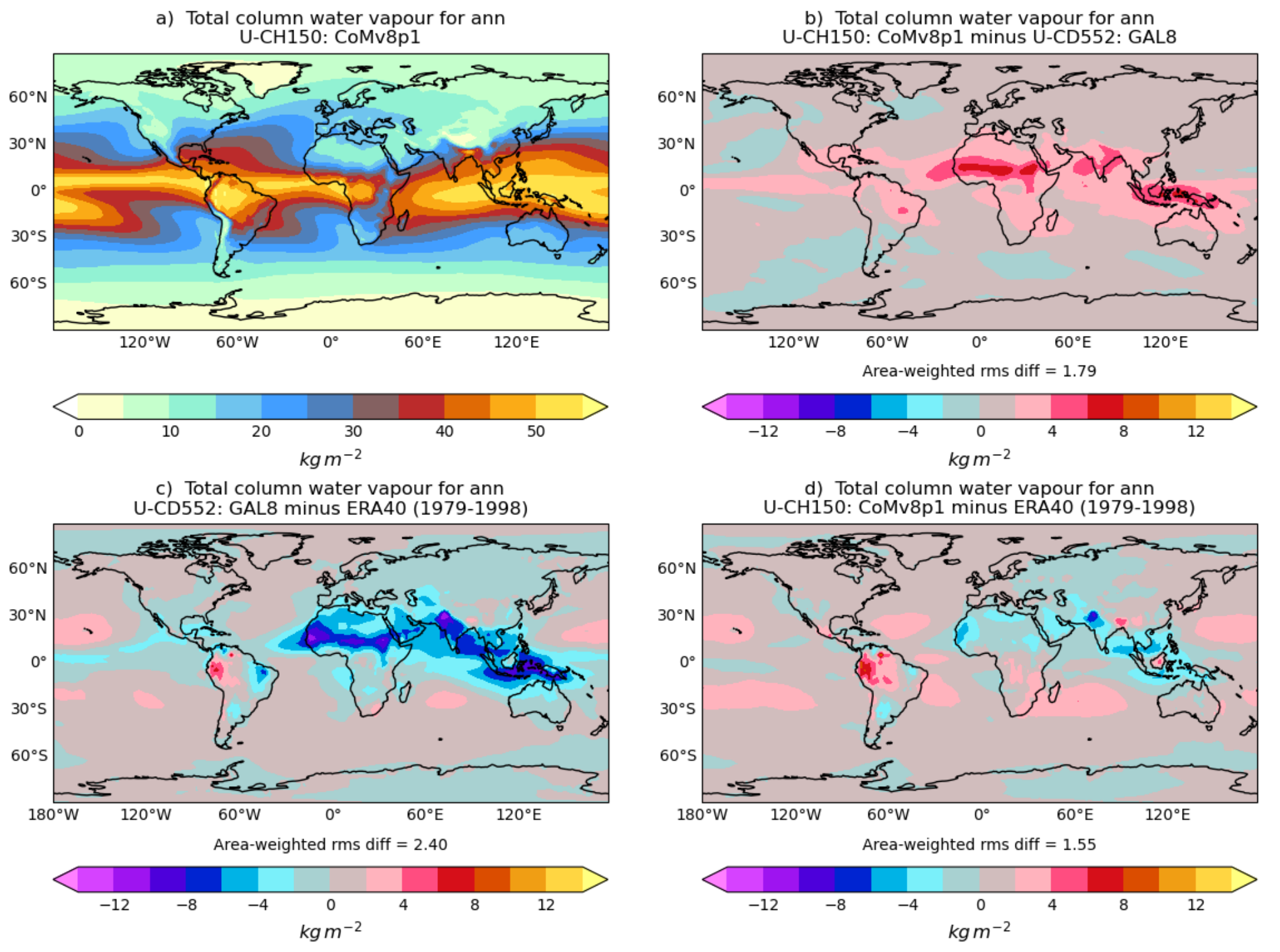
Met Office Unified Model N96 Atmosphere-only 20-year integrations performed to assess the model climatology.
CoMorph A is compared with a GAL8 control run (Global Atmosphere and Land 8, the current Met Office operational configuration).

Annual mean precipitation



CoMorph A increases rainfall over the Maritime Continent and most Tropical land, where GAL8 is too dry. It also strengthens the ITCZ wet bias. But overall the r.m.s. error of the climatology is reduced. More broadly, GAL8 and CoMorph A have similar rainfall biases, despite using different convection schemes. These biases must be linked to assumptions made by both schemes, or other aspects of the model physics.

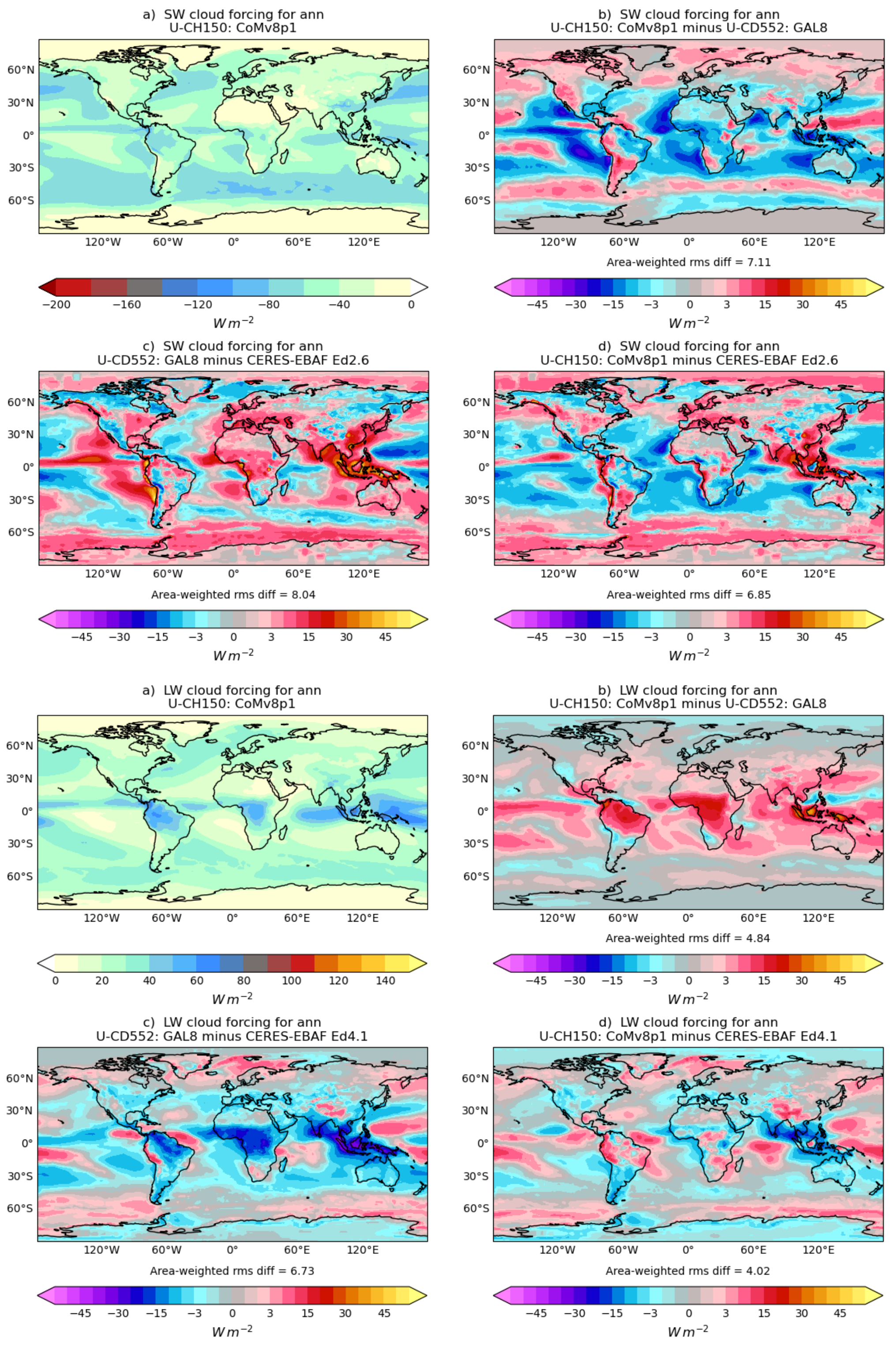
Column Water Vapour



CoMorph A largely removes dry bias in water-vapour over Tropical Africa, Asia and the Maritime Contintent.

SW and LW cloud forcings vs CERES-EBAF Ed 2.6

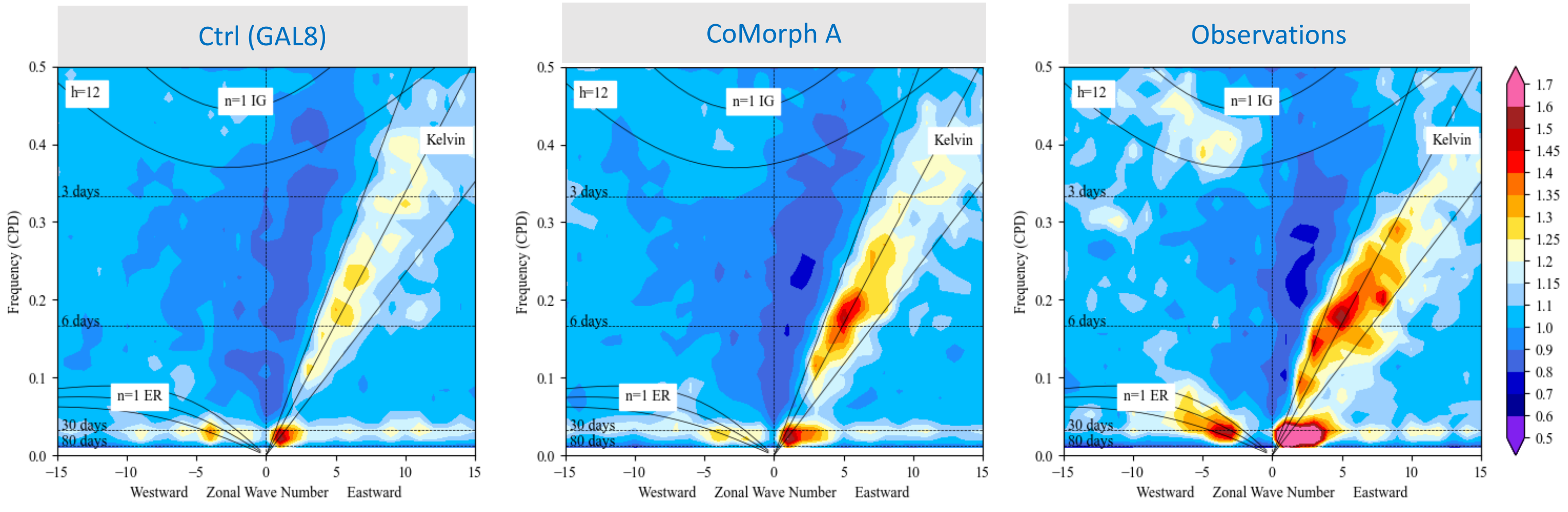
Cloud forcing = (clear-sky – total) outgoing TOA flux



Both SW and LW cloud radiative forcings are increased in magnitude in the Tropics and sub-Tropics, bringing both closer to observational estimates. The spatial patterns are also improved. Increased low-cloud likely due to the bimodal cloud-scheme, improved coupling between the convection, large-scale cloud and boundary-layer schemes, and more realistic treatment of warm rain production inside the convection scheme. GAL8 underestimates LW cloud forcing because convective snow is assumed to fall-out instantly. CoMorph detrains all ice to the "large-scale" prognostic fields instead of doing diagnostic rain-out, allowing it to influence the radiation.

Convectively Coupled Equatorial Waves

Tropical wavenumber-frequency spectrum for precipitation



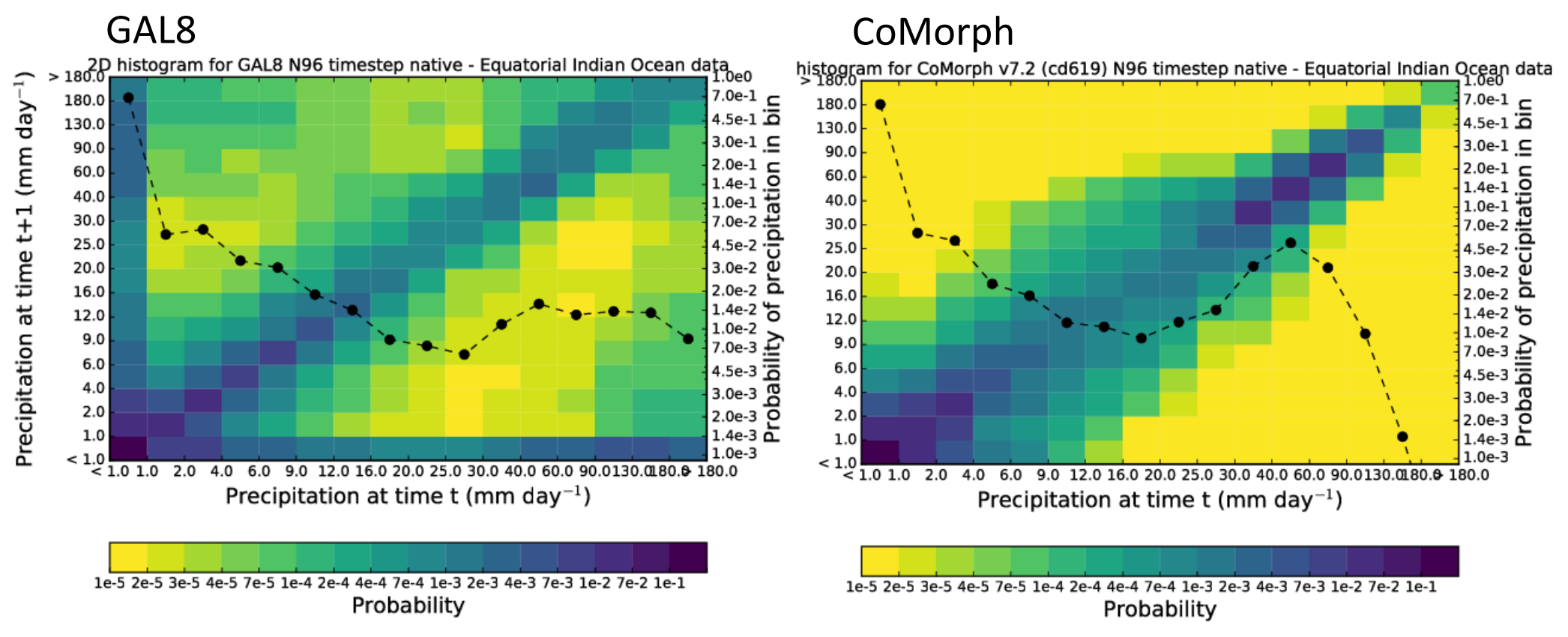
CoMorph A simulation has increased power in the Kelvin waves and MJO (although still less than observed).

CoMorph A also improves other features of the model climate and NWP performance not shown here, notably:

- Reduced mean track error for both Tropical and extra-Tropical cyclones.
- Increased (improved) intensity of Tropical cyclones.
- Reduced r.m.s.e. of the climatological mean winds in the Tropics.
- Net surface heat flux errors reduced, improving coupled simulations.
- Overall NWP scores improved by 0.5% in DJF, 2% in JJA, compared to GAL8.

Temporal Variability

Probability distribution for precip rate at the next timestep, as a function of precip rate at current time. Dashed line shows 1-D histogram of binned precip, using the right-hand vertical axis.

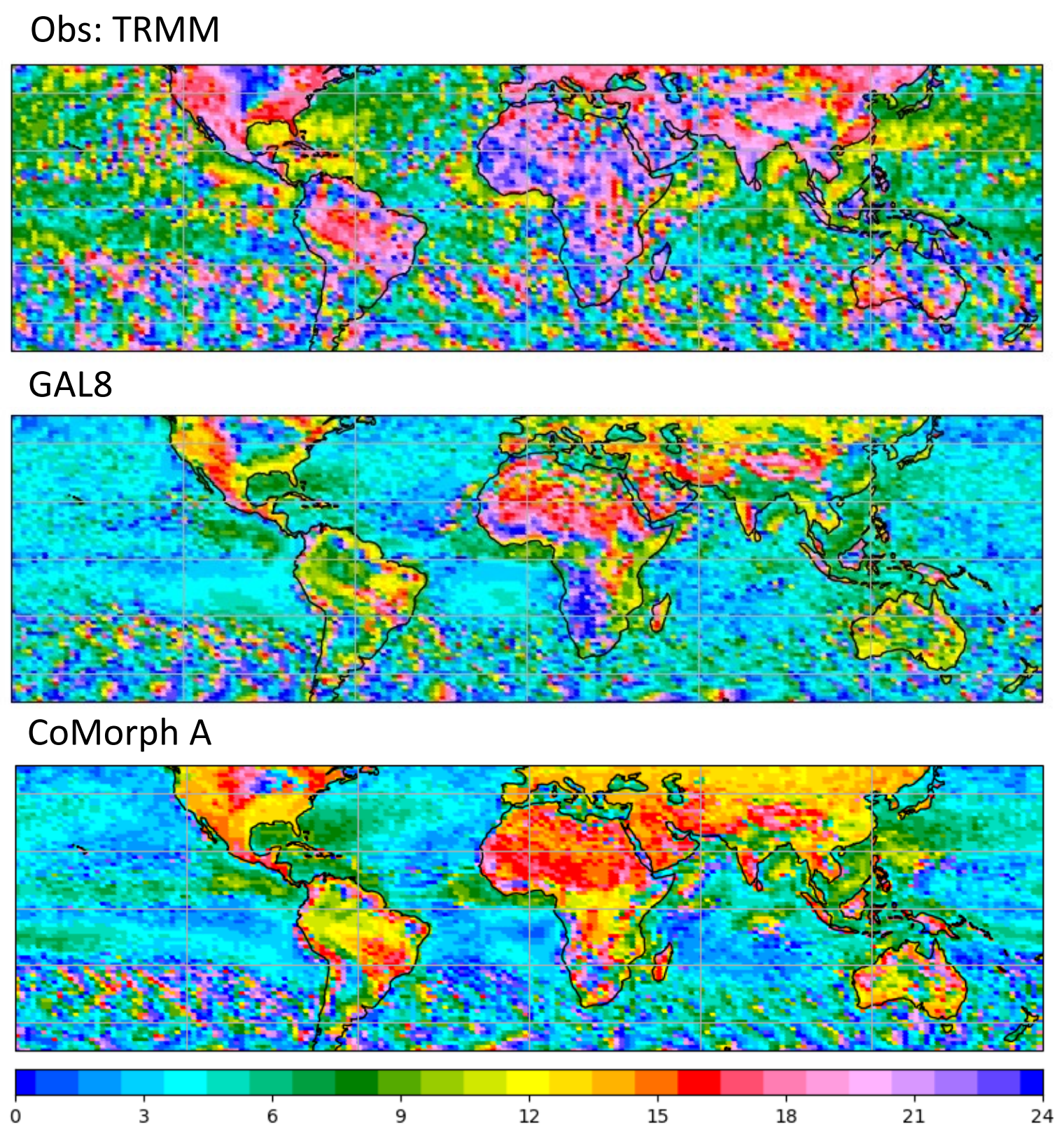


GAL8 shows high probability along the axes, indicating intermittency of the existing convection scheme (high probability of a very high rain-rate followed by a very low rain-rate at the next timestep, or vice-versa).

CoMorph's implicit detrainment scheme successfully removes the longstanding intermittency problem, giving coherent evolution over successive timesteps.

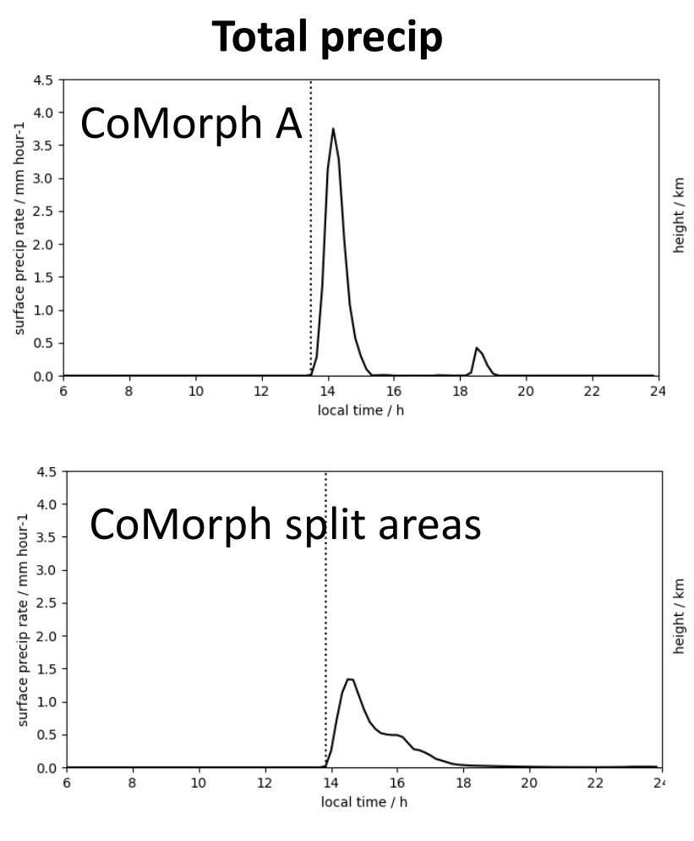
CoMorph rain-rate histogram has a strange peak at around 50 mm day-1. This corresponds to the precip rate at which the parameterised updraft radius scaling reaches its maximum value / minimum allowed entrainment rate.

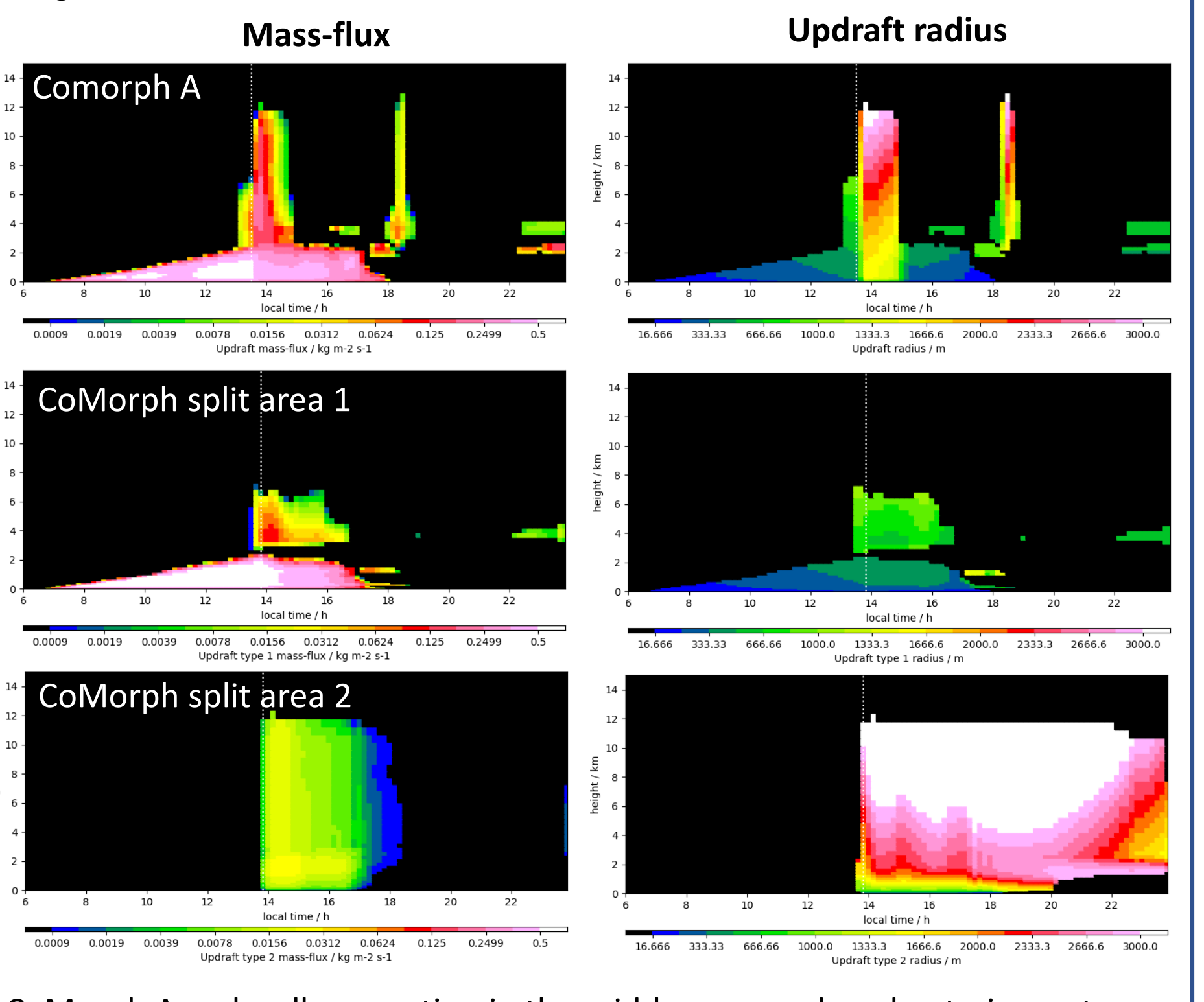
Diurnal Cycle of Precipitation



Simulated local time of diurnal peak rainfall is too early in most Tropical land areas, and CoMorph A increases this error in many areas (e.g.Tropical Africa).
CoMorph's entrainment formulation allows a too-rapid increase in updraft radius / decrease in entrainment rate following the onset of precipitation.
Note that GAL8 similarly modulates entrainment as a function of surface precip, but applies a 3-hour damping timescale to delay the response.

SCM simulations of the AMMA case; CoMorph A compared with the proposed modified version which splits the grid-box into organised and disorganised convection areas.





Can we improve the physical realism of the entrainment formulation?

Both GAL8 and CoMorph A make all convection in the grid-box use reduced entrainment as a function of the grid-mean precip rate. But in reality, organised convection may initially occur in only a small fraction of the grid-box, and gradually spread. In CoMorph B (under development), we split each grid-box into separate organised / disorganised areas, and apply the increased updraft radius / reduced entrainment only in the organised convection area. The updraft radius increase is a function of the local precip evaporation rate *within the rainy fraction* (using grid-mean precip rate causes undesirable sensitivity to model-resolution). These changes successfully remove the excessive early-afternoon rainfall peak.

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