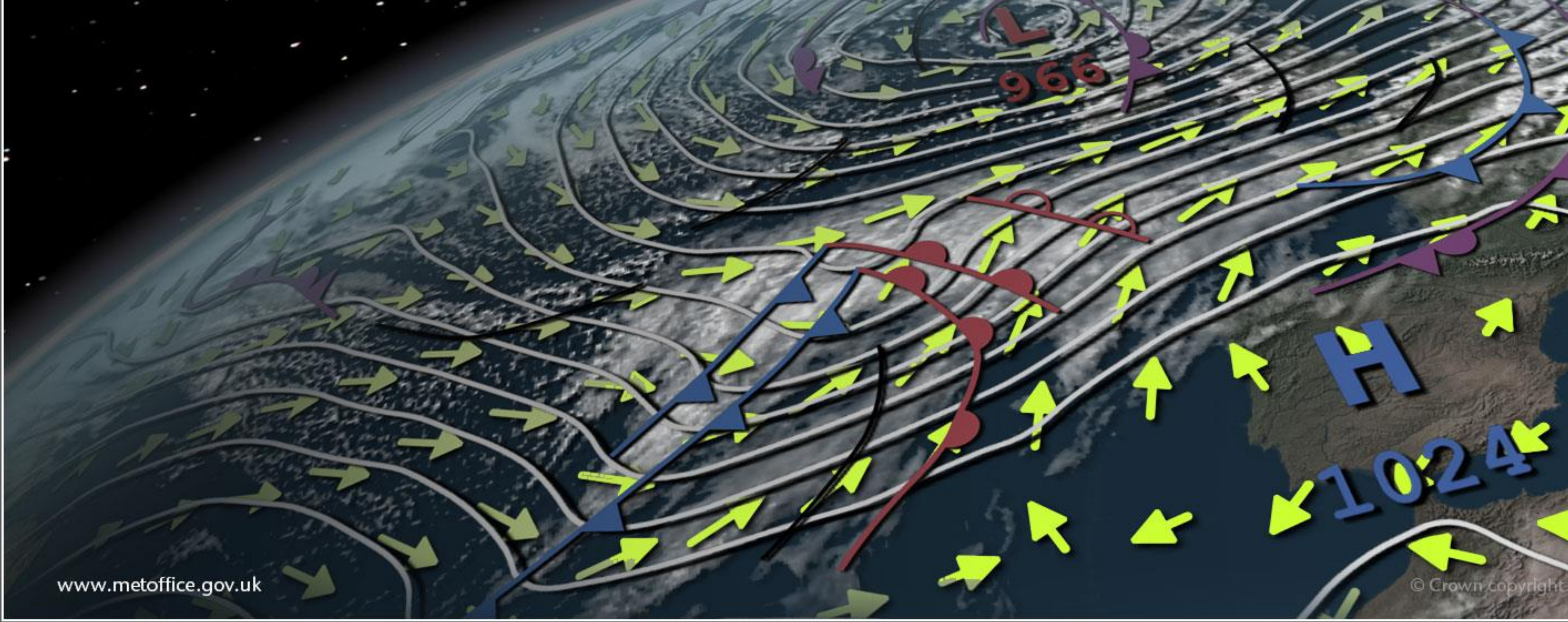
Some thoughts on convective “triggering”, “closure” and “cloud model”...

...and a new stochastic scale-aware scheme.

Mike Whitall   Alison Stirling   Kirsty Hanley

ECMWF grey-zone workshop
14 November 2017

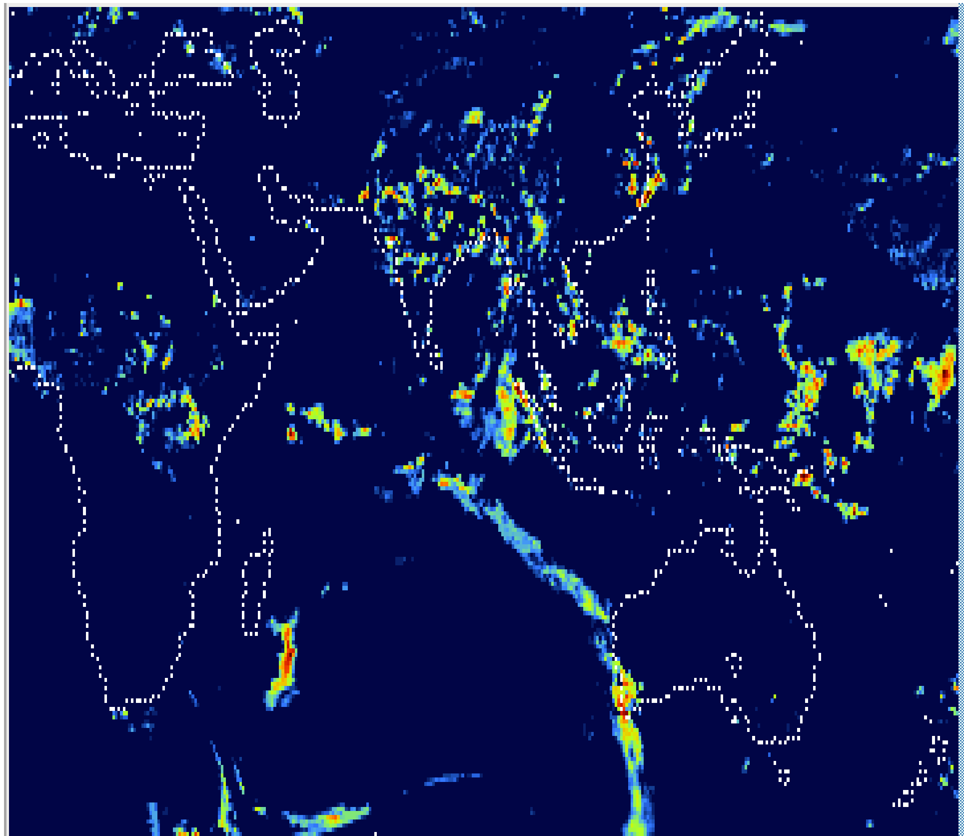


Existing UM convection scheme:

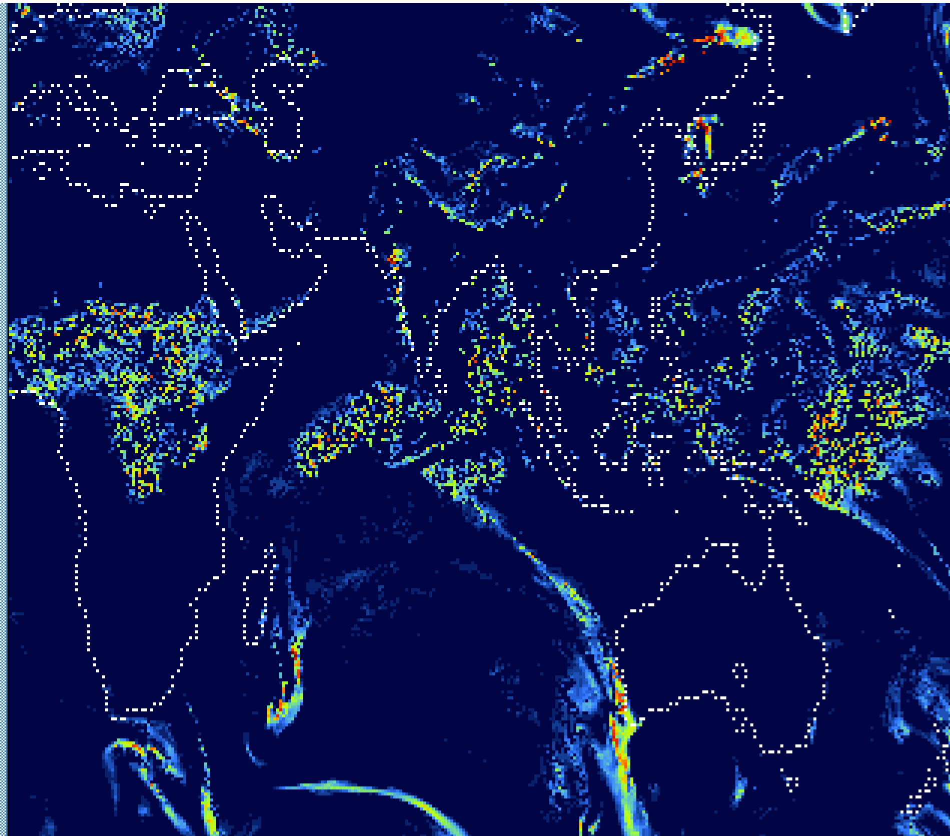
- Doesn't adapt with resolution (parameterises what should be resolvable).
- Deficient organisation on resolved scales (at all resolutions!)

Something has gone very wrong; if it is really an "equilibrium" scheme, why doesn't it yield a smooth, equilibrium behaviour?

TRMM



Met UM GA7 N320

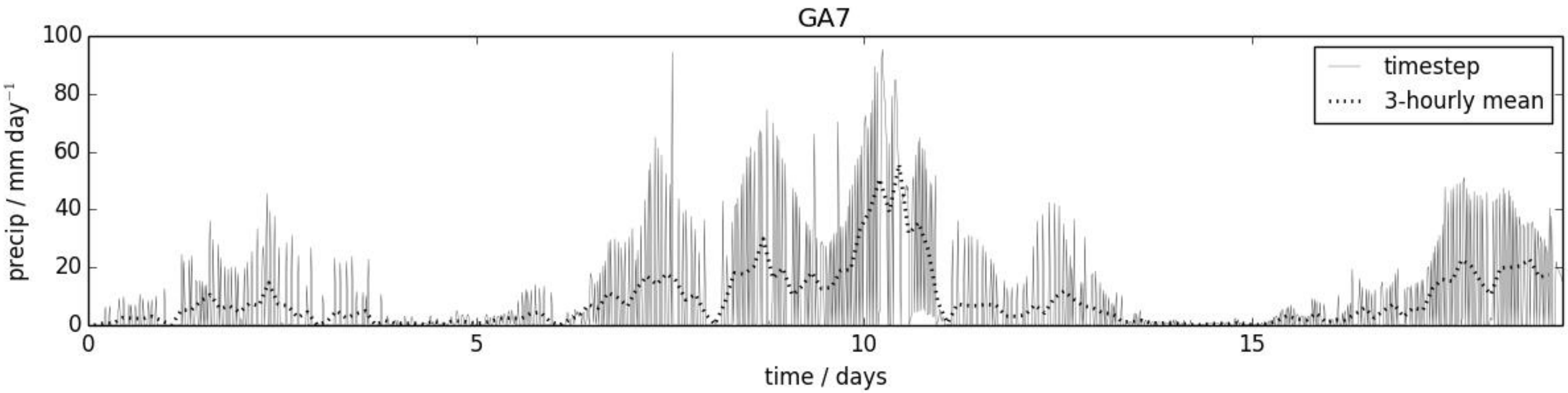


Where to start?

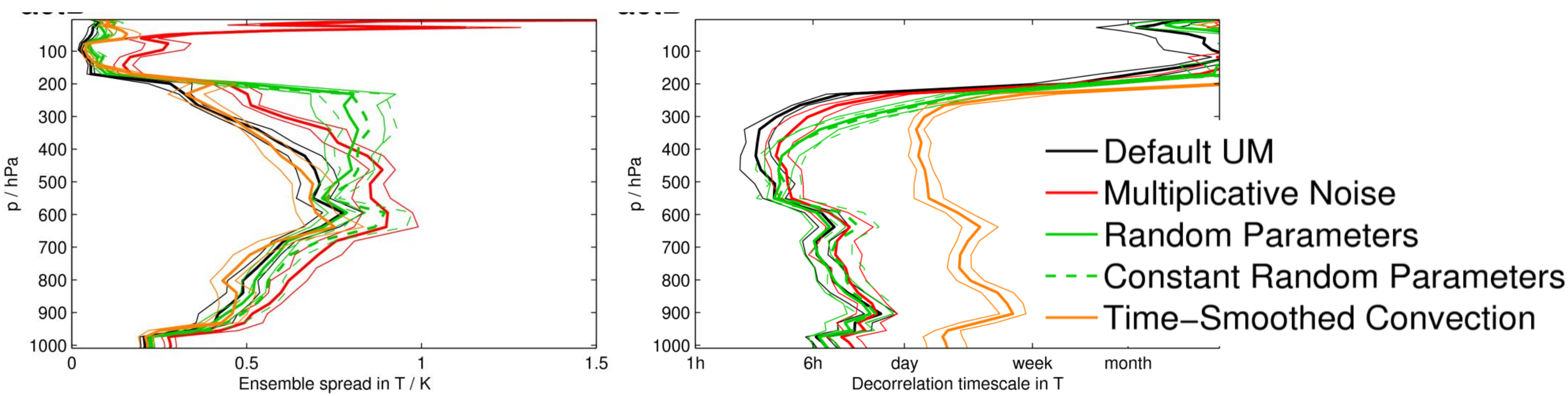
Many attempts to promote scale-awareness and/or improved organisation have focussed on modifying / perturbing the **convective closure** (c.f. SPT rescales the tendencies).

In the UM, this makes less difference than expected...

CAPE closure dysfunctional; trigger intermittency controls mean mass-flux and variability!



UM SCM ensemble (TOGA-COARE) – spread and decorrelation time-scale:



Problem with CAPE closure

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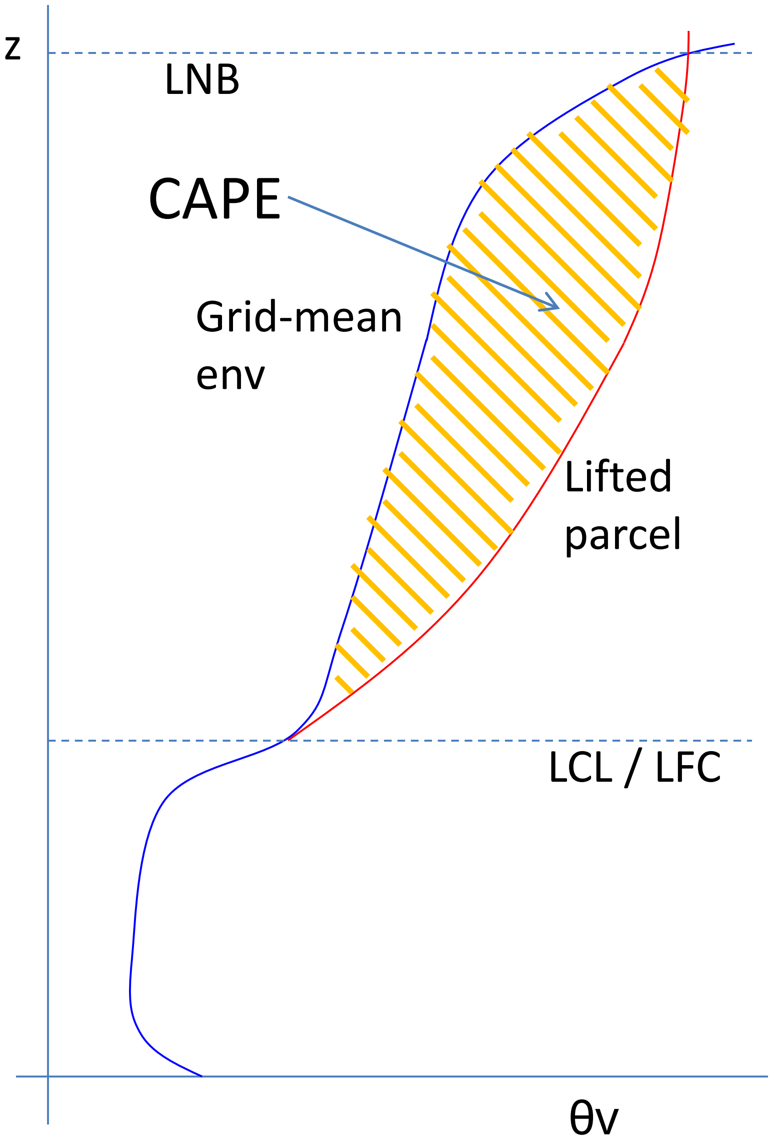

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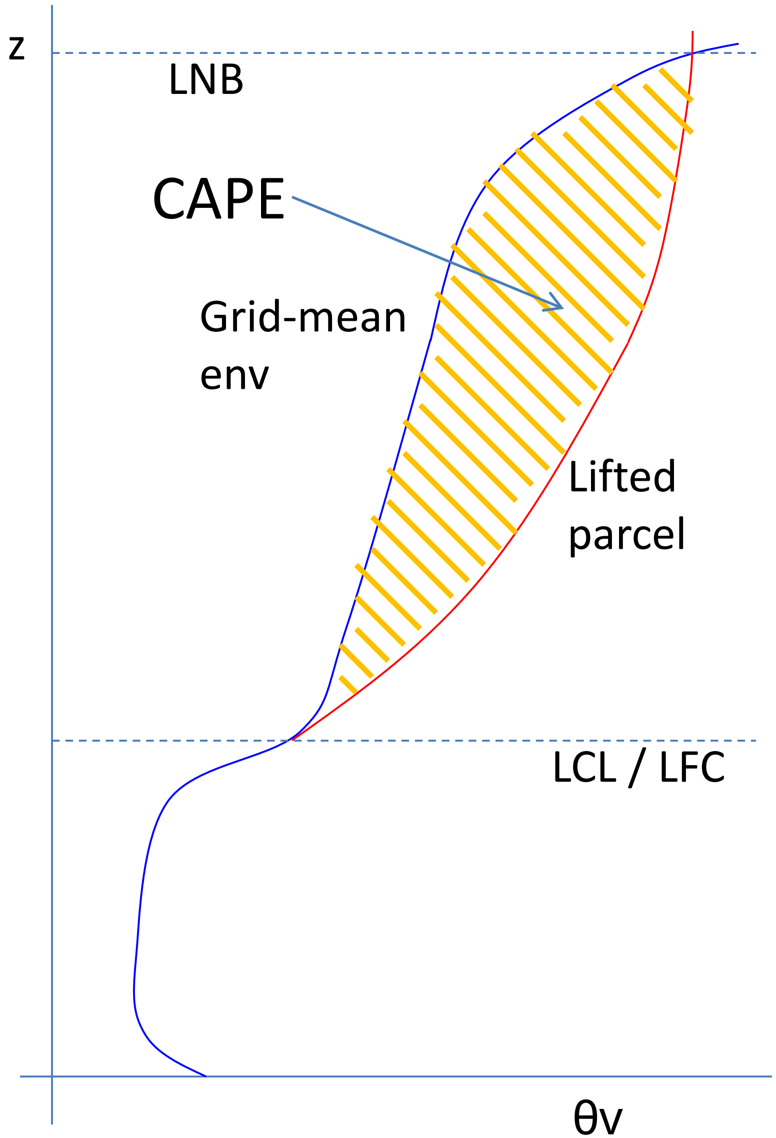

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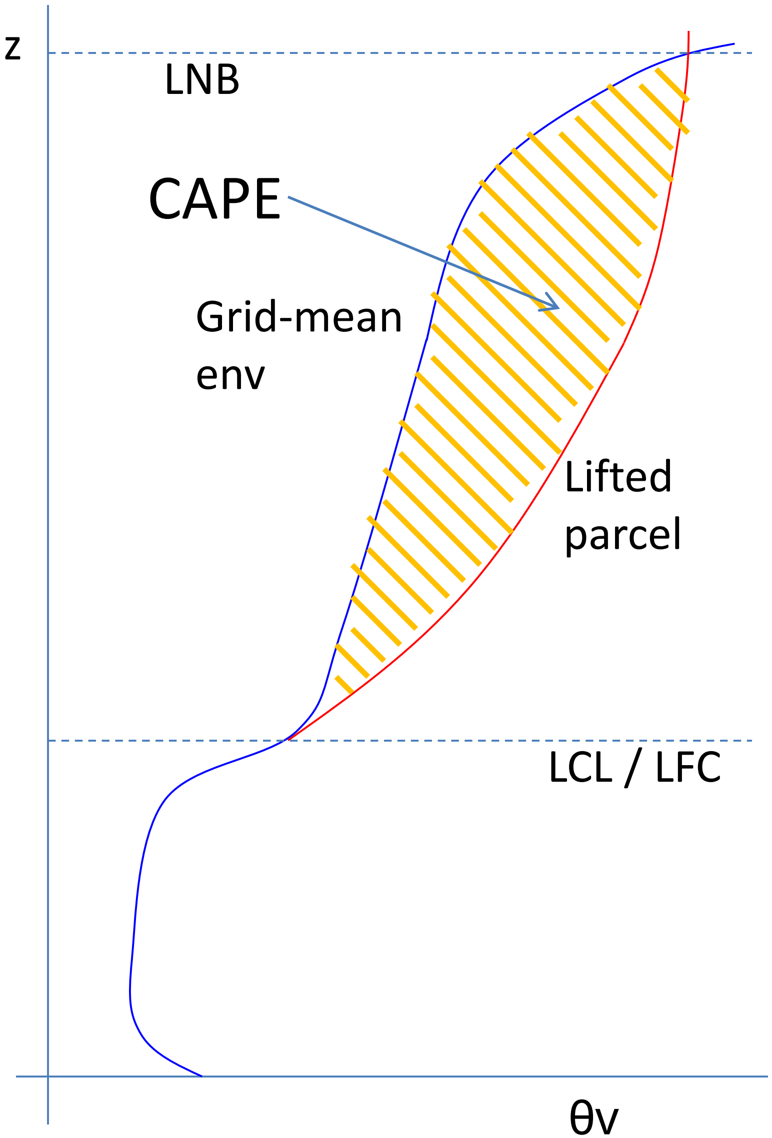

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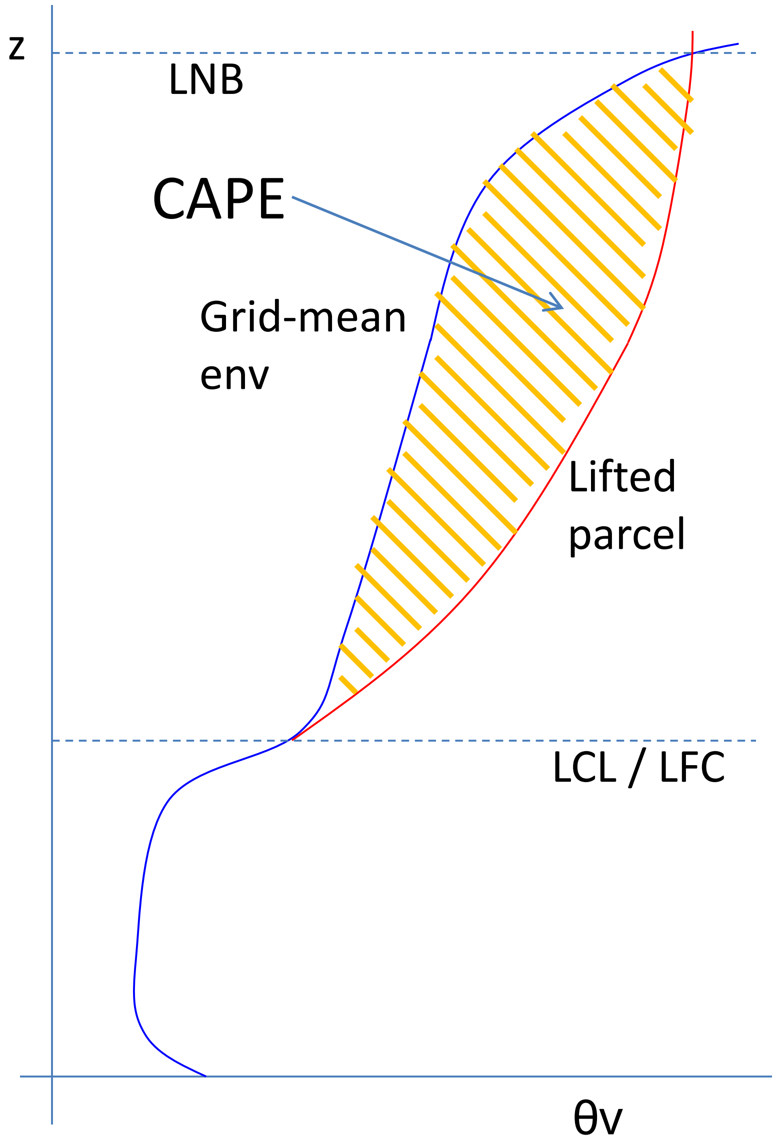

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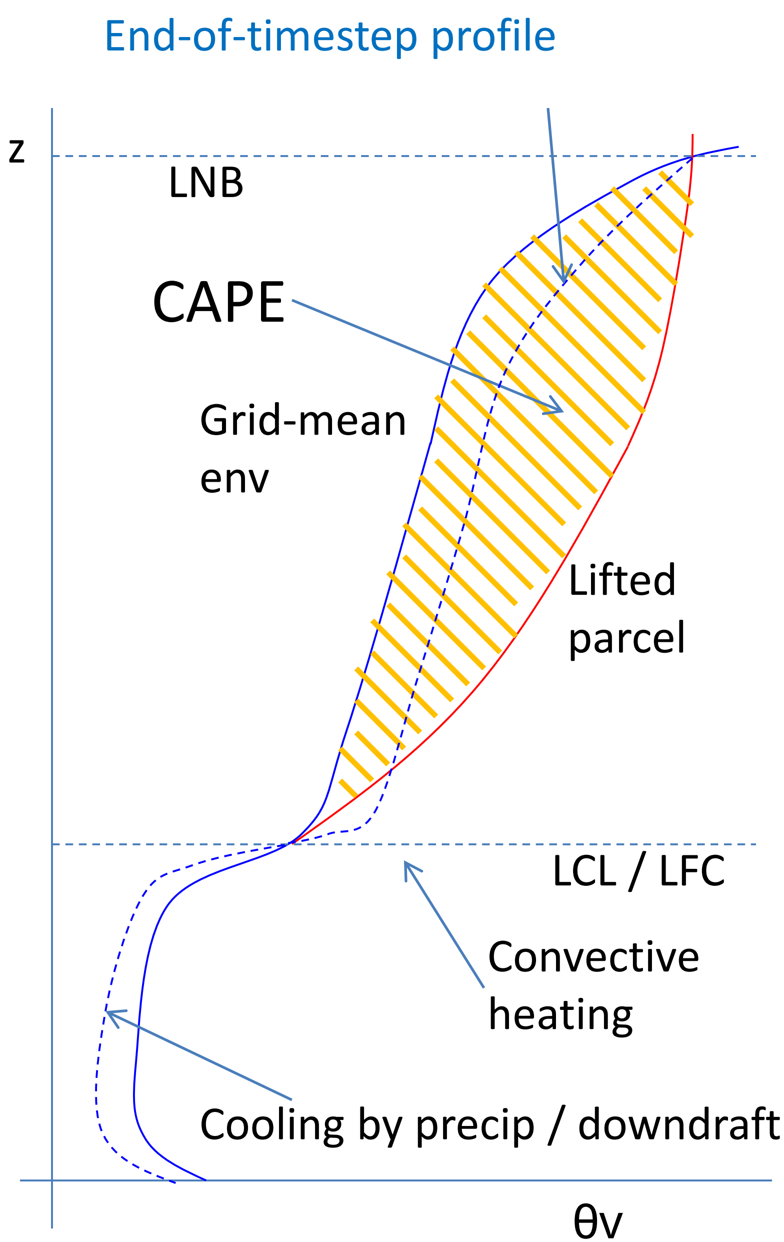

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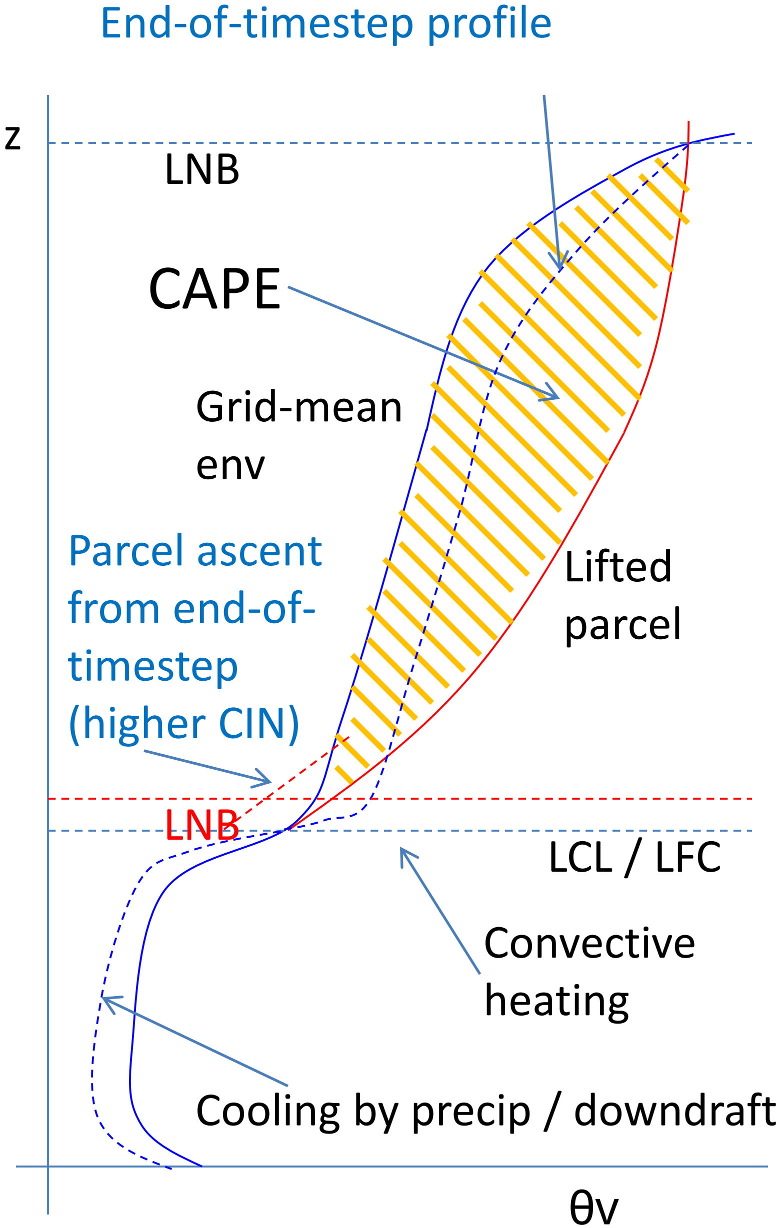

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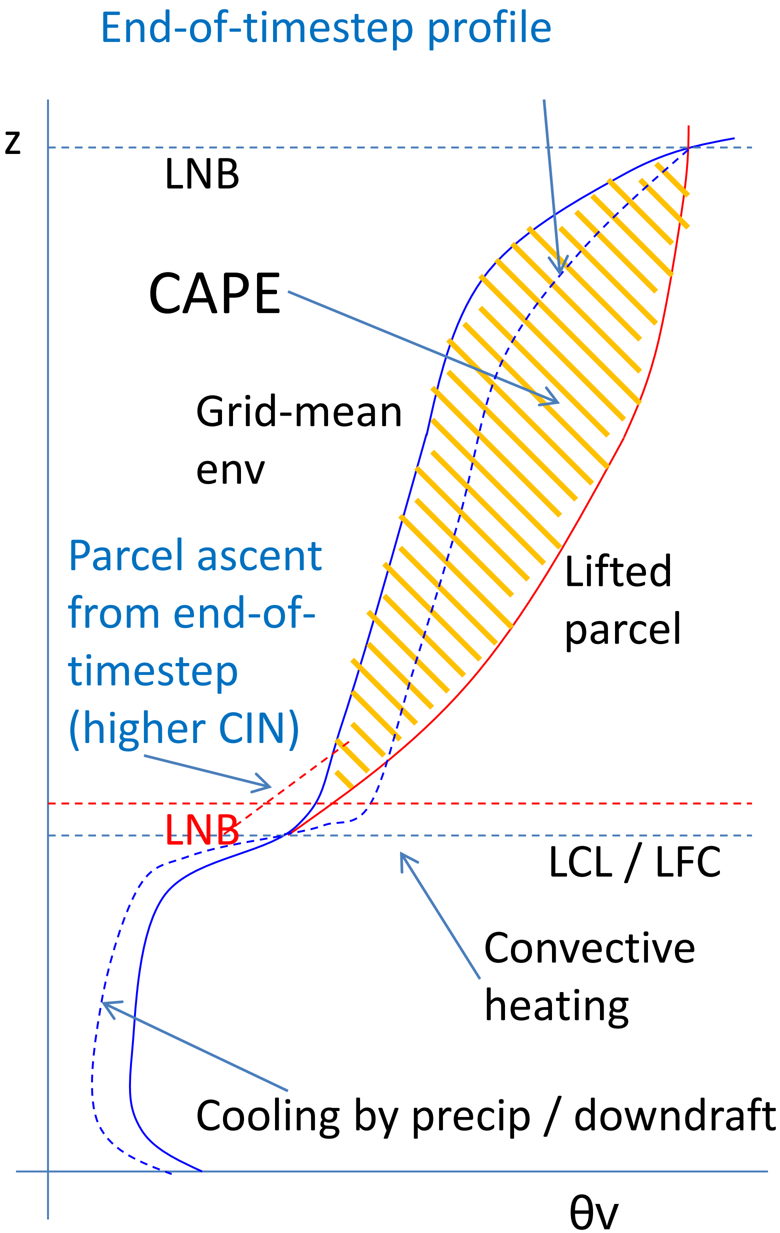

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But closure was meant to remove CAPE smoothly over time τ; what went wrong?

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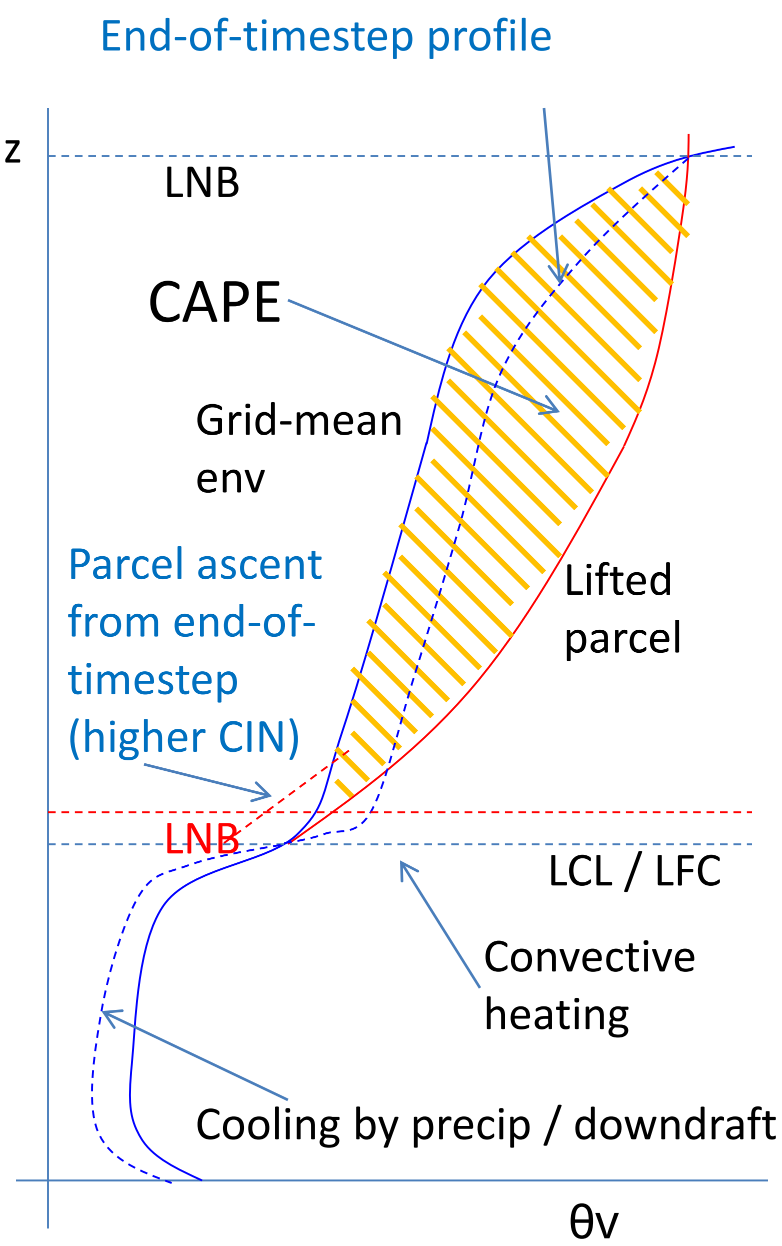

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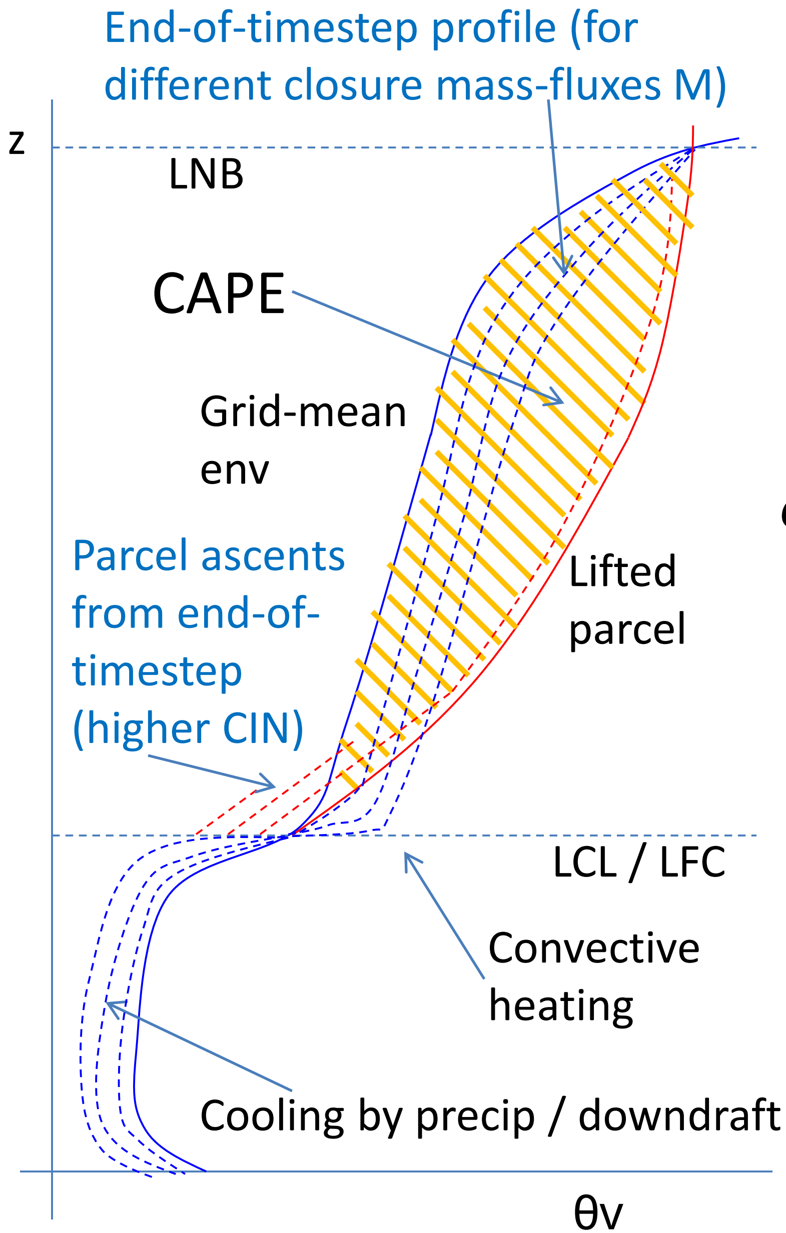
The dominant term modulating the parcel-integrated CAPE is change in z_{LNB} (neglected), when increased CIN causes the parcel to terminate below the LFC (→ CAPE suddenly drops to zero, convection not triggered).

Closure formula assumes ΔCAPE over the timestep scales linearly with M, but it doesn't...

Problem with CAPE closure



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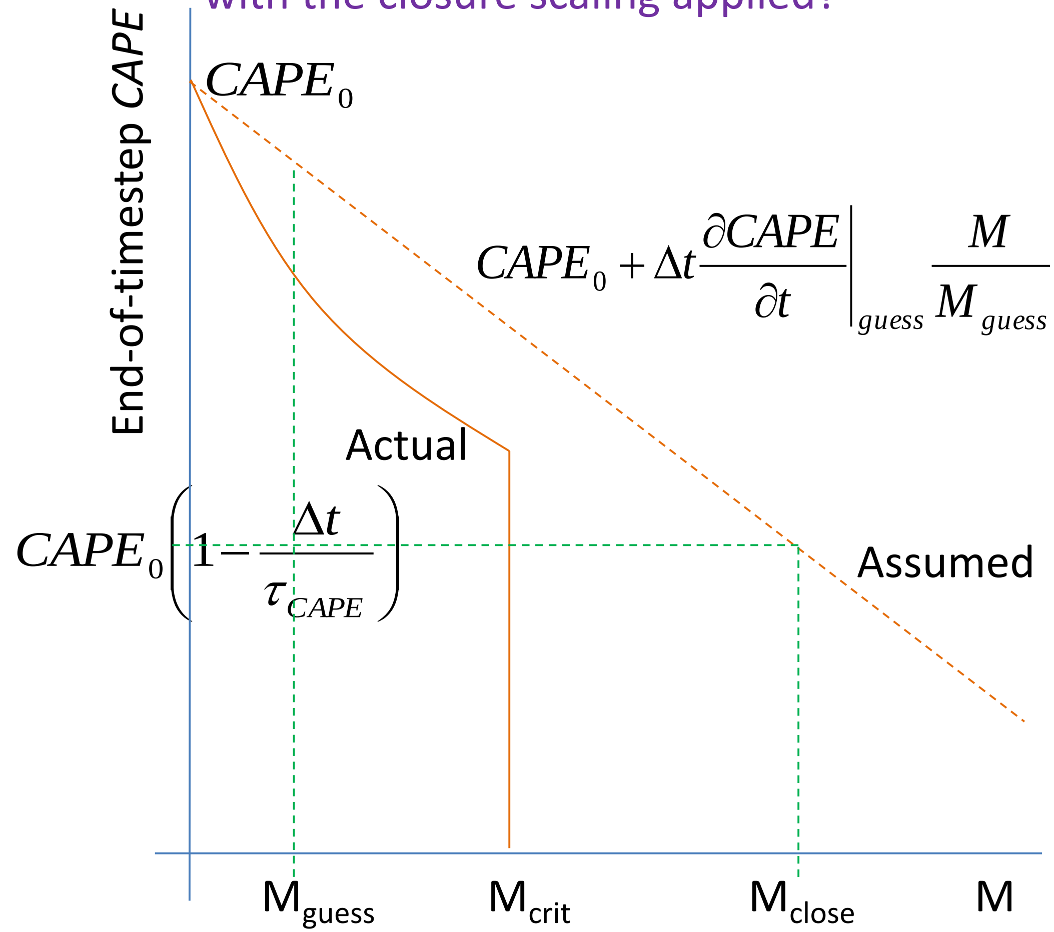

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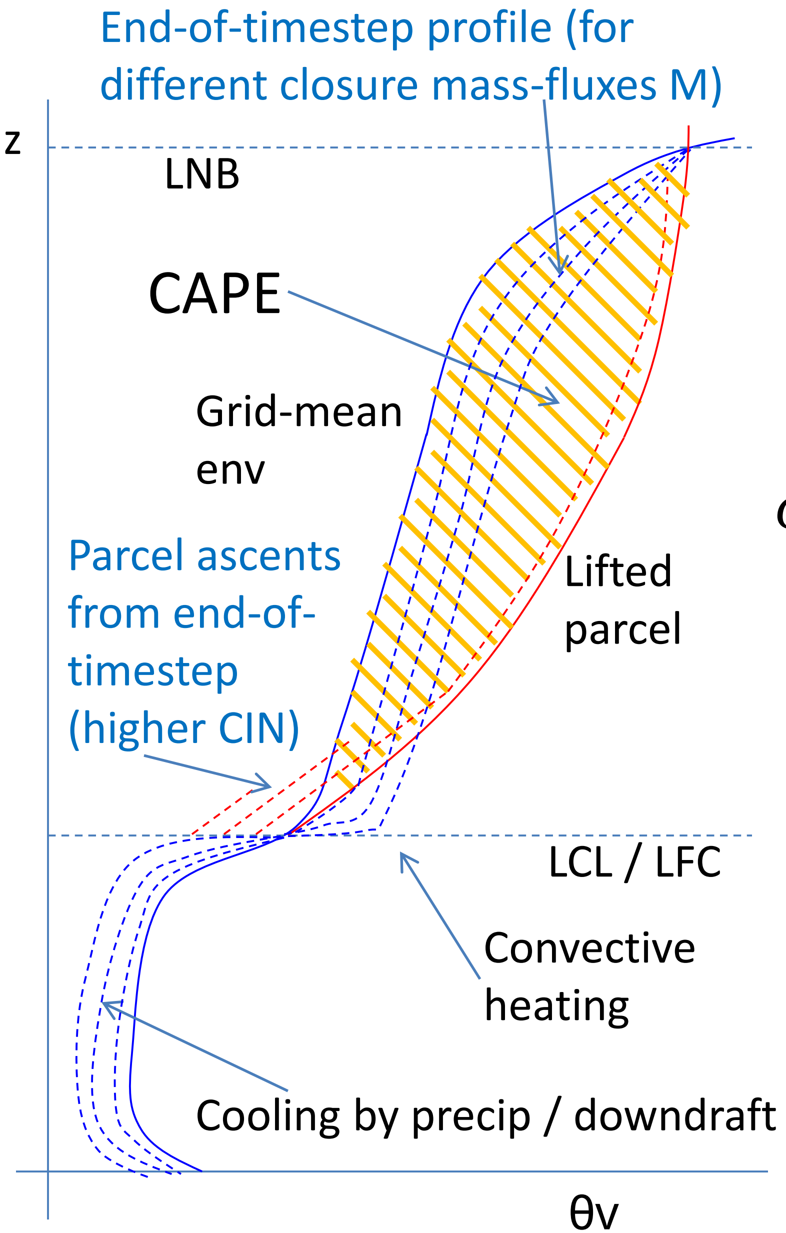

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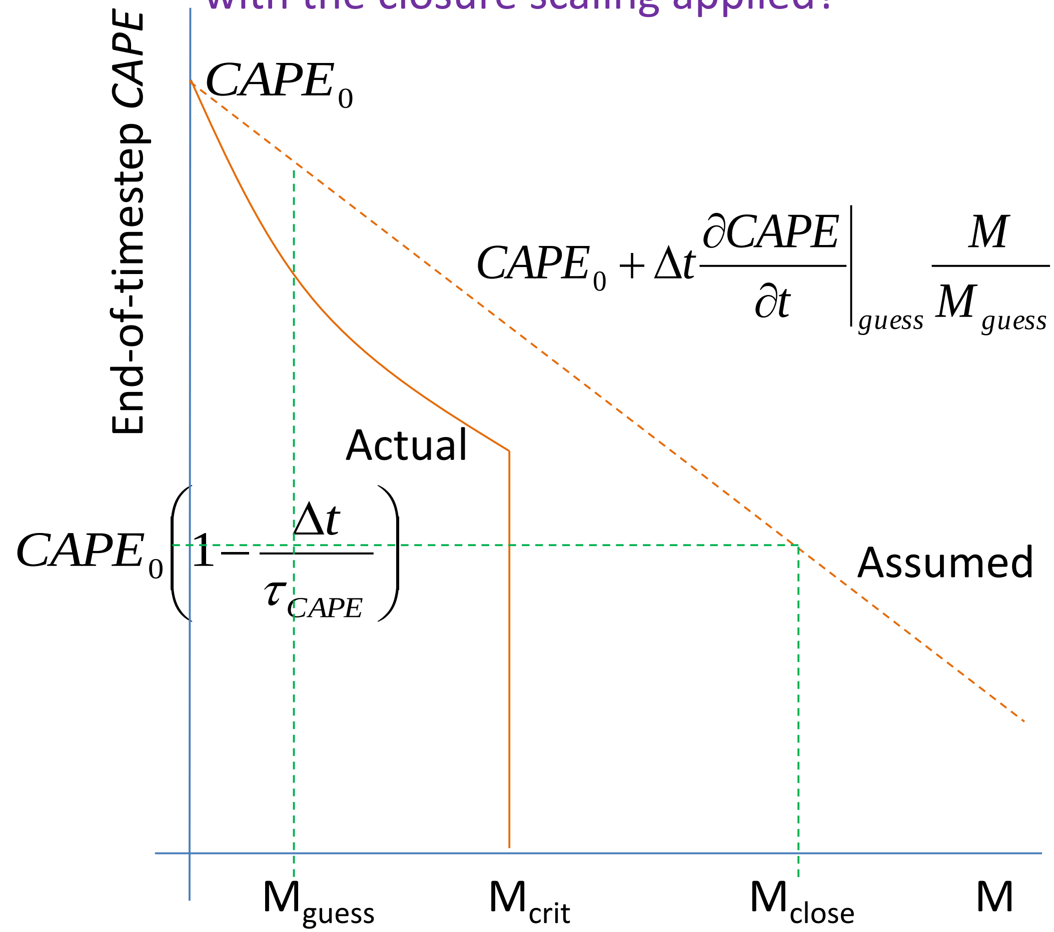

Final parcel-integrated CAPE highly non-linear function of mass-flux.

Often no solution yielding smooth reduction of CAPE over the timescale.

This closure is fundamentally ill-posed!

Problem with CAPE closure

Can't we just use a much longer CAPE timescale, so that we don't get into the "on-off" regime?

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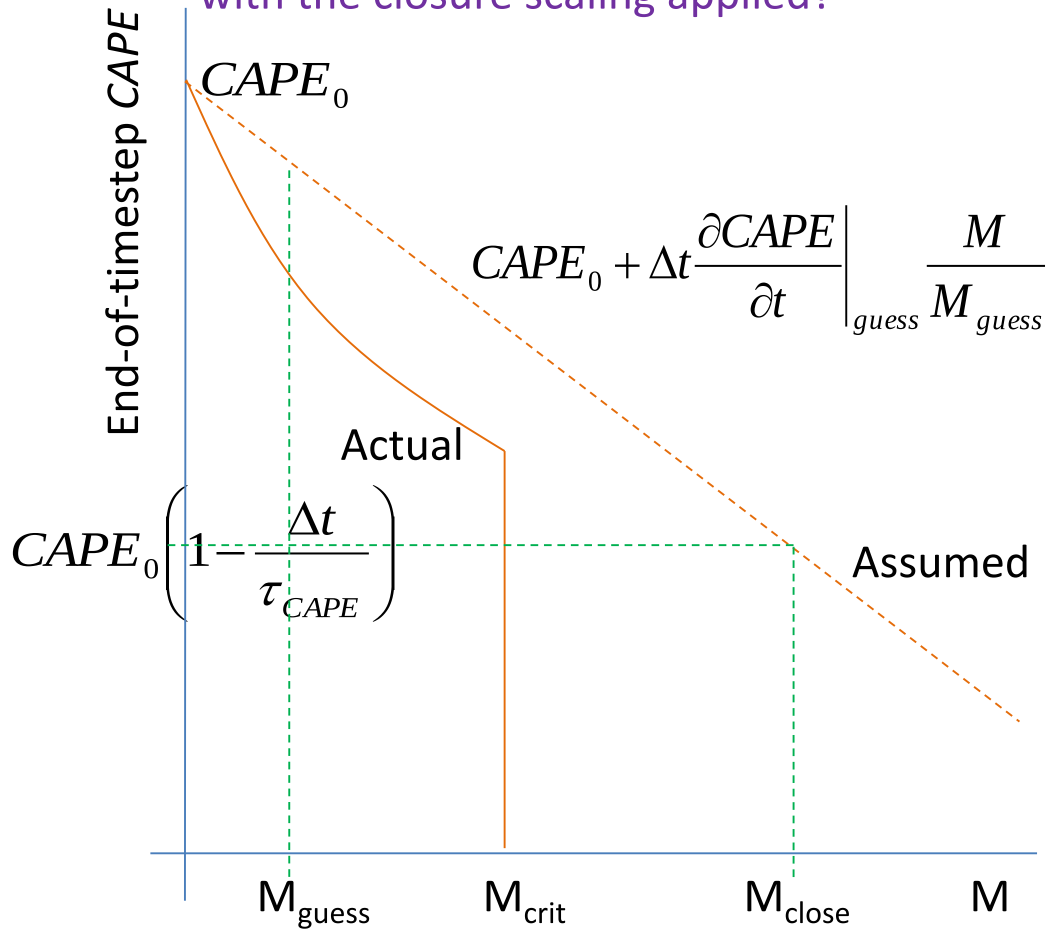

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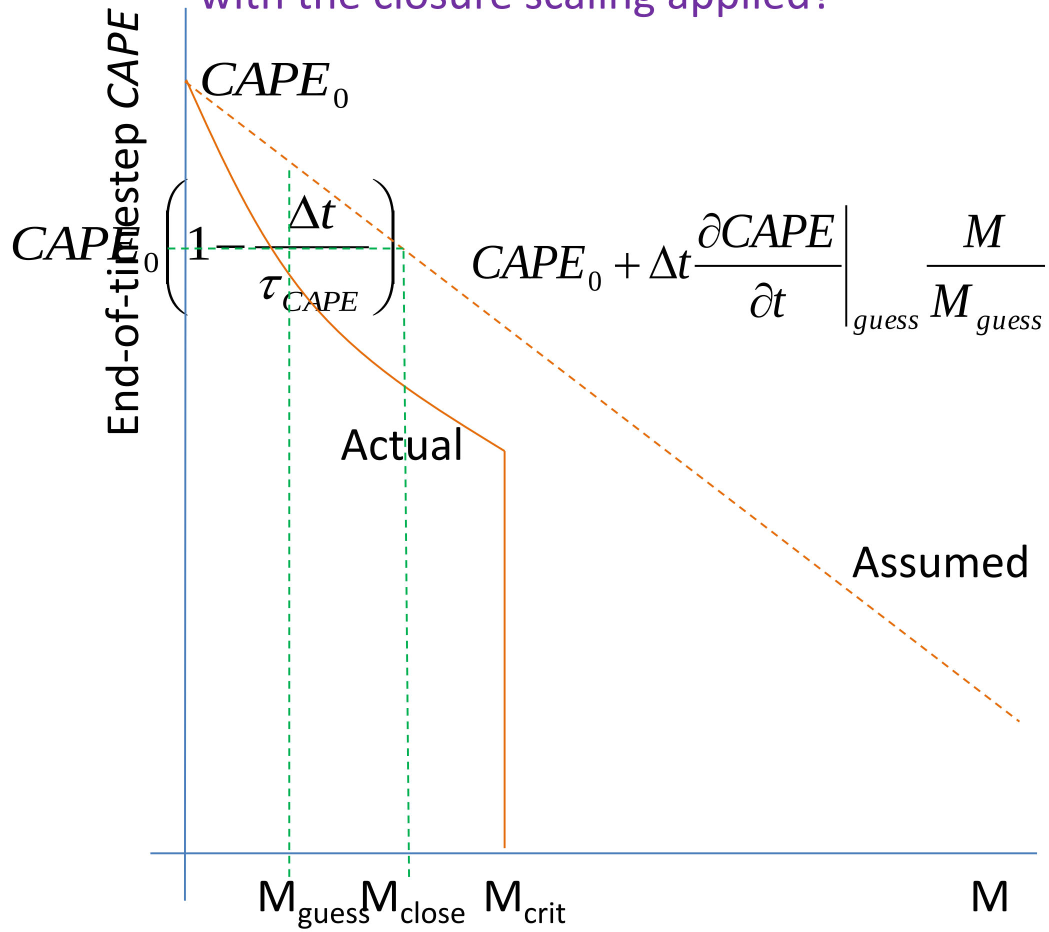

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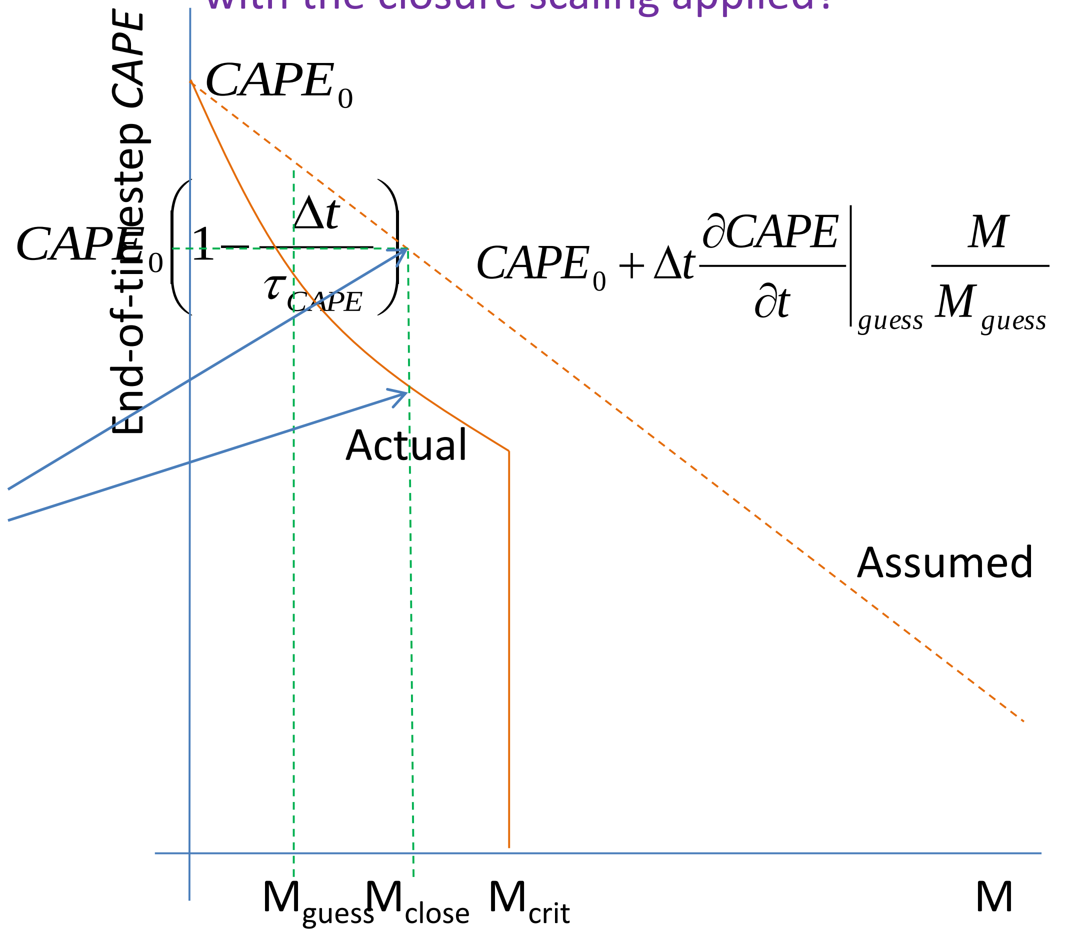

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Operationally, long CAPE timescales give poor performance. It is important that the convection scheme *can* give a strong response to a strong resolved-scale forcing, even when CAPE isn't that large

(otherwise, strongly forced systems such as Tropical cyclones spuriously dissipate!)

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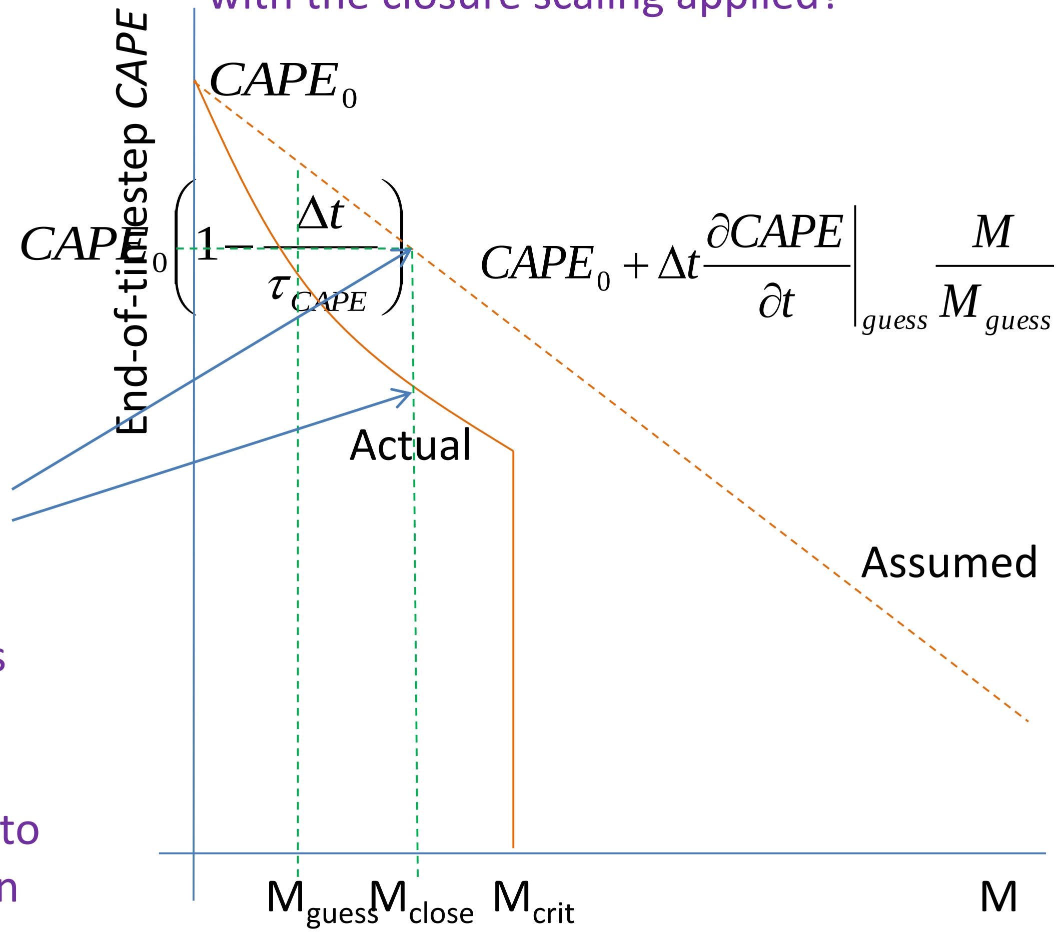

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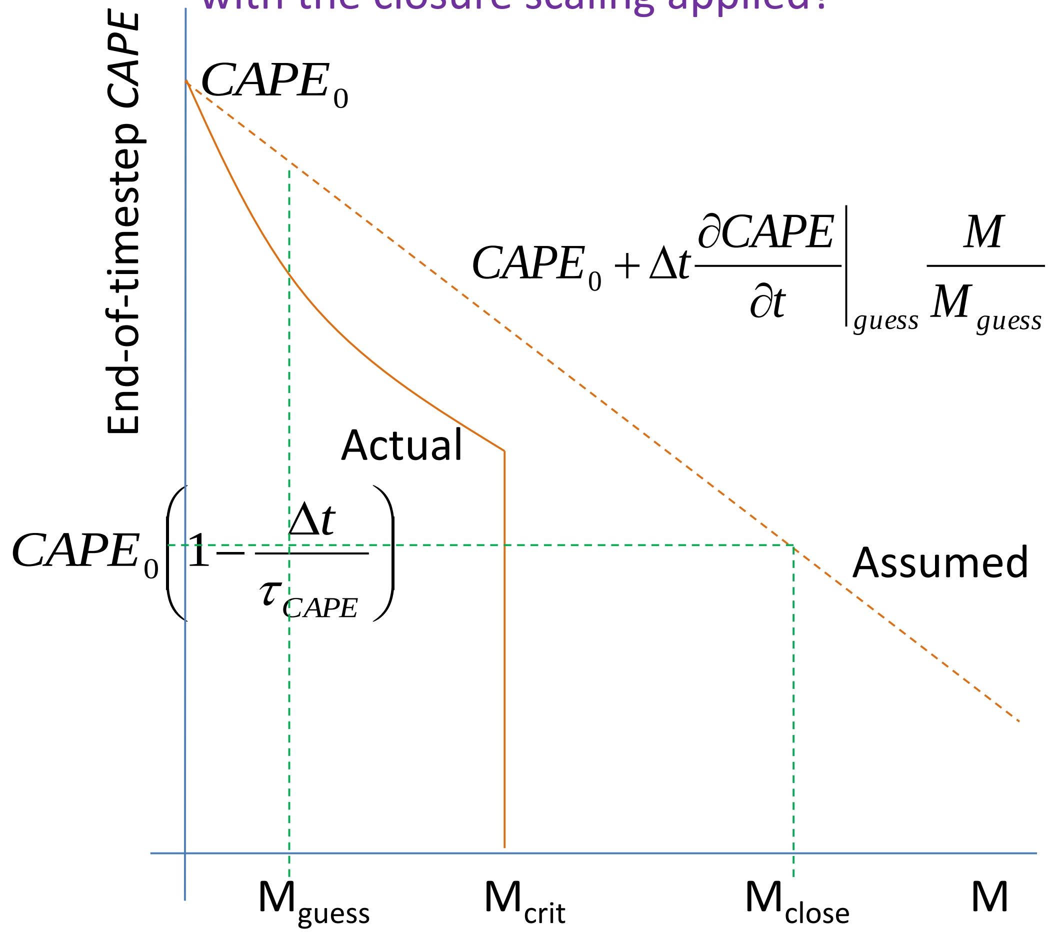

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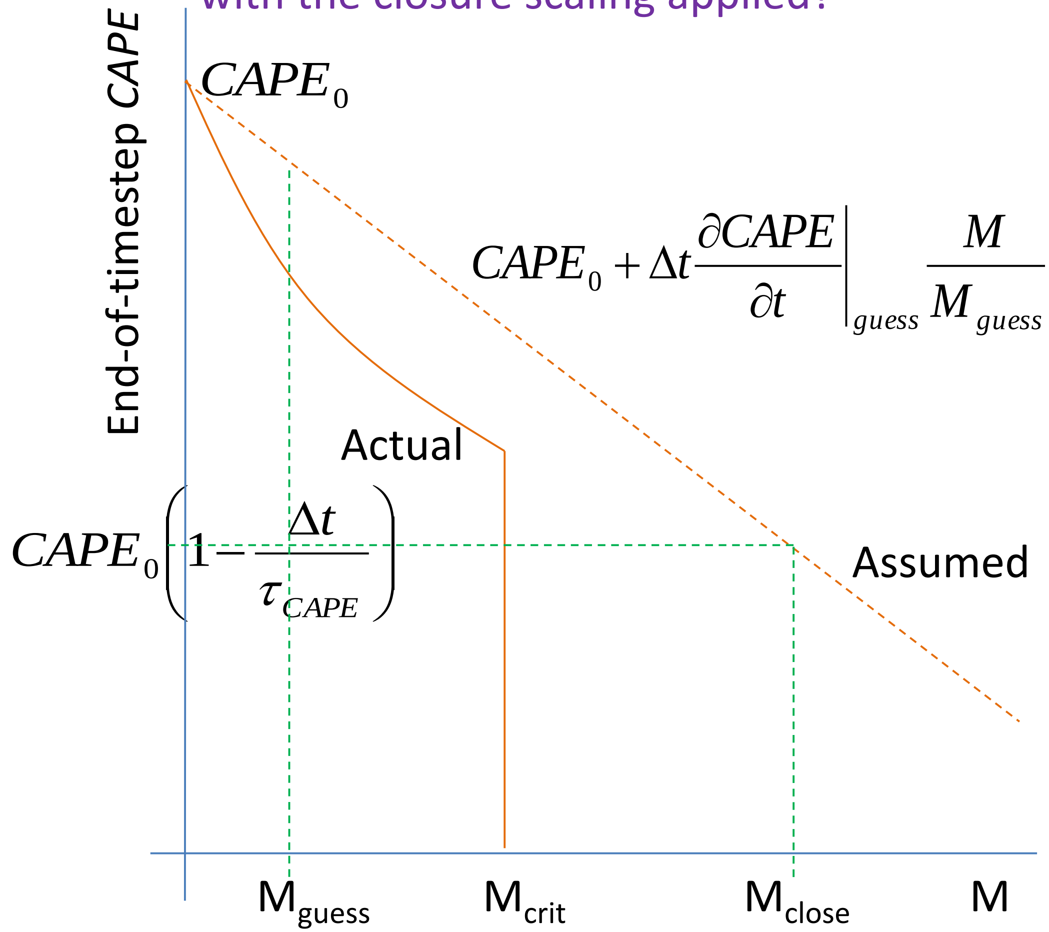

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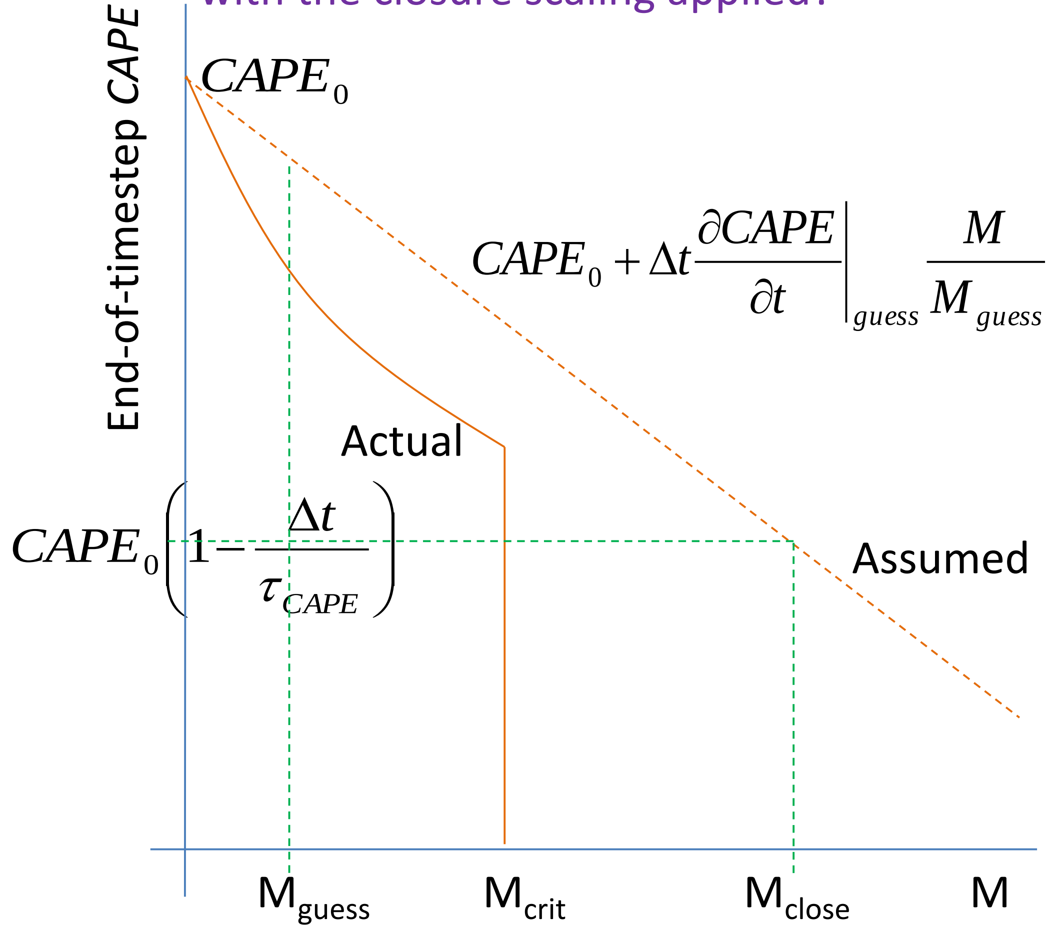

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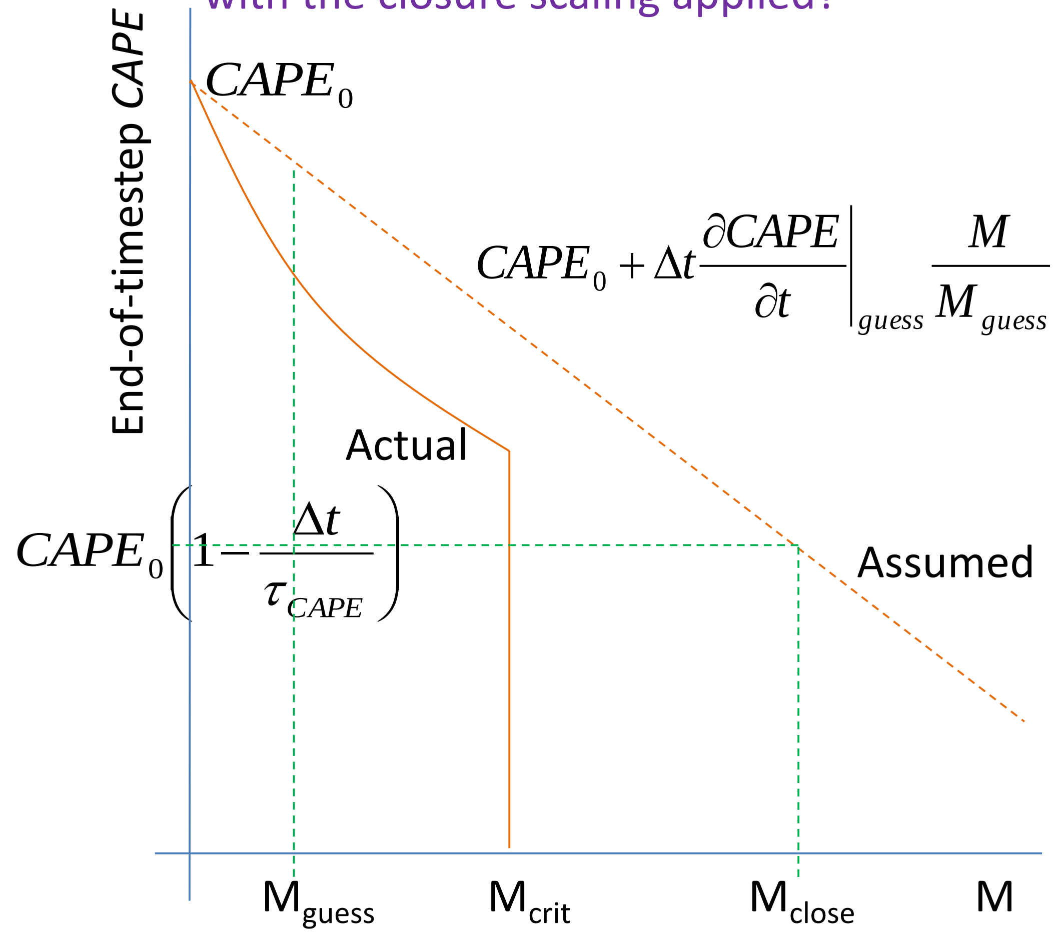

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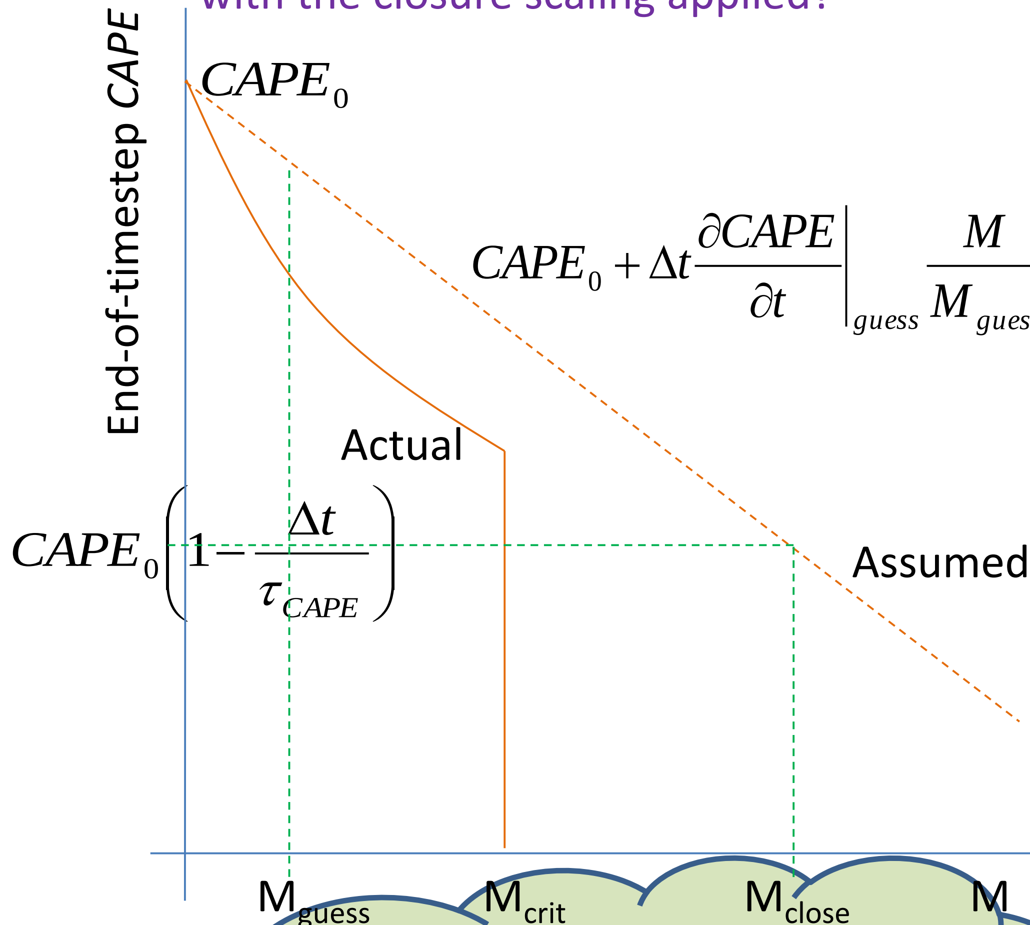

Now we're saying that, in order to make our *diagnostic equilibrium* CAPE closure work, we have to make the cloud model *prognostic*!

Does that make any sense?

Summary so far

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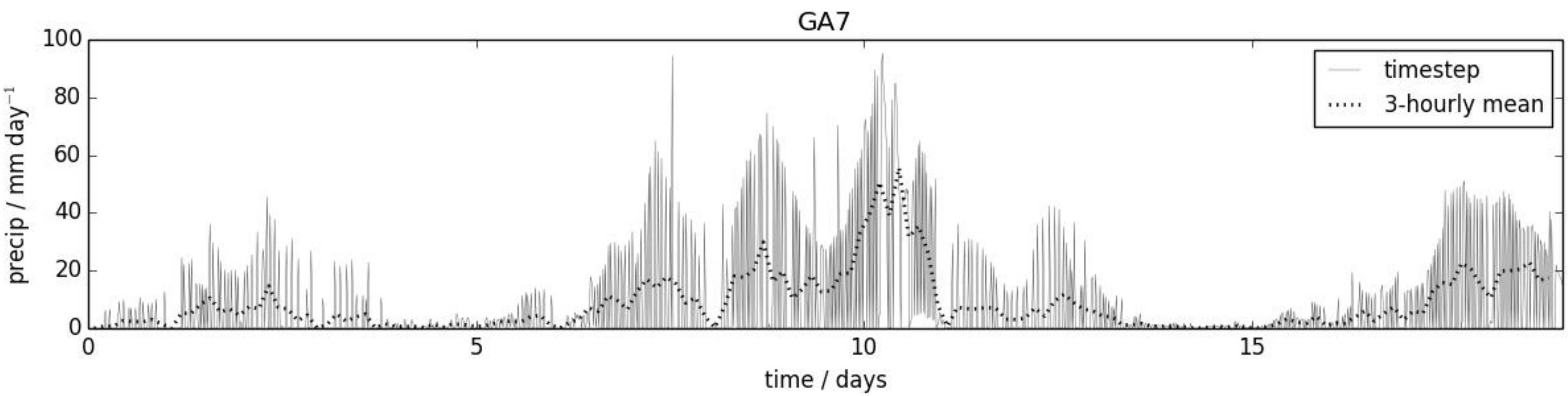

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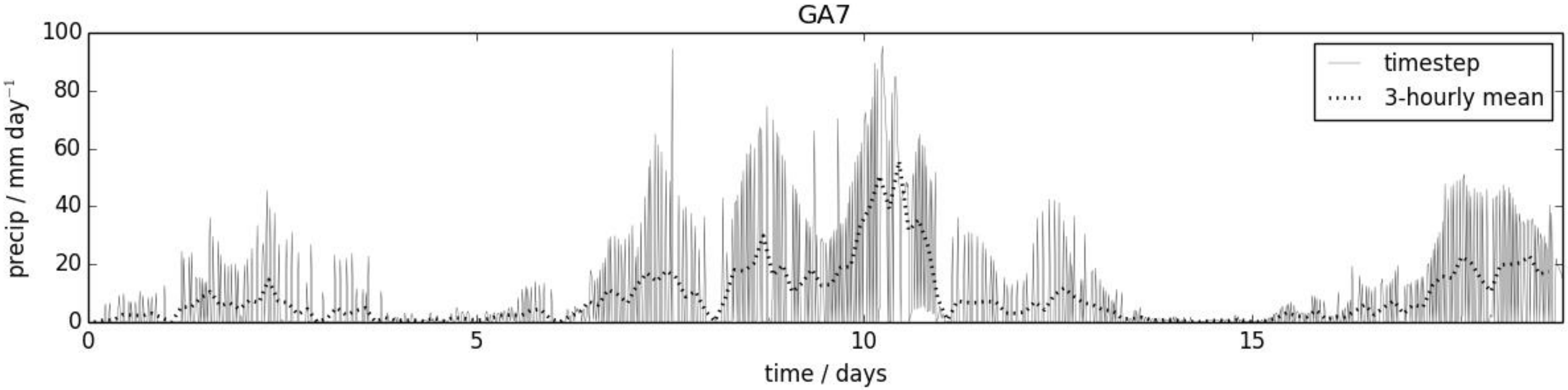

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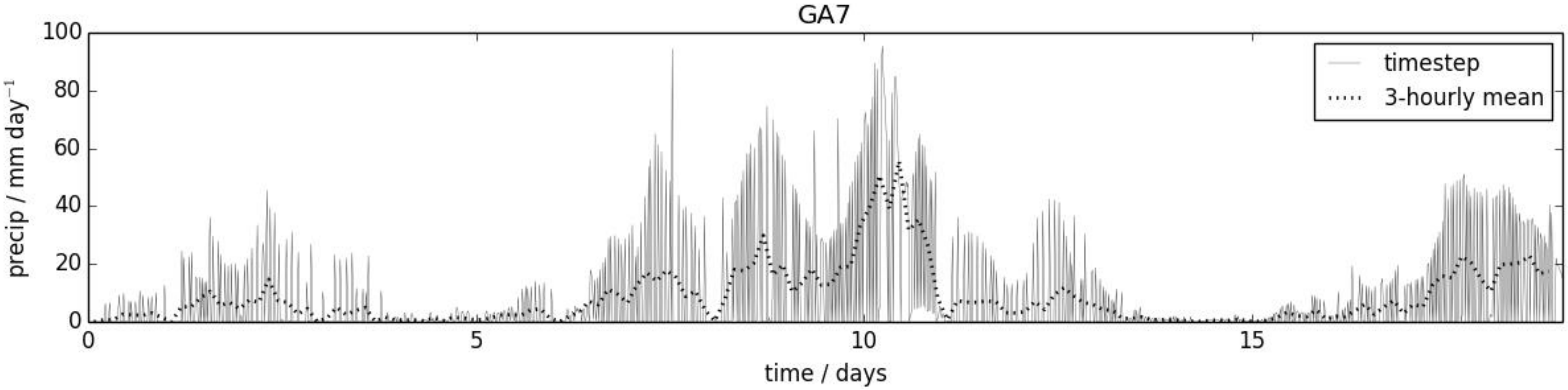

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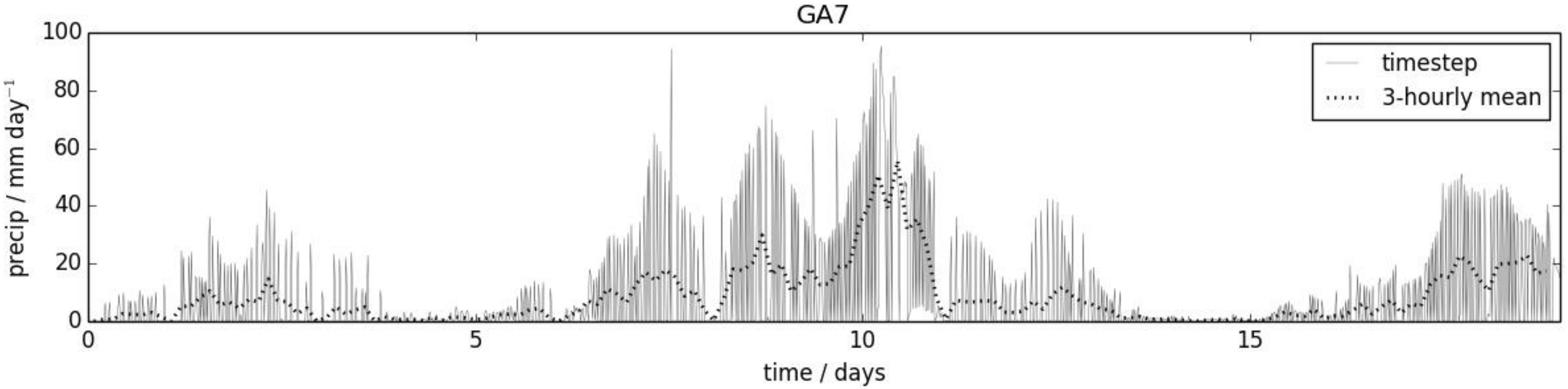

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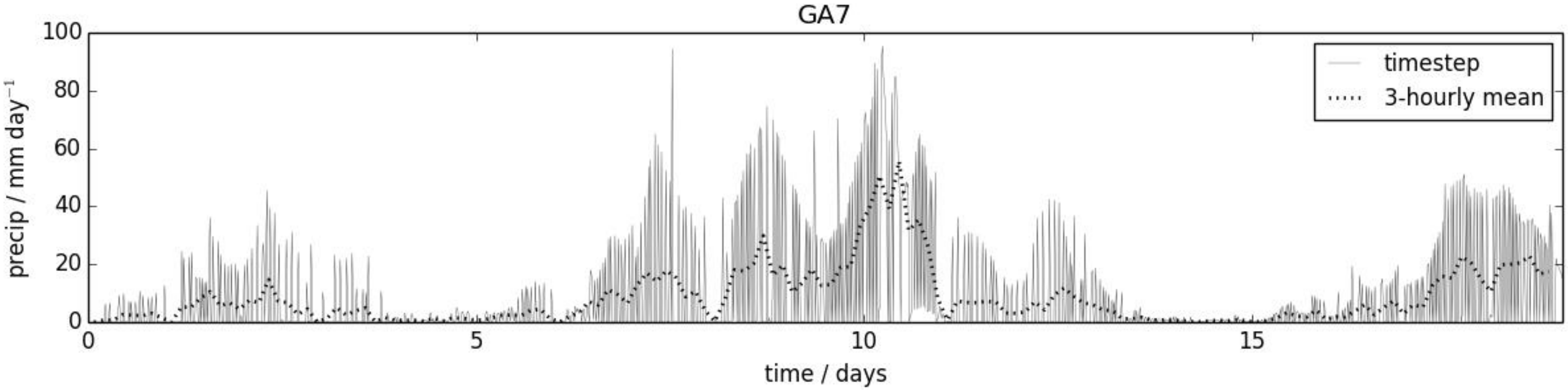

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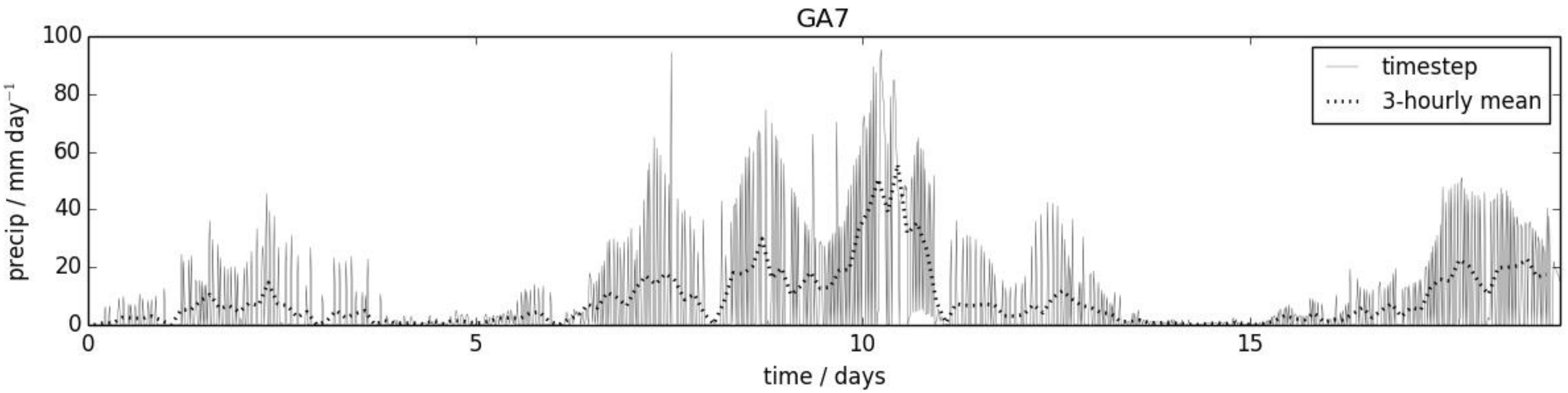

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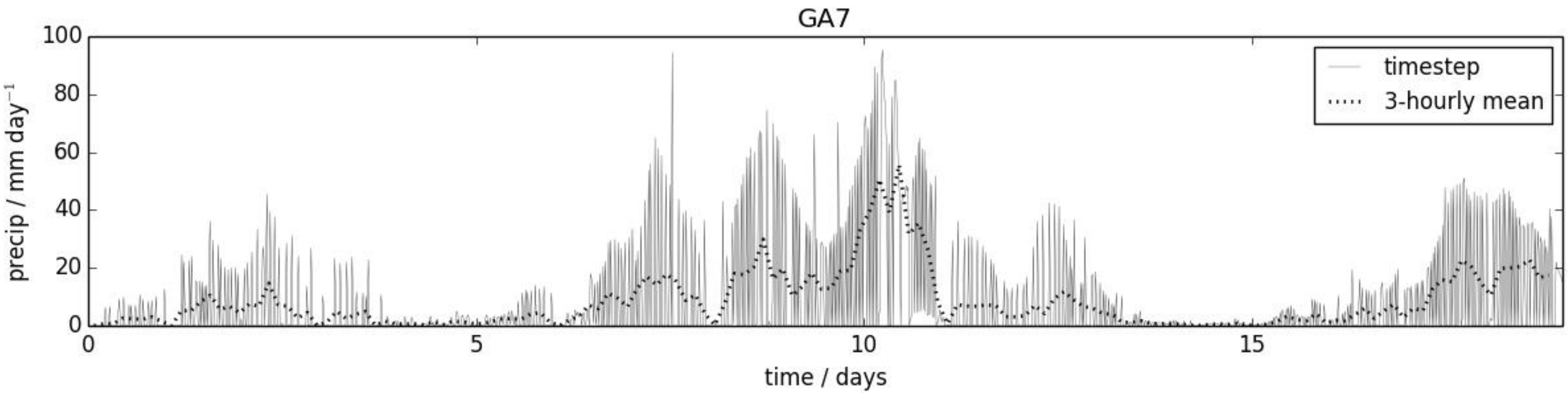
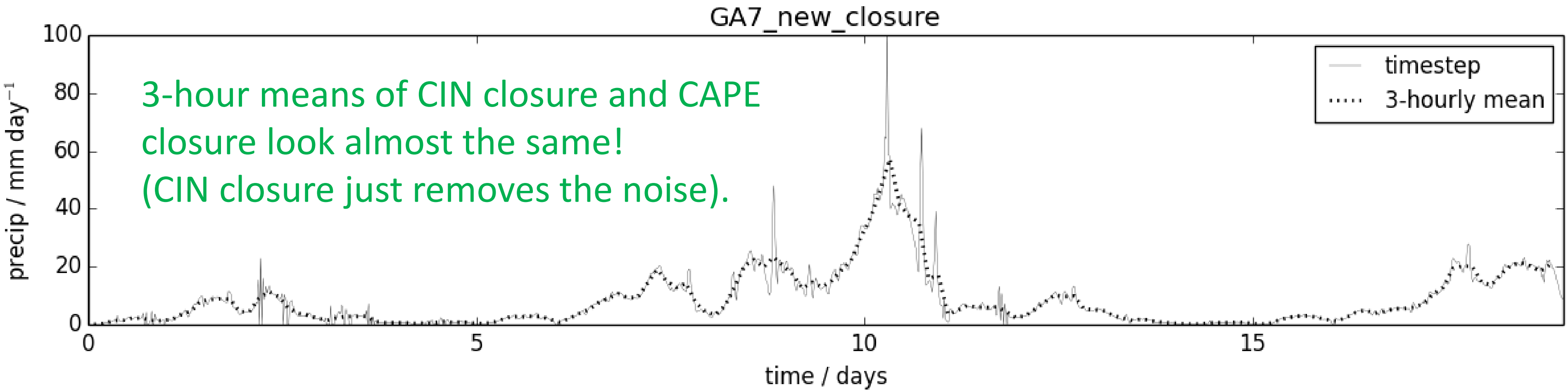
- Thinking of them as separate entities is what got us into this mess!

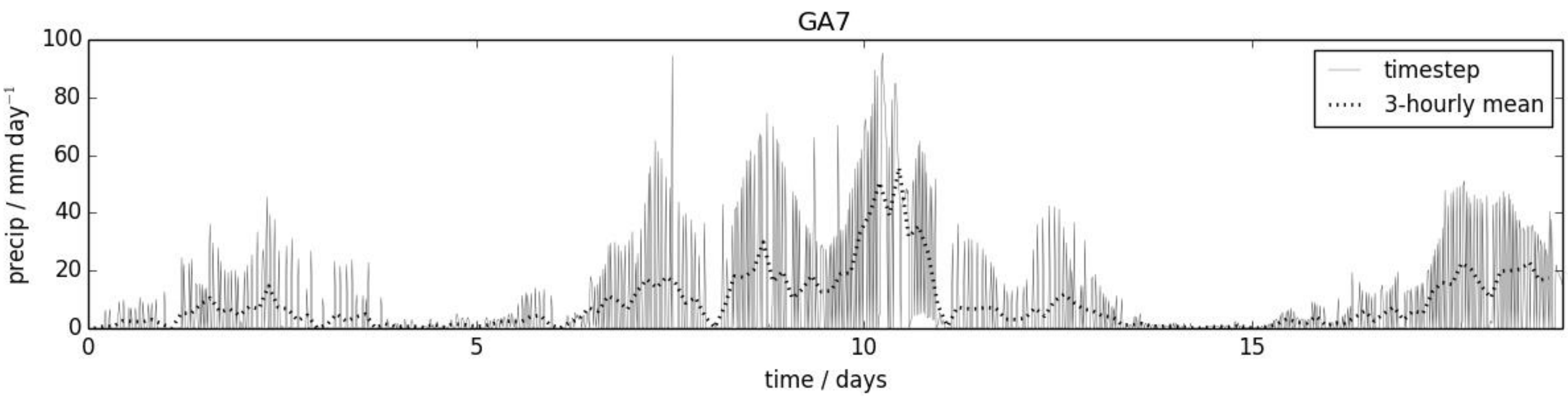


Summary so far

Experiment with CIN closure; just set mass-flux to largest value we can "get away with" without shutting off the convection on the next timestep (requires iteration):

3-hour means of CIN closure and CAPE closure look almost the same!
(CIN closure just removes the noise).





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Some wise words:

"If a scheme can't yield the right equilibrium behaviour, it doesn't stand a chance of behaving sensibly under non-equilibrium."

- Peter Clark

"Its hard to make music while listening to a pneumatic drill."

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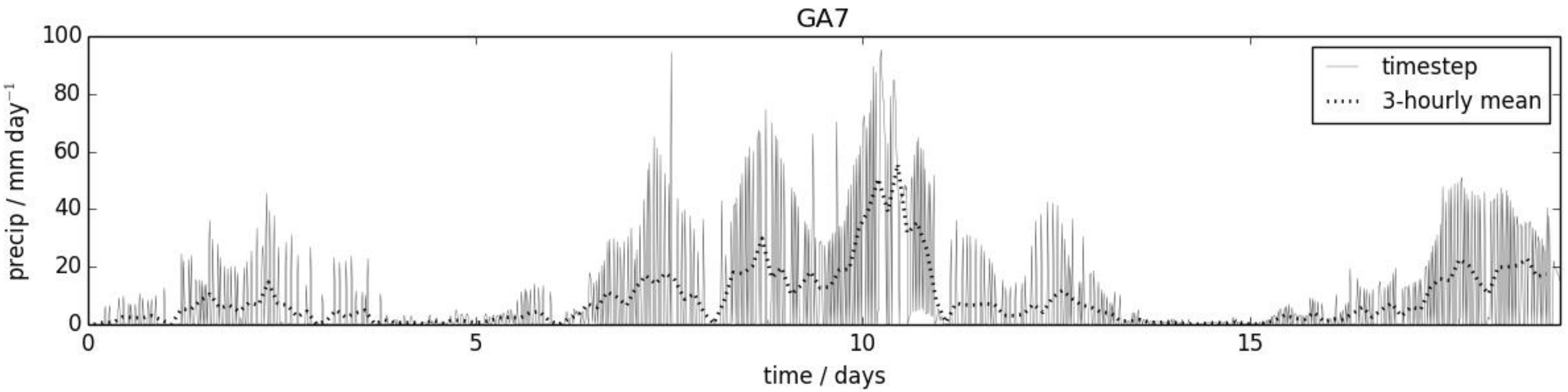

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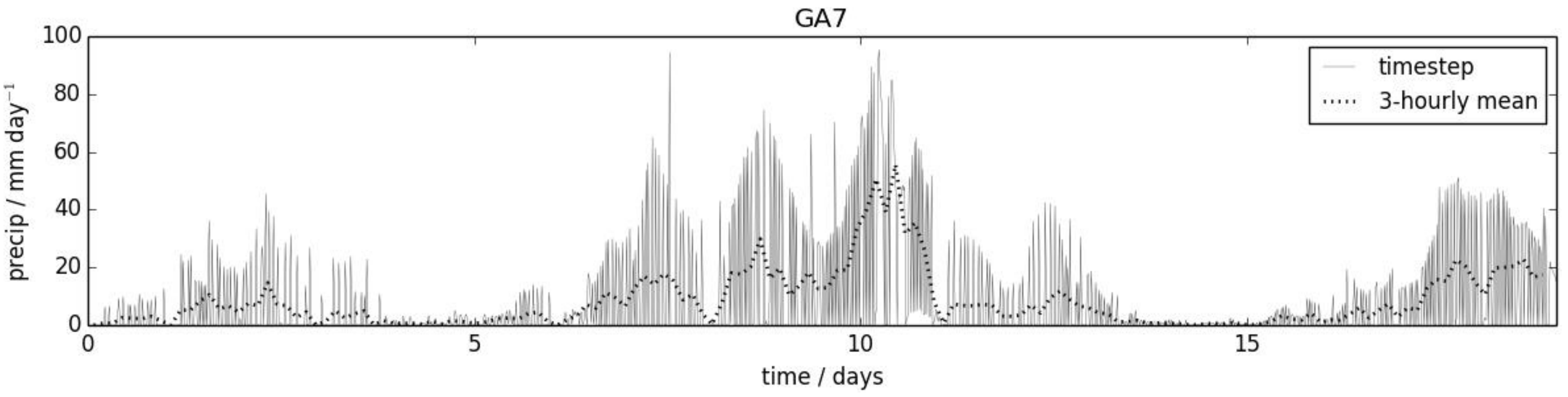
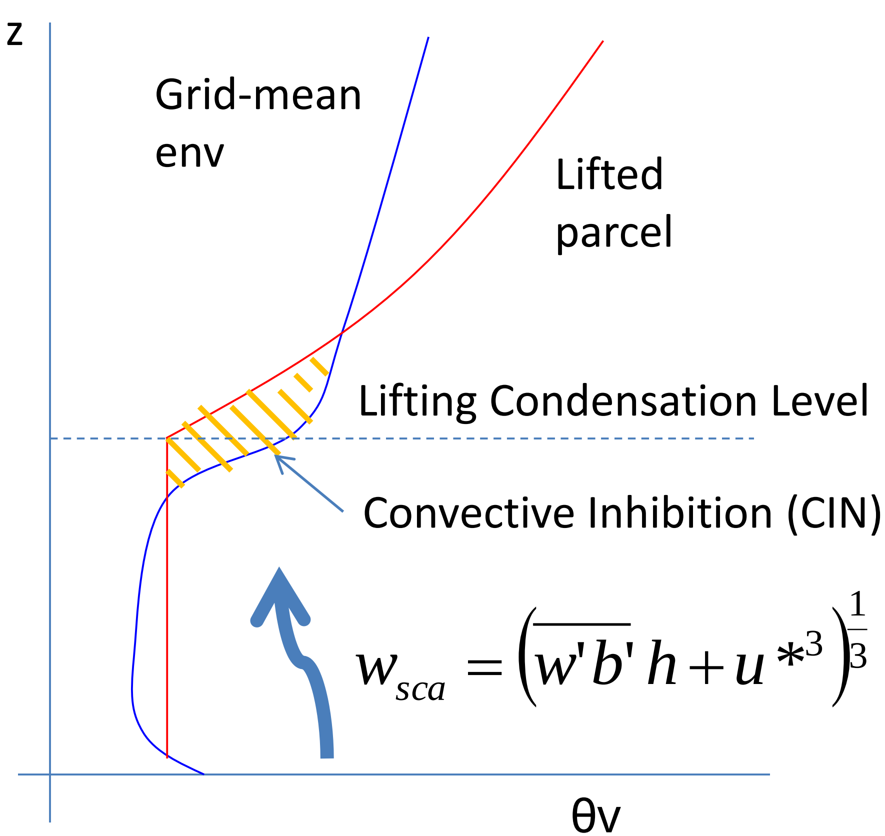
Need a rethink about how to effectively control the mass-flux, if we want to make it scale-aware and/or make variability more realistic.

Need to start from the triggering / cloud-model, not just the “closure”.



Convective Diagnosis

To meaningfully force the mass-flux, need to force the threshold for convection triggering (average mass-flux is controlled by the CIN-based diagnosis)....



$$w_{sca} = \left(\overline{w'b'}\,h + u*^{3}\right)^{\frac{1}{3}}$$

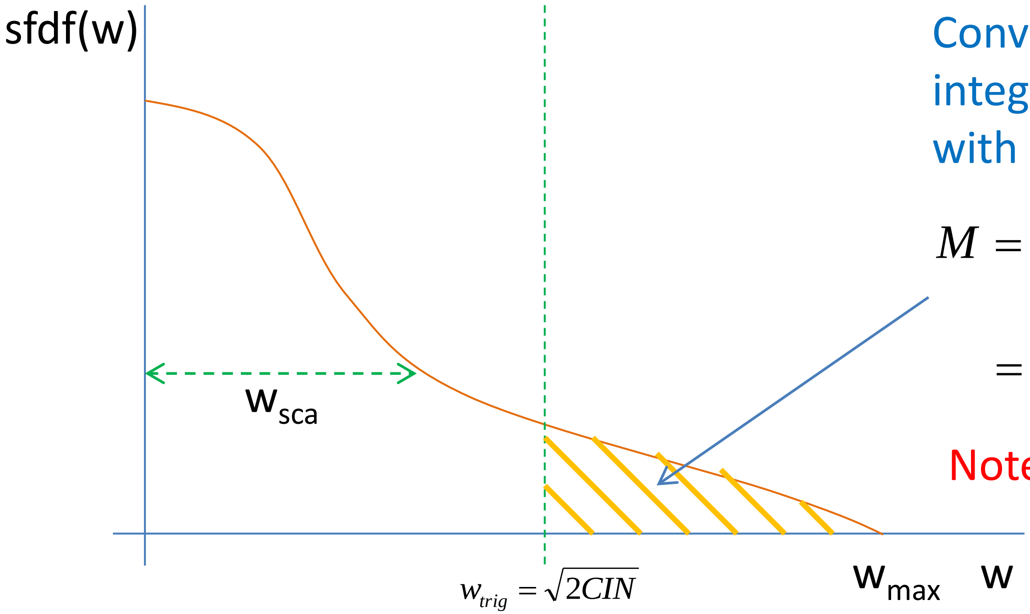
If KE < CIN, parcel top (where KE runs out) sets boundary-layer top height used to parameterise non-local turbulence.

If KE > CIN, parameterised non-local turbulence extends up to the LCL, with parameterised convection (shallow or deep) triggered from the LCL upwards.

Scale-awareness can be introduced by considering the sub-filter-scale distribution of w, and allowing the properties of that distribution to vary...

PDF-based triggering & closure framework

Assume some distribution of w inside the sub-filter-scale updrafts below cloud-base (which may or may not trigger convection out of the boundary-layer):



Convection base mass-flux is ρ * the integral over the part of the distribution with w large enough to overcome the CIN:

$$M = a_{ud}\rho \int_{w_{trig}}^{w_{max}} w\, sfdf(w)\, \mathrm{d}w$$

$$= a_{ud}\rho\ f\left(w_{max}, w_{sca}, w_{trig}(CIN)\right) \quad (1)$$

Note: if $w_{max} <= w_{trig}$ then M = f = 0

Assume a functional form for the distribution, such that it can be described by 3 parameters:

- its maximum w_{max}
- a shape parameter w_{sca}
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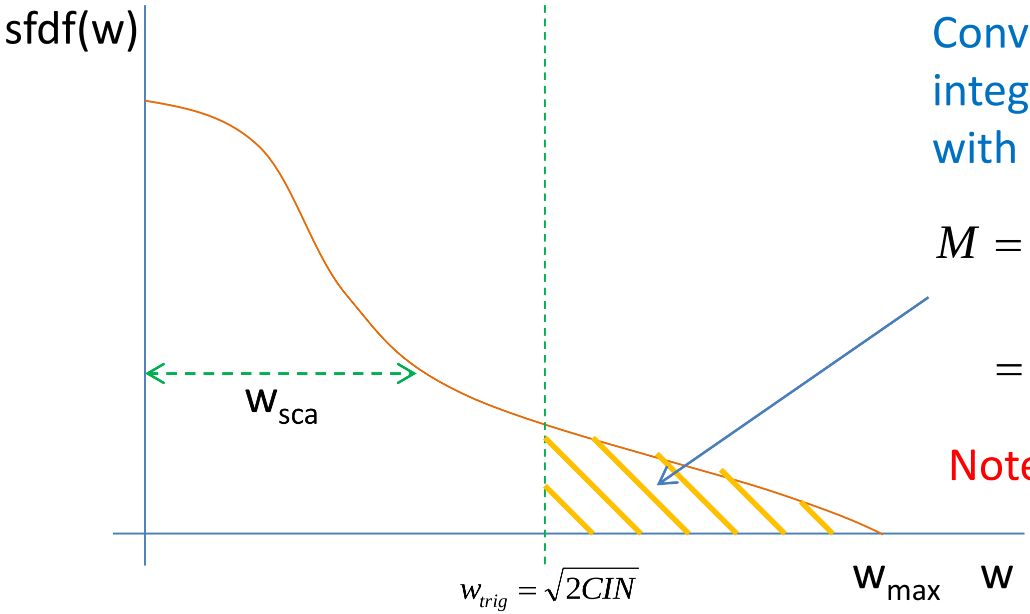

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c.f. Validation of this type of closure by
Fletcher & Bretherton (2010):
Evaluating Boundary Layer–Based Mass Flux Closures Using Cloud-Resolving Model Simulations of Deep Convection. *JAS.* **67**, 2212.

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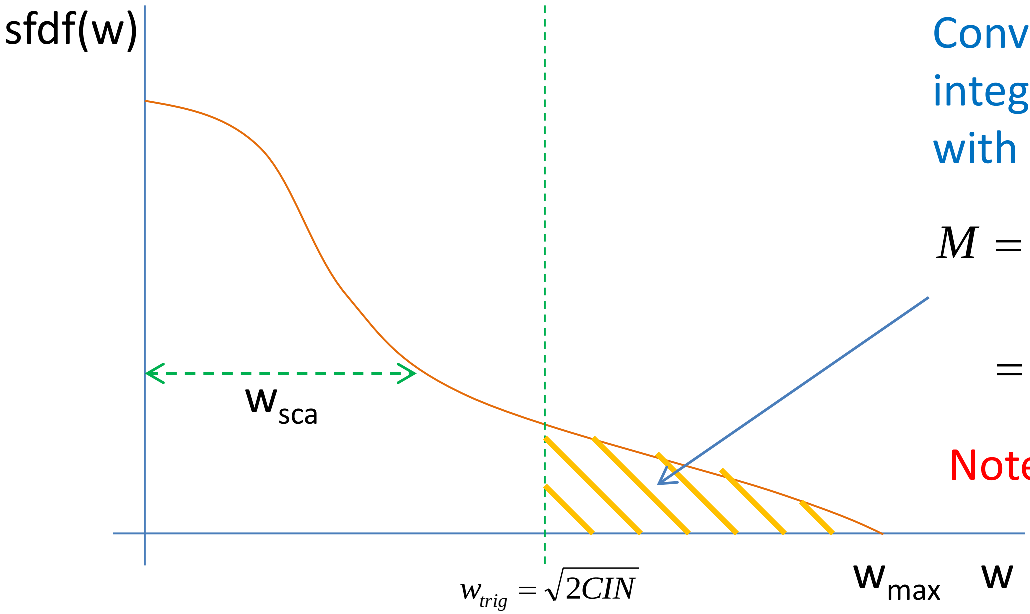

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For a numerically robust solution, this closure needs to be solved implicitly w.r.t. CIN (convection and other forcings adjust the CIN on timescales << Δt).

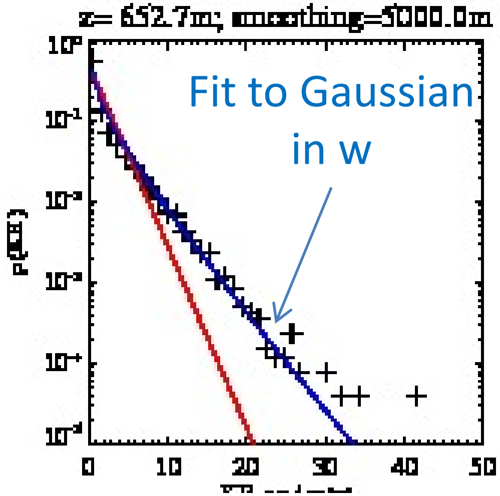
A scale-aware, stochastic approach to the triggering and closure can be found by considering the sampling distributions of the sub-filter distribution properties

w_{sca}, w_{max}, a_{ud} …

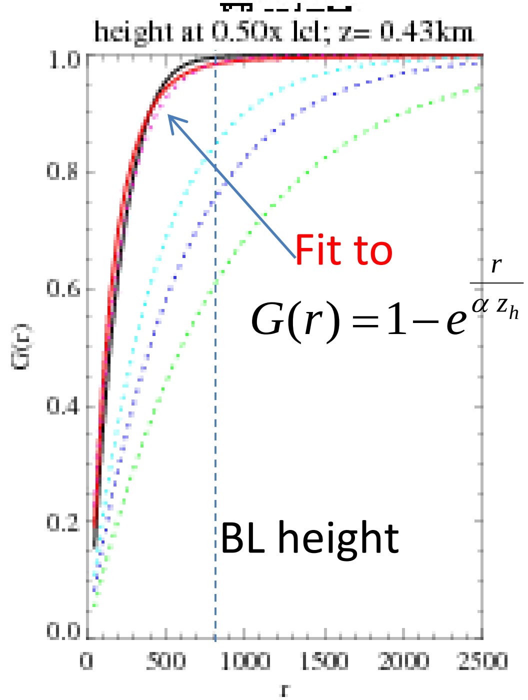
Use LES to construct statistical model for sub-filter-scale w distribution

Alison Stirling: LES of onset of deep convection, at 25m resolution.

PDF of BL updraft KE:



Apply Gaussian filter to estimate fraction of TKE G(r) below the filter-scale r.



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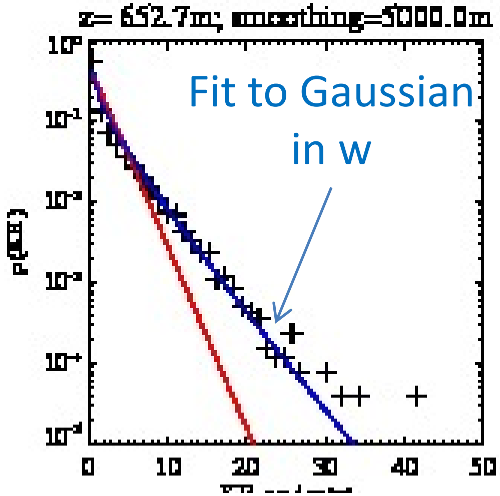

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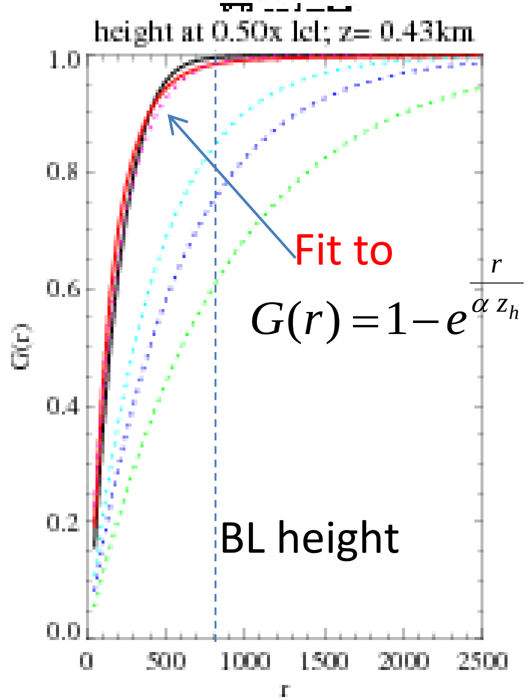

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$$w_{sca} = \left(\overline{w'b'}\, z_h + u*^3\right)^{\frac{1}{3}} \qquad L = \alpha\, z_h \qquad \tau = \frac{L}{w_{sca}}$$

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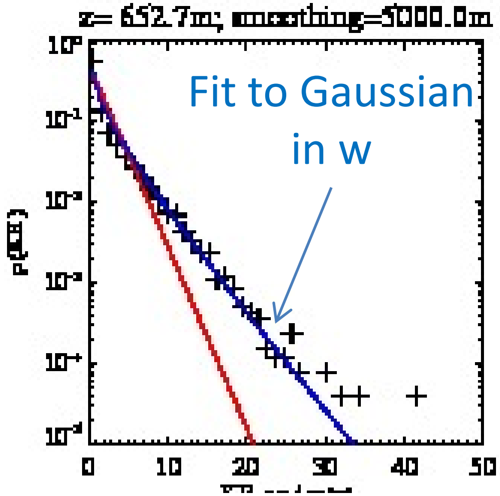

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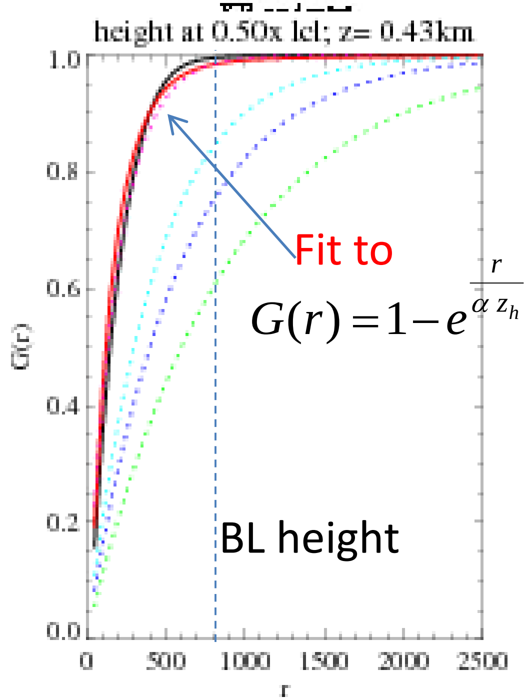

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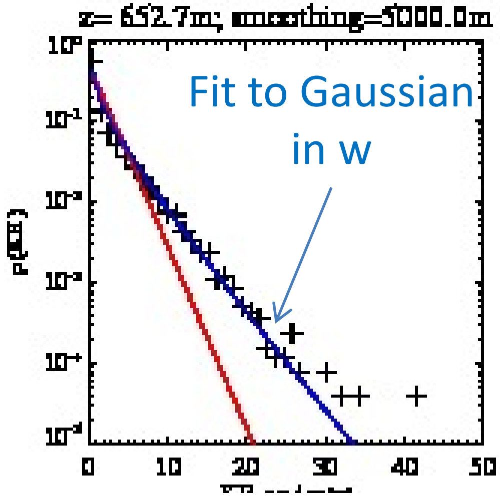

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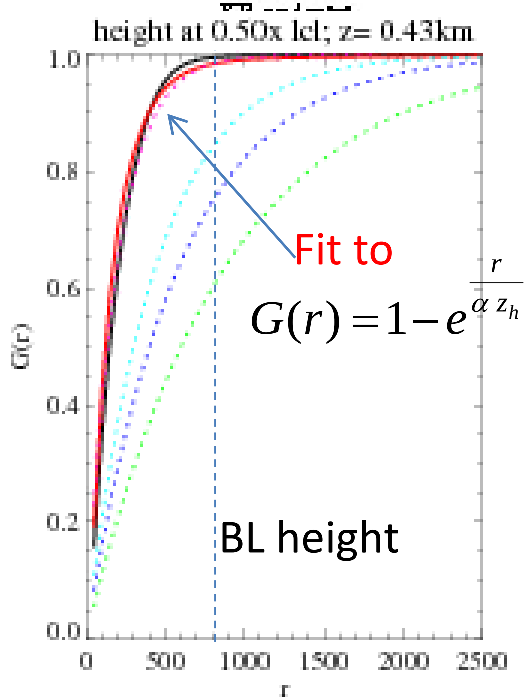

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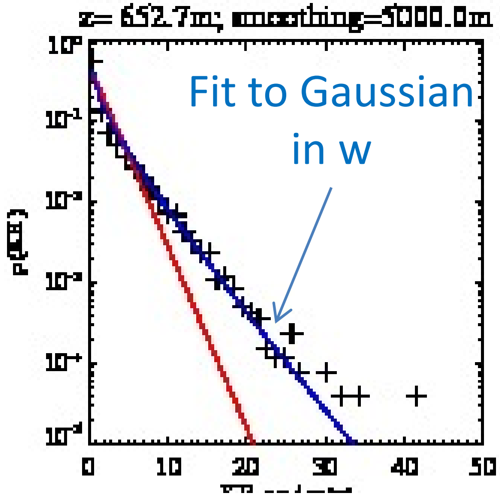

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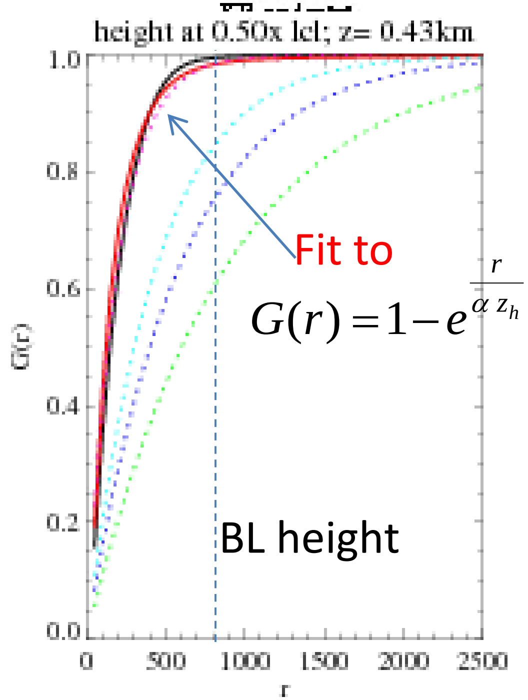

$$G(r) = 1 - e^{\frac{r}{\alpha z_h}}$$

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$$a_{ud} \approx \frac{1}{2}\frac{n_{Po}}{n_{eqm}}$$

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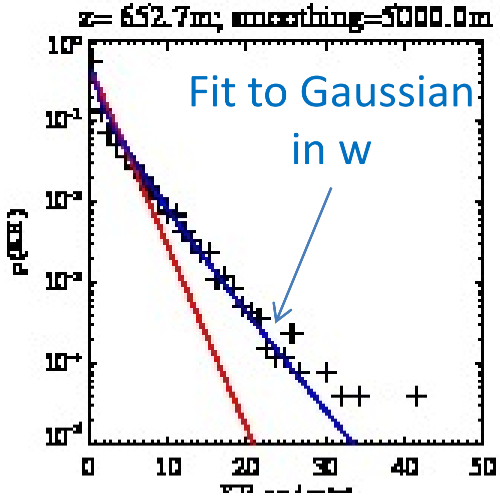

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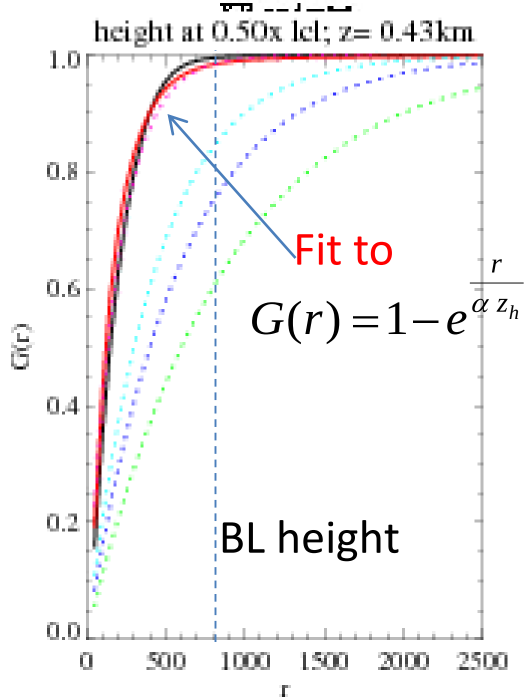

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Estimate sampling distributions for w_{sca}, w_{max} using updraft number, and stochastically sample these...

Scale-aware, stochastically-varying sub-filter-scale distribution

$$M = a_{ud}\rho \int_{w_{trig}}^{w_{max}} w \, sfdf(w) \, \mathrm{d}w$$

Fine grid-resolution

Few BL updrafts per grid-cell

Many grid-cells don't trigger

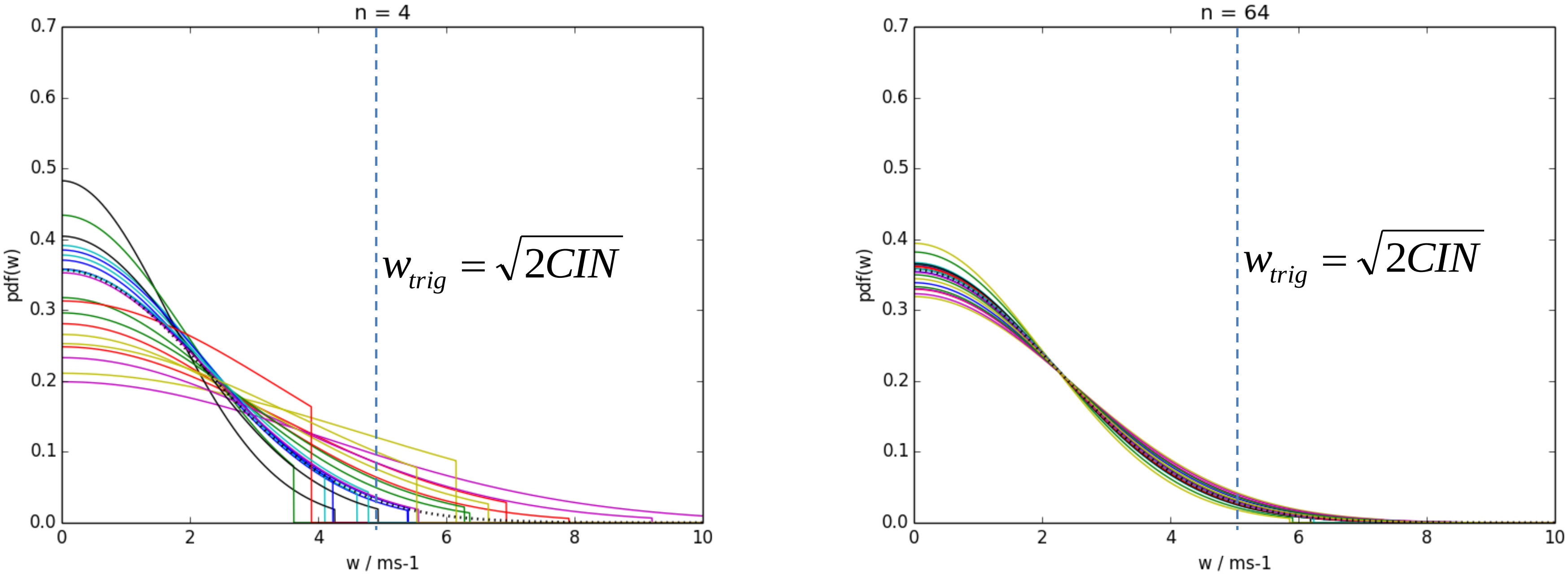
Large mass-flux in a few grid-cells

Coarse grid-resolution

Many BL updrafts per grid-cell

All grid-cells trigger

Small mass-flux in each grid-cell



In practice, most of the scale-awareness comes from the sampling distribution for w_{max};

A larger number of BL updrafts per filter-scale area increases the probability of having one or two exceptionally intense updrafts, which trigger convection.

Note: in the scheme, the random sampling is autocorrelated in time and space...

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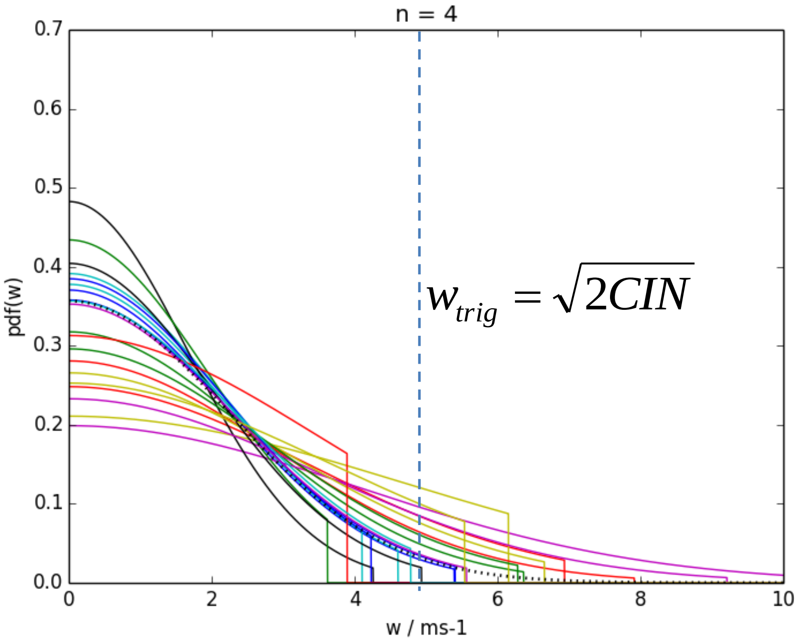
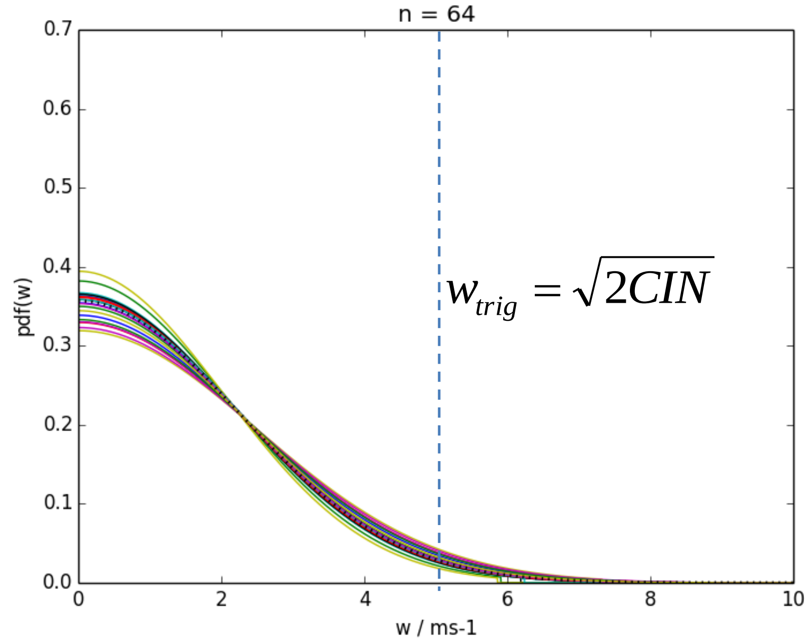
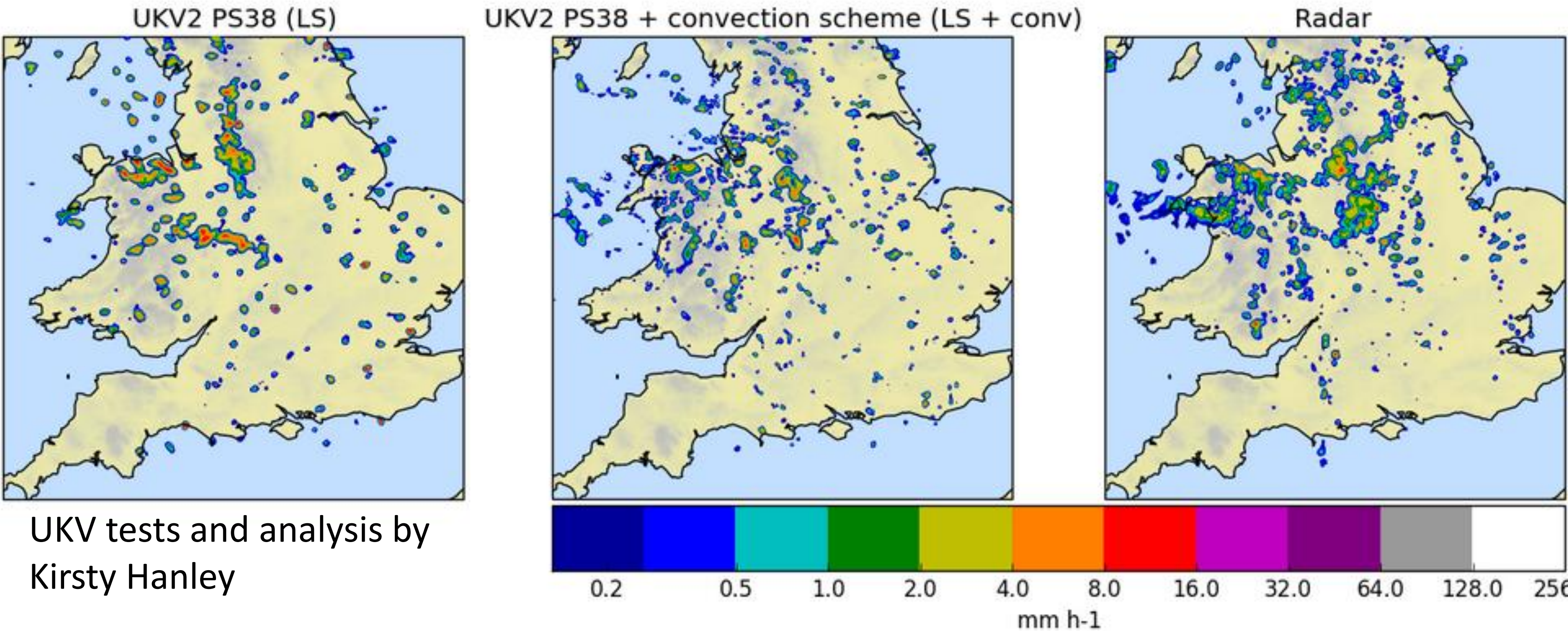




Entrainment rate: depends on 1/L

L is sub-filter-scale updraft horizontal size; adapts with resolution (smaller Δx means any updrafts which are sub-filter-scale must be smaller, so have higher entrainment rates).

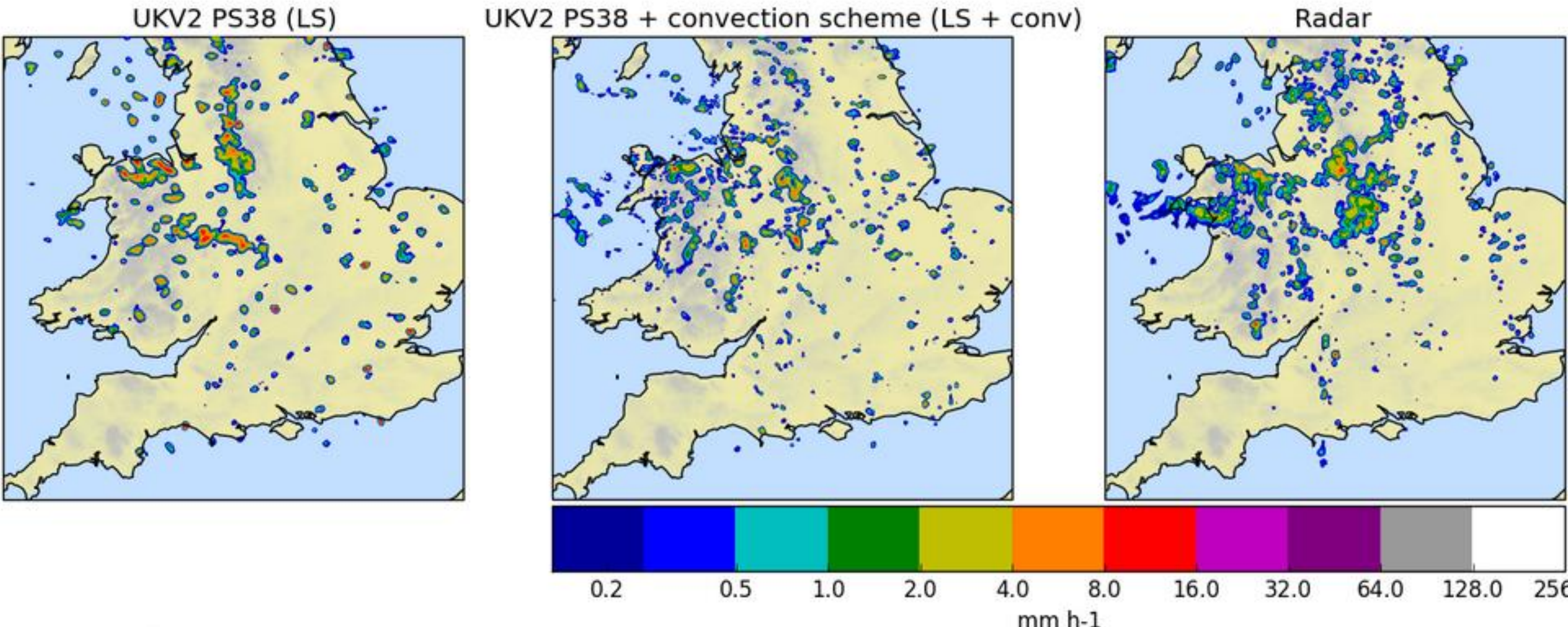
Also use ad-hoc "convective memory" to modulate entrainment and w-distribution properties as a function of recent convective precipitation.

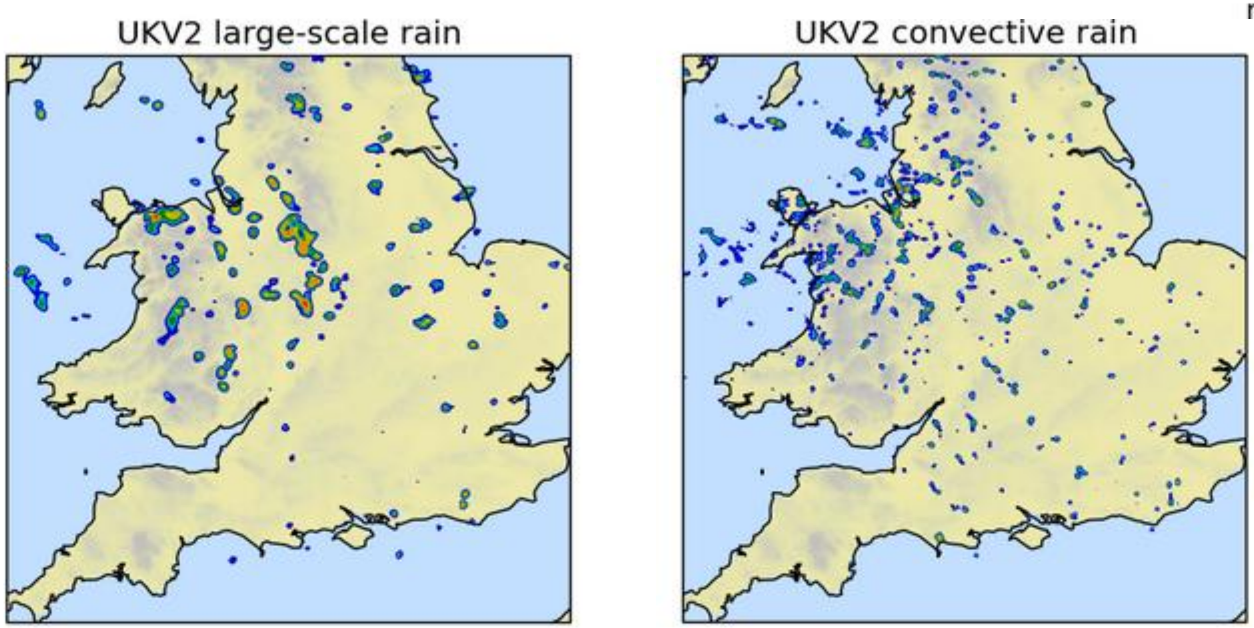


UKV tests and analysis by Kirsty Hanley

UKV 1.5 km forecast

Improved representation of sporadic small showers / lighter rain-rates from parameterised convection.





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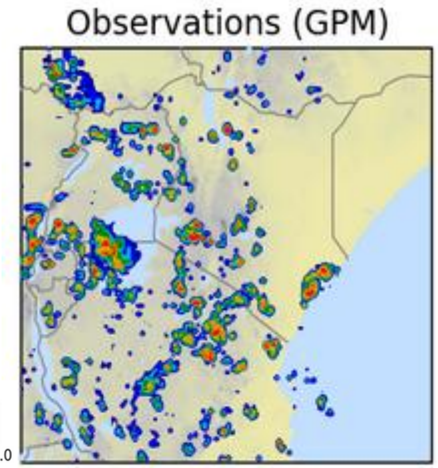
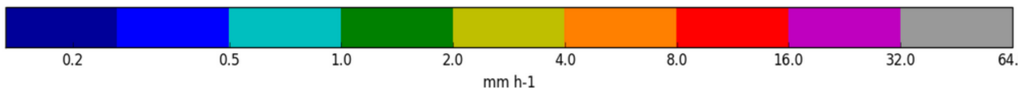
Improved representation of sporadic small showers / lighter rain-rates from parameterised convection.

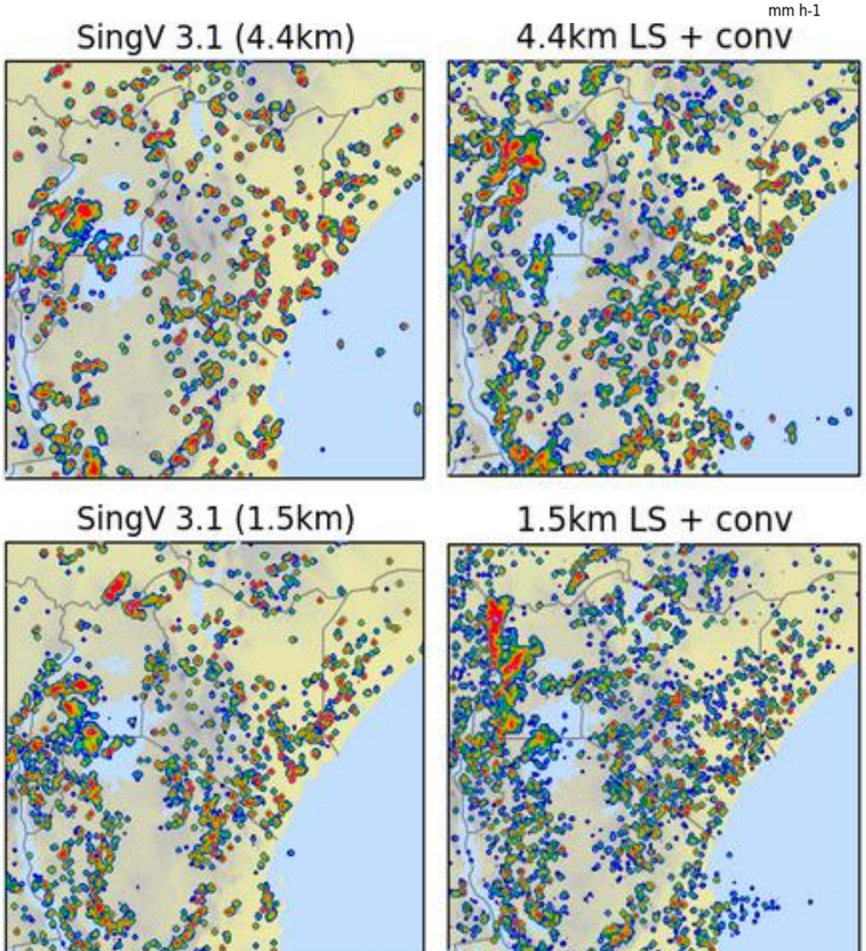
Larger, heavier showers still resolved.

E Africa convection-permitting model.

Model has too many small showers, and stochastic convection makes this worse...







E Africa model tests and analysis by Kirsty Hanley

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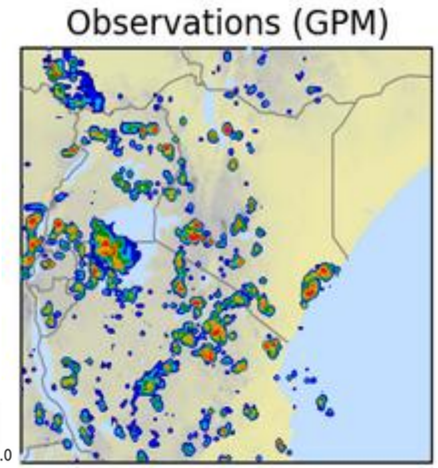

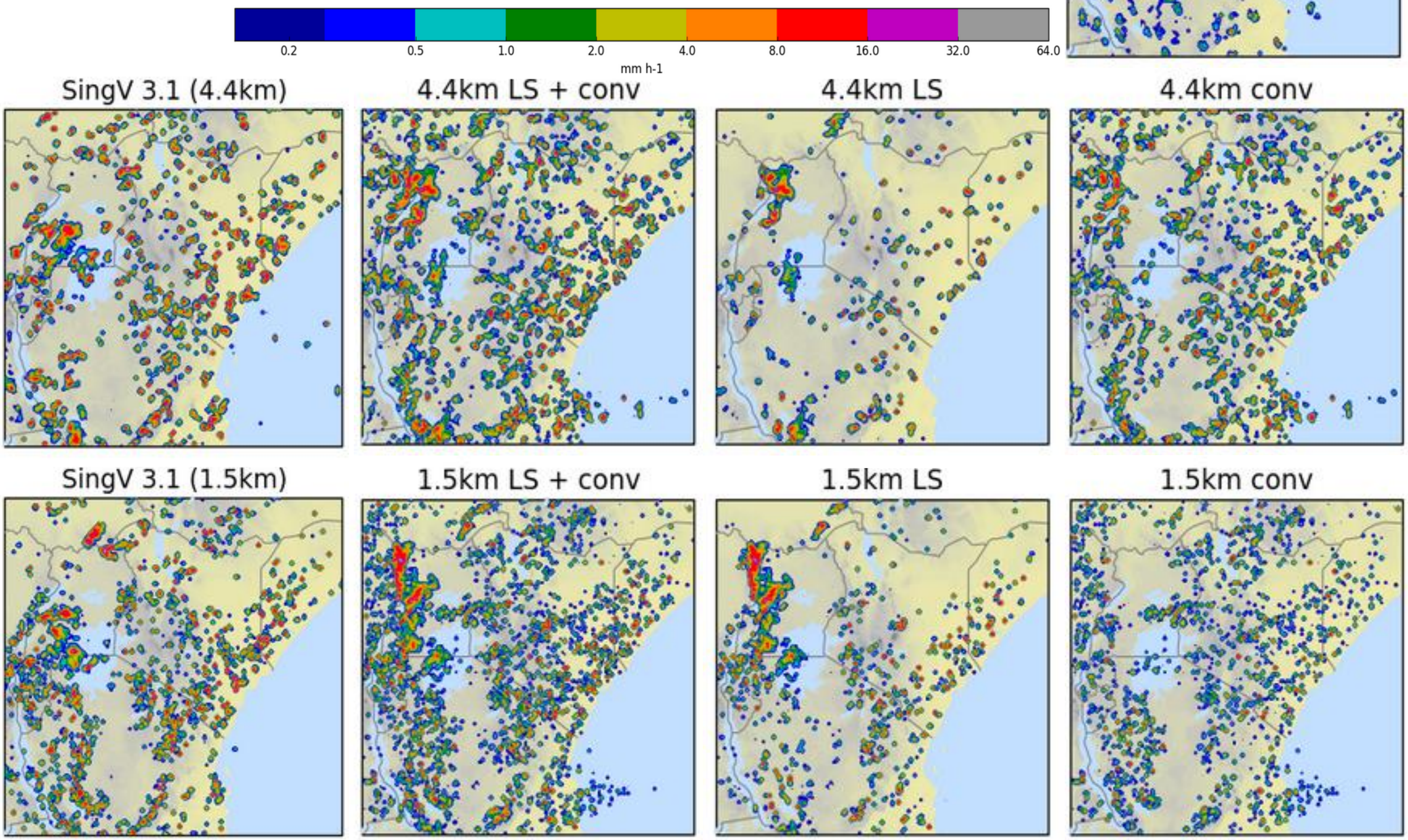

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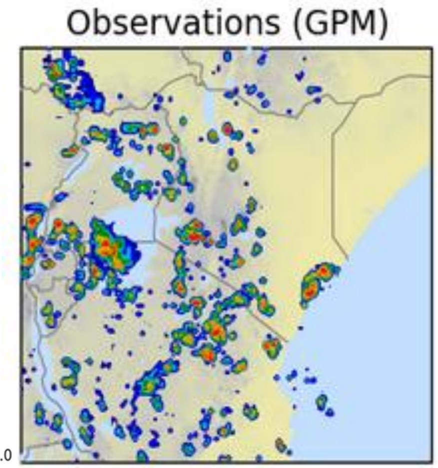
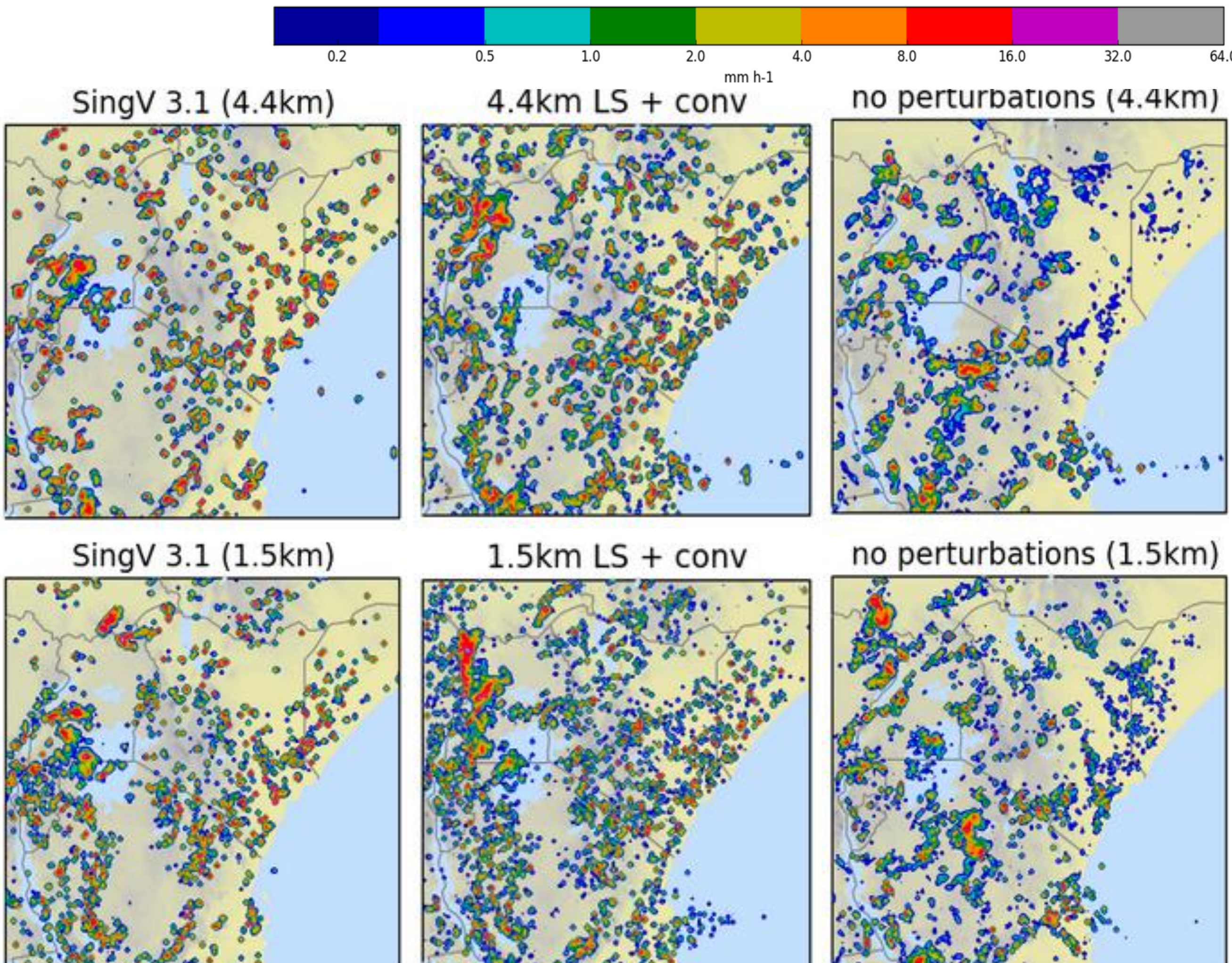
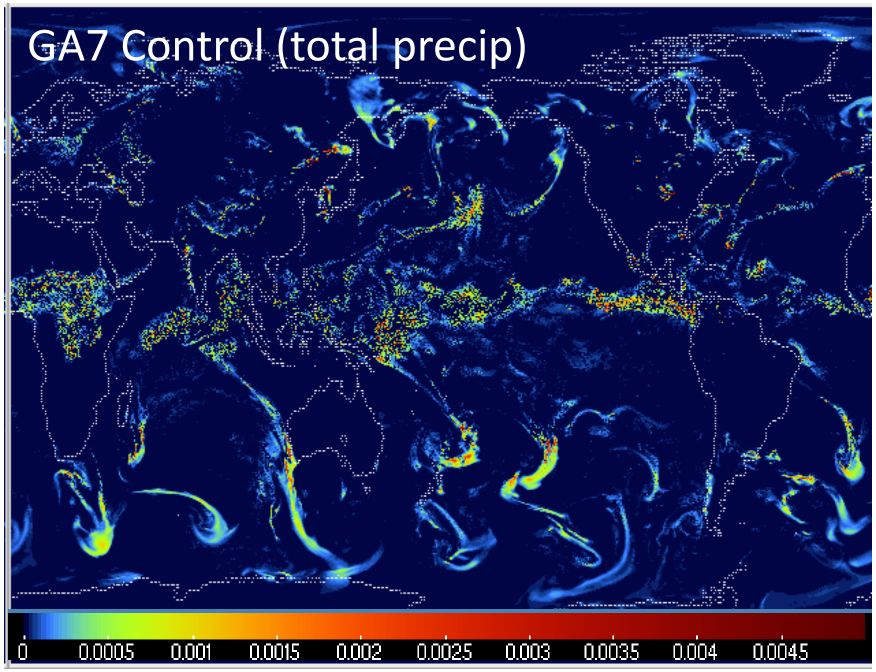
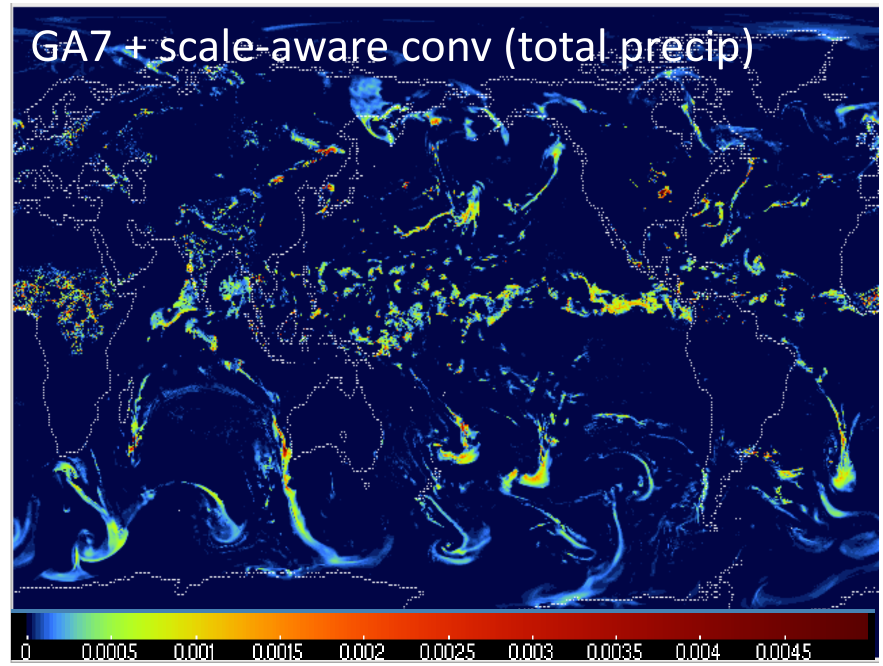




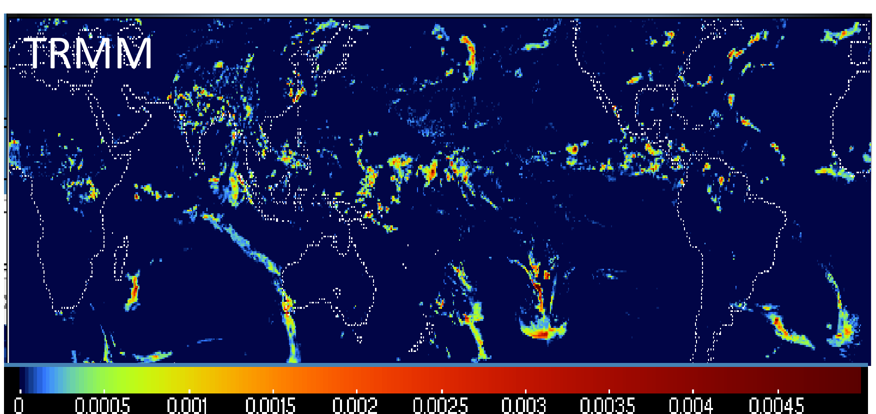
Control run already has stochastic BL perturbations.

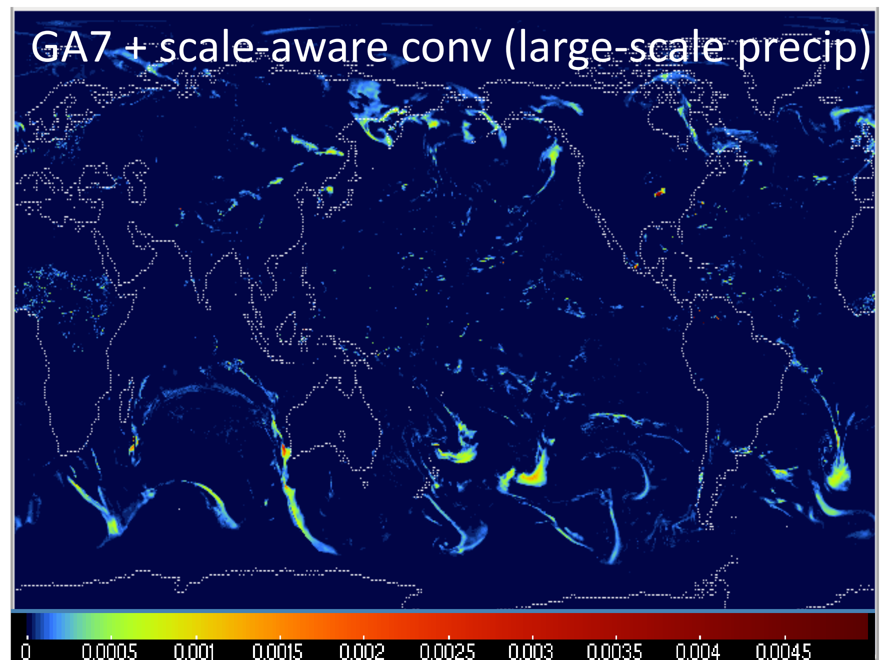
Adding stochastic convection but turning off BL perturbations, organisation is improved.



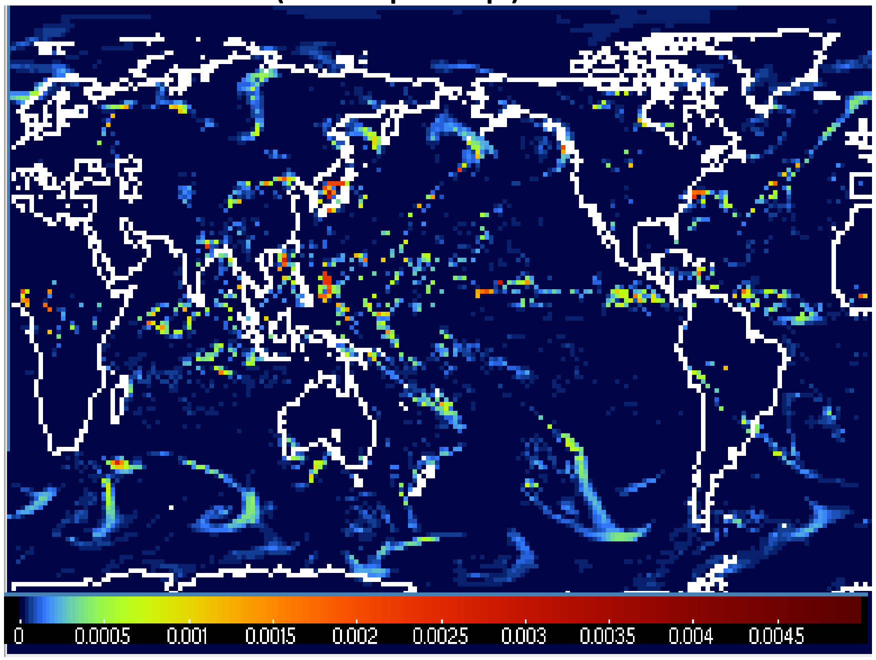


N320 global NWP run (5-day lead-time).
Convection scheme does nearly all the Tropical rainfall, as expected.
"Convective memory" used in new scheme makes rainfall more organised and persistent.

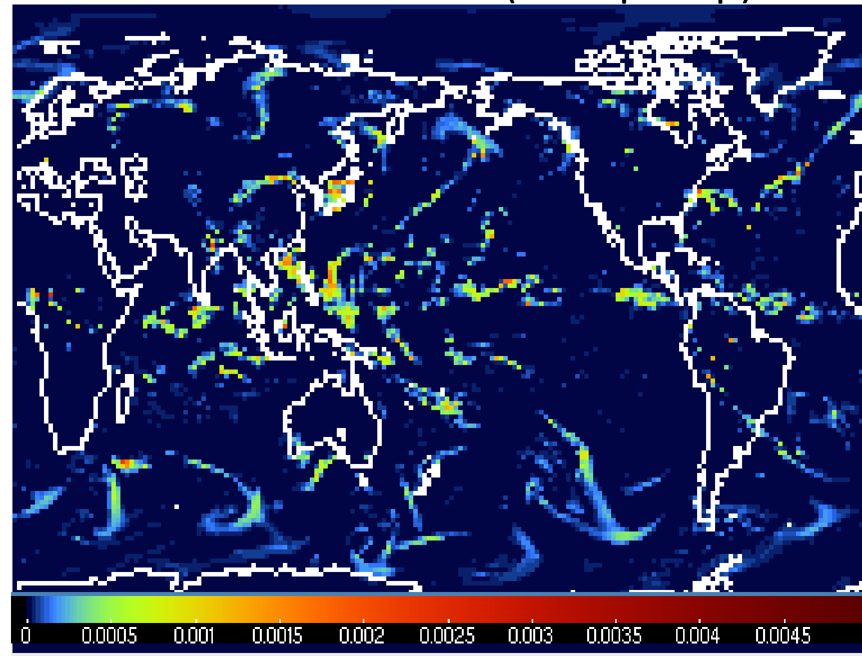




GA7 Control (total precip)



GA7 + scale-aware conv (total precip)



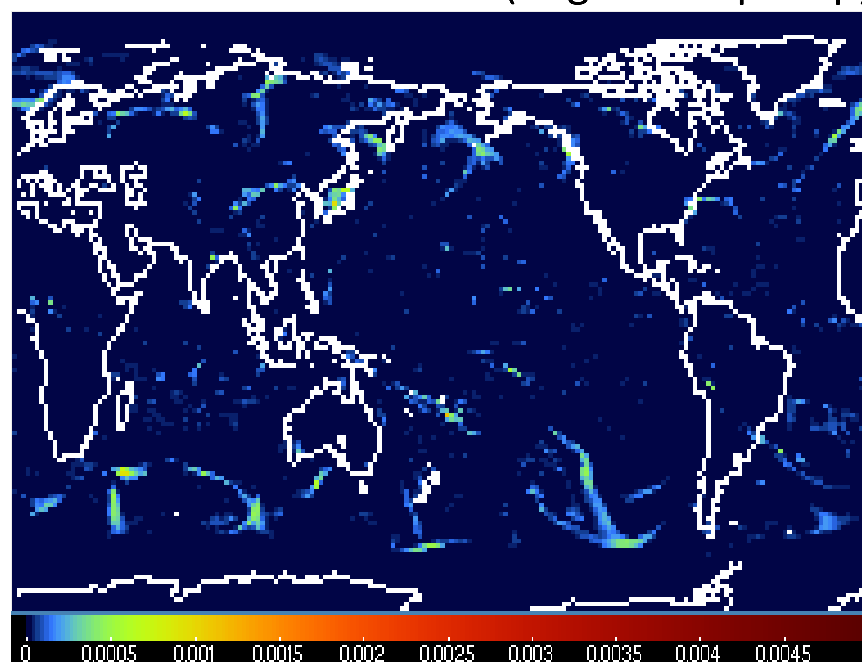
N96 climate-AMIP-style run.

Again, KE PDF vs CIN triggering / closure removes intermittency, while “convective memory” increases organisation.

Effect of scale-aware scheme at N96 similar to effect at N320, but difference looks less pronounced.

Because model resolution is closer to equilibrium scale?

GA7 + scale-aware conv (large-scale precip)



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    (c.f. Rio *et al.* 2013 found this was important).
  * Radiative effects of the diagnosed cumulus updrafts
    (GCM includes some, but cloud fractions for non-precipitating cumulus
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    Correcting this should slow down surface-heating, improving the diurnal cycle.

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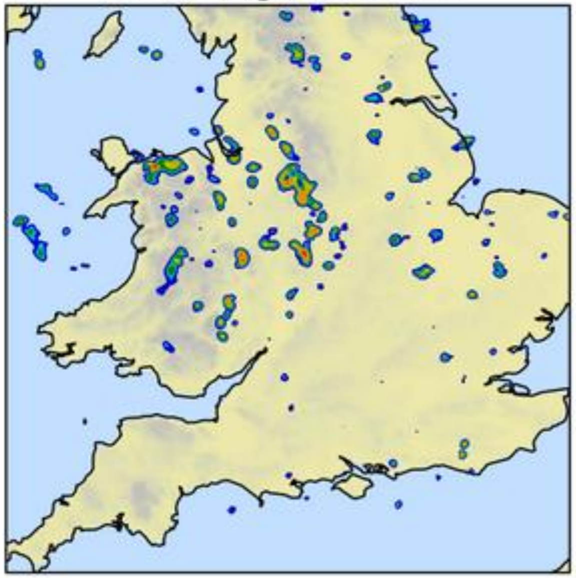
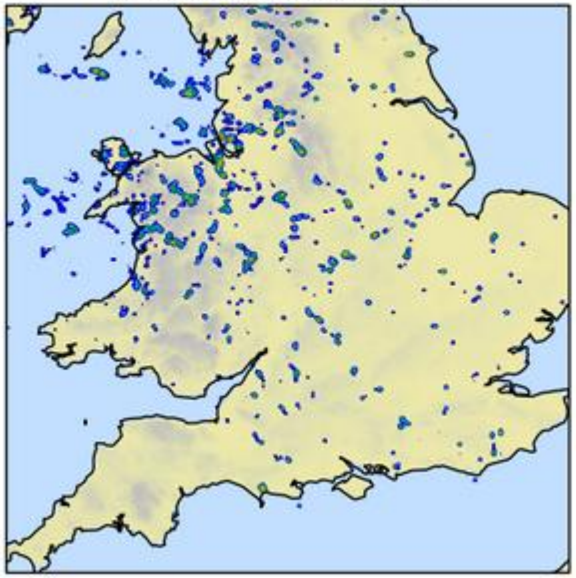
- Spurious spatial separation between parameterised and resolved showers (parameterisation should add unresolved cores within resolved cloud-systems, but fails to do this).
c.f. Problems with the UM "convective diagnosis" logic...

UKV2 large-scale rain



UKV2 convective rain



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Plan B: Try and rewrite the updraft model (ie the rest of the convection scheme!) in a consistent, PDF-based, unified framework (a work in progress)...

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Surely there are sound physical reasons for higher CAPE (buoyancy of convective updrafts) to force larger convective mass-fluxes!

Scale-aware triggering / closure based on PDF of w, but updraft model / detrainment calculation based on PDF of buoyancy (no w equation).
Nasty fudges required to combine the two.

Modifications implemented in the “deep” convection scheme; not addressed shallow or mid-level convection schemes
(elevated convection is a particular challenge for the UKV forecast)

Plan B: Try and rewrite the updraft model (ie the rest of the convection scheme!) in a consistent, PDF-based, unified framework (a work in progress)...

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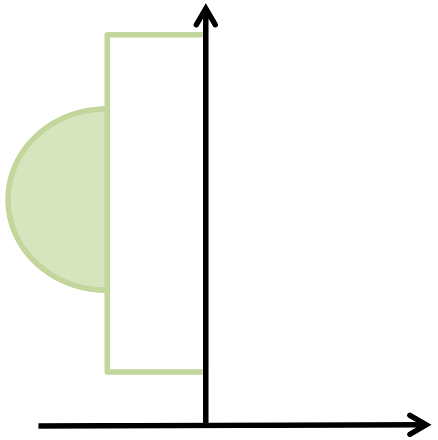
Thought experiment: What if we started from RCE and suddenly cooled a layer in the free troposphere, well above the BL-top; how would the cloud-base mass-flux respond? (CAPE closure philosophy says this should directly translate into higher cloud-base mass-flux, since CAPE has suddenly increased)



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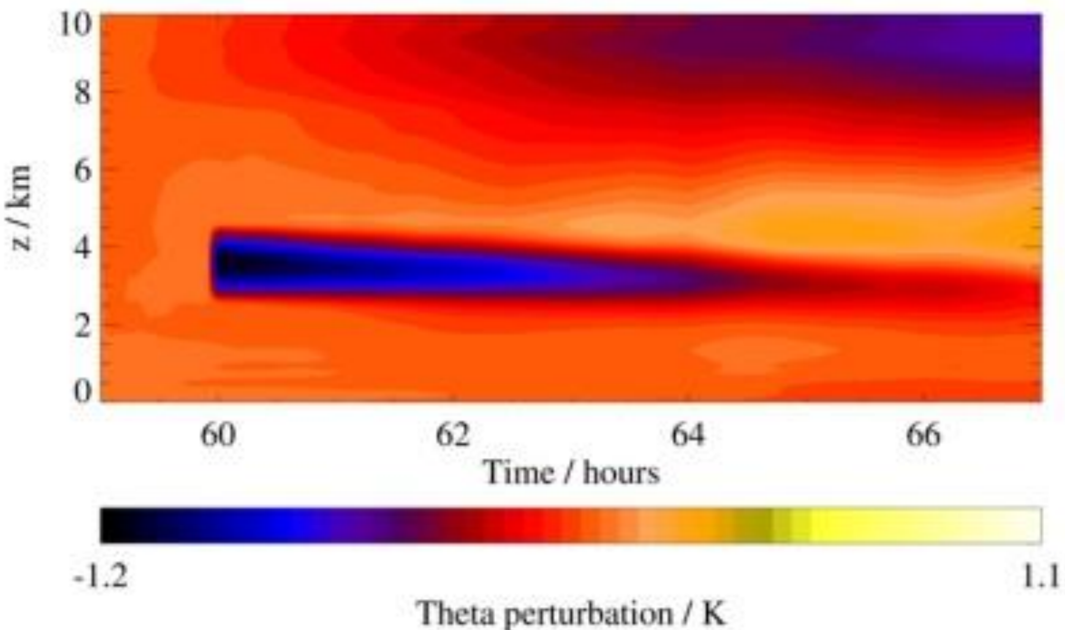

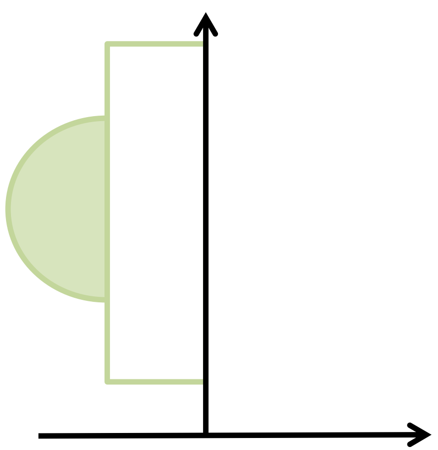

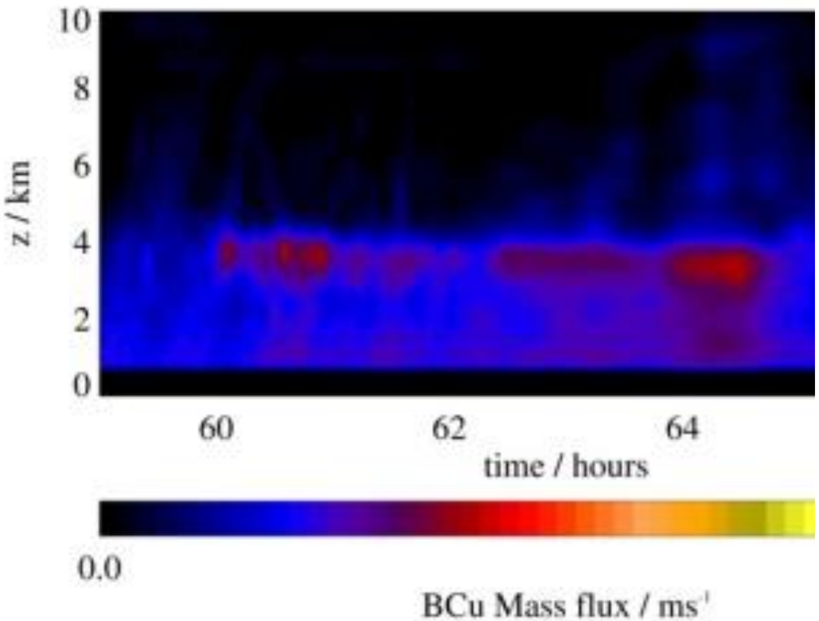

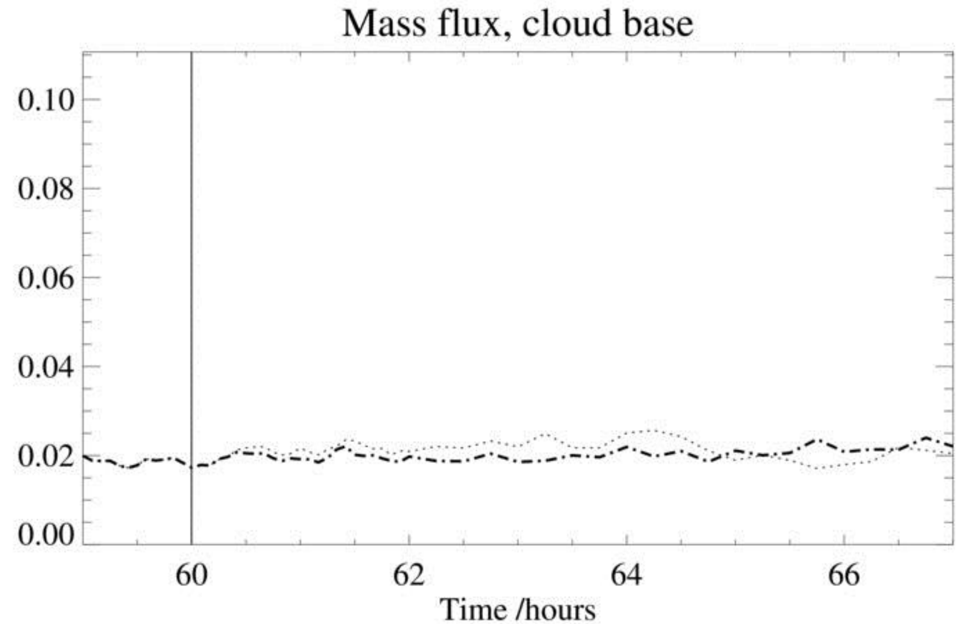

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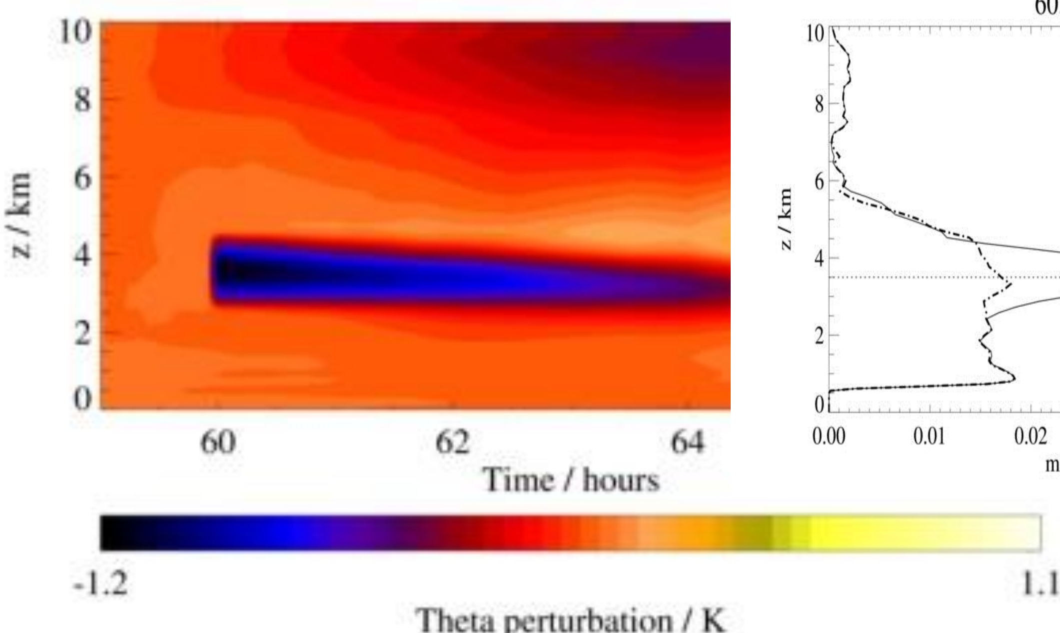
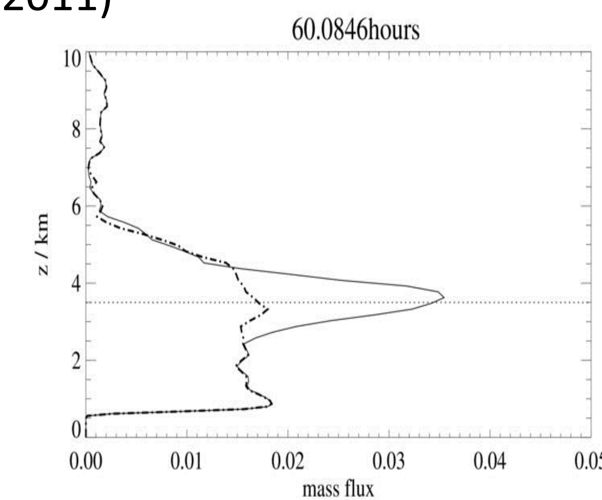
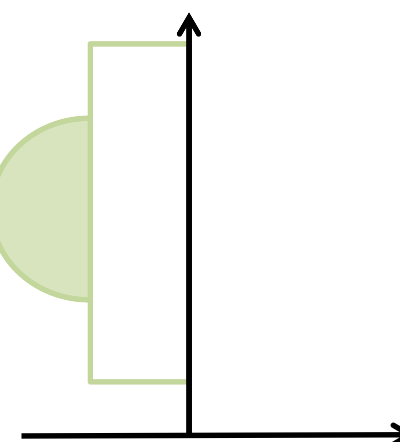
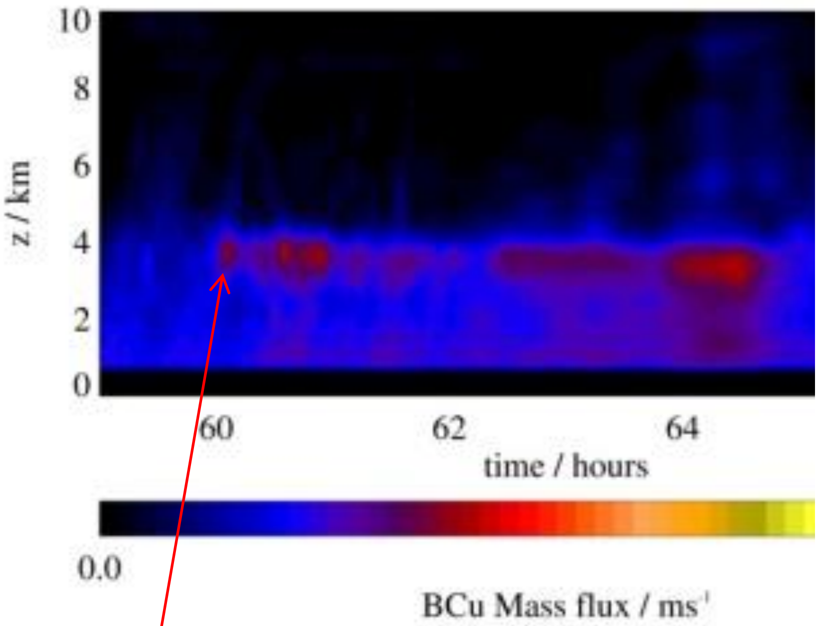
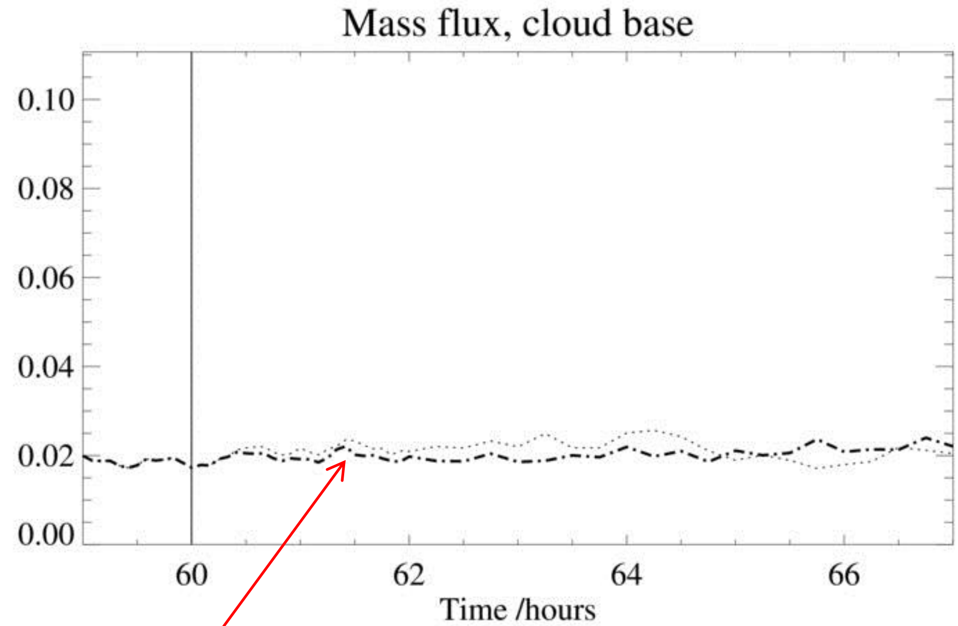




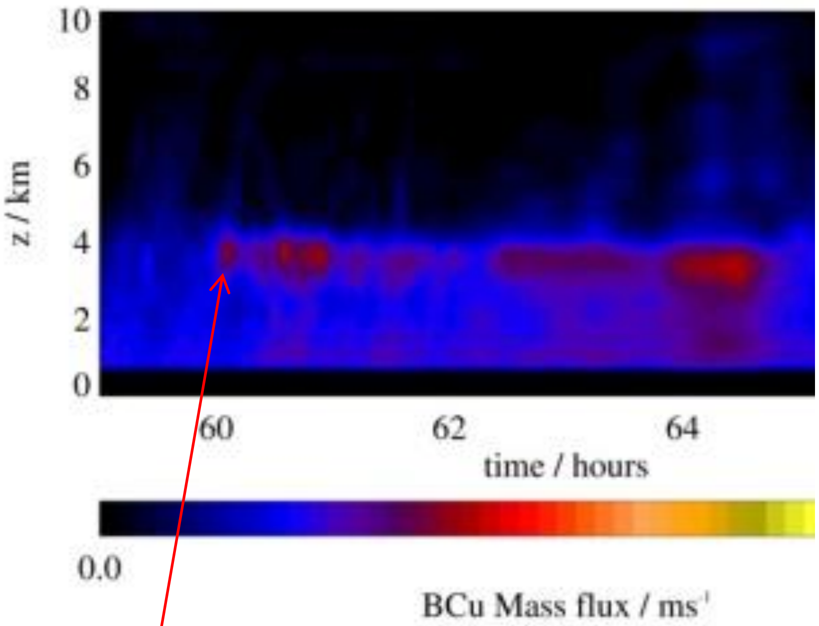


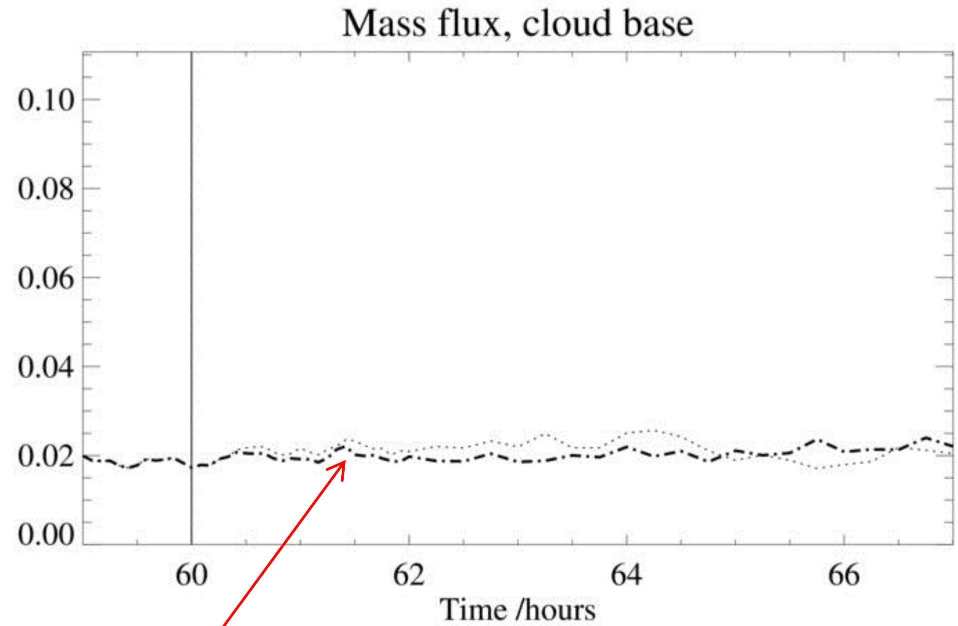




Immediate large increase in mass-flux in the layer destabilised by the forcing (from increase in updraft area fraction, not just w).

Only modest increase in mass-flux at cloud-base, and only ~hours after the forcing is applied.
(seems to be related to cold-pools driven by increased rainfall produced aloft).





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Implications:

Increased buoyancy of convective updrafts in the free-troposphere increases the mass-flux primarily through lateral entrainment, *not* the cloud-base mass-flux.

Vertically-integrated (CAPE) closure philosophy is not justified.

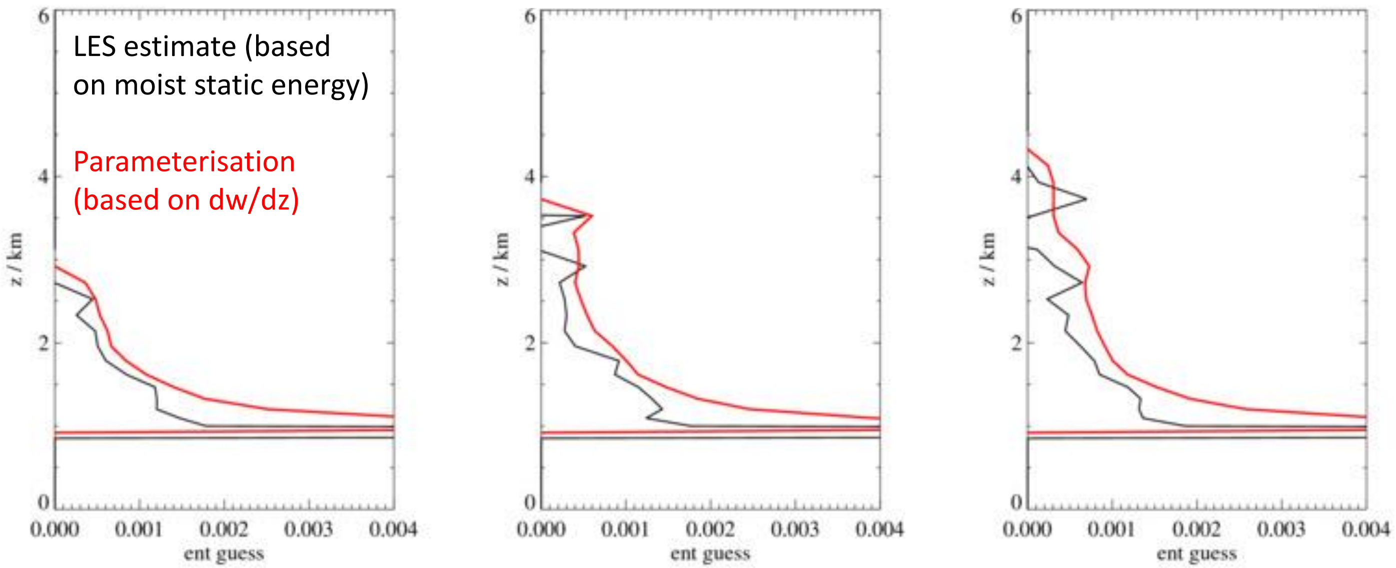
Sensitivity of mass-flux to CAPE is via a process normally in a convection scheme's cloud-model. Again; "closure" and "cloud-model" are not really separable.

Adapting Entrainment

Control of the mass-flux via cloud-base by CIN / triggering / intermittency alone means it lacks sensitivity to tropospheric forcing.

We can address this by making entrainment depend on vertical acceleration of the updraft by buoyancy.

Analysis of entrainment in LES: Alison Stirling



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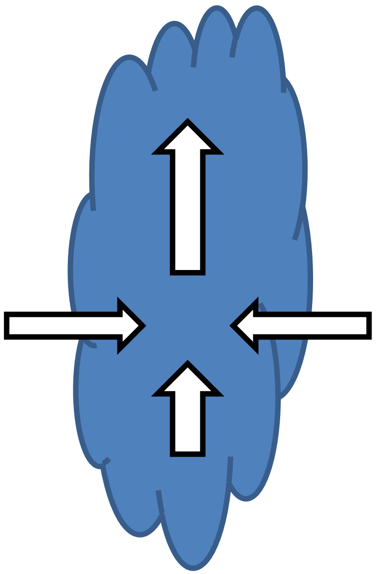

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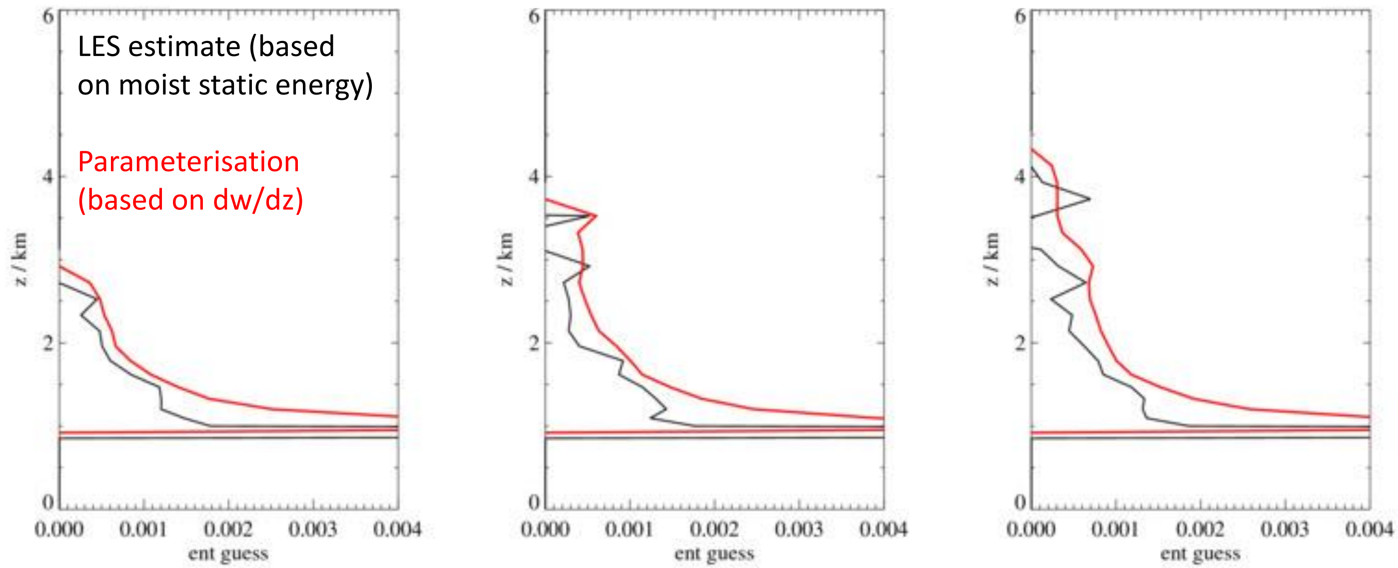


Hypothesis: where convective updrafts accelerate, they try to preserve fractional area instead of contracting with height. From continuity, this means they must entrain laterally:

$$M = \rho\sigma w \qquad \frac{\partial \sigma}{\partial z} = 0 \qquad \Rightarrow \varepsilon = \frac{1}{M}\frac{\partial M}{\partial z} = \frac{1}{\rho w}\frac{\partial \rho w}{\partial z}$$

A new convection scheme - CoMorph

Updraft dynamics:

Entrainment based on a combination of mixing (scales with 1/r) and lateral convergence forced by vertical acceleration of the updraft (1/w dw/dz).

Vertical velocity equation; w modified by buoyancy, entrainment, and drag. Drag depends on updraft radius r and environment static stability N^2.

Rain-out of precipitation depends on updraft vertical velocity (faster updrafts shed less water).

Acceleration of updrafts leads to higher entrainment and higher water-loading, which reduce the acceleration; this naturally regulates the updraft velocities.

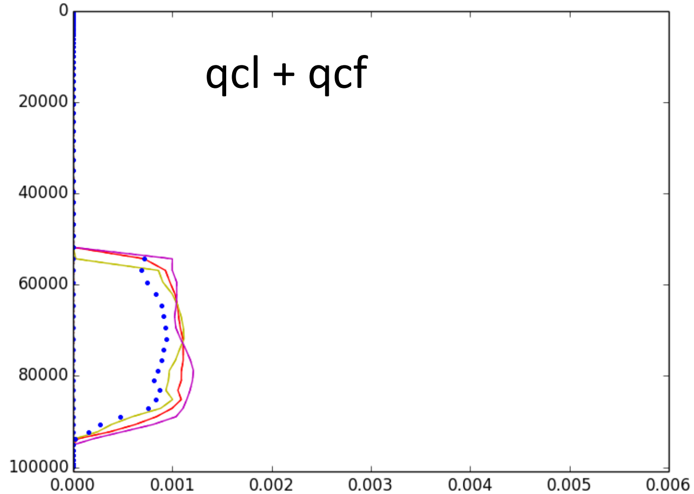
Convective Momentum Transport: u, v transported in the plume, with parameterised drag force between updraft and environment.

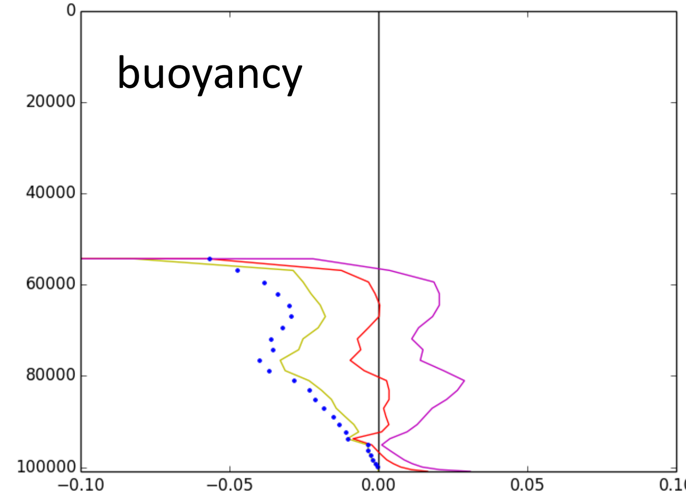
Other features

Option for convection to interact directly with microphysics prognostics (e.g precip output directly to prognostic rain and graupel fields).

Formulated in mixing ratios, with flexibility to modify thermodynamics assumptions consistently in all parts of the scheme (eg under future work on conservation).

New scheme can be made to behave like shallow, congestus, deep just by varying the updraft radius...

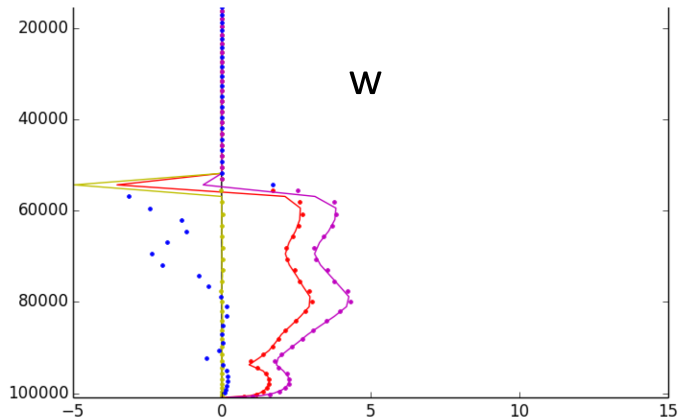


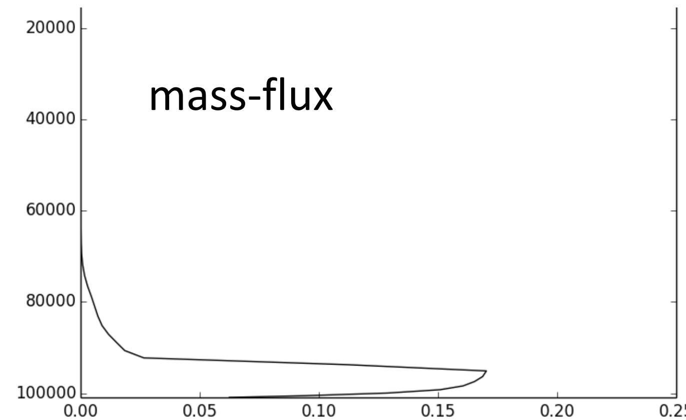


Updraft core

Updraft mean

Updraft edge

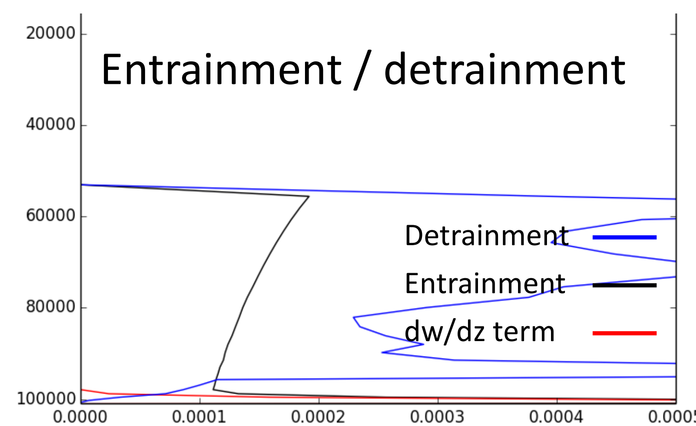




Detrainment is determined by the proportion of the updraft PDF no longer rising relative to the grid-mean flow.

Updraft radius r = 250m (“shallow” mode)

Launched from surface using TOGA-COARE sounding.



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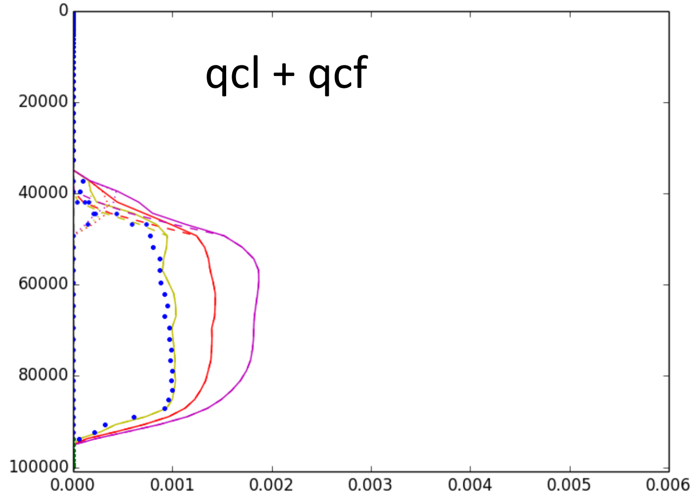

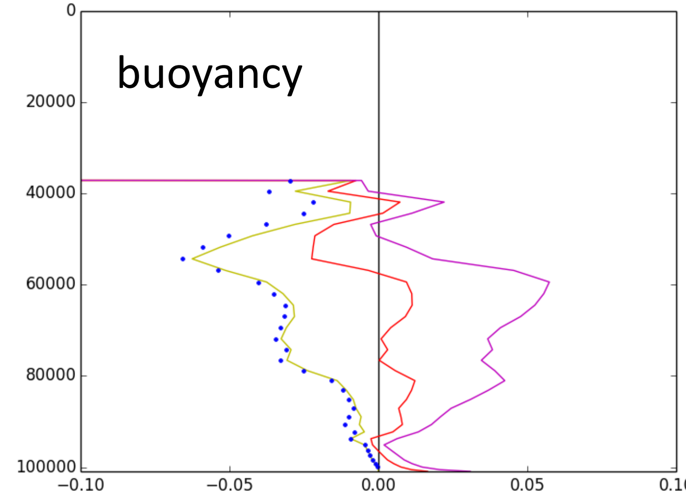

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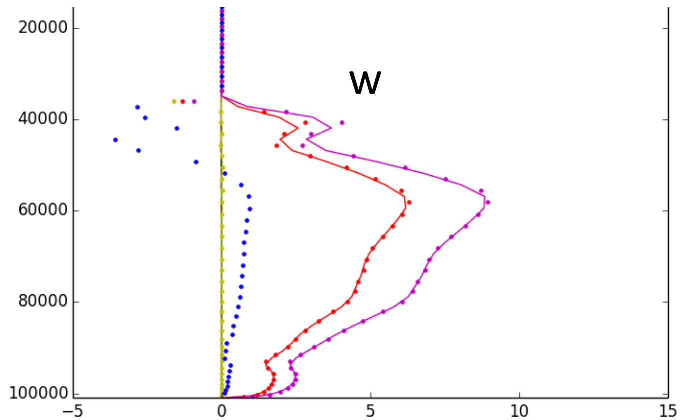

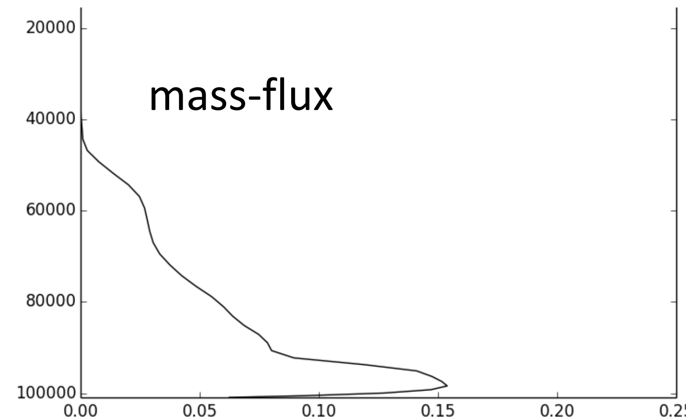

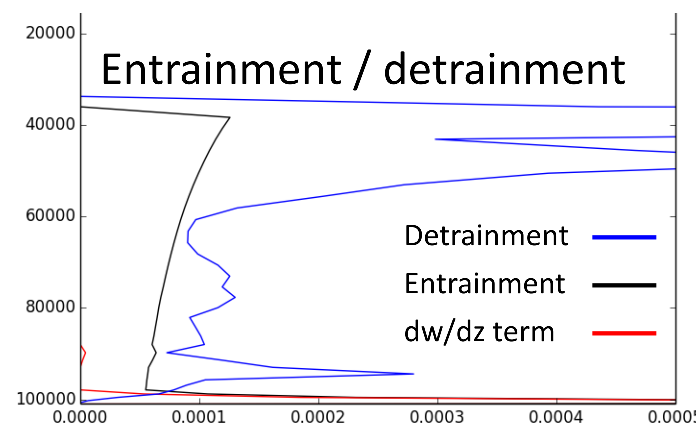

Detrainment is determined by the proportion of the updraft PDF no longer rising relative to the grid-mean flow.

Updraft radius r = 500m (“congestus” mode)

Launched from surface using TOGA-COARE sounding.

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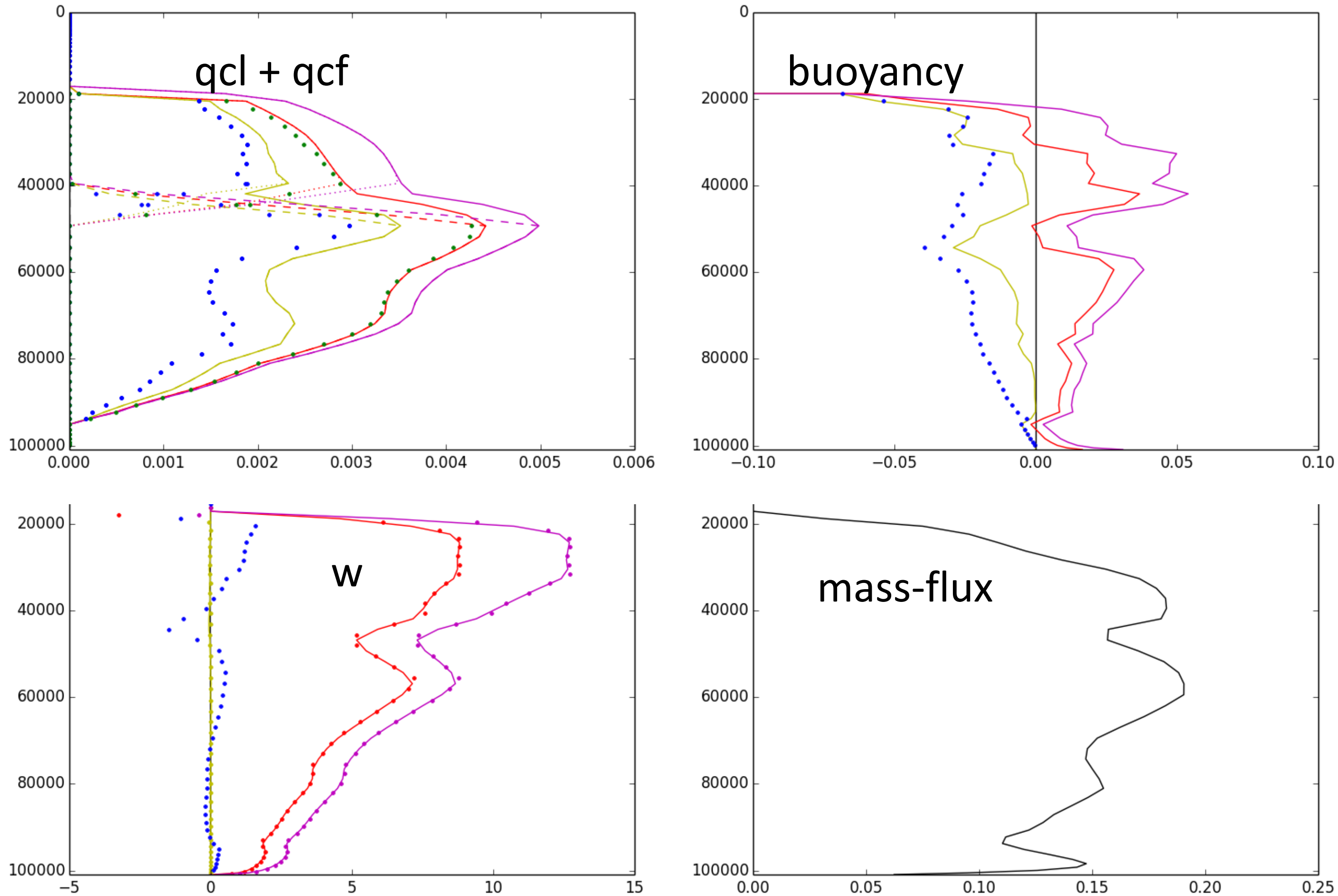


Updraft core

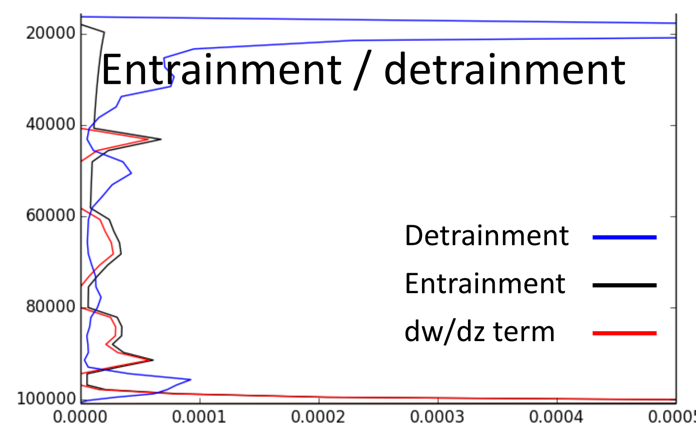
Updraft mean

Updraft edge

Detrainment is determined by the proportion of the updraft PDF no longer rising relative to the grid-mean flow.

Updraft radius r = 2000m (“deep” mode)

Launched from surface using TOGA-COARE sounding.



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- A new convection scheme is being developed, including entrainment due to buoyant acceleration, and a joint-PDF of w and thermodynamic variables within the updraft. It predicts triggering and mass-fluxes in the unified framework of the updraft dynamics.