Representing convection in large-scale models

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Includes material from Martin Willett (Met Office)

Contents

This presentation covers the following areas

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- Challenge 1-convection/wave coupling
- Challenge 2-the moist rearrangement problem
- Challenge 3-designing models to reflect this reality

Overall challenge

Model resolution

Atmospheric moist convection takes the form of localised small-scale, but often highly structured, activity in limited regions of the atmosphere.

Acceptable direct simulations of these regions require a horizontal grid of 2km or less. This is unaffordable.

Even using adaptive mesh refinement in convecting regions is unaffordable.

Specific challenges

Therefore have to use a local subgrid model in convecting regions-but this has to be properly coupled to the rest of the atmosphere.

To advance our ability to do this, we present 3 specific challenges:

- Describe the effect of a local convecting region on wave propagation
- Describe the leading order effect of convection on an unstable atmospheric profile
- Define an interface between a local convection submodel and a conventional atmospheric model.

Convection/wave coupling

Basic simple model

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Assume the atmosphere away from the convecting region is a rotating stratified fluid with a uniform static stability. Represent the convecting region by a region of reduced static stability.

Inertia-gravity waves can propagate with frequency depending on vertical and horizontal wavelength as well as static stability. Propagation different in convecting region-so must match solutions.

Need also to consider forced travelling waves, where convection region regarded as a local heat source.

Simple problem 1

Response to impulsive convection:

Need to represent source in terms of normal modes of the wave equation. Response changes as convection becomes deeper. Issues with realism of vertical structure.

Most previous work oversimplified.

Simple problem 2

Interaction with propagating inertia-gravity wave:

Represent as region of reduced static stability, but don't change reference temperature profile.

Extent of convection depends on vertical structure. This will change the structure of an incoming wave.

Create solutions by matching wave solutions across boundary of convecting region.

Simple problem 3

Interaction with geostrophic disturbances (mid latitude weather):

Use semi-geostrophic equation to represent the response to forcing. This calculates the fluid trajectory required to maintain geostrophic and hydrostatic balance.

The **Q** matrix in the equation has near-zero eigenvalues in the presence of convective instability.

This should be a valuable illustration of the effects of convection on weather systems.

Equation

The evolution of the pressure field is then

$$\mathbf{Q}\begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix} + \frac{\partial}{\partial t}\nabla p = \begin{pmatrix} f^2 u_{g1} \\ f^2 u_{g2} \\ S \end{pmatrix}$$

$$\mathbf{Q} = \begin{pmatrix} f^2 + f\dfrac{\partial u_{g2}}{\partial x_1} & f\dfrac{\partial u_{g2}}{\partial x_2} & f\dfrac{\partial u_{g2}}{\partial x_3} \\ -f\dfrac{\partial u_{g1}}{\partial x_1} & f^2 - f\dfrac{\partial u_{g1}}{\partial x_2} & -f\dfrac{\partial u_{g1}}{\partial x_3} \\ g\dfrac{\partial \vartheta_e}{\partial x_1} & g\dfrac{\partial \vartheta_e}{\partial x_2} & g\dfrac{\partial \vartheta_e}{\partial x_3} \end{pmatrix}$$

$$(fu_{g2}, -fu_{g1}, g\vartheta_e = \nabla p$$

Simple problem 4

Tropical waves:

Tropical waves depend on both horizontal coordinates, and are symmetric about the equator. Very important for tropical variability

So a 3d model is needed to study interactions with convection.

Otherwise approach is as for inertia-gravity waves. Use matching at boundary of convection region and normal modes of equations, or seek forced solutions.

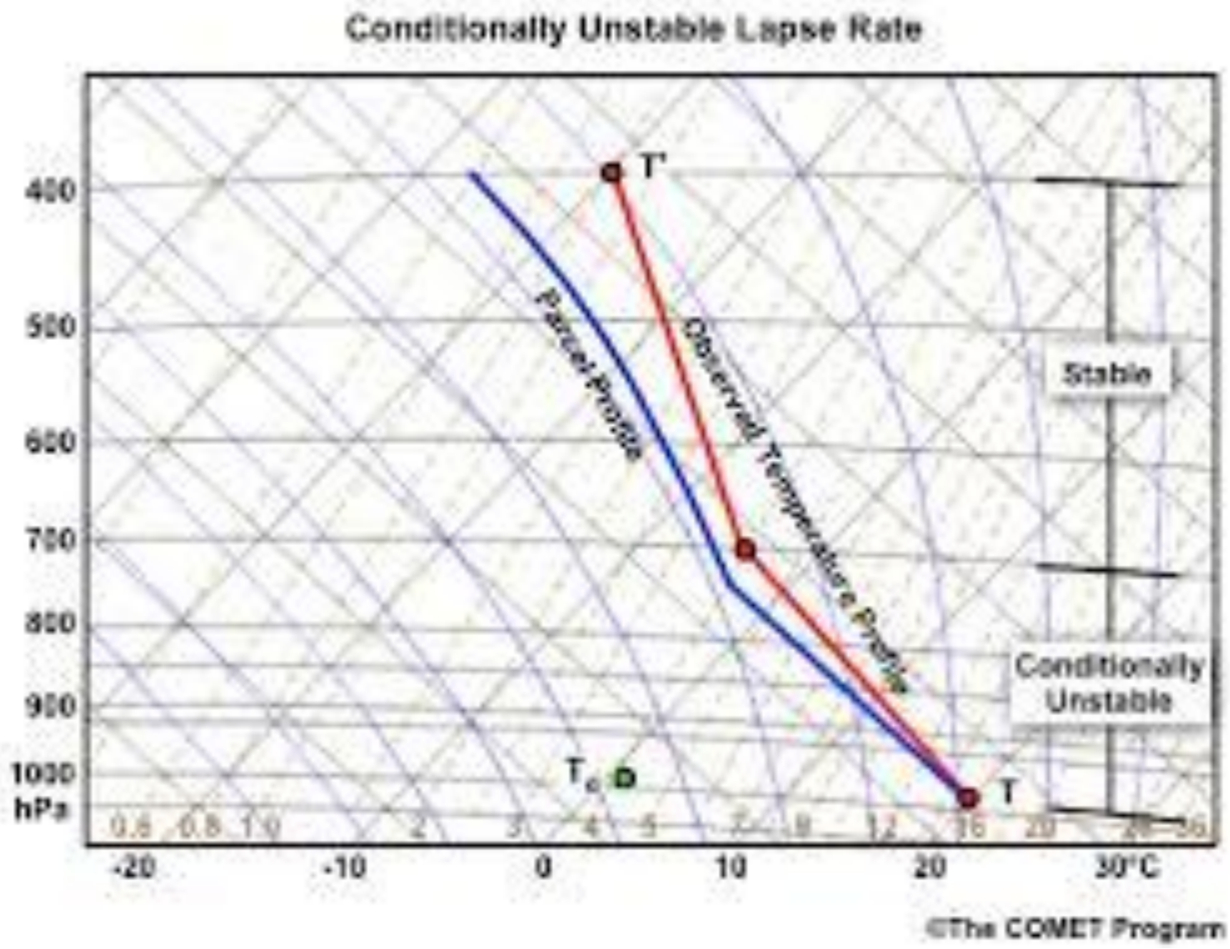
The moist rearrangement problem

The basic problem

If moisture is ignored, the static stability of a column of air is determined by $\partial\theta/\partial z$ where θ is the potential temperature. There is a unique stable rearrangement of a column of air with arbitrary θ.

In the presence of moisture, the stability of a saturated column of air is determined by $\partial\theta_e/\partial z$ where θ_e is the equivalent potential temperature which also depends on the moisture content and is conserved under phase changes. If the air is not saturated, the stability only depends on $\partial\theta/\partial z$. There is no longer a unique stable rearrangement.

Example 1



Conditionally Unstable Lapse Rate
T'
400
500
600
700
800
900
1000
hPa
Parcel Profile
Observed Temperature Profile
Stable
Conditionally
Unstable
T
-20
-10
0
10
20
30°C
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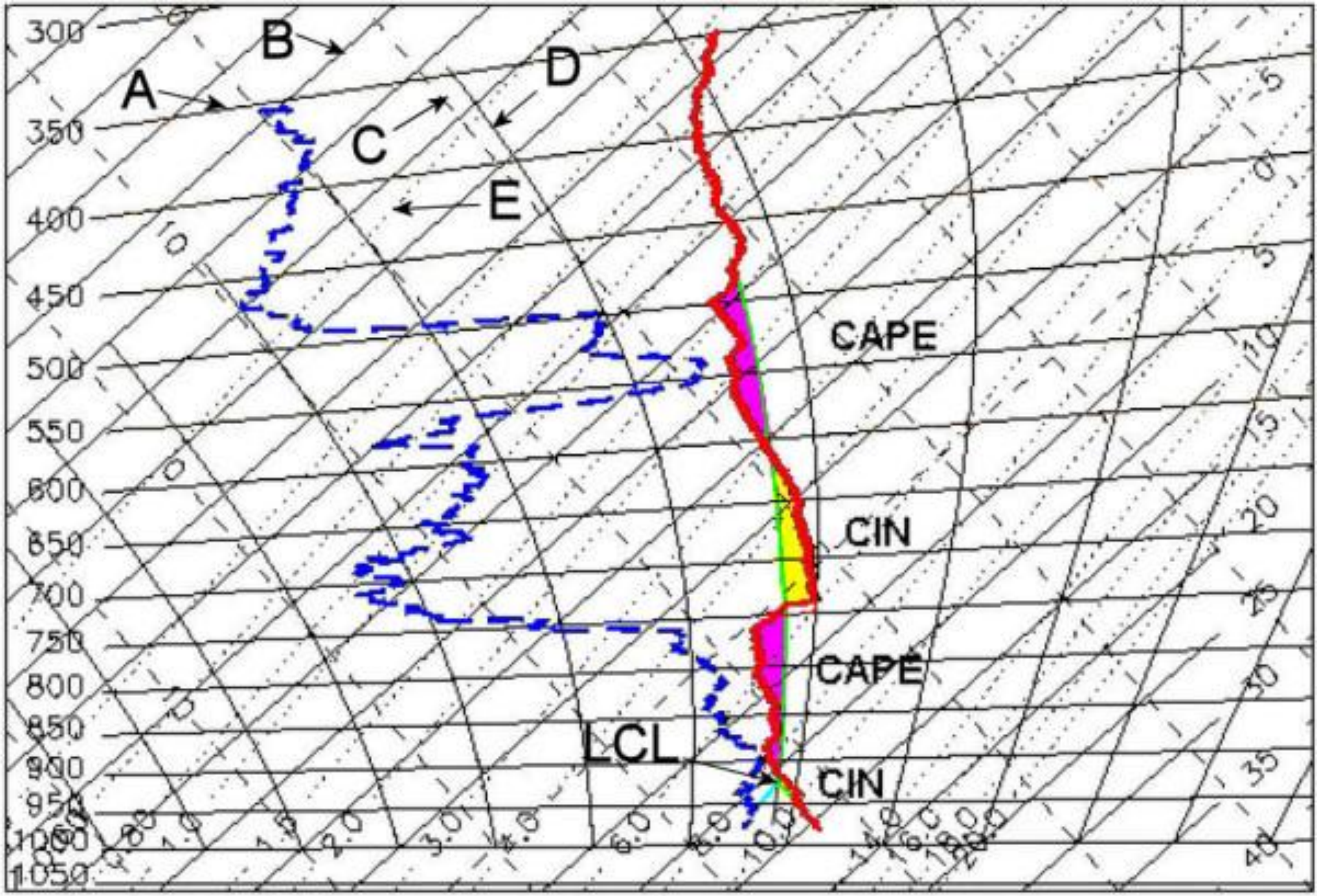
Comments

As a parcel ascends, θ follows the blue curve (θ=constant). Once it becomes saturated, the blue curve changes its slope (θ increases with z). If the actual (red) θ profile is always above the blue curve, then the column is stable.

Example 2


A
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950
1000
1050

Comments

In this example, there are several layers where the (green) curve of an ascending parcel crosses the red curve of the existing profile. These are unstable layers.

The presence of multiple moist and dry layers means that the moist rearrangement problem is very hard.

The practical problem

In reality we do not need arbitrary rearrangements. We need to consider what happens when a column of air is bodily moved upwards. Is there then a well-posed stable solution?

If not, there is a fundamental loss of predictability in the presence of moist convection which would be a serious limitation on overall predictive skill.

Previous work

Goldman (2008) solved a simple version of this problem. He only obtained well-posedness if $\theta(z)+q(z)$ is a non-increasing function of z, where q is the moisture content.

He then found weak Lagrangian solutions using optimal transport methods.

This does not cover all physically important cases. Can this result be improved?

Model design

Key points

It is likely that if adaptive mesh refinement were affordable, it would give a much better result.

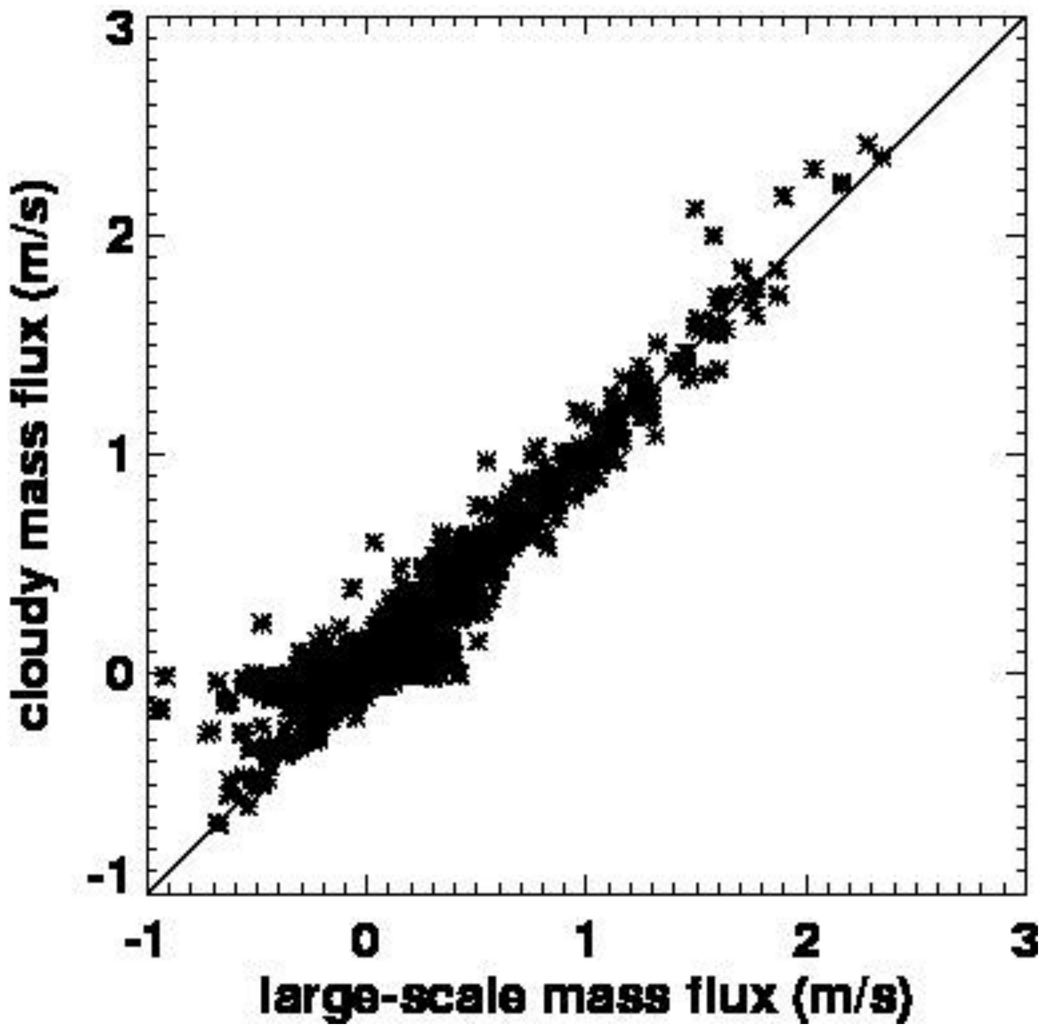
For example use a local 2km grid in a model with a 25km grid.

Illustrate results from a 2km model averaged to 25km.

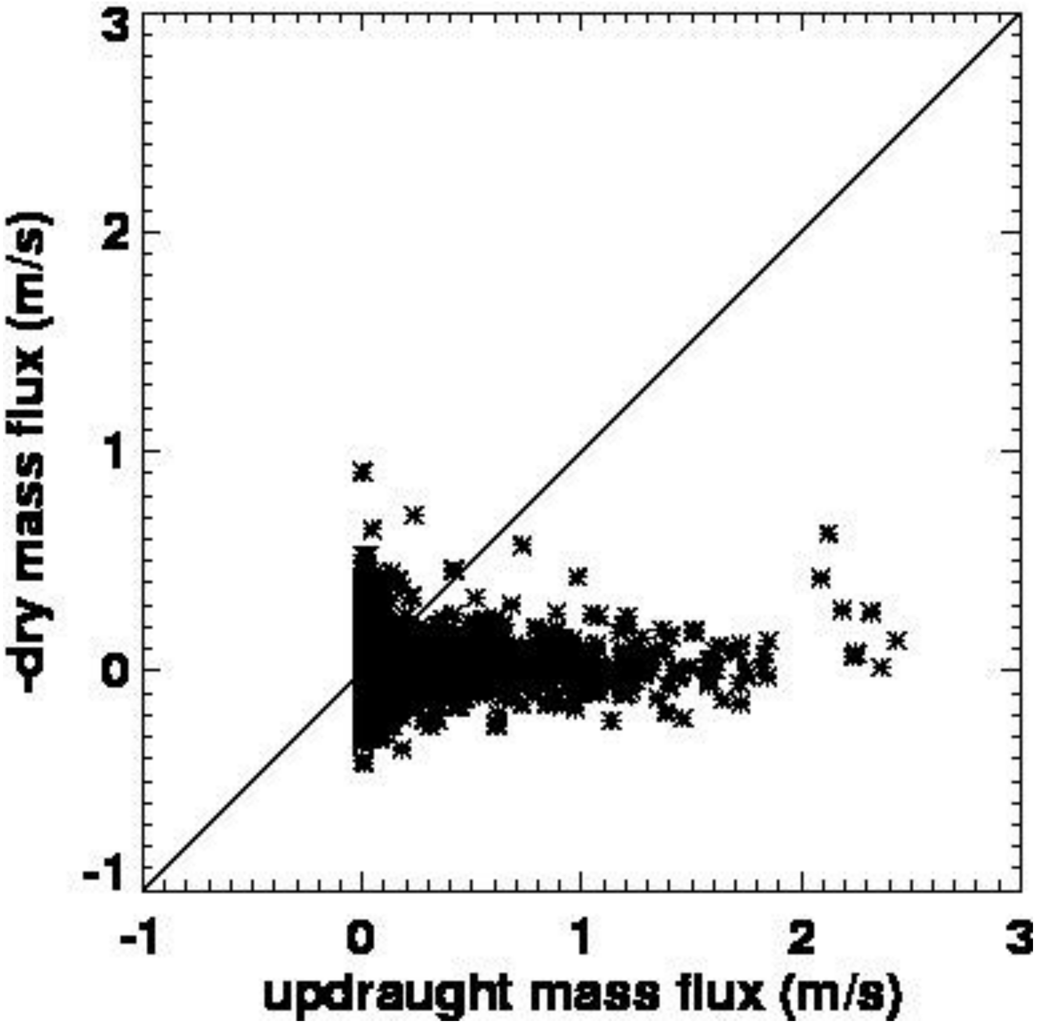
The upward mass fluxes in cloudy (convecting) 2km grid boxes are aggregated and compared with those deduced from 25km boxes.

They are also compared with the downward mass fluxes in dry 2km boxes.

Compare upward mass fluxes



And downward mass fluxes



Comments

Results show that the averaged upward mass flux is essentially the same as the upward mass flux in convecting regions.

The upward and downward mass fluxes do not balance over individual 25km grid boxes.

Hence a convection submodel need only represent the collective updraughts, but now coupling to the larger scale model becomes challenging.

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Parameterized convection

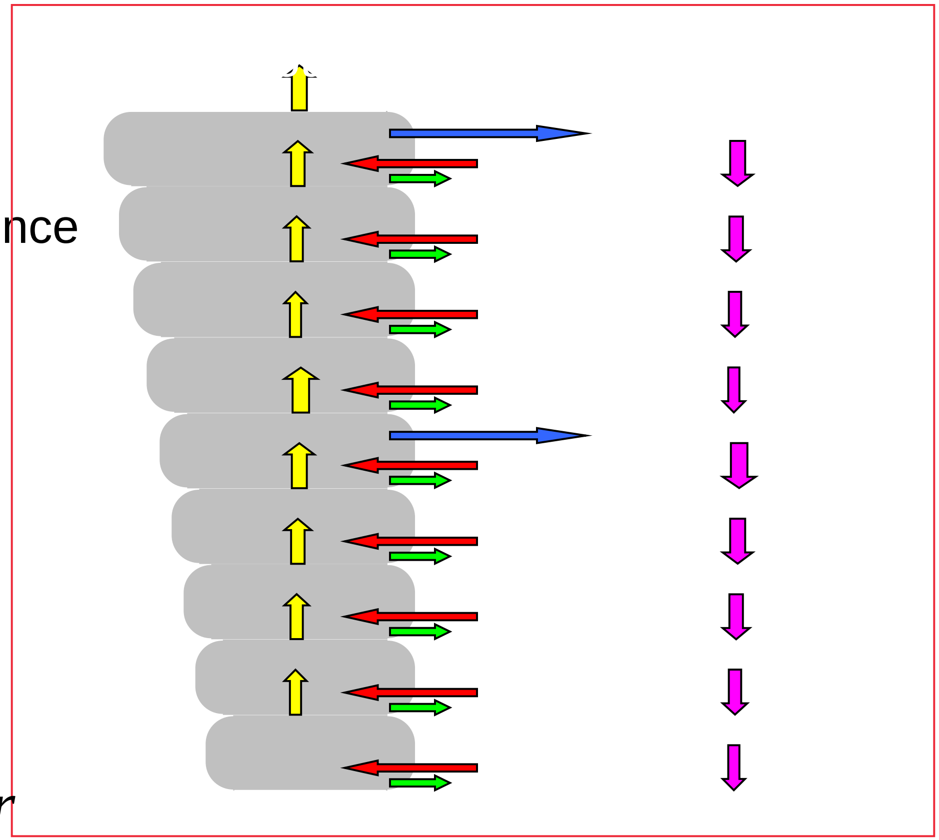
Updraught mass-flux

Compensating subsidence

Entrainment

Mixing detrainment

Forced detrainment



Large-scale Dynamics

$$\frac{\partial \phi}{\partial t} - \frac{\partial M\phi}{\partial p} = 0$$

$$\phi = \theta, q, qcl, qcf, tracer$$

Φ(ls) = σ Φ(ud) + (1-σ) Φ(env) but σ << 1 => Φ(env) ≈ Φ(ls)

M(ud)+M(env) = 0   Not M(ls)

Aim of challenge

In current convection submodels it is assumed there is no net upward mass transport, so relatively easy to add submodel on top of large-scale model.

Couple a convection plume model (i.e. the current model without the environmental subsidence) to the large-scale dynamics. The large-scale dynamics is not used where the convection plume model operates.

Produce a stable formulation that satisfies overall mass and energy balances.

Questions