Convective Parameterisation in the Grey-Zone: An Overview of Recent Research

Michael Whitall

Overview

1) What's wrong with convection in the grey-zone? (and why bother parameterising it?)

2) Theoretical considerations (why we shouldn't expect GCM convection parameterisations to work in the grey-zone!)

3) Recent advances (attempts to make them work, in operational and research contexts)

5) Summary / what next?

What's wrong with convection?

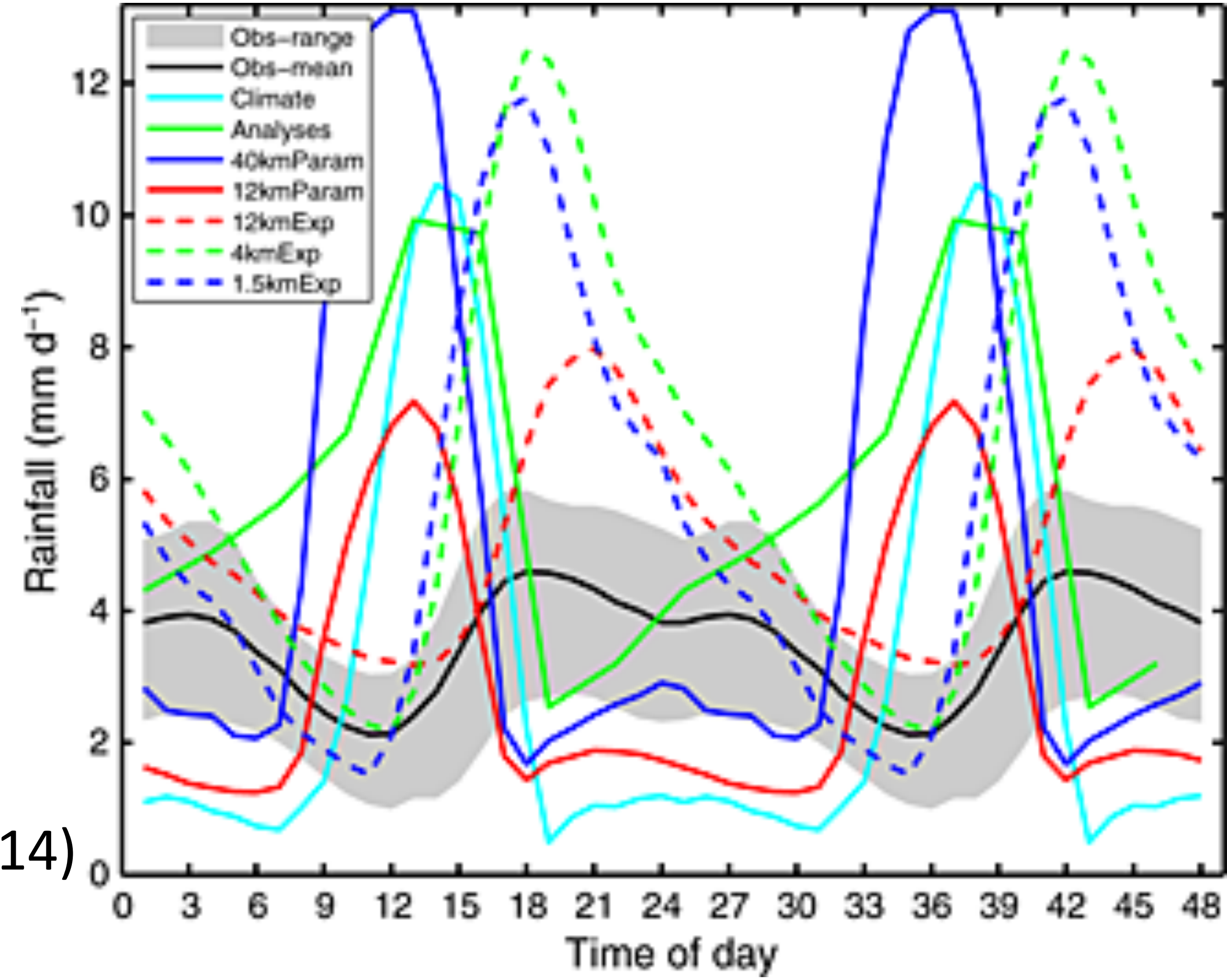
CASCADE project; Met Office UM simulations of the entire West African Monsoon system.

Various horizontal resolutions; convection parameterisation on / off.

Diurnal cycle of precipitation:

- Parameterised convection; all simulations (and analyses) trigger convective rain erroneously at mid-day.

- Explicit convection; diurnal cycle good, but excessive rainfall!



Birch et al. (2014)

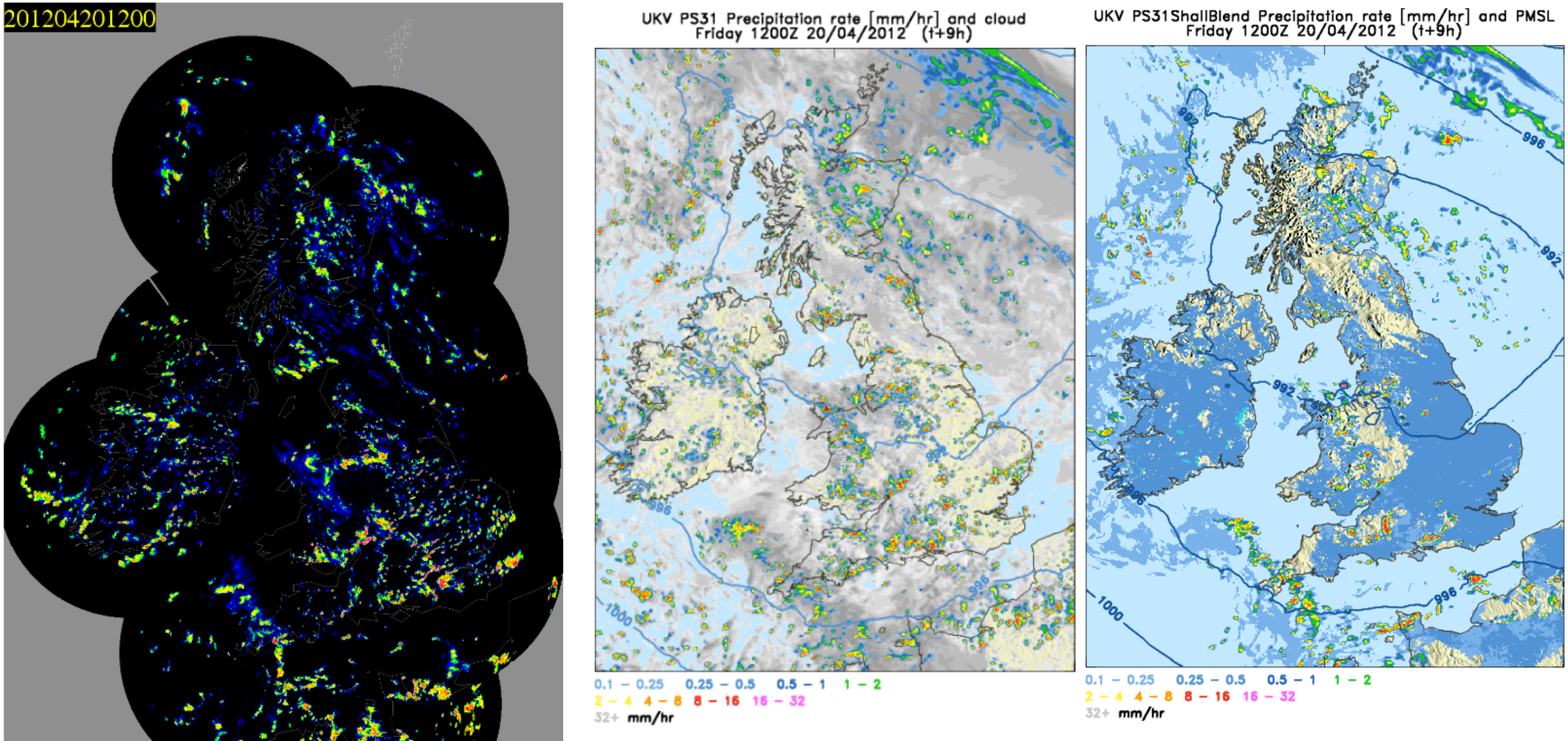
What’s wrong with convection?

- Explicit simulations with resolutions in the 1-10 km range tend to produce unrealistically-intense cells; either grid-scale (not really resolved) or artificially large.

- Need to represent unresolved fluxes from partially / marginally-resolved convection.

- But introducing current convection parameterisations makes things worse!

Example from UK convective-scale forecast



Radar

1.5 km explicit

1.5 km parameterised

2) Theoretical considerations:

- What assumptions are made in mass-flux convection schemes?

- What scales of motion can be resolved / parameterised at a given grid-size?

The 1st step in deriving the Mass-Flux formulation:

An atmospheric variable ϕ follows the equation:

$$\frac{\partial \rho\phi}{\partial t} = -\nabla.(\rho\underline{u}\phi) + \rho S_{\phi}$$

"Source" term

Advection (flux convergence)

Reynold's decomposition:

$$\rho\underline{u} = \overline{\rho\underline{u}} + \rho\underline{u}'$$

$$\phi = \bar{\phi} + \phi'$$

So by definition

$$\overline{\rho\underline{u}'} = 0$$

$$\overline{\phi'} = 0$$

(over-bar means grid-box mean; we equate this with Reynold's average over the ensemble of possible sub-grid fluctuations)

Assumption (a): **Unresolvable motions have no projection on to the grid-scale**

$$\frac{\partial \rho(\bar{\phi}+\phi')}{\partial t} = -\nabla.\left((\overline{\rho\underline{u}} + \rho\underline{u}')(\bar{\phi}+\phi')\right) + \rho S_{\phi(res)} + \rho S_{\phi(s.g.)}$$

So that cross-terms are zero

Take the grid-box mean of both sides:

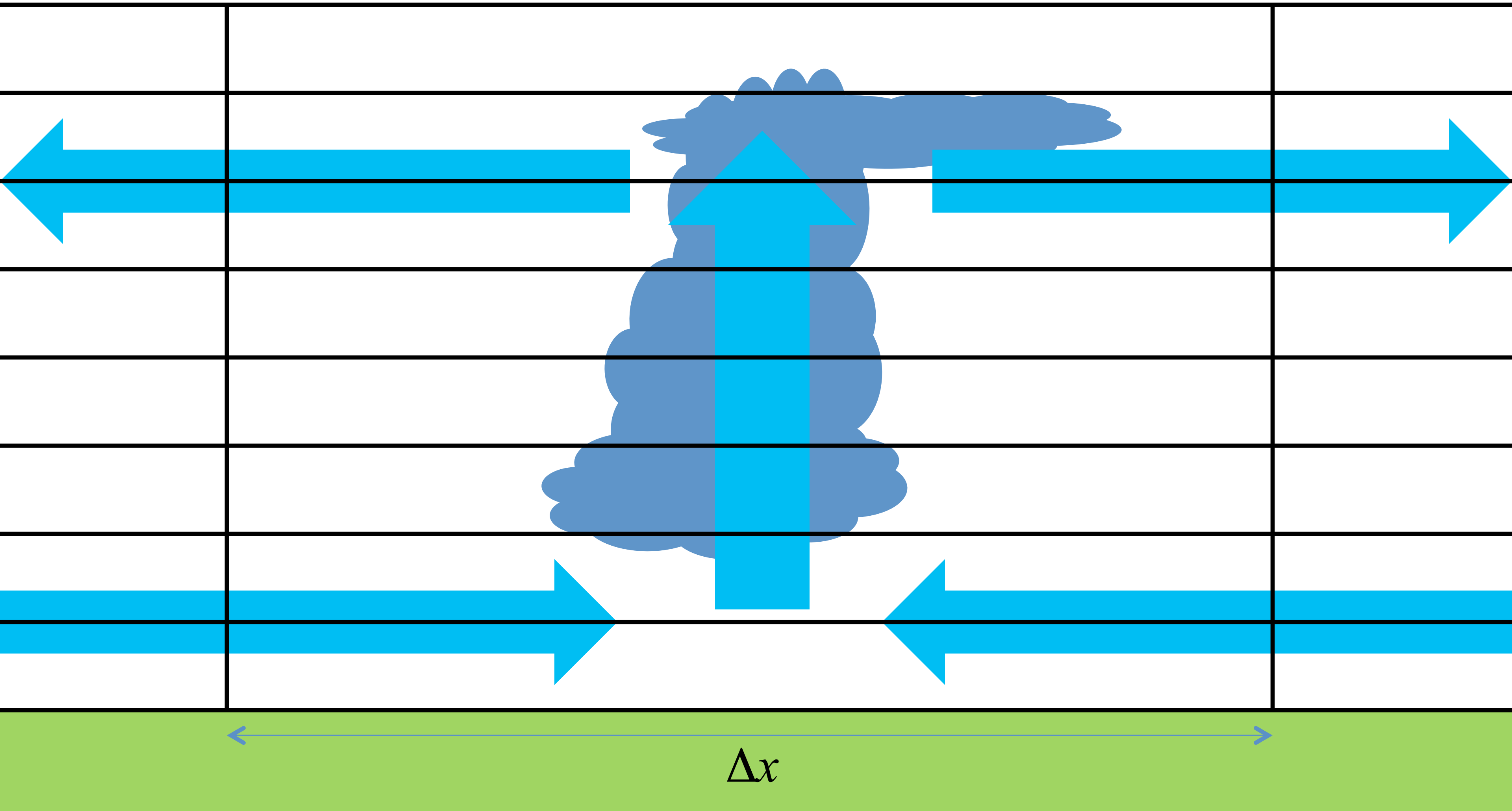
$$\frac{\partial \rho\bar{\phi}}{\partial t} = -\nabla.\left(\overline{\rho\underline{u}}\;\bar{\phi}\right) + \rho S_{\phi(res)} \boxed{-\nabla.\left(\overline{\rho\underline{u}'\phi'}\right) + \overline{\rho S_{\phi(s.g.)}}}$$

Parameterised tendency

This circulation is NOT resolvable on the grid-length Δx

But $\overline{\rho w'} \neq 0$

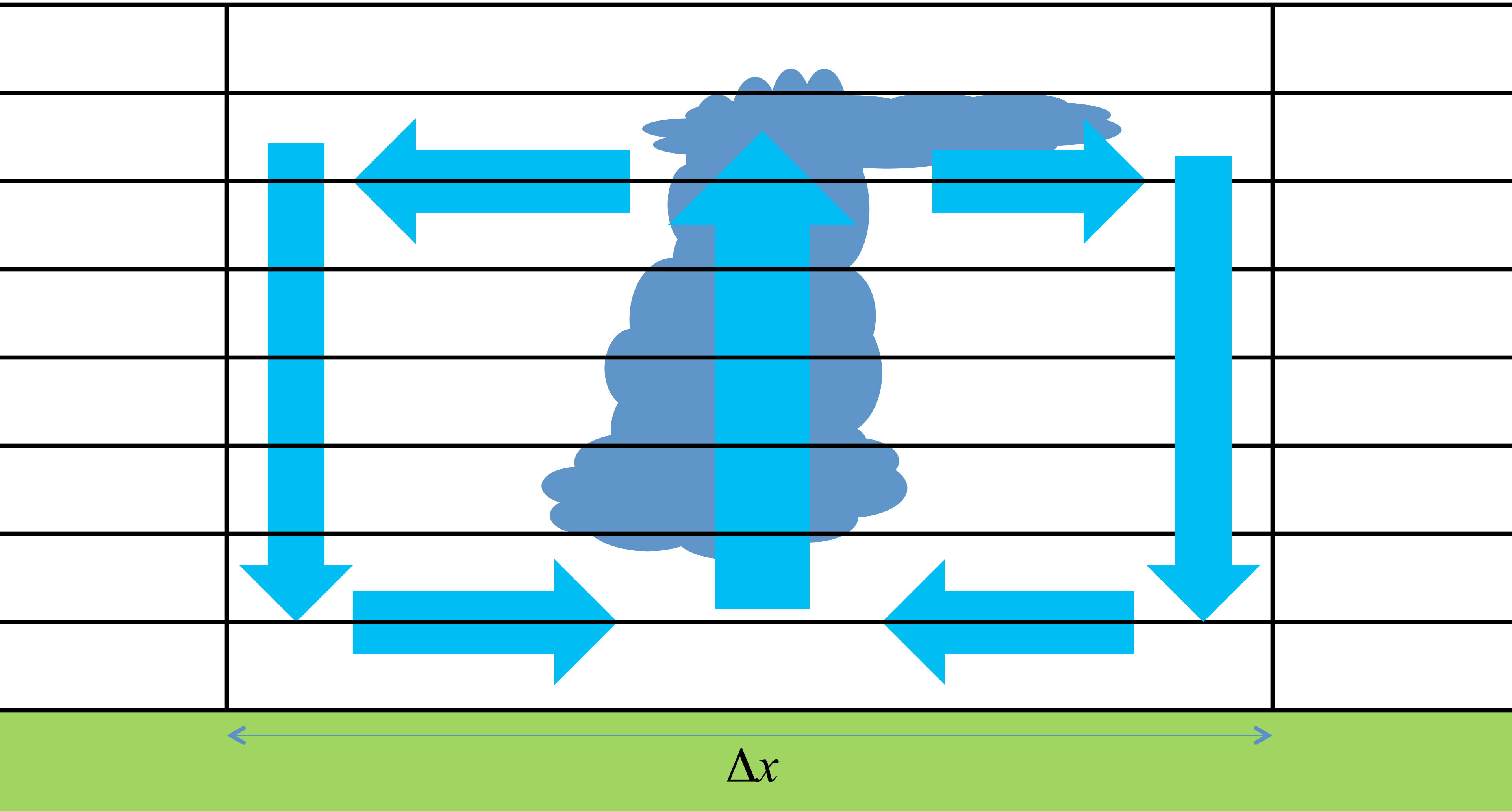
The grid-mean vertical velocity is the unresolvable cumulus updraft aliased onto the grid; it could not have been predicted from the grid-mean variables!



In order to use $\overline{\rho w'} = 0$

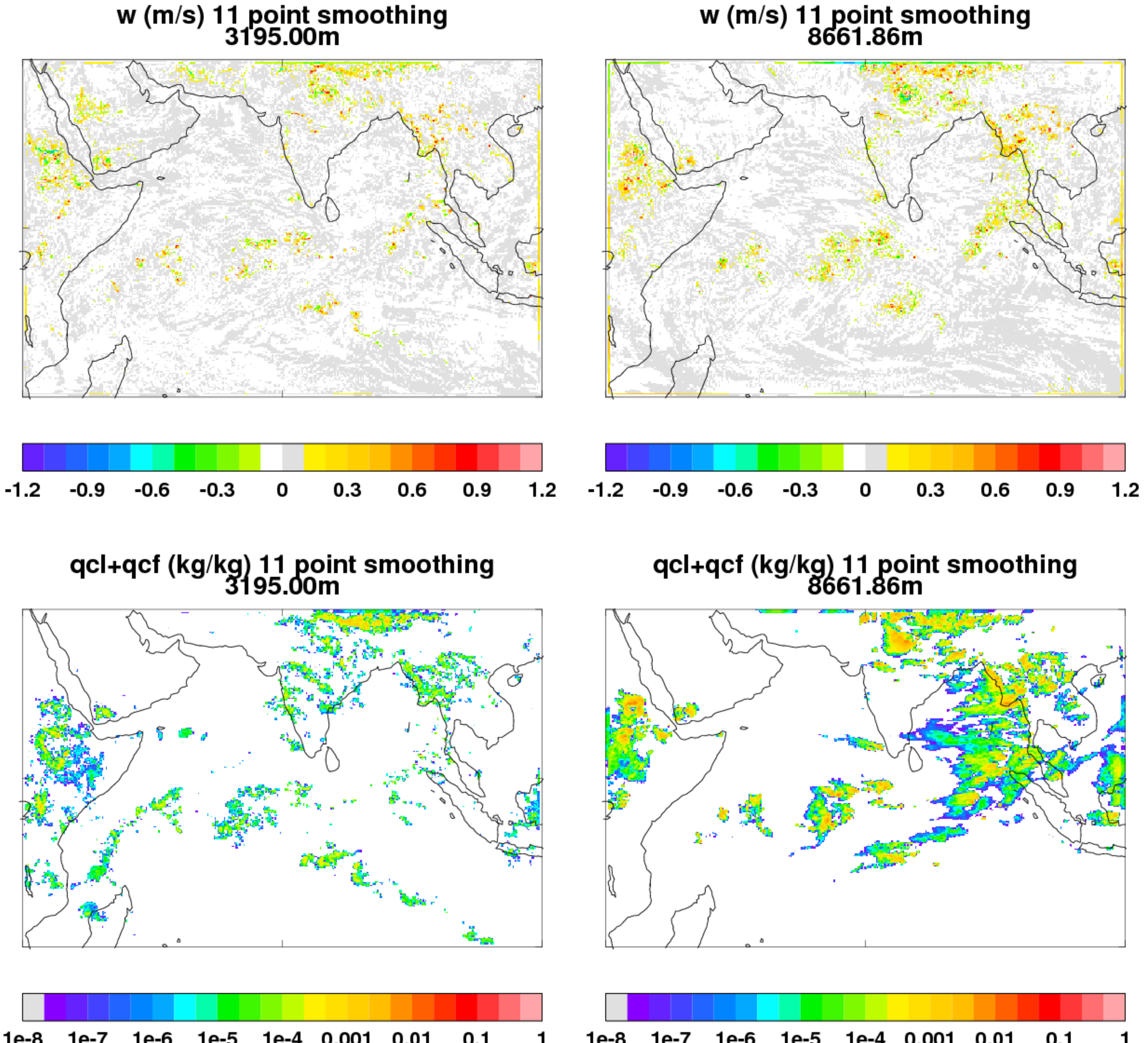
we must assume that unresolvable motions always consist of a closed circulation within the grid-box.

Local Compensating Subsidence



EMBRACE - 1.5 km simulation of Indian Ocean

(plots from Martin Willet)

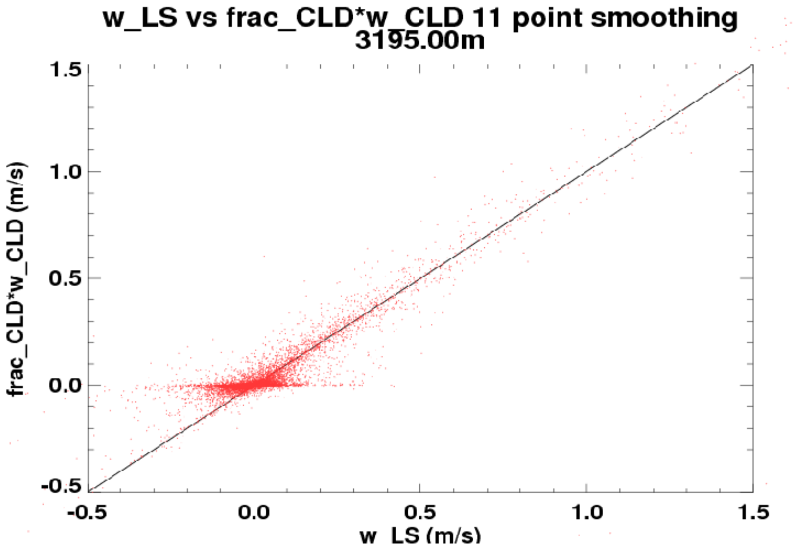


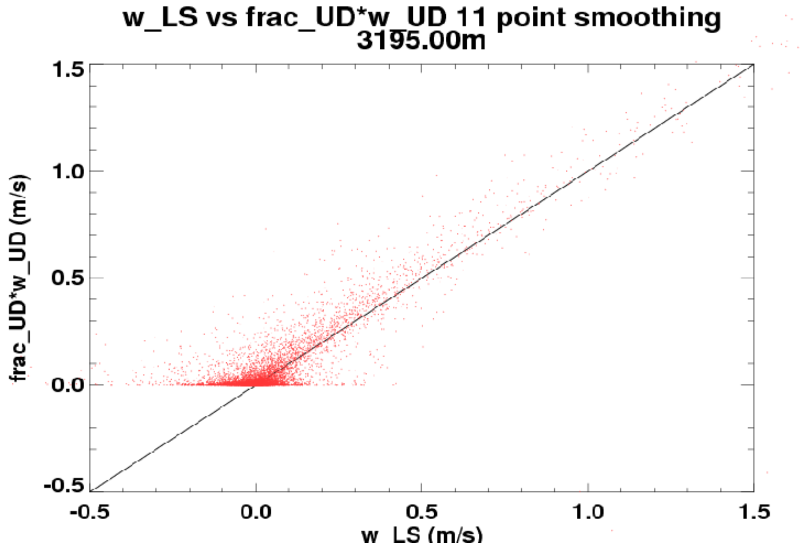
Analyse updraft, downdraft and environment fluxes within 11-by-11 grid-point (16.5 km) squares.

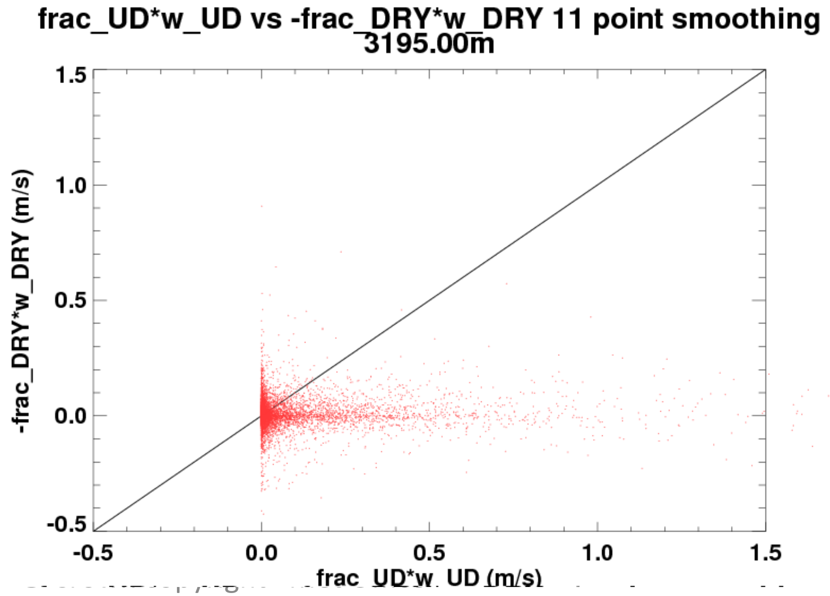
Define $\mathbf{W}_{LS}$ as the mean vertical velocity over each square.

EMBRACE - 1.5 km simulation of Indian Ocean

(plots from Martin Willet)







- In-cloud flux ≈ mean-flux over whole square.

- "Updraft" flux slightly larger than mean-flux due to moist downdrafts.

- Environment flux has no relationship with updraft flux (i.e. no sign of local compensating subsidence).

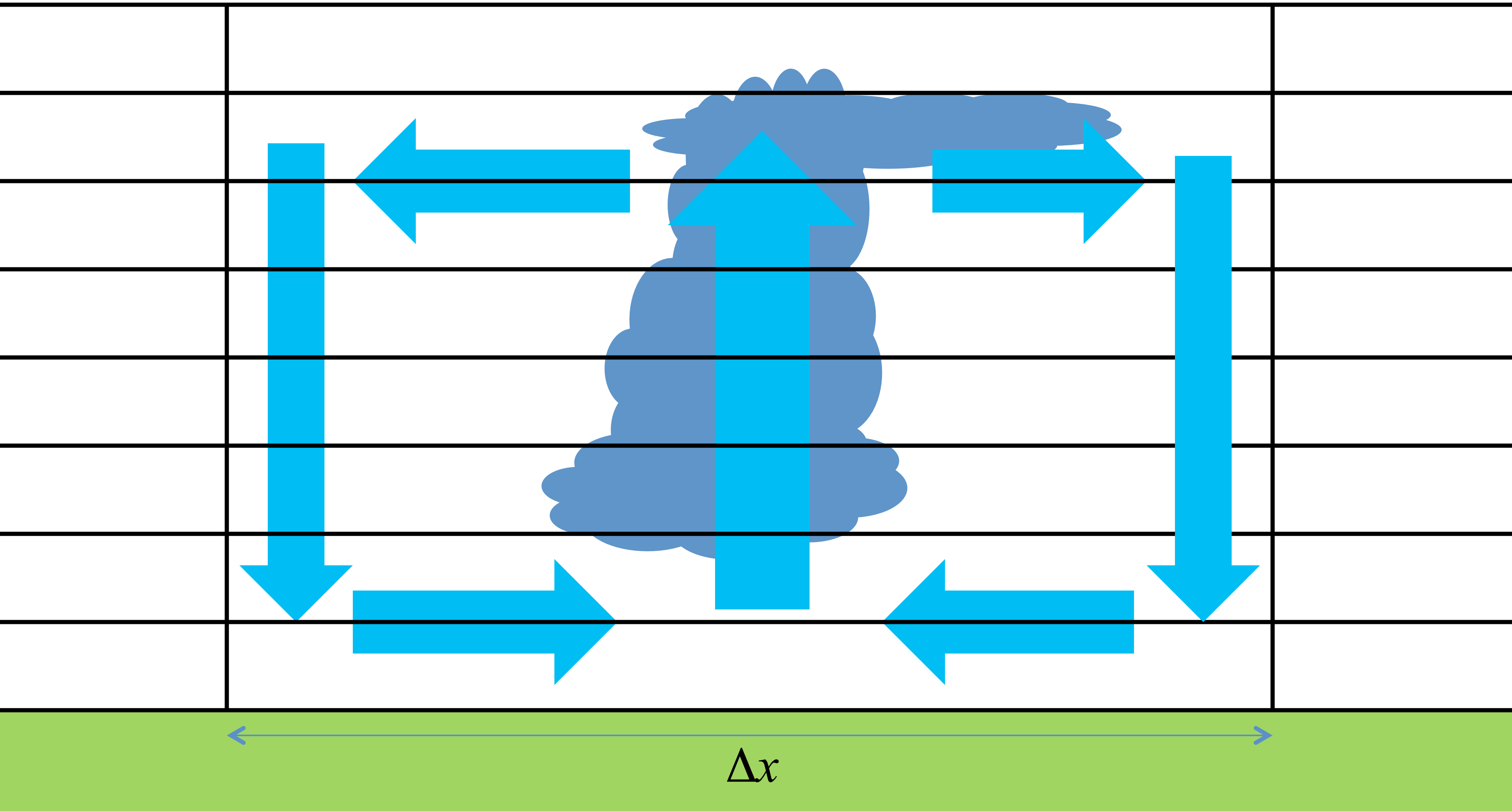
- Large-scale ascent not forcing the convection, it IS the convection (aliased onto the scale of interest).

In order to use $\overline{\rho w'} = 0$

we must assume that unresolvable motions always consist of a closed circulation within the grid-box.

Local Compensating Subsidence

Has anyone tried to change this?



Mass-flux formulation further assumes:

(b) **Sub-grid convective motions don't cause any net horizontal fluxes**

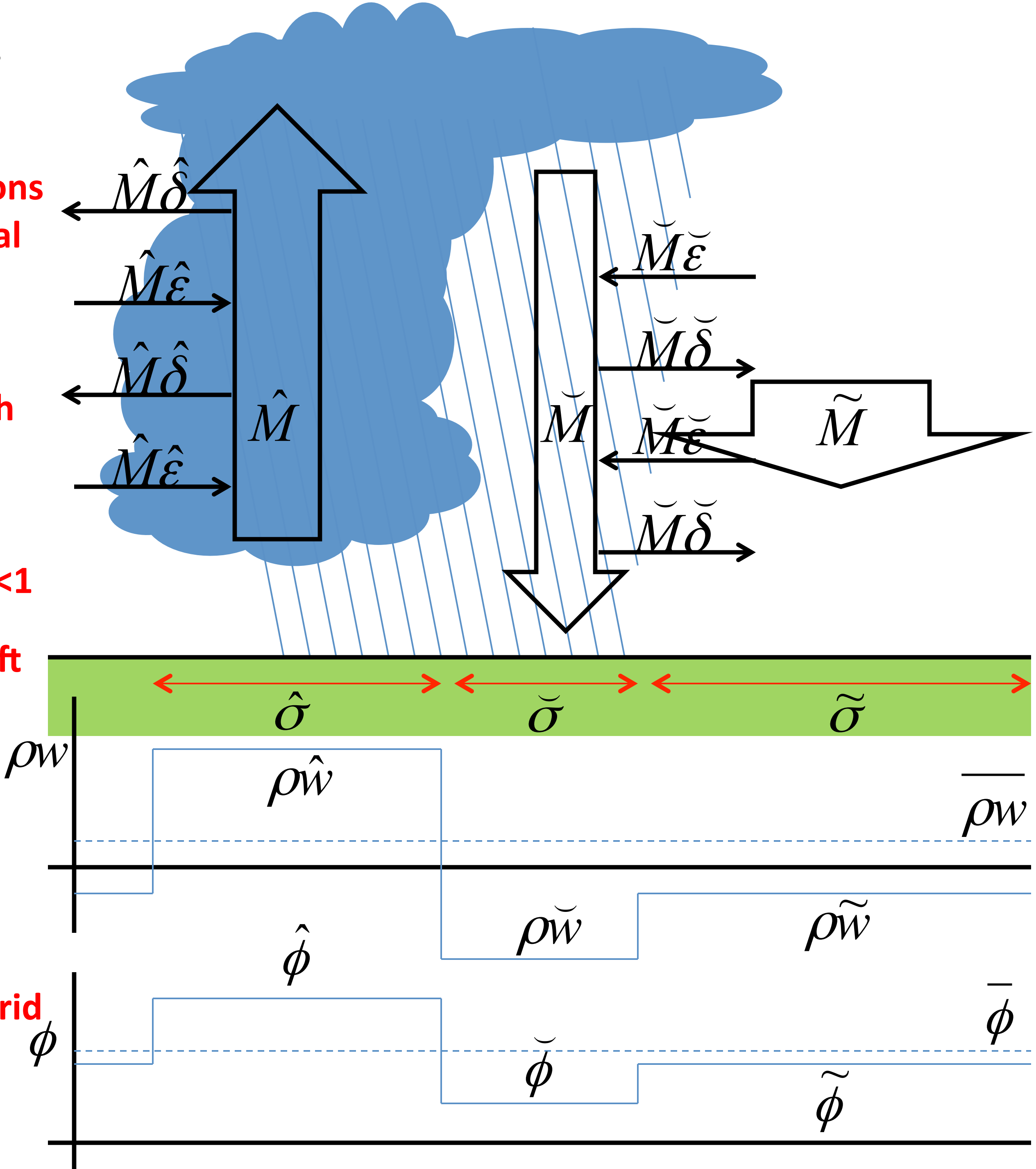
(c) **Updraft, downdraft and environment regions are each homogeneous**

(d) **The fractional area of updrafts and downdrafts is <<1**

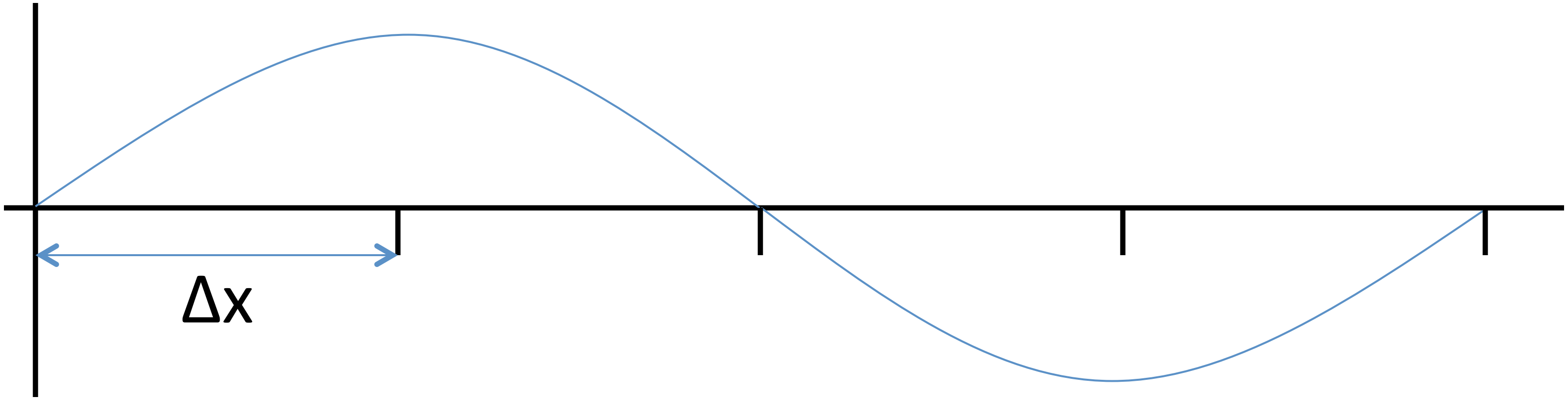
(e) **The updraft and downdraft profiles are in equilibrium**

(f) **Air entrained into the plume has the grid-mean (environment) properties**

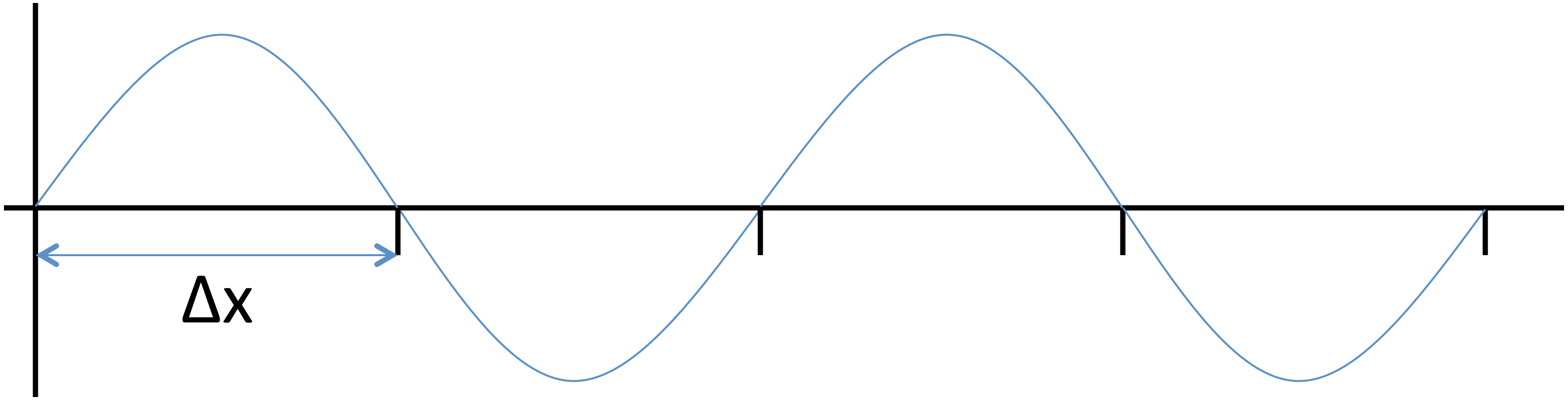
(g) **Convective Quasi-equilibrium (the whole sub-grid state is diagnosable from the environment and forcings).**



What scales can be *resolved* at a given grid-size?

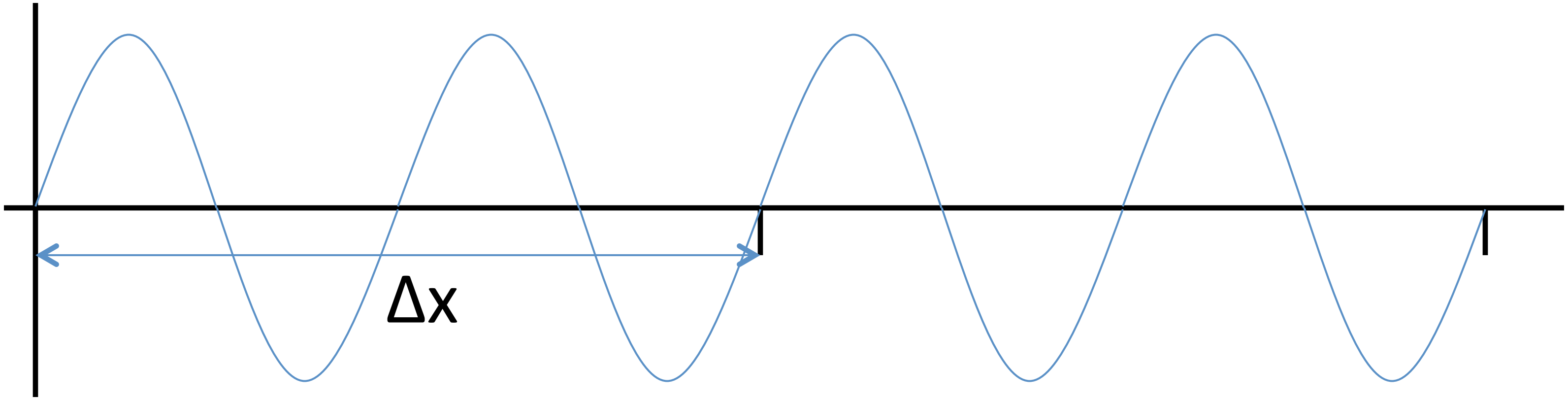


Shortest dynamically resolvable mode: $4\Delta x \leq \lambda_x$



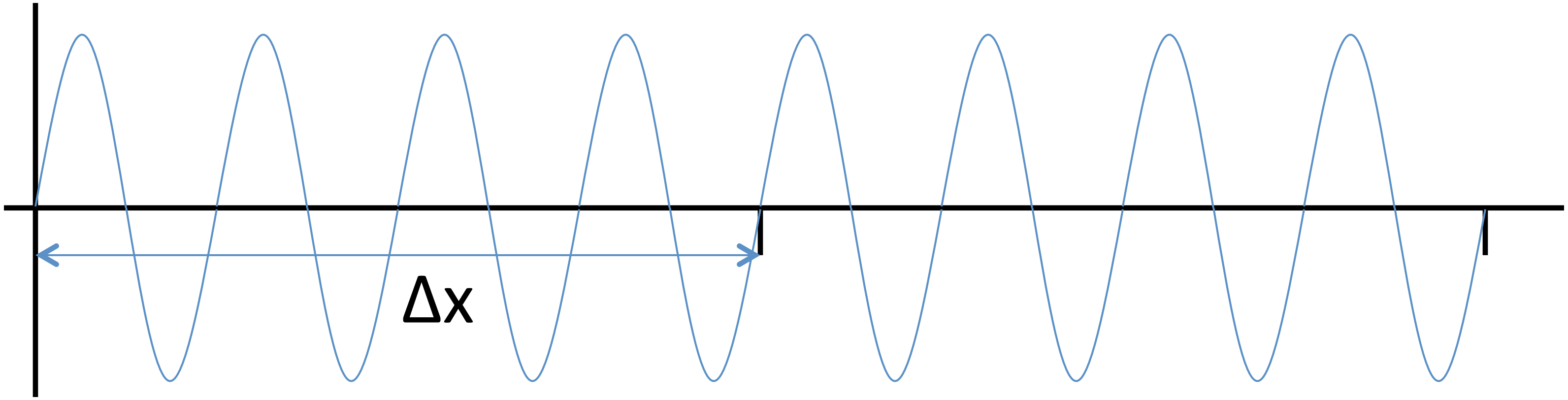
Not resolvable, not sub-grid either; grey-zone grid-scale “noise”: $\Delta x < \lambda_x < 4\Delta x$

What scales can be *parameterised* at a given grid-size?



Sub-grid, but too few features per grid-length to assume statistical equilibrium; grey-zone sub-grid scales:

$$\frac{\Delta x}{4} < \lambda_x < \Delta x$$



Let's (arbitrarily) assume that scales smaller than a quarter-grid-length can be averaged over assuming sub-grid statistical equilibrium:

$$\lambda_x < \frac{\Delta x}{4}$$

Resolvability bands:

$4\Delta x \leq \lambda_x$

Resolvable - can be treated by the model's explicit dynamics.

$\Delta x < \lambda_x < 4\Delta x$

Grid-scale grey-zone – not resolvable or sub-grid (has significant projection onto grid-scale); not clear how to represent these scales!

$\frac{\Delta x}{4} < \lambda_x < \Delta x$

Sub-grid grey-zone – relatively small, uncertain projections onto grid-scale; well-suited to treatment by stochastic versions of traditional parameterisations.

$\lambda_x < \frac{\Delta x}{4}$

Sub-grid statistical equilibrium - can be treated by traditional equilibrium-based parameterisations.

The "grey-zone" around the filter-scale (in terms of whether something can be resolved, or parameterised using equilibrium assumptions) is spectrally quite broad!

Spectral decomposition of convective updraft mass-flux in a 250m resolution Radiative-Convective Equilibrium simulation using the Met Office LEM:

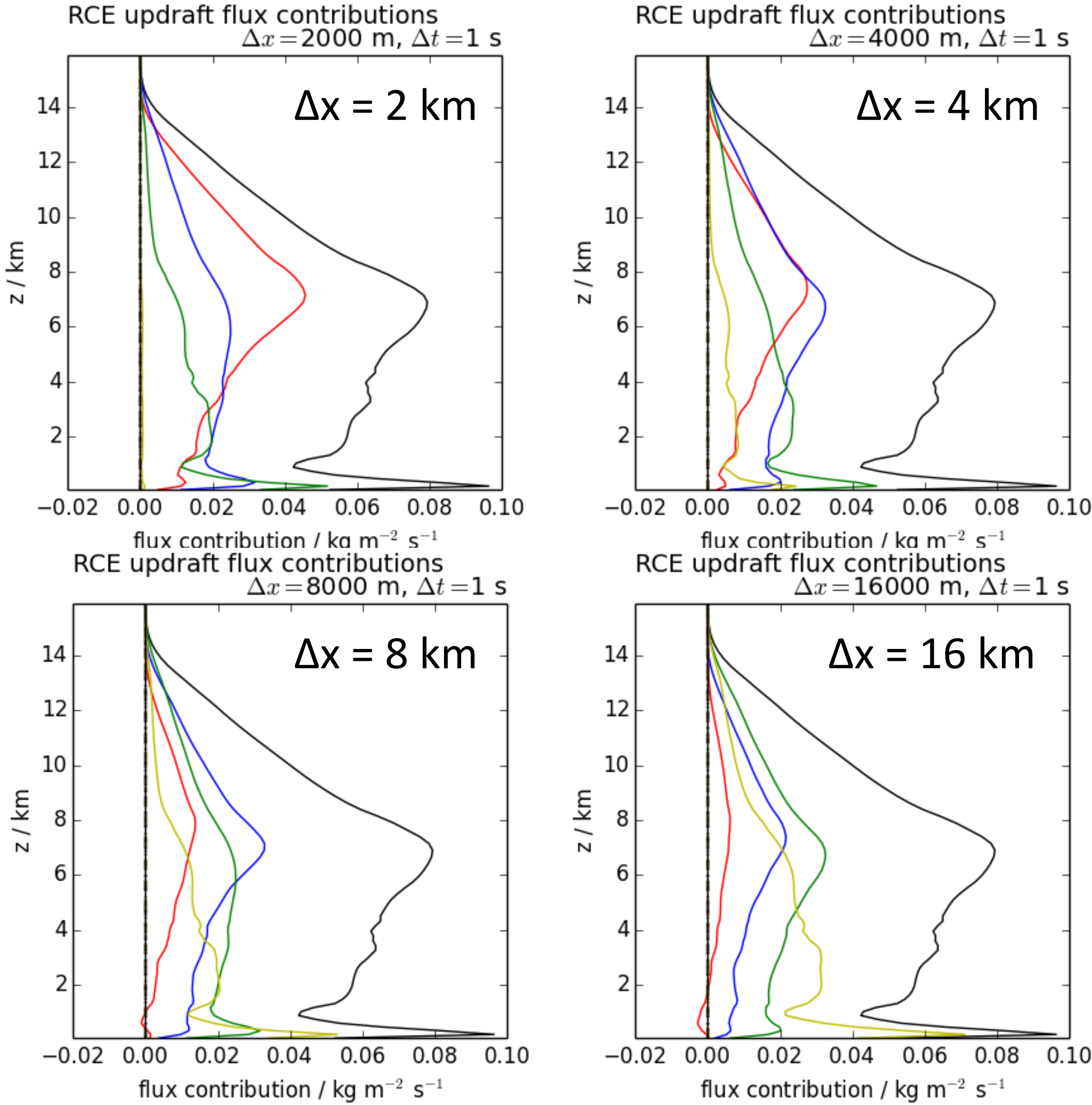
Resolvable
Grid-scale grey-zone
Sub-grid grey-zone
Sub-grid statistical equilibrium
Total updraft mass-flux

- Grey-zone scales significant at all resolutions.

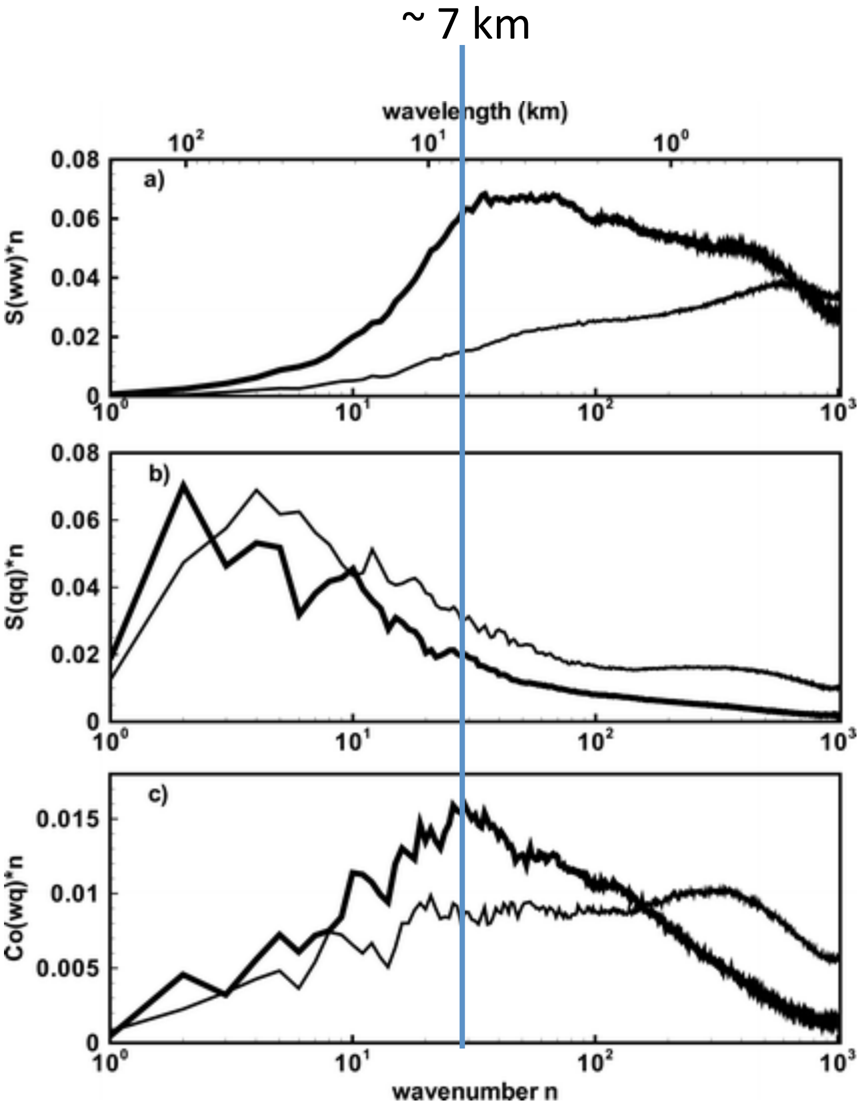
- Even at 2 km, only ~50% of the updraft mass-flux is resolvable.

- Even at 16 km, only ~50% of the mass-flux is in sub-grid statistical equilibrium.

- Updrafts are better-resolved in the upper troposphere than in the lower troposphere.



Moeng et al. 2010 – similar conclusions from spectral analysis of 100m-resolution LEM simulation of deep convection.



W variance

q variance

Moisture flux

CRM resolutions (1-10km) cut right through the scales responsible for most of the vertical moisture transport!

What might be wrong with convection in the grey-zone?

- Conceptual problem of representing motions on scales which are neither resolvable nor parameterisable using current assumptions.

And there’s more...

What might be wrong with convection in the grey-zone?

- Missing processes:
- Triggering / maintenance of convection by cold-pool uplift.
- Mixing-driven downdrafts
- Convective overshoot and subsequent fall-back
- Sensitivity to wind-sheer (downdrafts / organisation)
- Microphysical processes in updrafts

- Missing interactions between parameterised and resolved processes:
- Forcing of grid-mean vertical velocity by sub-grid updrafts & downdrafts.
- Forcing of sub-grid updrafts & downdraft by resolved T, q, p gradients.

- Invalid assumptions:
- Convective quasi-equilibrium (assume convection is entirely diagnostic)
- Statistical Equilibrium (average over many "features" per grid-box)
- Segmentally-constant / homogeneous / "top-hat" updrafts & downdrafts
- Instantaneous ascent
- Small updraft area fraction
- Local compensating subsidence

- Lack of "scale-awareness"; as resolution increases:
- Sub-grid mass-flux should reduce (more is resolved)
- Sub-grid perturbation of plume properties should reduce (more is resolved).
- Fractional mixing rates for sub-grid plumes should increase (smaller features).

What might be wrong with convection in the grey-zone?

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Become more obvious when part of the convection is resolved and behaves differently!

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Applies to both parameterised and poorly-resolved motions.

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3) A patchy survey of efforts to overcome these problems!

a) Academic advances

b) Operational developments at the Met Office

Addressing the assumption of Convective Quasi-Equilibrium:
a) departures from diagnostic statistical-equilibrium

Plant & Craig (2008): A Stochastic Parameterization for Deep Convection Based on Equilibrium Statistics.

AKIO ARAKAWA AND WAYNE HOWARD SCHUBERT

- At equilibrium, an ensemble of updrafts with different sizes (and entrainment rates) exists.

- But for a given grid-size, we may only have a small sub-sample of this ensemble in a grid-area.

- By treating the ensemble of updrafts using statistical mechanics, we can show that the equilibrium distribution of cloud-base mass-flux *per cloud* is exponential:

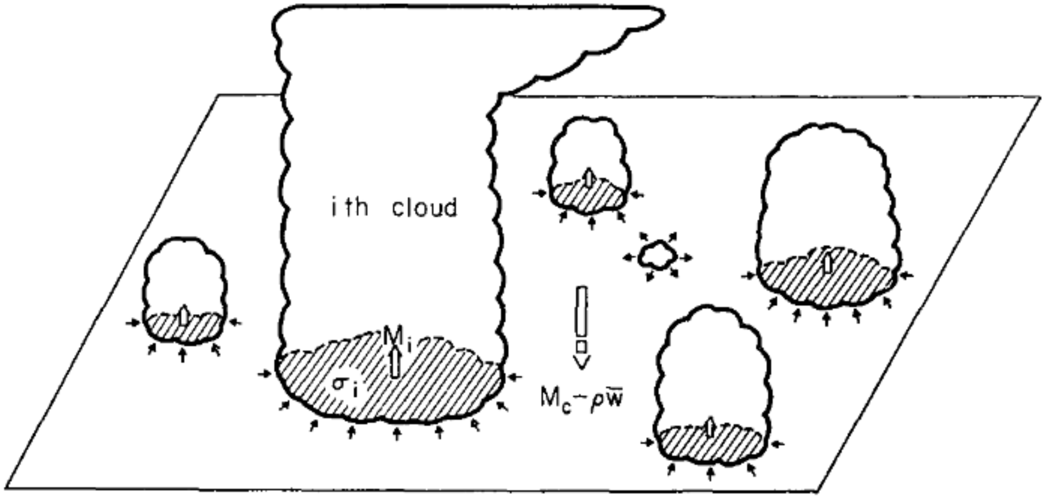


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

$$p(m_b)\mathrm{d}m_b = \frac{1}{\langle m_b \rangle} e^{-\frac{m_b}{\langle m_b \rangle}} \mathrm{d}m_b$$

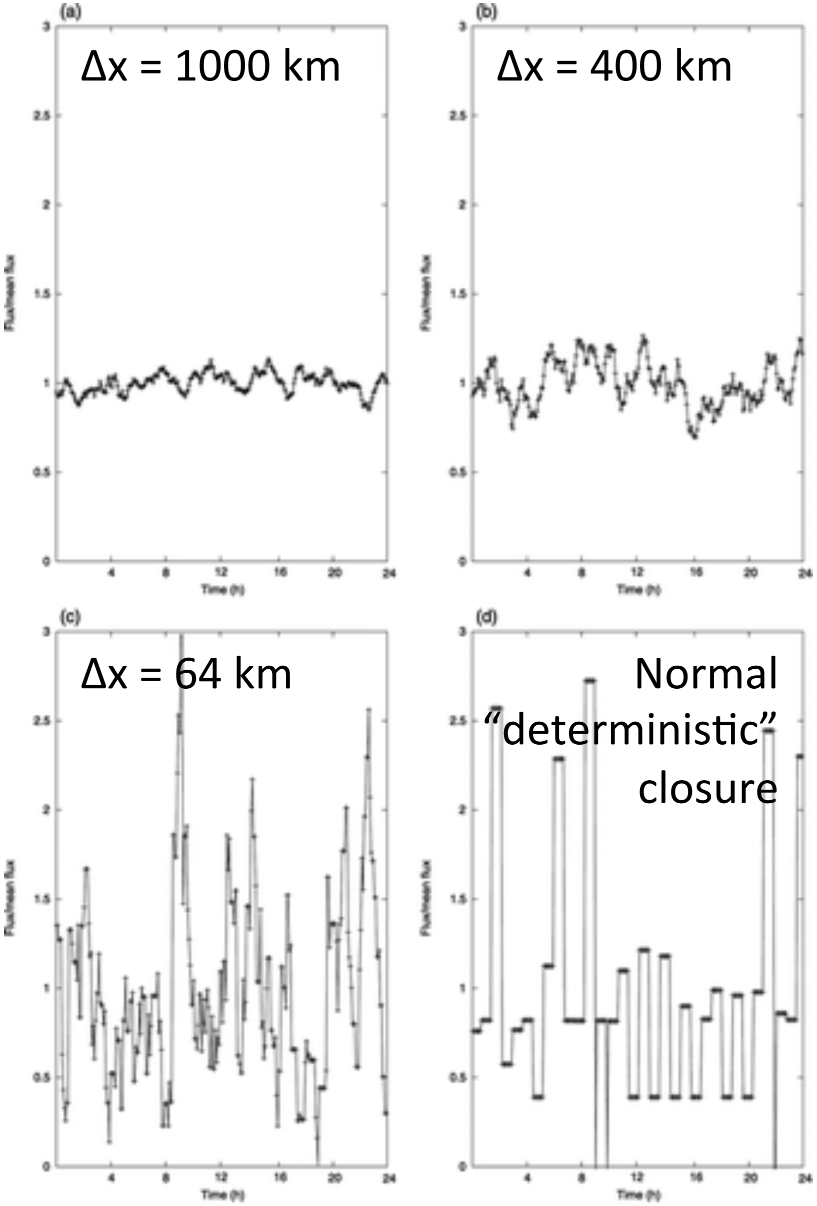
(Craig & Cohen 2006)

Addressing the assumption of Convective Quasi-Equilibrium: a) departures from diagnostic statistical-equilibrium

Implementation:

1) Assume the equilibrium holds over a scale many grid-cells across; average over this area to obtain the CAPE and closure mass-flux.
2) At each grid-point, randomly sample the equilibrium distribution (number of clouds drawn scales with grid-area, and the equilibrium mass-flux from closure).
3) Compute updraft properties for each individual cloud.
4) Sum over the sample of cloud mass-fluxes / detrainment-fluxes to get grid-mean tendencies.

Grid-scale variability increases as grid-length decreases, consistent with coarse-grained LES.



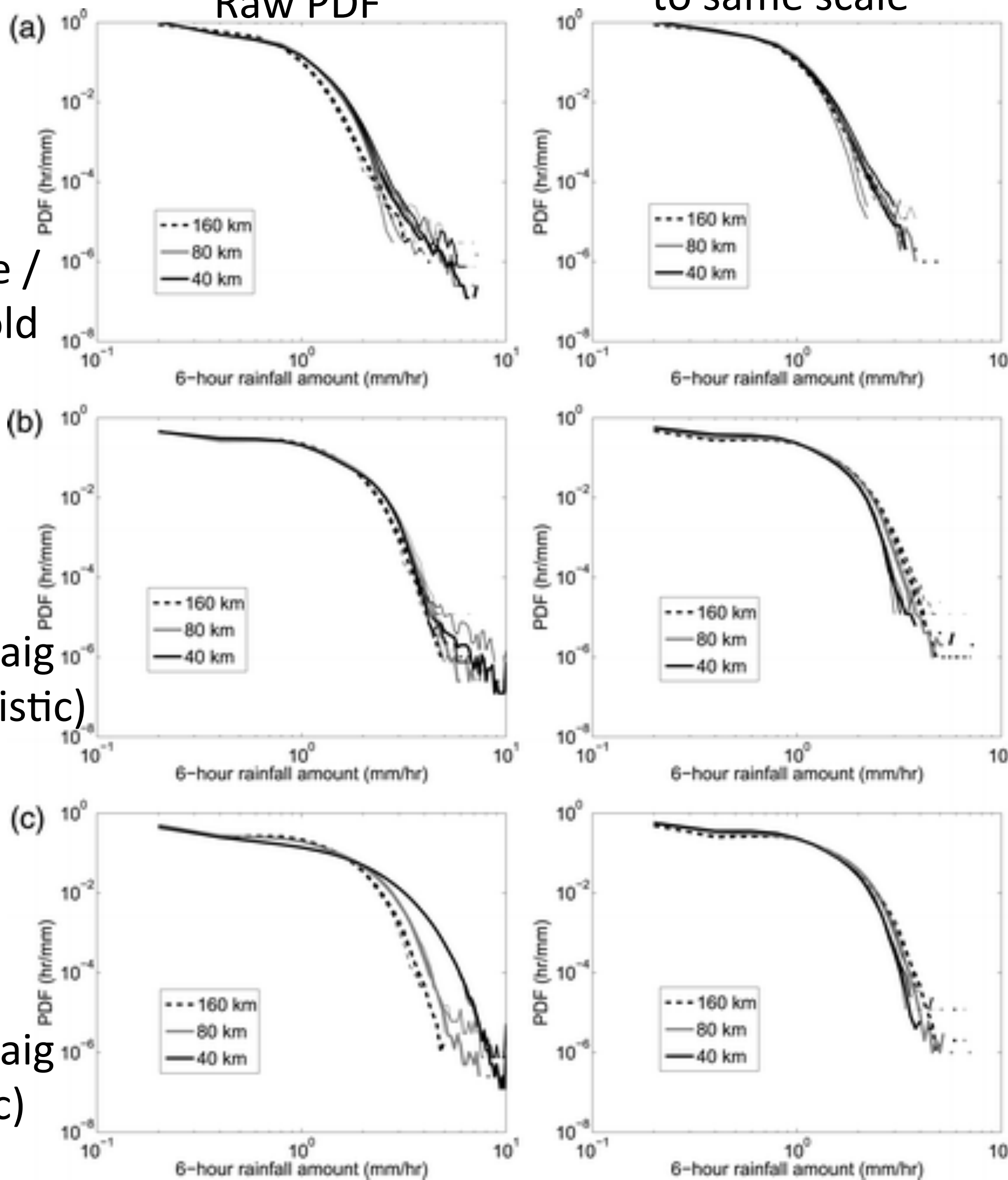
Addressing the assumption of Convective Quasi-Equilibrium:
a) departures from diagnostic statistical-equilibrium

Keane, et al. (2014): The Plant–Craig Stochastic Convection Scheme in ICON and Its Scale Adaptivity.

- PDF's of 6h mean rain-rate in ICON aqua-planet at 3 resolutions.

- Determinisitc schemes; give same PDF regardless of scale!

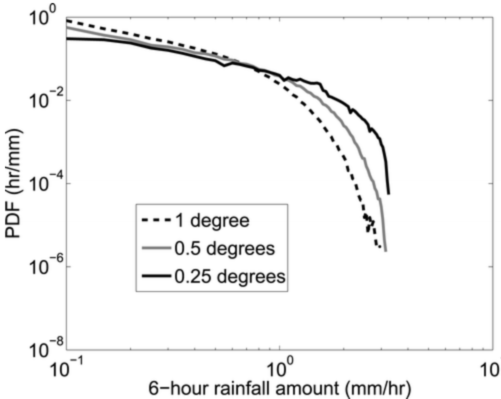
- Plant & Craig stochastic adapts with scale, consistent with TRMM obs.



Tietdke / Bechtold

Plant & Craig (deterministic)

Plant & Craig (stochastic)



TRMM (Tropical Pacific)

Addressing the assumption of Convective Quasi-Equilibrium: b) vertical inertia

Gerard & Geleyn (2005): Evolution of a subgrid deep convection parameterisation in a limited-area model with increasing resolution.

Mass-flux convection scheme, with prognostic closure.

Sub-grid mass-flux: $M = \sigma_u (w_u - w_e)$

Then there is a prognostic vertical momentum equation for ***w*** on each level:

$$\frac{\partial(\omega_u - \omega_e)}{\partial t} = -\underbrace{\frac{\rho g^2}{1+\gamma'} \frac{T_{vu} - \overline{T}_v}{\overline{T}_v}}_{\text{Buoyancy}} + \underbrace{\left(\frac{1}{p} + \frac{1}{\rho}\left(E_u + \frac{K_d}{g}\right)\right)(\omega_u - \omega_e)^2}_{\text{Drag}} - \underbrace{\frac{1}{2}\frac{\partial(\omega_u - \omega_e)^2}{\partial p}}_{\text{Vertical advection}}$$

...and a prognostic equation for the updraft fraction σ, which is constant on all levels where convection is active: (prognostic moisture convergence closure)

$$\underbrace{\frac{\partial \sigma_u}{\partial t} \int_{p_{top}}^{p_{bottom}} (h_u - \bar{h}) \frac{\mathrm{d}p}{g}}_{\text{Storage}} = \underbrace{L \int_{p_{top}}^{p_{bottom}} \sigma_u (\omega_u - \omega_e) \frac{\partial \bar{q}}{\partial p} \frac{\mathrm{d}p}{g}}_{\text{-Consumption (vertical flux)}} + \underbrace{L\left(F_{q\,\mathrm{surf}} - \int_{p_{top}}^{p_{bottom}} \underline{\nabla}_h . q \begin{pmatrix} u \\ v \end{pmatrix} \frac{\mathrm{d}p}{g}\right)}_{\text{Input (moisture convergence)}}$$

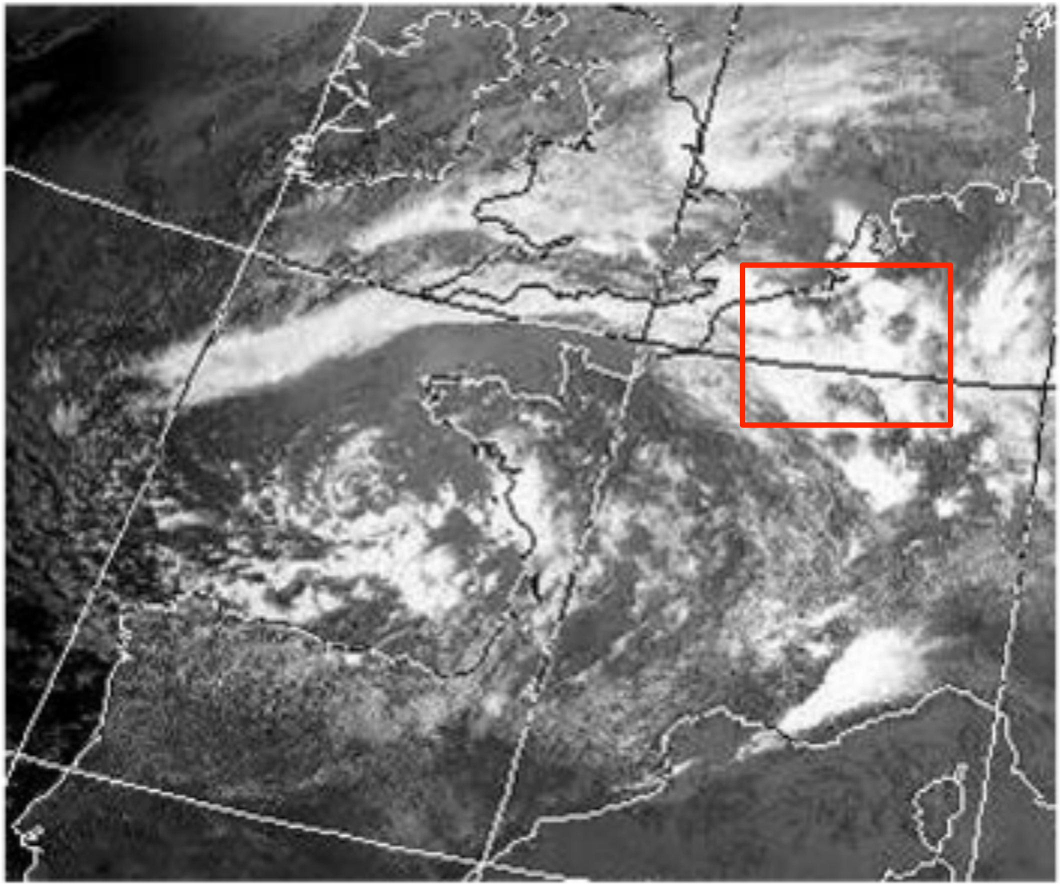
Addressing the assumption of Convective Quasi-Equilibrium: b) vertical inertia

Gerard (2007): An integrated package for subgrid convection, clouds and precipitation compatible with meso-gamma scales.

Implemented the prognostic closure with a comprehensive microphysics scheme.

All updraft condensate is detrained, so that precipitation and phase changes are handled consistently for updraft and resolved condensate.

- NWP case of heavy convective storms rainfall over Belgium.
- LAM forecasts run at 7, 4 and 2 km horizontal grid-spacing.

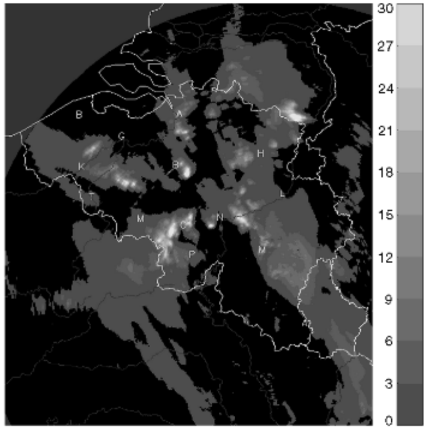


Addressing the assumption of Convective Quasi-Equilibrium: b) vertical inertia

Prognostic parameterisation mitigates blobby behaviour when poorly resolved.

Successfully reproduces intense cores and wider areas of light rain.

Radar



Explicit and parameterised simulations both give increase of domain-total rainfall with resolution.

Because spatially-correlated fluctuations in w and q get better resolved:

$$F_q = \overline{w'q'}$$

increases.

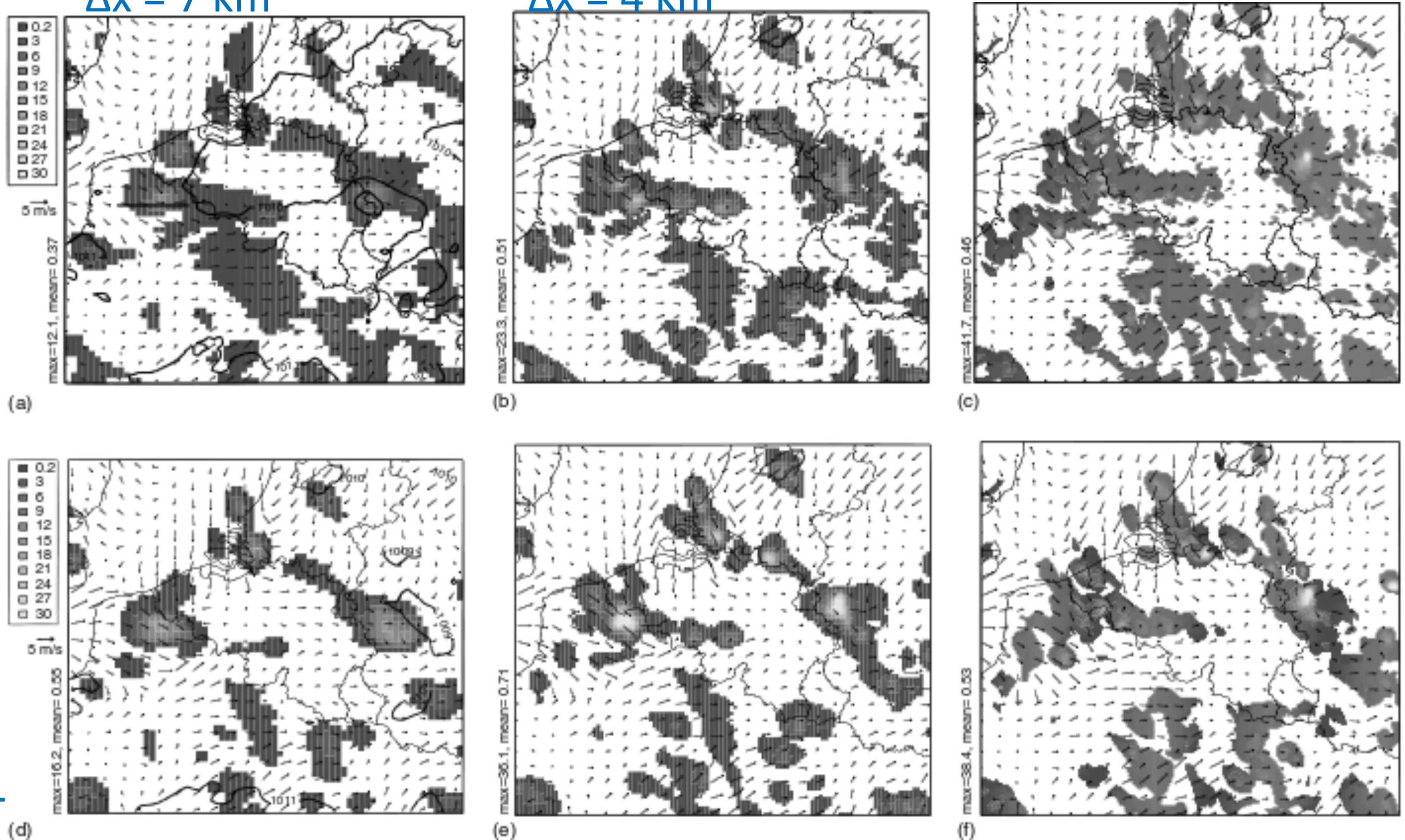
Δx = 7 km

Δx = 4 km

Δx = 2 km

Prognostic convection

No convetection parameterisation



Addressing the assumption of homogeneous updrafts

Moeng et al (2010): A Mixed Scheme for Subgrid-Scale Fluxes in Cloud-Resolving Models.

Analyse “Giga-LES” deep convection simulation (Δx = 100 m, domain-size = 200 km).

Use a low-pass filter to decompose the flow into resolved vs sub-grid components at a 4 km filter-scale.

Further decompose the sub-grid flow:
(NOT assuming that filter (~) averages sub-filter scales to zero!)

$$\widetilde{F}_{q\,\mathrm{s.g.}} = \widetilde{wq} - \widetilde{w}\widetilde{q} = \widetilde{(\widetilde{w}+w')(\widetilde{q}+q')} - \widetilde{(\widetilde{w}+w')}\,\widetilde{(\widetilde{q}+q')}$$

$$= \underbrace{\widetilde{\widetilde{w}\widetilde{q}} - \widetilde{\widetilde{w}}\widetilde{\widetilde{q}}}_{\text{“Leonard” term}} + \underbrace{\widetilde{\widetilde{w}q'} + \widetilde{w'\widetilde{q}} - \widetilde{\widetilde{w}}\widetilde{q'} - \widetilde{w'}\widetilde{\widetilde{q}}}_{\text{“Cross” term}} + \underbrace{\widetilde{w'q'} - \widetilde{w'}\widetilde{q'}}_{\text{“Reynolds” term}}$$

The L and C terms are non-zero if the grid-scale filter is not a precise spectral cut-off.

Explicitly calculate each of these terms from the low-pass filtered LES data, and examine their spatial variability...

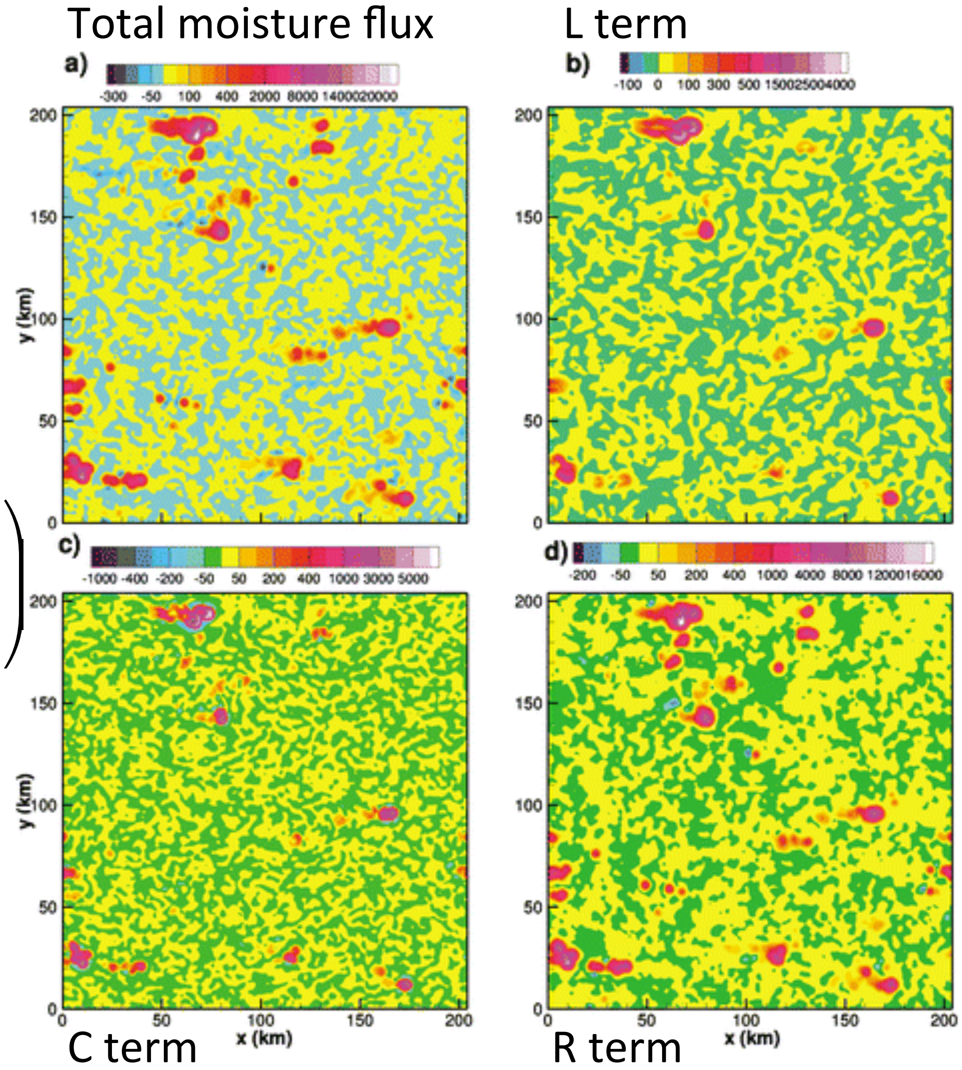
Addressing the assumption of homogeneous updrafts

Moeng et al (2010): A Mixed Scheme for Subgrid-Scale Fluxes in Cloud-Resolving Models.

X-Y cross-section at height 5 km.

All 3 terms dominated by positive values where we have deep convection!

"Using a tensor diffusivity model to invert the filtering" can express the L term as a function of only resolved scales...


Total moisture flux

L term

C term

R term

$$\widetilde{\widetilde{w}\widetilde{q}} - \widetilde{\widetilde{w}}\,\widetilde{\widetilde{q}} \approx \frac{\Delta x_{filter}}{12}\left(\frac{\partial\widetilde{w}}{\partial x}\frac{\partial\widetilde{q}}{\partial x}+\frac{\partial\widetilde{w}}{\partial y}\frac{\partial\widetilde{q}}{\partial y}\right)$$

Noting that the C term has equal magnitude to the L term, and nearly the same pattern, parameterise

C term = L term,   so:

$$\widetilde{F}_{q\,\mathrm{s.g.}} = 2\frac{\Delta x_{filter}}{12}\left(\frac{\partial\widetilde{w}}{\partial x}\frac{\partial\widetilde{q}}{\partial x}+\frac{\partial\widetilde{w}}{\partial y}\frac{\partial\widetilde{q}}{\partial y}\right) + R\ \mathrm{term}$$

Parameterise as eddy-diffusion

Addressing the assumption of homogeneous updrafts

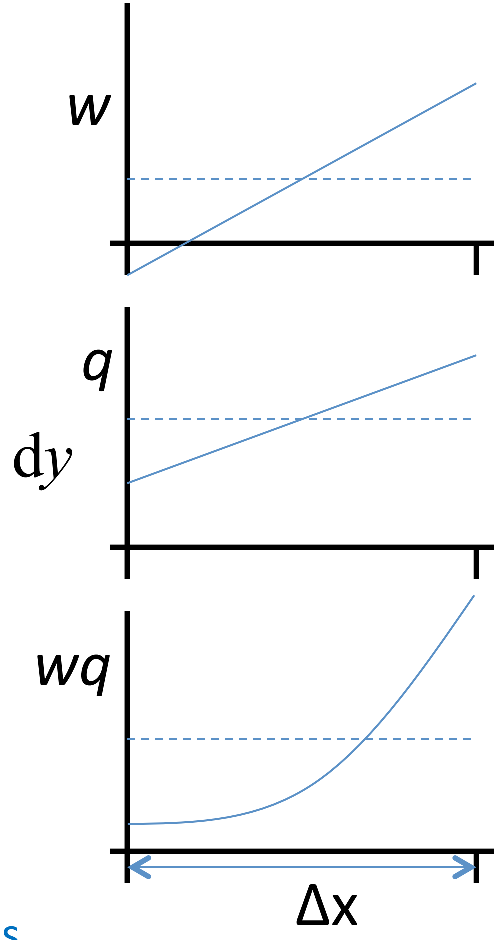
An aside on: $\widetilde{\tilde{w}\tilde{q}} - \tilde{\tilde{w}}\tilde{\tilde{q}} \approx \frac{\Delta x_{filter}}{12}\left(\frac{\partial \tilde{w}}{\partial x}\frac{\partial \tilde{q}}{\partial x} + \frac{\partial \tilde{w}}{\partial y}\frac{\partial \tilde{q}}{\partial y}\right)$

Can get the same answer from finite element thinking:

$$F_q = \int_{y=-\frac{\Delta y}{2}}^{\frac{\Delta y}{2}} \int_{y=-\frac{\Delta x}{2}}^{\frac{\Delta x}{2}} wq \,\mathrm{d}x\,\mathrm{d}y$$

$$= \int_{y=-\frac{\Delta y}{2}}^{\frac{\Delta y}{2}} \int_{y=-\frac{\Delta x}{2}}^{\frac{\Delta x}{2}} \left(\overline{w} + \frac{\partial w}{\partial x}x + \frac{\partial w}{\partial y}y\right)\left(\overline{q} + \frac{\partial q}{\partial x}x + \frac{\partial q}{\partial y}y\right)\mathrm{d}x\,\mathrm{d}y$$

$$= \overline{w}\,\overline{q} + \underbrace{\frac{1}{12}\left(\Delta x^2 \frac{\partial w}{\partial x}\frac{\partial q}{\partial x} + \Delta y^2 \frac{\partial w}{\partial y}\frac{\partial q}{\partial y}\right)}$$



Multiplying this term by 2 amounts to assuming that sub-grid fluctuations are correlated the same as the local grid-scale gradients.

i.e. Self-Similarity (evidence for this in Moeng (2010)'s results).

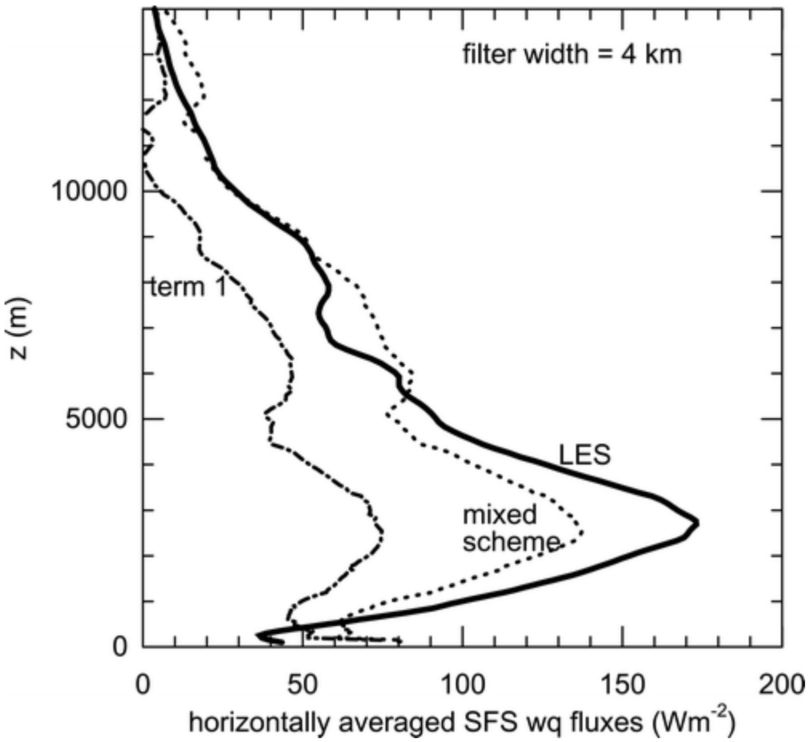
Addressing the assumption of homogeneous updrafts

Moeng et al (2010): A Mixed Scheme for Subgrid-Scale Fluxes in Cloud-Resolving Models.

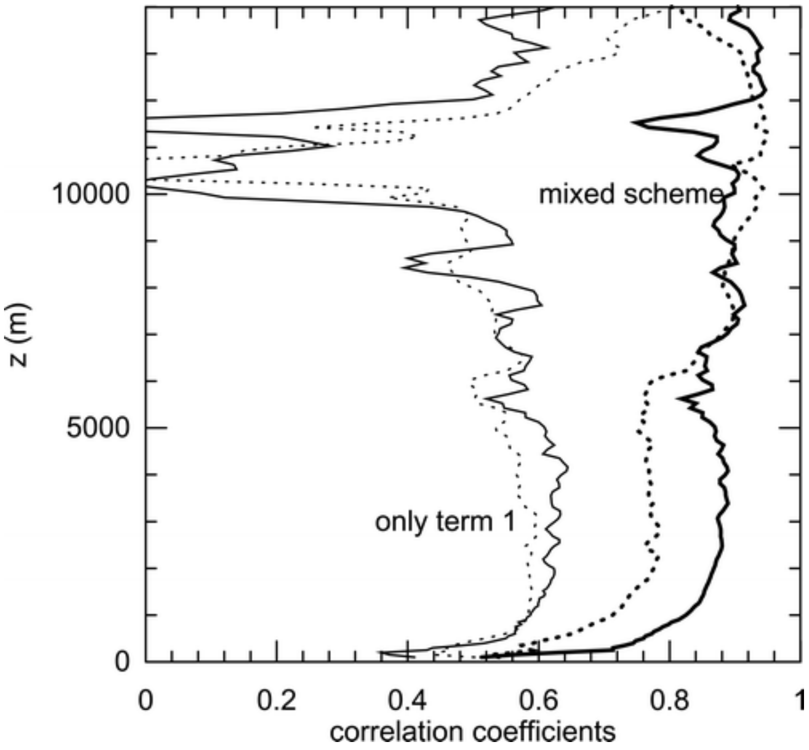
Define a parameterised sub-grid flux as:

$$\widetilde{F}_{q\,\mathrm{s.g.}} = -K_h \frac{\partial \tilde{q}}{\partial z} + 2\frac{\Delta x_{filter}}{12}\left(\frac{\partial \tilde{w}}{\partial x}\frac{\partial \tilde{q}}{\partial x} + \frac{\partial \tilde{w}}{\partial y}\frac{\partial \tilde{q}}{\partial y}\right)$$

Offline comparison with directly computed sub-grid flux from the LES:



Domain-mean moisture flux



Spatial correlation with LES

Addressing the assumption of homogeneous updrafts

Moeng. 2014: A Closure for Updraft–Downdraft Representation of Subgrid-Scale Fluxes in Cloud-Resolving Models.

Extend the same sub-grid flux closure to replace the eddy-viscosity term all-together!

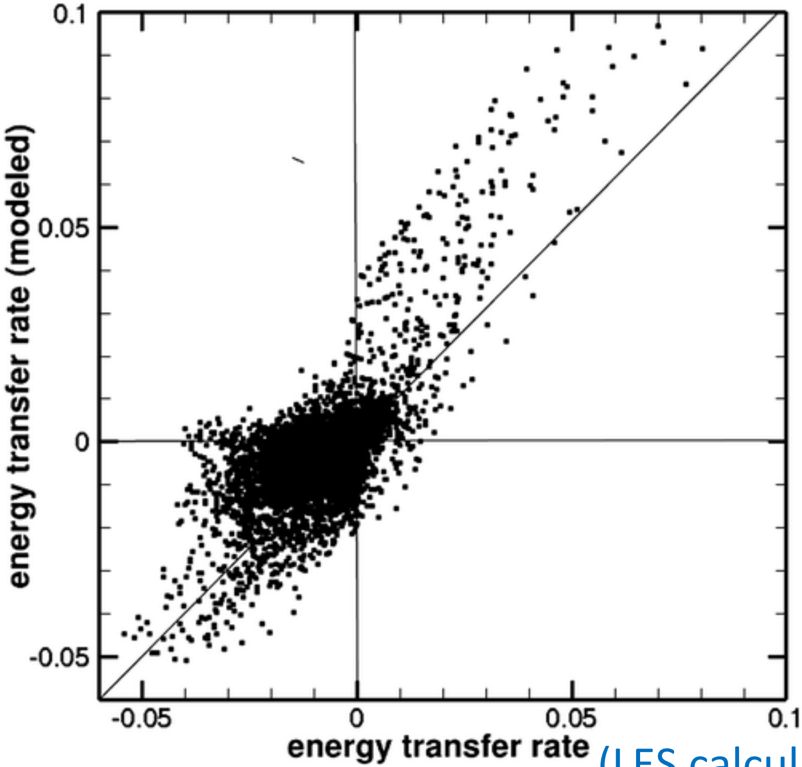
$$\widetilde{F}_{q\,\text{s.g.}} \approx 6.0\,\frac{\Delta x_{filter}}{12}\left(\frac{\partial \widetilde{w}}{\partial x}\frac{\partial \widetilde{q}}{\partial x}+\frac{\partial \widetilde{w}}{\partial y}\frac{\partial \widetilde{q}}{\partial y}\right)$$

(tuneable parameter)

Rate of KE-transfer between resolved and sub-grid scale motions.

Eddy-diffusion schemes can ONLY go down-scale!

Could this scheme solve the problem of moisture fluxes (and hence rainfall) increasing with resolution in explicit convection simulations?



(Off-line parameterised)

(LES calculated)

Addressing the assumption of small updraft area fraction

Arakawa et al (2011): Toward unification of the multiscale modeling of the atmosphere.

Suggest 2 routes to getting a consistent treatment of sub-grid processes between GCM and CRM resolutions:

I: A convective parameterisation without the small σ assumption.
II: Super-parameterisation (embedding a small CRM in each grid-cell).

They go on to formulate a framework for I:

Without the small area assumption, the mass-flux formulation can be written:

$$F_{q\,\text{s.g.}} = \overline{wq} - \overline{w}\,\overline{q} = \frac{\sigma}{1-\sigma}(w_u - \overline{w})(q_u - \overline{q}) \qquad (1)$$

They then propose that:

$$(w_u - \overline{w})(q_u - \overline{q}) = (1-\sigma)^2 \underbrace{\left[(w_u - \overline{w})(q_u - \overline{q})\right]_{\sigma \to 0}} \qquad (2)$$

This is just the simplest form that guarantees (1) doesn't blow-up when σ→1. No obvious justification!?

What the cloud-model gives you if you assume small area, as is traditional.

Addressing the assumption of small updraft area fraction

Arakawa et al (2011): Toward unification of the multiscale modeling of the atmosphere.

But how to determine the updraft fractional area, and its dependence on model-resolution?

Take (1), and state that...

Flux required to adjust the large-scale profile (according to the closure hypothesis; e.g. removal of CAPE)...

Occurs for the sub-grid-state predicted at large-scale equilibrium (σ→0):

$$\left[\overline{wq}-\overline{w}\,\overline{q}\right]_{closure}=\frac{\sigma}{1-\sigma}\left[(w_u-\overline{w})(q_u-\overline{q})\right]_{\sigma\to 0}$$

$$\Rightarrow\sigma=\frac{\left[\overline{wq}-\overline{w}\,\overline{q}\right]_{closure}}{\left[\overline{wq}-\overline{w}\,\overline{q}\right]_{closure}+\left[(w_u-\overline{w})(q_u-\overline{q})\right]_{\sigma\to 0}}\qquad(3)$$

Substituting (2) and (3) into (1) and re-arranging, we get:

$$F_{q\,\mathrm{s.g.}}=\overline{wq}-\overline{w}\,\overline{q}=(1-\sigma)^2\left[\overline{wq}-\overline{w}\,\overline{q}\right]_{closure}$$

Addressing the assumption of small updraft area fraction

Arakawa et al (2011): Toward unification of the multiscale modeling of the atmosphere.

In summary, the proposed scheme diagnoses the updraft fractional area using:

$$\sigma = \frac{\left[\overline{wq} - \overline{w}\,\overline{q}\right]_{closure}}{\underbrace{\left[\overline{wq} - \overline{w}\,\overline{q}\right]_{closure}}_{\text{Determined from closure hypothesis.}} + \underbrace{\left[(w_u - \overline{w})(q_u - \overline{q})\right]_{\sigma \to 0}}_{\text{Determined from an updraft plume model; should naturally decrease as more of the variability of w and q becomes resolved, leading to σ→1.}}}$$

The sub-grid flux is then calculated using:

$$F_{q\,\mathrm{s.g.}} = (1-\sigma)^2 \left[\overline{wq} - \overline{w}\,\overline{q}\right]_{closure}$$

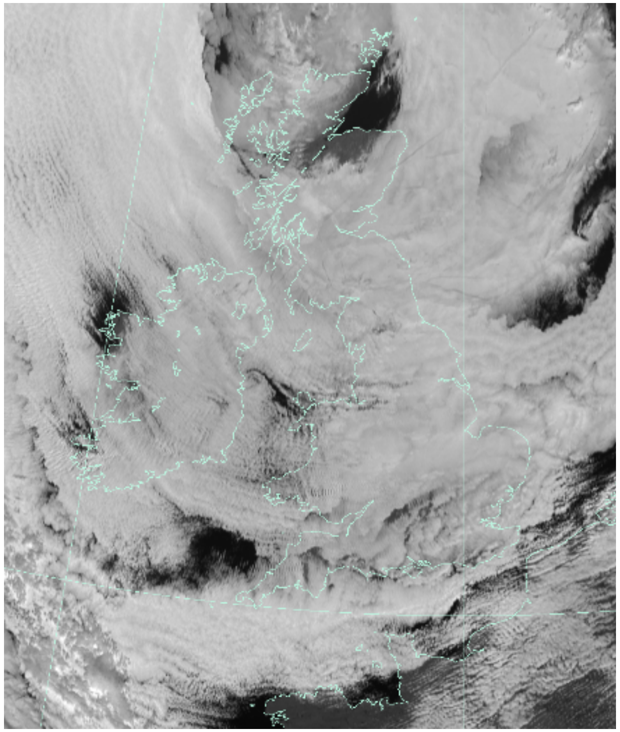
Smoothly de-activates the parameterised flux as σ→1.

Grey-zone developments in Met Office NWP forecasts

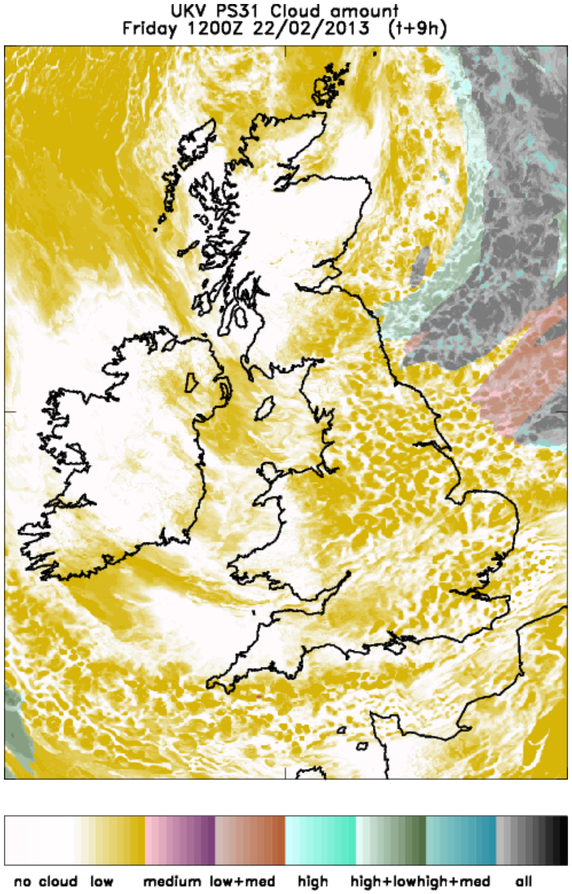
UKV - Operational forecasts at 1.5 km horizontal resolution over UK domain

- Excessive mesoscale variability in UKV leading to spurious gaps in cloud – not present in old 4 km version!
- Using UM 1-D boundary-layer parameterisation; not good for 3-D turbulence.

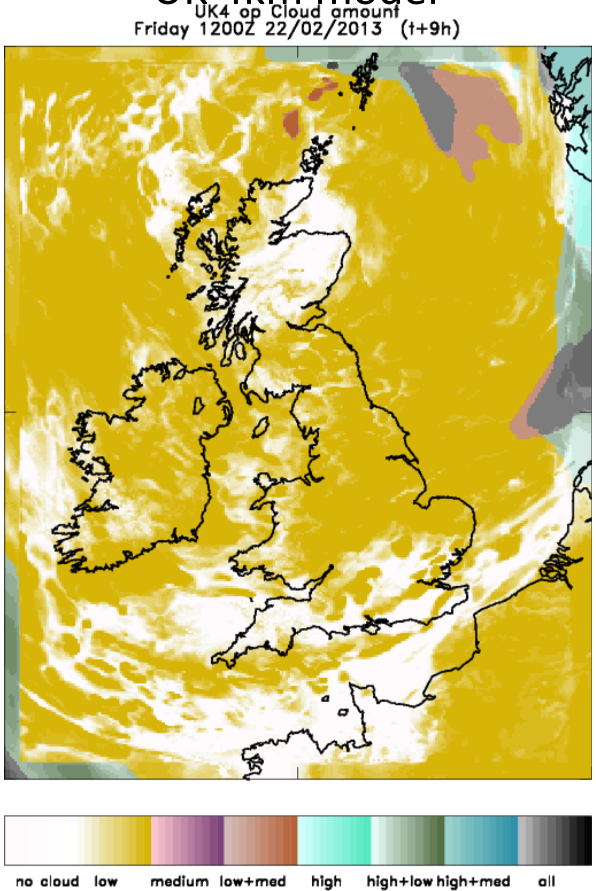
Visible Satellite



UKV control



UK 4km model



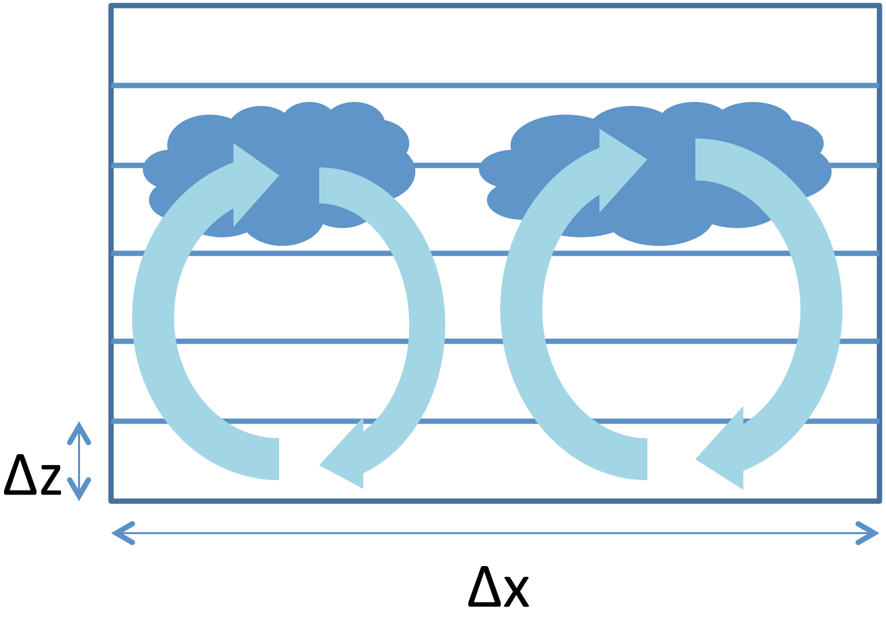
Grey-zone developments in Met Office NWP forecasts

When resolving 3-D over-turning, strong justification for a local 3-D turbulence closure.

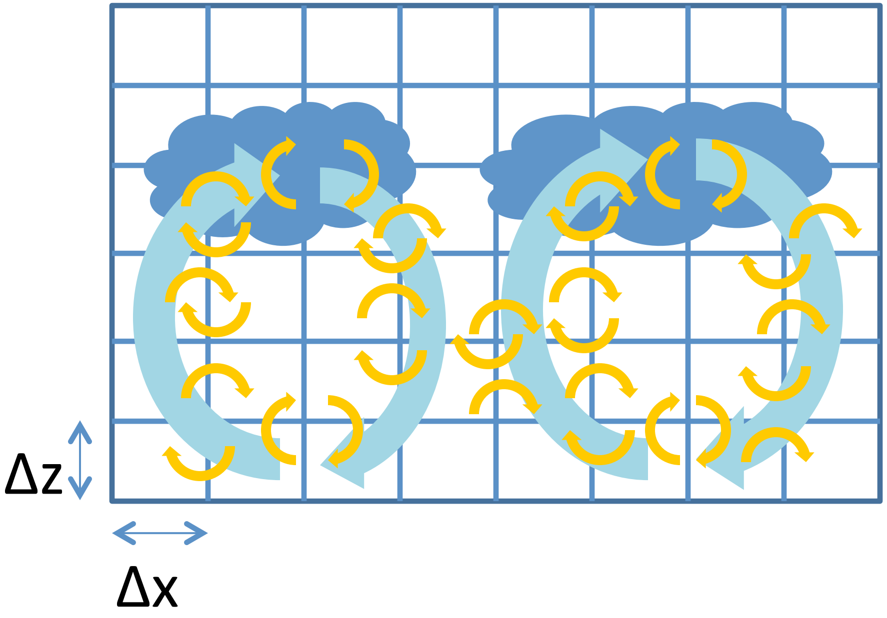
But could “double-count” vertical fluxes also handled by the boundary-layer scheme!

Which approach is more appropriate (3-D turbulence vs 1-D non-local vertical flux) depends on how much of the over-turning we expect to be resolved.

Parameterised vertical flux due to unresolved over-turning.



Resolved over-turning with sub-grid 3-D turbulence.



Grey-zone developments in Met Office NWP forecasts

A pragmatic approach; blend smoothly from the boundary-layer scheme to the 3-D turbulence closure as a function of grid-size (how much of the over-turning we expect to resolve):

$$\left.\frac{\partial\phi}{\partial t}\right|_{s.g.} = W_{1\mathrm{D}}\frac{\partial}{\partial z}\left.\overline{\phi' w'}\right|_{BL} + (1-W_{1\mathrm{D}})\underline{\nabla}.\phi'\left.\begin{pmatrix}u'\\ v'\\ w'\end{pmatrix}\right|_{\mathrm{3D\,turb}}$$

The blending function $W_{1\mathrm{D}}$ is a function of both horizontal grid-size and model-state.

(Boutle et al. 2014 – in fact, since the 1-D BL and 3-D turbulence schemes are both closed on a K-diffusion mixing-length *L*, $W_{1\mathrm{D}}$ is used to scale *L*, with limits for consistency, instead of weighting the overall tendency).

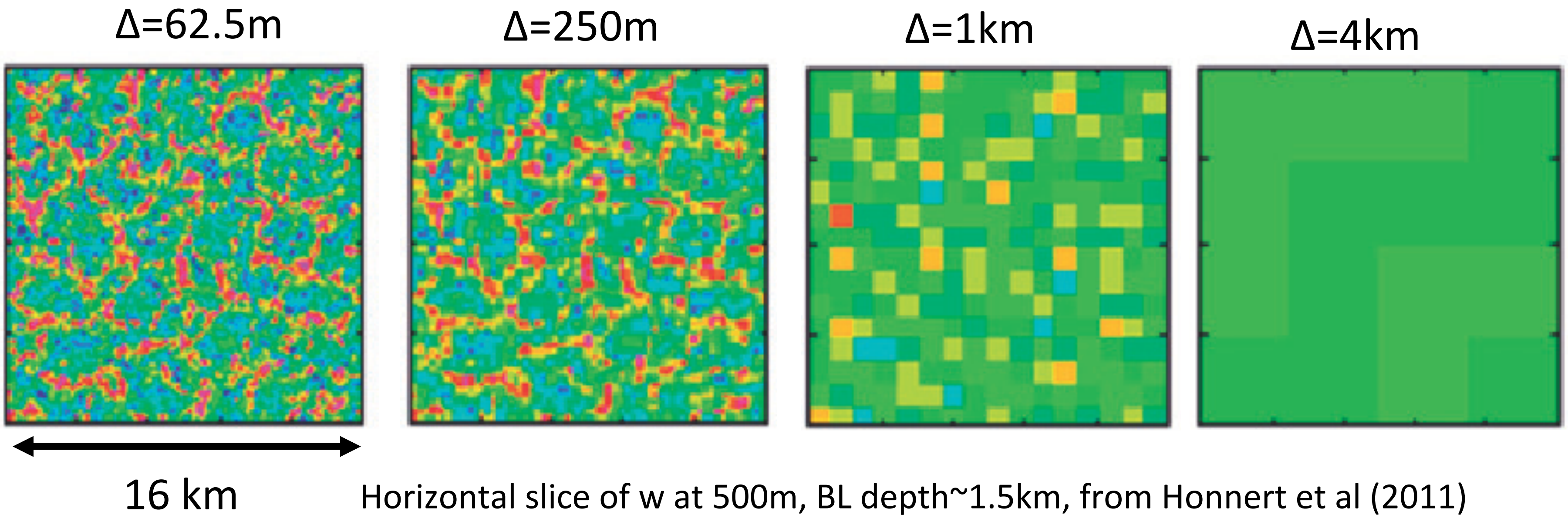
Determine the functional form of $W_{1\mathrm{D}}$ from analysis of resolved vs sub-grid TKE in LES...

Grey-zone developments in Met Office NWP forecasts

Honnert et al (2011).

Progressively coarse-grain LES of non-precipitating convective boundary-layer cases.

Calculate residual TKE and fluxes at each coarse-grained resolution



Horizontal slice of w at 500m, BL depth~1.5km, from Honnert et al (2011)

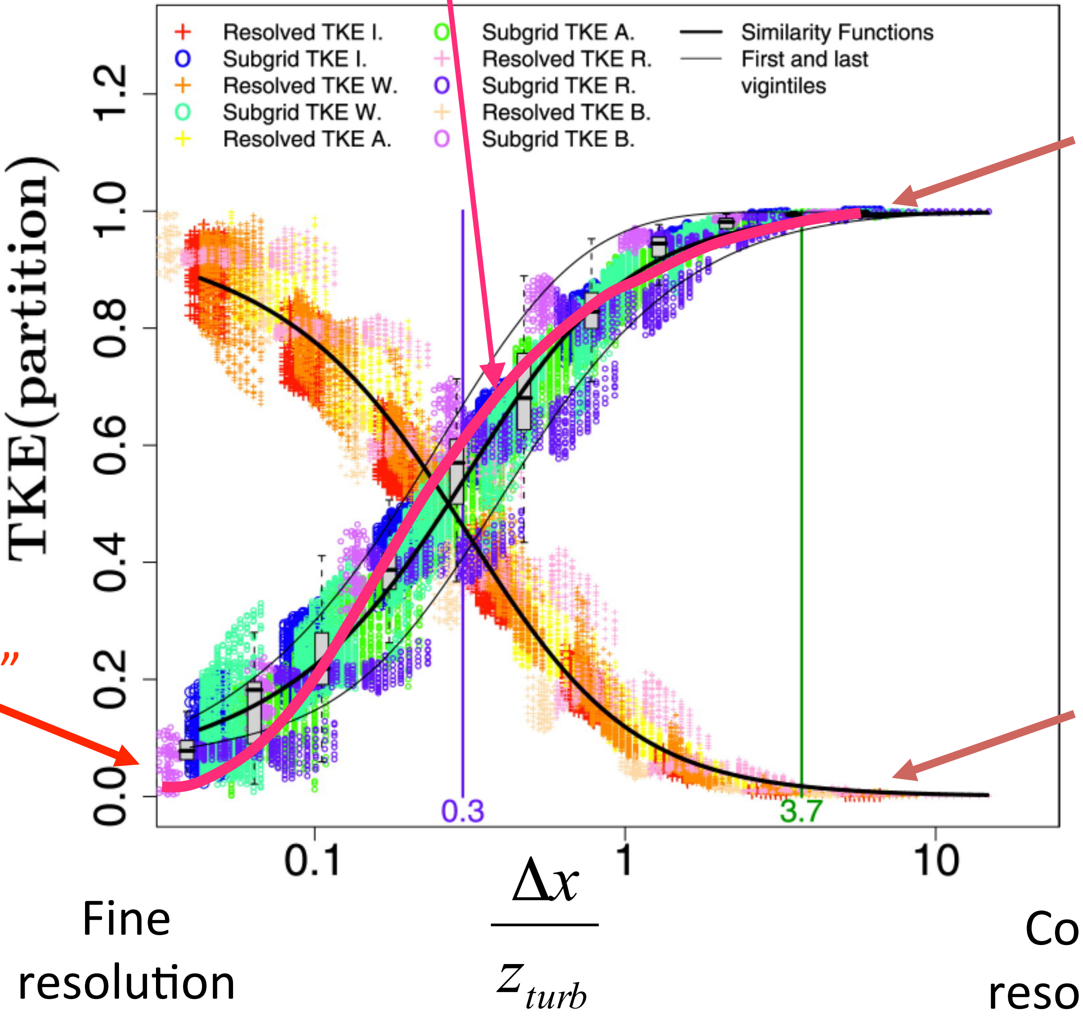
Grey-zone developments in Met Office NWP forecasts

Sub-grid fraction of TKE a good fit to a function of ratio of Δx to boundary-layer depth.

$$W_{1D} \approx 1 - \tanh\left(\beta \frac{z_{turb}}{\Delta x} \right)$$

Use this form to blend between 1-D BL scheme and 3-D turbulence closure as BL-depth changes relative to grid-size.

Honnert et al (2011)



Subgrid TKE

Length scale of flow is typically the BL depth

Resolved TKE

Tends to zero for “well resolved” limit

Fine resolution

Coarse resolution

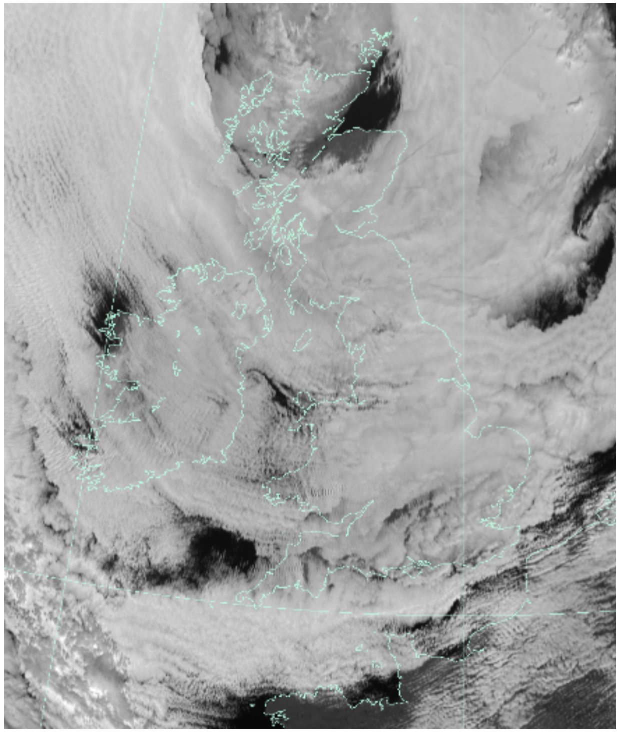
Grey-zone developments in Met Office NWP forecasts

Trial the new blended BL / turbulence scheme in UKV:

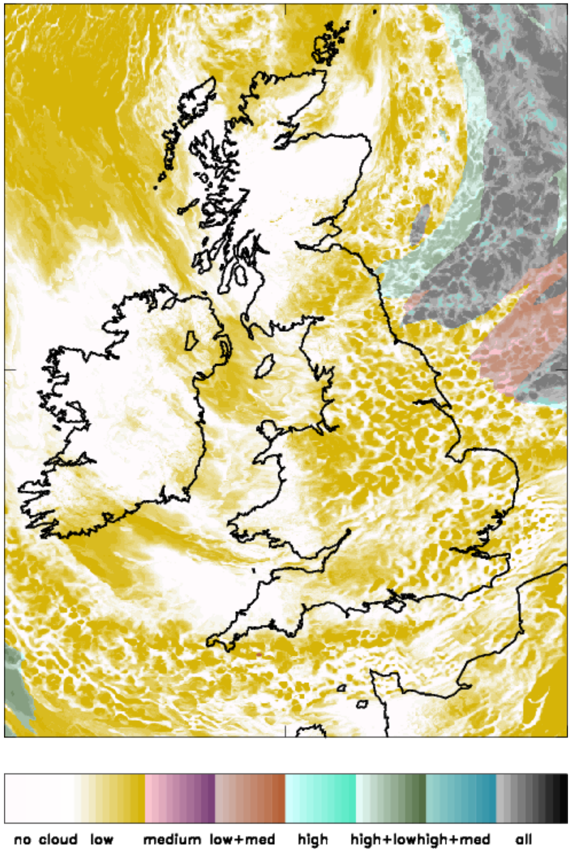
Winter stratocumulus case... Success!

Weighting of 3-D turbulence scheme gives appropriate eddy-diffusion to suppress spurious mesoscale circulations.

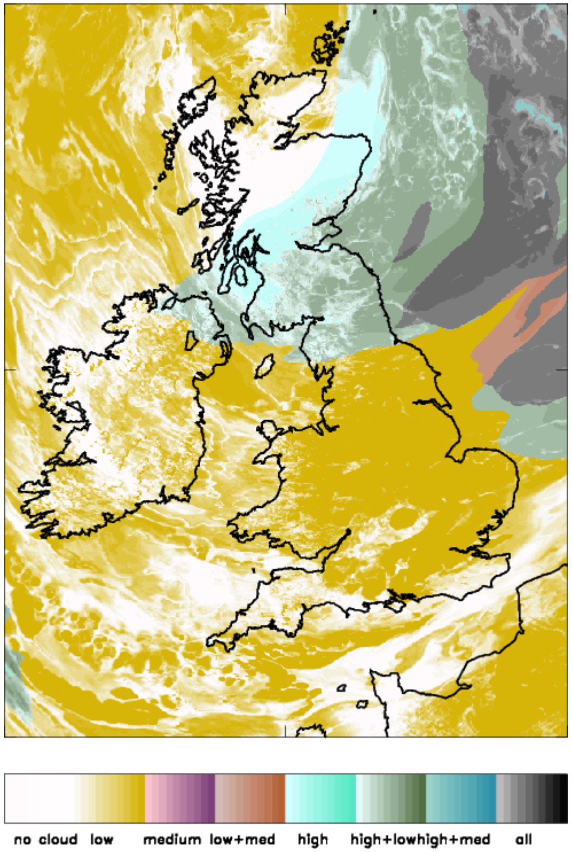
Visible Satellite



UKV control



Blended scheme
(plus scale-adaptive microphysics)

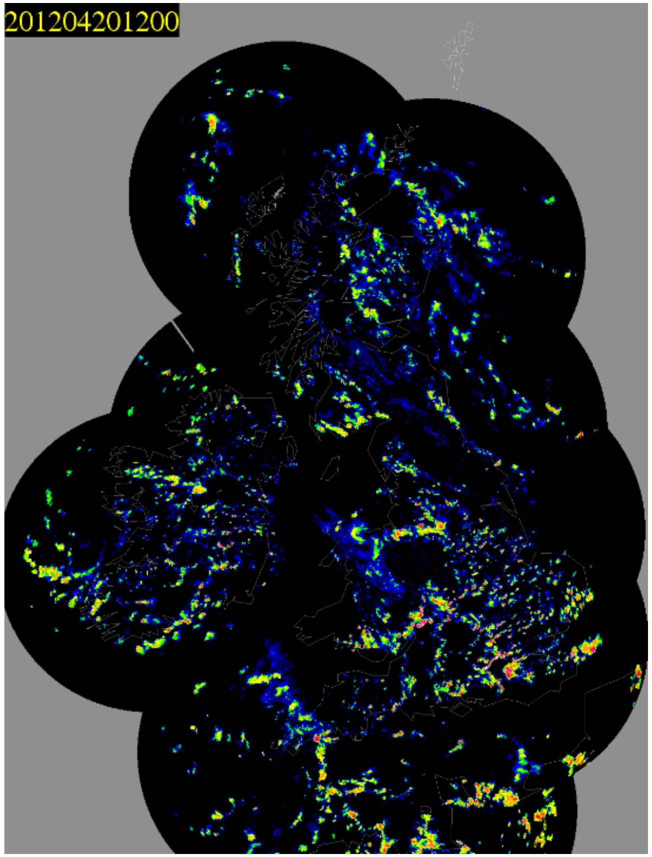


Grey-zone developments in Met Office NWP forecasts

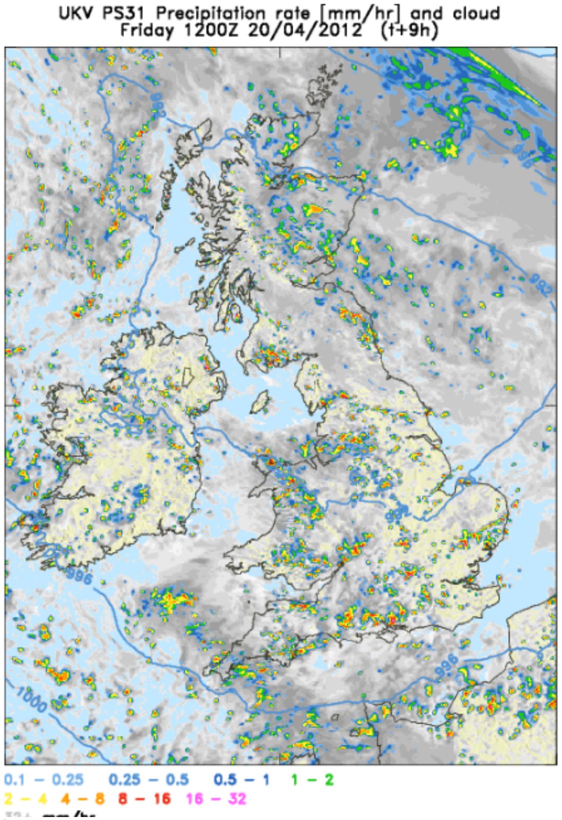
Trial the new blended BL / turbulence scheme in UKV:

Spring-time convective showers case (20th April 2012 – DYMECS) ...

Radar

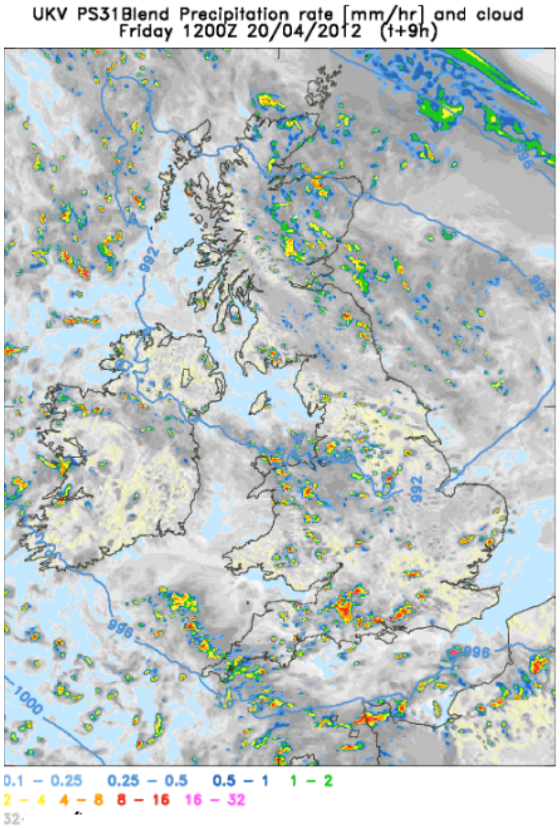


UKV control



Some large, some small showers

Blended scheme



Suppresses small showers

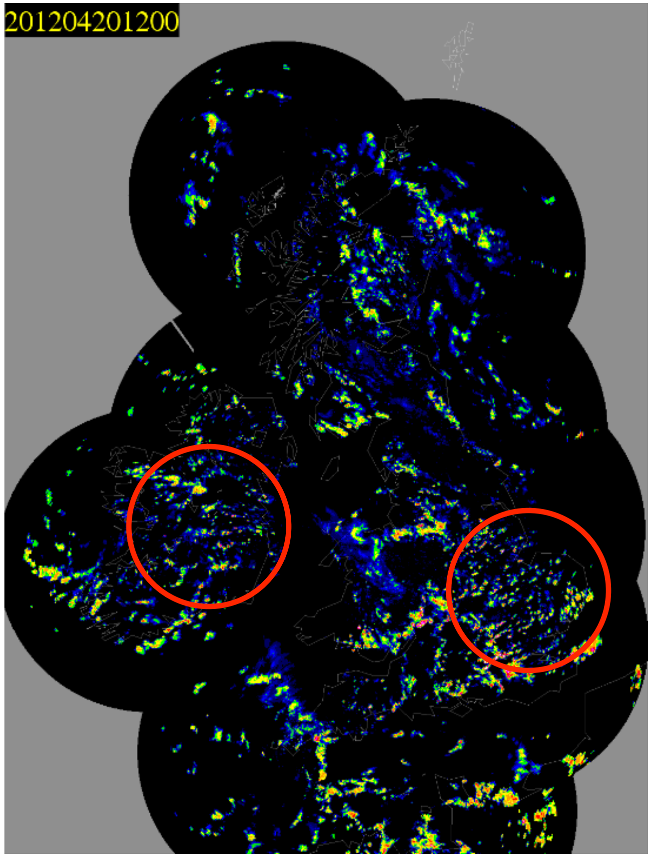
Grey-zone developments in Met Office NWP forecasts

Trial the new blended BL / turbulence scheme in UKV:

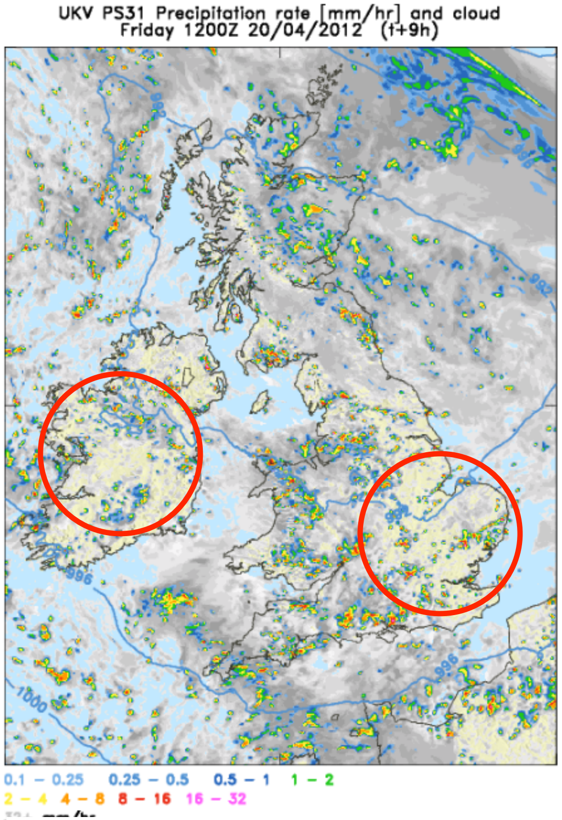
Spring-time convective showers case (20th April 2012 – DYMECS) ...

Extra 3-D turbulent eddy-diffusion stops small-scale showers from spinning-up.
(note: no convection parameterisation in UKV)

Radar

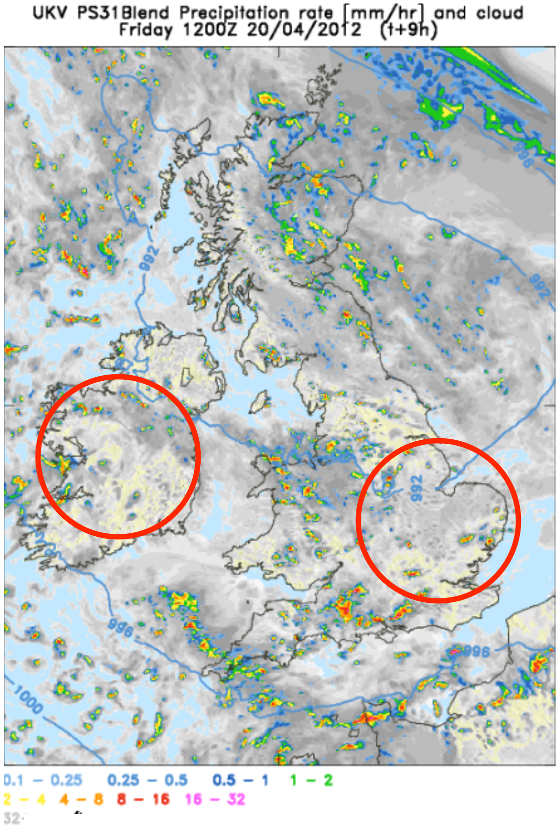


UKV control



Some large, some small showers

Blended scheme



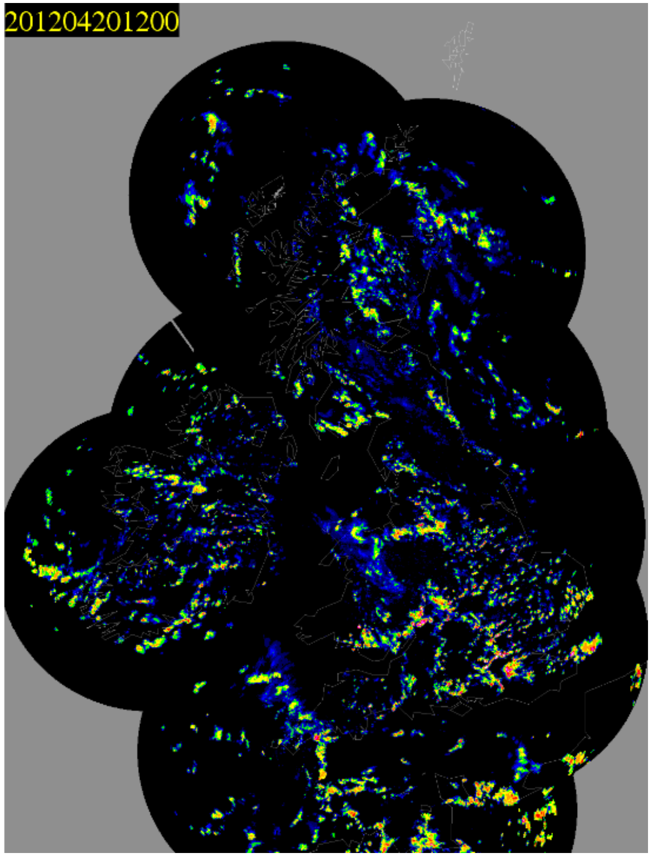
Suppresses small showers

Grey-zone developments in Met Office NWP forecasts

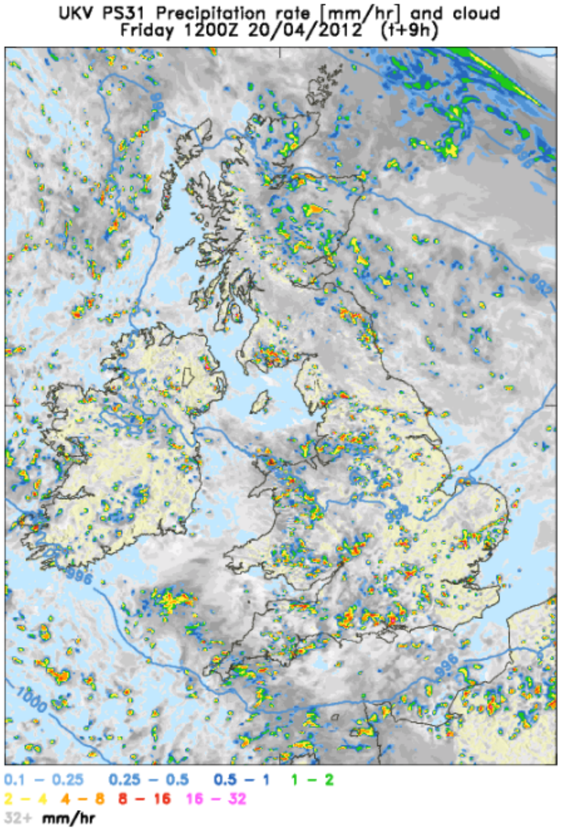
But the showers that have been suppressed weren't realistically resolvable at 1.5 km grid (UKV control represents them poorly as grid-scale noise or spuriously increases their size).

Try turning on the shallow convection scheme to parameterise them!

Closed on surface-flux, so rains uniformly everywhere.

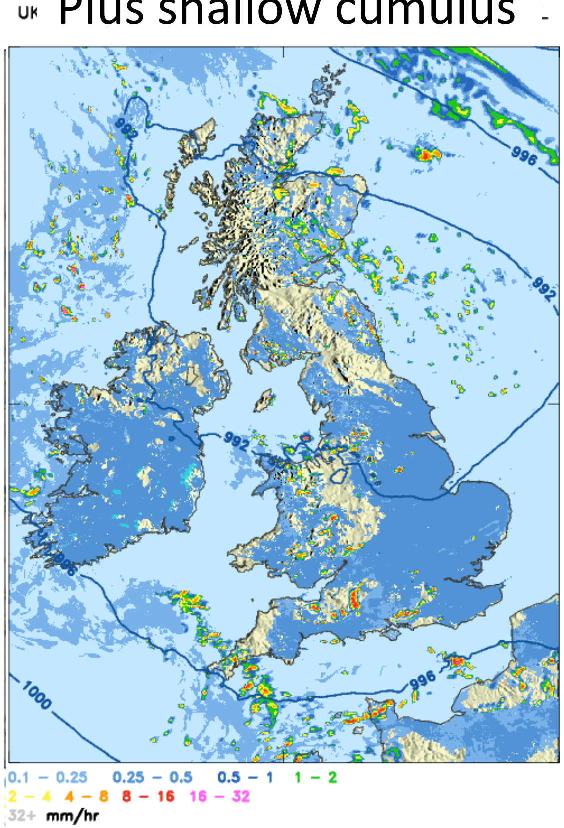


UKV control



Blended scheme

Plus shallow cumulus



Grey-zone developments in Met Office NWP forecasts

Design new blended closure for cloud-base mass-flux in the shallow convection scheme for the grey-zone:

$$m_b = W_{1D}\left(\left(1 - z'\right) m_b^{sh} + z' m_b^{dp} \right)$$

Shallow closure based on surface-flux

Deep closure based on removal of CAPE over a timescale.

$$W_{1D} \approx 1 - \tanh\left(\beta \frac{z_{cloud-top}}{\Delta x} \right)$$

z' = linear ramp from 0 at $z_{cloud\text{-}top}$ = 1500 m
to 1 at $z_{cloud\text{-}top}$ = 4 km.

Smoothly de-activates parameterised convection as it becomes large enough to be resolved.

Transitions smoothly from shallow to deep closure as height of convective cloud-top increases. Retains shallow entrainment / detrainment rates (consistent with small horizontal scale).

Additional triggering condition: w_{LCL} > 5 cm s^{-1}
(gives more realistic concentration of showers where we have resolved convergence).

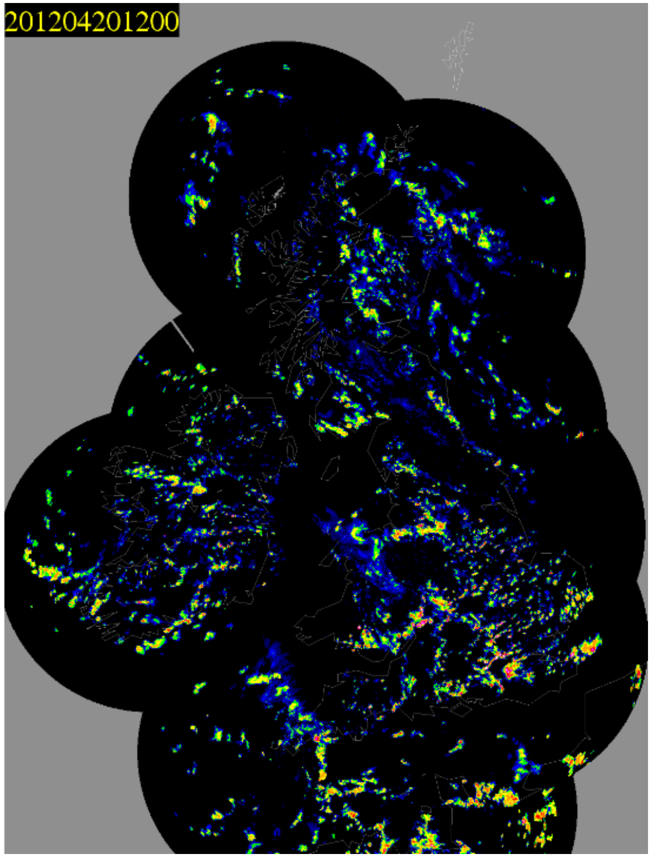
Grey-zone developments in Met Office NWP forecasts

Trial the blended scheme plus grey-zone shallow cumulus closure in UKV:

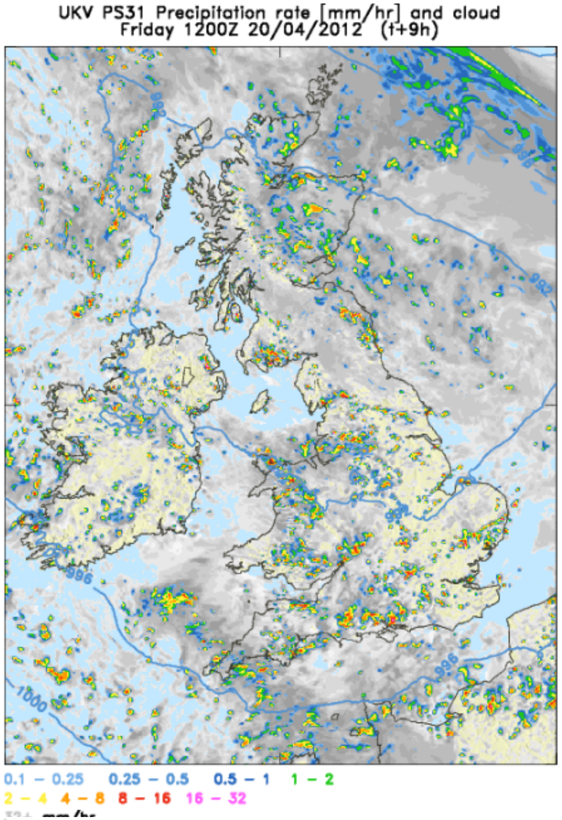
Spring-time convective showers case (20th April 2012 – DYMECS) ...

Success! (now have scattered small showers in the right areas).

Radar

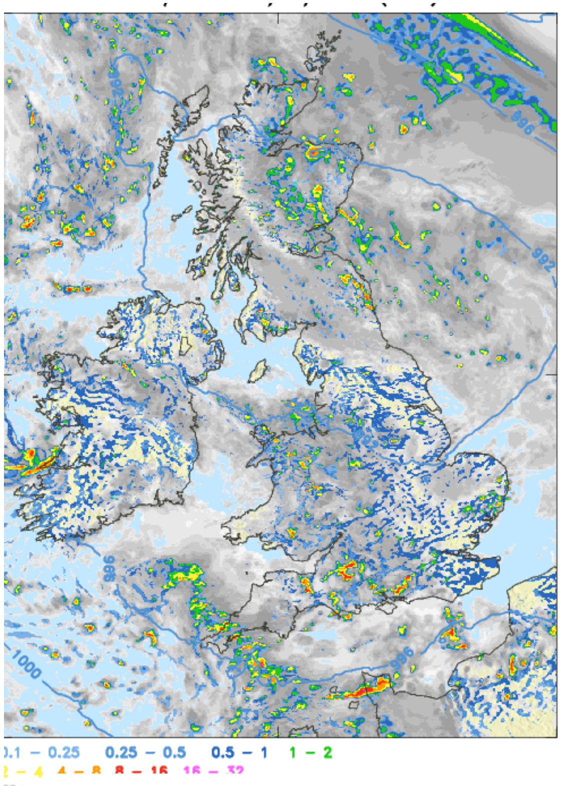


UKV control



Some large, some small showers

Blended plus grey-zone shallow cumulus closure



Some resolved, some param^d showers

Grey-zone developments in Met Office NWP forecasts

Summary:

1) “Scale-aware” smooth transition from 1-D vertical turbulent flux to 3-D eddy-diffusion when Δx gets smaller than the overturning length-scale (BL-height).

2) “Scale aware” smooth de-activation of convection parameterisation when Δx gets smaller than the convection length-scale (height of cloud-top).

Note: 2) not yet used operationally; instead, the turbulence blending is switched off when the BL-scheme diagnoses a convective boundary-layer.

This was done because the blending still delayed onset of some deep convective events; don’t want to risk missing a high-impact convective storm!

Ongoing development: introduce stochastic variations to surface fluxes in convective boundary-layer, to represent “missing” development of resolved-scale convection from parameterised sub-grid buoyant motions.

4) Where are we now? What next?

What might be wrong with convection in the grey-zone?

- **Missing processes:**
  - Triggering / maintenance of convection by cold-pool uplift.
  - Mixing-driven downdrafts
  - Convective overshoot and subsequent fall-back
  - Sensitivity to wind-sheer (downdrafts / organisation)
  - Microphysical processes in updrafts

Has anyone developed an experimental fix?
Yes
No
Sort of

- **Missing interactions** between parameterised and resolved processes:
  - Forcing of grid-mean vertical velocity by sub-grid updrafts & downdrafts.
  - Forcing of sub-grid updrafts & downdraft by resolved T, q, p gradients.

- **Invalid assumptions**:
  - Convective quasi-equilibrium (assume convection is entirely diagnostic)
  - Statistical Equilibrium (average over many “features” per grid-box)
  - Segmentally-constant / homogeneous / “top-hat” updrafts & downdrafts
  - Instantaneous ascent
  - Small updraft area fraction
  - Local compensating subsidence

- **Lack of “scale-awareness”;** as resolution increases:
  - Sub-grid mass-flux should reduce (more is resolved)
  - Sub-grid perturbation of plume properties should reduce (more is resolved).
  - Fractional mixing rates for sub-grid plumes should increase (smaller features).

Outstanding Questions...

Do we need to get ALL of these things right to get a good simulation in the grey-zone?

Or is it really just 1 (or a few) of these deficiencies causing most of the problems?

If so, which?

Could we get a step-change improvement just by combining all the ideas already in the literature in a single parameterisation-set?

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- Developments in UKV (blended turbulence / blended shallow grey-zone closure / stochastic forcing of surface fluxes)
- Vertical velocity-dependent CAPE closure in the UM.
- New convective adjustment timescale closure in the ECMWF IFS (Bechtold et al 2014), and maybe mention their entrainment formulation (Bechtold et al 2008) if time.
- EDMF boundary-layer / shallow cumulus unification (Rio & Hourdin 2008, Neggers et al 2009).
- LMD cold-pool model with ALE / ALP deep convective closure (Grandpeix & Lafore 2010, Rio et al 2013, Rochetin et al 2014).
- Stochastic multi-plume non-statistical equilibrium approach (Plant & Craig 2008, Keane et al 2014).
- Highly interactive, high-complexity multi-process approach (Park 2014).

- CASCADE 12km simulation with / without convection parameterisation (ref)
- EMBRACE (Martin's result showing no evidence of "compensating subsidence")
- EDMF shallow cumulus scheme in WRF (TEMF; Wayne Angevine)