Convection Parameterization

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`With thanks to: all involved in COST Action ES0905!`

NWP Physics Lectures 4 and 5

Nanjing Summer School

July 2014

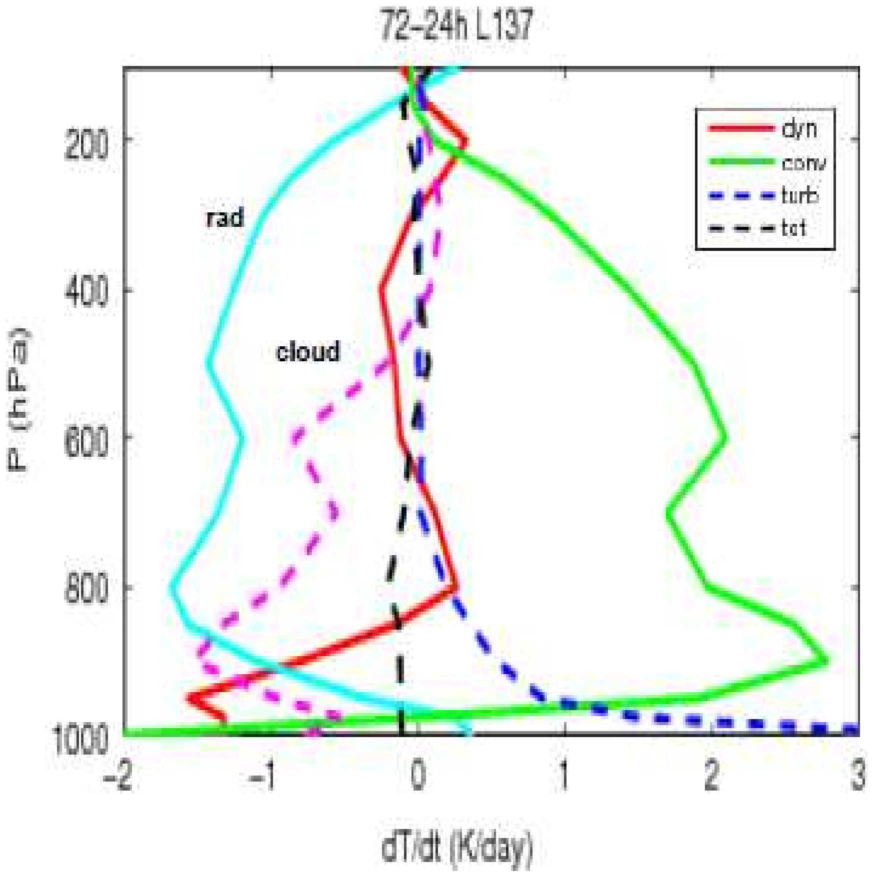
The University of Reading

Outline

- Motivation
- The mass flux idea
- Justifications for “bulk” schemes
- Main ingredients of a typical bulk scheme:
  - Vertical structure of convection
  - Overall amount of convection
- Other new ideas

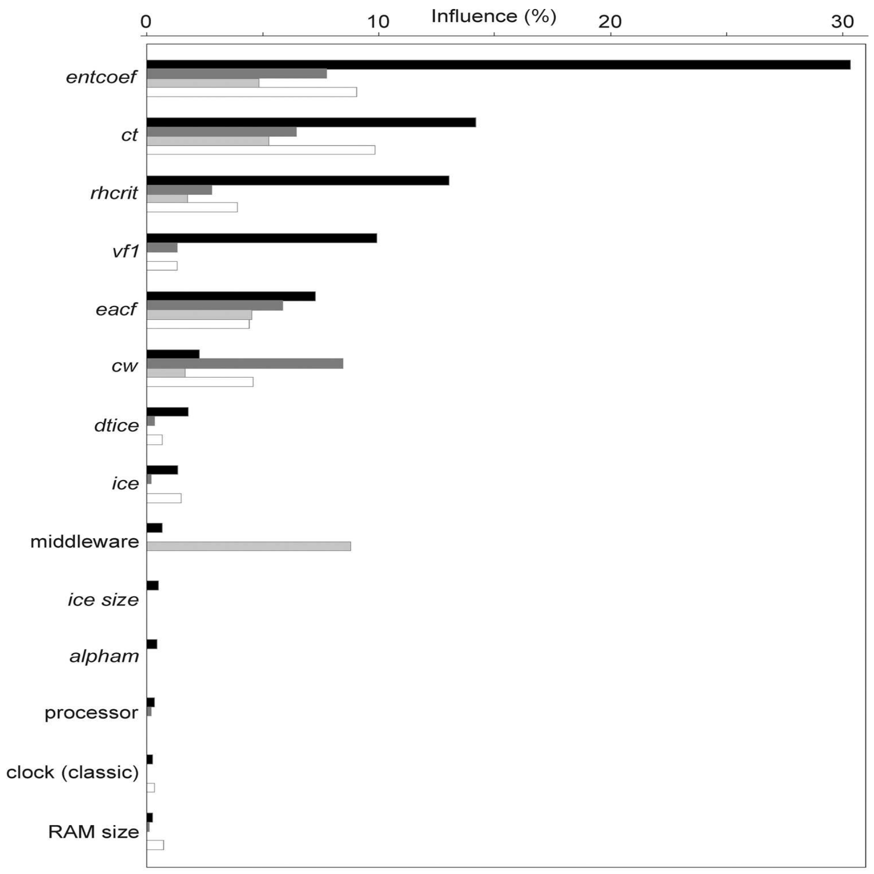
Motivation

Tropical T budget



Budget within ECMWF model

Importance of entrainment



- entrainment parameter is one of the most sensitive aspects of GCMs
- plot shows variation in climate sensitivity explained by varying different parameters in UM
(Knight 2007)

The mass flux idea

Basic equations

$$\frac{\partial\overline{\theta}}{\partial t} = -\overline{\mathbf{v}}.\nabla\overline{\theta} - \overline{w}\frac{\partial\overline{\theta}}{\partial z} - \frac{\partial}{\partial z}\overline{w'\theta'} + \frac{\Pi L}{c_p}(c-e) + Q_{\mathrm{rad}}$$

- Large-scale “forcing” produced by modelled advection
- Convection scheme needs to provide the balance to that with contributions to vertical turbulent transport $\overline{w'\theta'}$ and net condensation, $c-e$
- Analogous equations for moisture and momentum

The aim

- Interactions of convection and large-scale dynamics crucial
- Need for a convective parameterization in GCMs and (most) NWP

  Assume we are thinking of a parent model with grid length 20 to 100km
- Basic idea: represent effects of a set of hot towers / plumes / convective clouds within the grid box

$\Rightarrow$

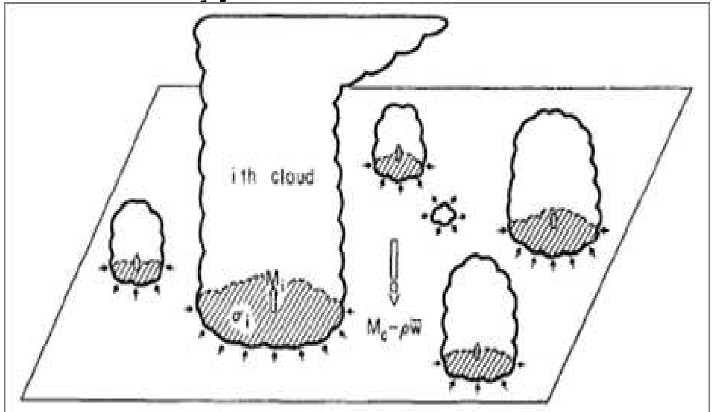


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

Starting Assumptions

- Assume that there exists a meaningful "large-scale" within which the convective systems are embedded
- Assume that the "large-scale" is well described by the grid box state in the parent model

  this is a little suspect
- Aim of the parameterization is to determine the tendencies of grid-box variables due to convection, given the grid-box state as input

Starting Picture

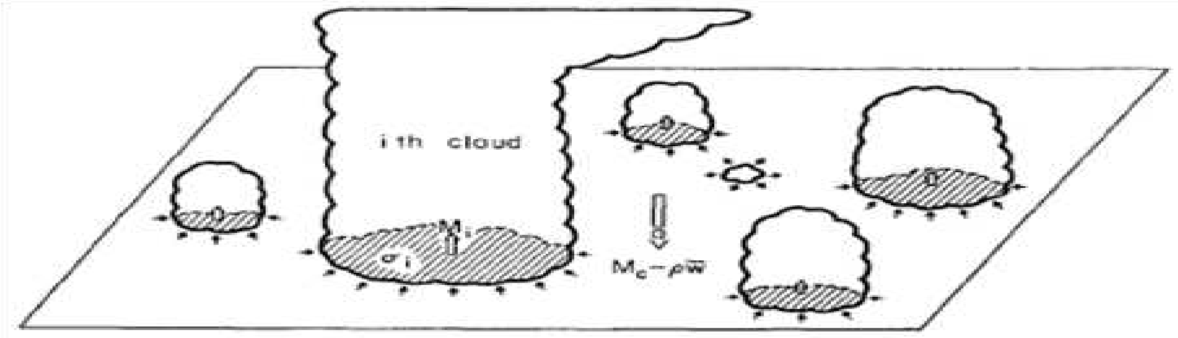
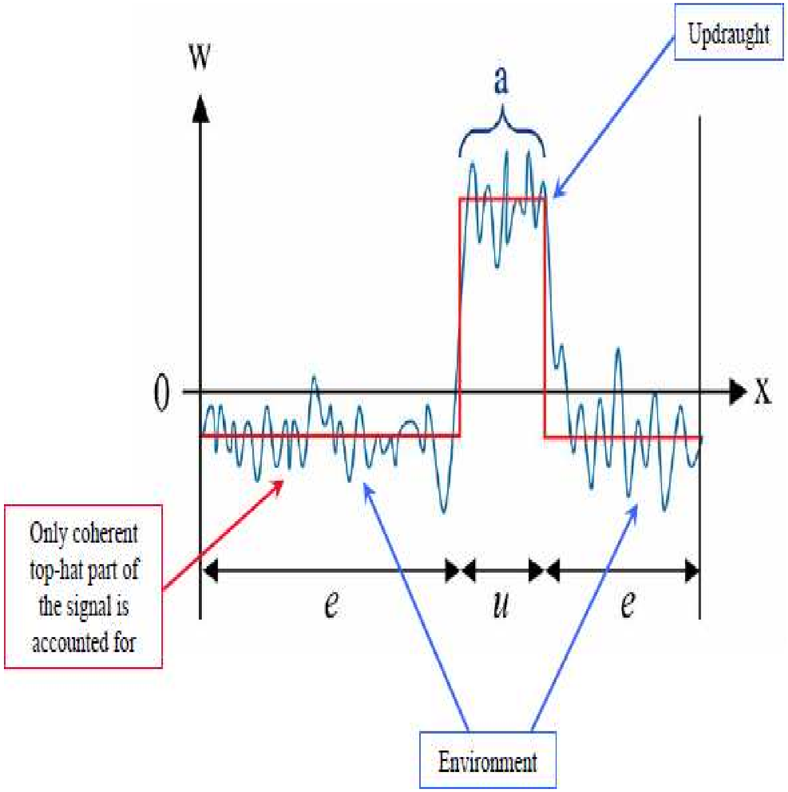


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

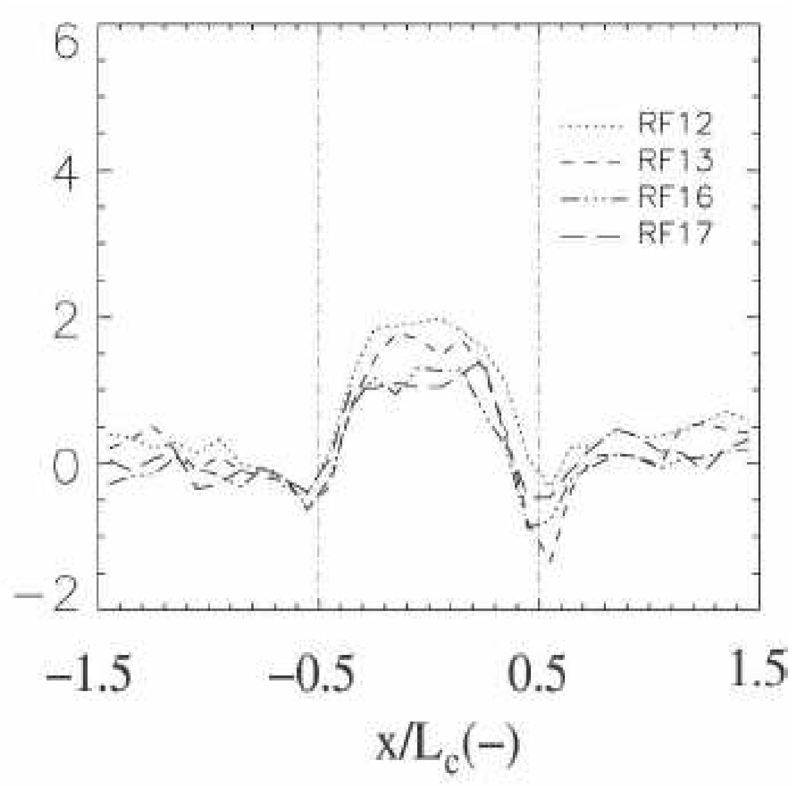
- Convection characterised by ensemble of non-interacting convective plumes within some area of tolerably uniform forcing
- Individual plume equations formulated in terms of mass flux, $M_i = \rho\sigma_i w_i$

Top hat decomposition



- split between convective updraught and weakly-subsiding environment
- updraught and environment both assumed uniform

Homogeneity in-cloud?



- w from aircraft data
- LES diagnoses $\Longrightarrow$ top-hat representation captures $\sim$ 90% of the turbulent transport

Defining the mass flux

For some variable $\chi = T, q, q_l \ldots$

$$\overline{\chi} = \sigma\chi_u + (1-\sigma)\chi_e$$

where σ is the fractional area of the updraught.
Vertical flux of a fluctuating variable:

$$\rho\overline{w'\chi'} = \rho\sigma(w_u - \overline{w})(\chi_u - \overline{\chi}) + \rho(1-\sigma)(w_e - \overline{w})(\chi_e - \overline{\chi})$$

For $\sigma \ll 1$ and $w_u \gg \overline{w}$ then

$$\rho\overline{w'\chi'} \approx \rho\sigma(w_u - \overline{w})(\chi_u - \overline{\chi}) \approx \rho\sigma w_u(\chi_u - \chi_e) = M(\chi_u - \chi_e)$$

with

$$M = \rho\sigma w_u$$

Basic questions

Supposing we accept all the above, we still need to ask...

1. How should we formulate the entrainment and detrainment?
   ie, what is the vertical structure of the convection?
2. How should we formulate the closure?
   ie, what is the amplitude of the convective activity?
3. Do we really need to make calculations for every individual plume in the grid box?
   ie, is our parameterization practical and efficient?

We consider 3 first, because the answer has implications for 1 and 2.

Do we really need to make calculations for every individual plume in the grid box?

Basic idea of spectral method

- Group the plumes together into types defined by a labelling parameter λ
- In Arakawa and Schubert (1974) this is the fractional entrainment rate, $\lambda = E/M$, but it could be anything
- e.g. cloud top height $\lambda = z_T$ is sometimes used
- a generalization to multiple spectral parameters would be trivial

Basic idea of bulk method

- Sum over plumes and approximate ensemble with a representative “bulk” plume
- This can only be reasonable if the plumes do not interact directly, only with their environment
- And if plume equations are almost linear in mass flux
- Summation over plumes will recover equations with the same form so the sum can be represented as a single equivalent plume

Mass-flux weighting

We will use the mass-flux-weighting operation (Yanai et al. 1973)

$$\chi_{\mathrm{bulk}} = \frac{\sum M_i \chi_i}{\sum M_i}$$

χ_{bulk} is the bulk value of χ produced from an average of the χ_i for each individual plume

Plume equations

$$\frac{\partial \rho \sigma_i}{\partial t} = E_i - D_i - \frac{\partial M_i}{\partial z}$$

$$\frac{\partial \rho \sigma_i s_i}{\partial t} = E_i s - D_i s_i - \frac{\partial M_i s_i}{\partial z} + L \rho c_i + \rho Q_{Ri}$$

$$\frac{\partial \rho \sigma_i q_i}{\partial t} = E_i q - D_i q_i - \frac{\partial M_i q_i}{\partial z} - \rho c_i$$

$$\frac{\partial \rho \sigma_i l_i}{\partial t} = -D_i l_i - \frac{\partial M_i l_i}{\partial z} + \rho c_i - R_i$$

- $s = c_p T + gz$ is the dry static energy
- Q_R is the radiative heating rate
- R is the rate of conversion of liquid water to precipitation
- c is the rate of condensation

Using the plume equations

Average over the plume lifetime to get rid of $\partial/\partial t$:

$$E_i - D_i - \frac{\partial M_i}{\partial z} = 0$$

$$E_i s - D_i s_i - \frac{\partial M_i s_i}{\partial z} + L\rho c_i + \rho Q_{Ri} = 0$$

$$E_i q - D_i q_i - \frac{\partial M_i q_i}{\partial z} - \rho q_i = 0$$

$$D_i l_i + \frac{\partial M_i l_i}{\partial z} + \rho c_i + R_i = 0$$

Integrate from cloud base z_B up to terminating level z_T where the in-cloud buoyancy vanishes

Effects on the environment

Taking a mass-flux weighted average,

$$\rho\overline{\chi' w'} \approx \sum_i M_i(\chi_i - \chi) = M(\chi_{\text{bulk}} - \chi)$$

where

$$M = \sum_i M_i$$

Recall that the aim is for the equations to take the same form as the individual plume equations but now using bulk variables like M and χ_{bulk}

Equivalent bulk plume I

Now look at the weighted-averaged plume equations

$$E - D - \frac{\partial M}{\partial z} = 0$$

$$Es - \sum_i D_i s_i - \frac{\partial M s_{\mathrm{bulk}}}{\partial z} + L\rho c + \rho QR = 0$$

$$Eq - \sum_i D_i q_i - \frac{\partial M q_{\mathrm{bulk}}}{\partial z} - \rho c = 0$$

$$-\sum_i D_i l_i - \frac{\partial M l_{\mathrm{bulk}}}{\partial z} + \rho c - R = 0$$

The same bulk variables feature here

Equivalent bulk plume II

$$E - D - \frac{\partial M}{\partial z} = 0$$

$$Es - \sum_i D_i s_i - \frac{\partial M s_{\text{bulk}}}{\partial z} + L\rho c + \rho Q_R = 0$$

$$Eq - \sum_i D_i q_i - \frac{\partial M q_{\text{bulk}}}{\partial z} - \rho c = 0$$

$$- \sum_i D_i l_i - \frac{\partial M l_{\text{bulk}}}{\partial z} + \rho c - R = 0$$

where

$$E = \sum_i E_i \quad ; \quad D = \sum_i D_i$$

The entrainment dilemma

- E and D encapsulate both the entrainment/detrainment process for an individual cloud and the spectral distribution of cloud types
- Is it better to set E and D directly or to set E_i and D_i together with the distribution of types?

Equivalent bulk plume III

$$Es - \sum_i D_i s_i - \frac{\partial M s_{\rm bulk}}{\partial z} + L\rho c + \rho Q_R = 0$$

where

$$Q_R(s_{\rm bulk}, q_{\rm bulk}, l_{\rm bulk}, \ldots) = \sum_i Q_{Ri}(s_i, q_i, l_i, \ldots)$$

is something for the cloud-radiation experts to be conscious about

Equivalent bulk plume IV

$$Es - \sum_i D_i s_i - \frac{\partial M s_{\text{bulk}}}{\partial z} + L\rho c + \rho Q_R = 0$$

$$Eq - \sum_i D_i q_i - \frac{\partial M q_{\text{bulk}}}{\partial z} - \rho c = 0$$

$$-\sum_i D_i l_i - \frac{\partial M l_{\text{bulk}}}{\partial z} + \rho c - R = 0$$

where

$$c(s_{\text{bulk}}, q_{\text{bulk}}, l_{\text{bulk}}, \ldots) = \sum_i c_i(s_i, q_i, l_i, \ldots)$$

$$R(s_{\text{bulk}}, q_{\text{bulk}}, l_{\text{bulk}}, \ldots) = \sum_i R_i(s_i, q_i, l_i, \ldots)$$

is something for the microphysics experts to be conscious about

A Note on Microphysics

In Arakawa and Schubert 1974, the rain rate is

$$R_i = C_0 M_i l_i$$

where C_0 is a constant. Hence,

$$R = C_0 M l_{\mathrm{bulk}}$$

- If C_0 were to depend on the plume type then we couldn't write R as a function of the bulk quantities but would need to know how l_{bulk} is partitioned across the spectrum $\Longrightarrow$ A bulk scheme is committed to crude microphysics
- But microphysics in any mass-flux parameterization has issues anyway

Equivalent bulk plume V

$$E - D - \frac{\partial M}{\partial z} = 0$$

$$Es - \sum_i D_i s_i - \frac{\partial M s_{\text{bulk}}}{\partial z} + L\rho c + \rho Q_R = 0$$

$$Eq - \sum_i D_i q_i - \frac{\partial M q_{\text{bulk}}}{\partial z} - \rho c = 0$$

$$-\sum_i D_i l_i - \frac{\partial M l_{\text{bulk}}}{\partial z} + \rho c - R = 0$$

How can we handle these terms?

(a) Below the plume tops?

(b) At the plume tops?

(a) Below the plume tops

One option is to consider all the constitutent plumes to be entraining-only (except for the detrainment at cloud top)

- If $D_i = 0$ then $\sum_i D_i \chi_i = 0$ and the problem goes away!
- This is exactly what Arakawa and Schubert did

(a) Below the plume tops

If we retain entraining/detraining plumes then we have

$$\sum_i D_i \chi_i \equiv D_\chi \chi_{\rm bulk}$$

$$D_\chi = M \frac{\sum_i D_i \chi_i}{\sum_i M_i \chi_i}$$

- The detrainment rate is $\neq \sum_i D_i$
- i.e., it is different from the D that we see in the vertical mass flux profile equation
- and it is different for each in-plume variable

$\Longrightarrow$ A bulk parameterization can only be fully equivalent to a spectral parameterization of entraining plumes

(b) At the plume tops

- There are the contributions to $\sum_i D_i \chi_i$ from plumes the that have reach neutral buoyancy at the current level
- But the expressions simplify here because of the neutral buoyancy condition

$$Es - D\widehat{s} - \frac{\partial M s_{\text{bulk}}}{\partial z} = 0$$

$$Eq - D\widehat{q}^* - \frac{\partial M q_{\text{bulk}}}{\partial z} = 0$$

$$-D\widehat{l} - \frac{\partial M l_{\text{bulk}}}{\partial z} = 0$$

so now these equations use the same D as in the mass flux profile equation. But what about $\widehat{s}, \widehat{q}, \widehat{l}$?

(b) At the plume tops

Because of the neutral buoyancy condition:

$$s_i = \widehat{s} = s - \frac{L\varepsilon}{1+\gamma\varepsilon\delta}\left(\delta(q^* - q) - \widehat{l}\right)$$

$$q_i = \widehat{q}* = q^* - \frac{\gamma\varepsilon}{1+\gamma\varepsilon\delta}\left(\delta(q^* - q) - \widehat{l}\right) \qquad ; \qquad l_i = \widehat{l}$$

- where L, ε, γ and δ are thermodynamic functions of the environment
- Everything on the RHS is known in the bulk system, apart from $\widehat{l}$
- $\widehat{l}(z)$ can only be calculated by integrating the plume equations for a plume that detrains at $z_i = z$

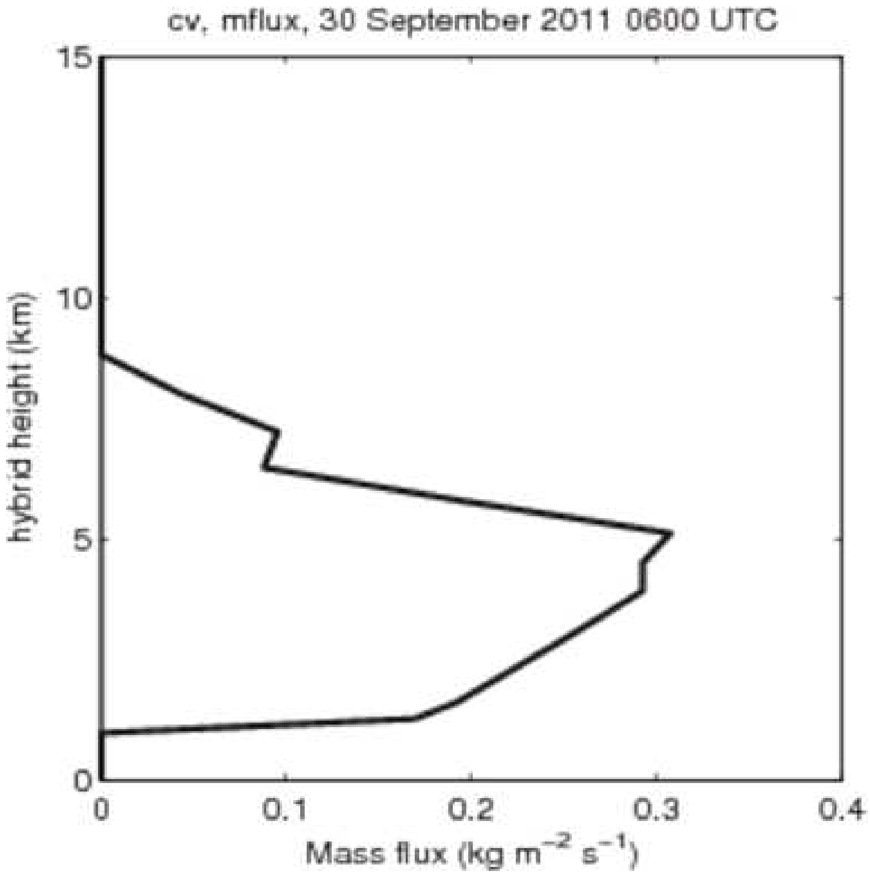
Key bulk assumption

At the heart of bulk models is an ansatz that the liquid water detrained *from each individual plume* is given by the *bulk value*

$$l_i = l_{\text{bulk}}$$

Yanai et al (1973): "gross assumption but needed to close the set of equations"

Spectral decomposition of bulk system

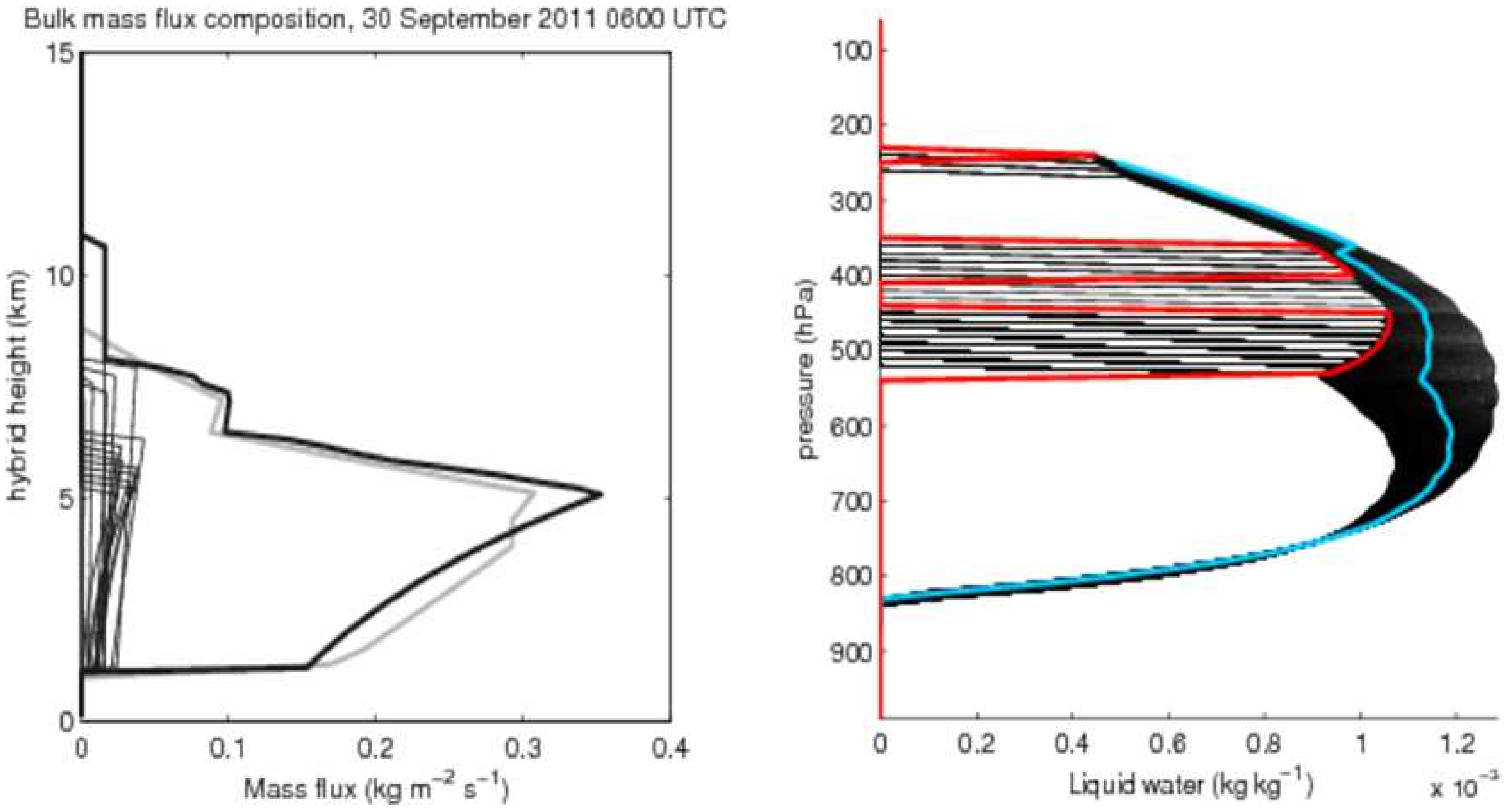


- Output from UM bulk scheme of convection embedded within cold front
- Construct plume ensemble using

$$\min \left| M(z) - \sum c_i M_i(z) \right| \quad c_i \geq 0$$

with M_i for entraining plumes

Spectral decomposition

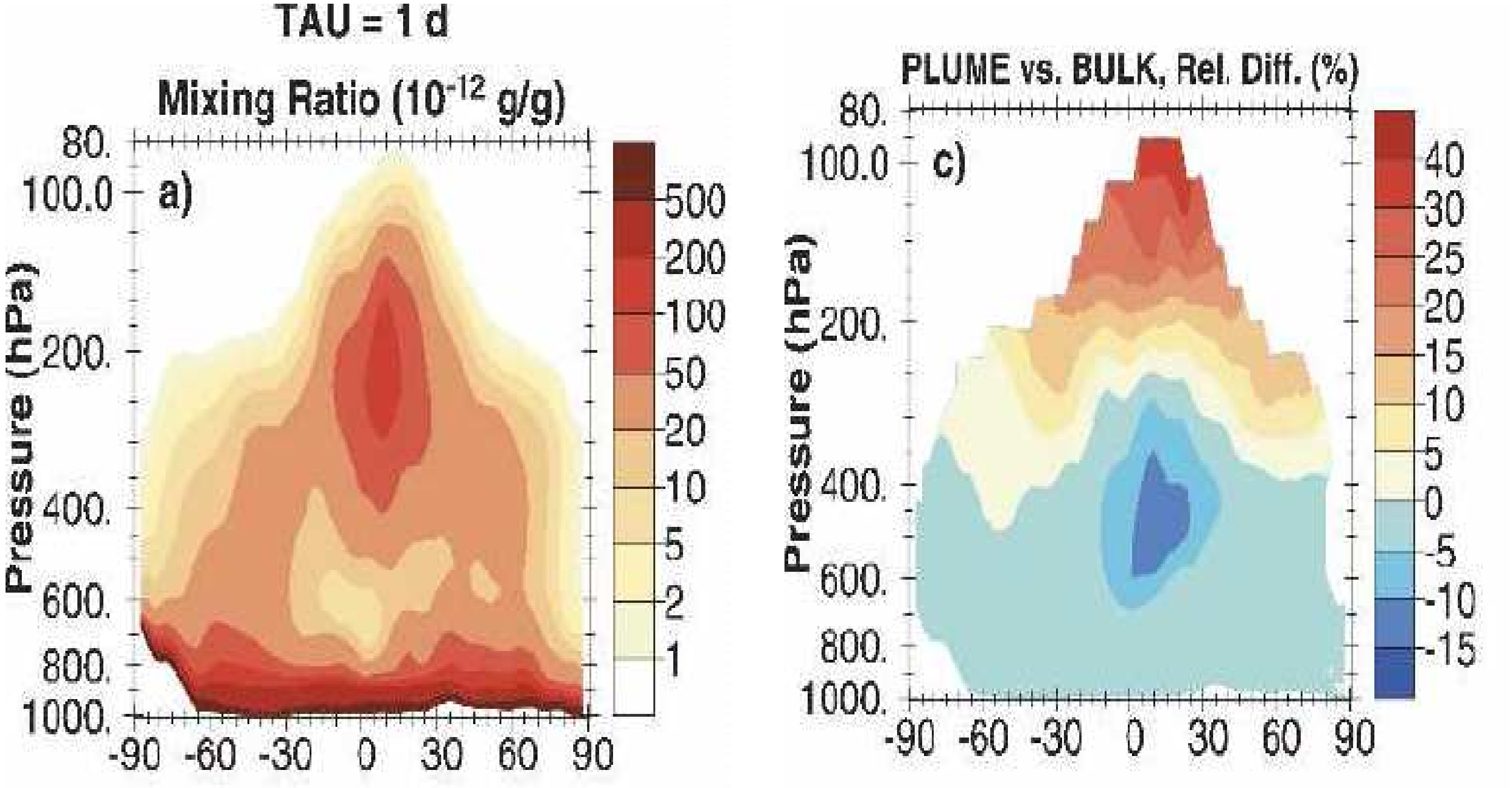


Other transports

- Contributions to $\sum_i D_i \chi_i$ from detrainment at plume top can be simplified for s, q and l from the neutral-buoyancy condition (with l ansatz)
- But no simplification occurs for other transports (e.g., tracer concentrations, momentum)
- Needs further ansatze, $\widehat{\chi}_i = \chi_{\mathrm{bulk}}$
- Or decompose bulk plume into spectrum of plumes

Example for passive scalar

Passive scalar distribution for bulk and spectral systems



From decomposition of ZM outputs (Lawrence and Rasch 2005)

Conclusions I

- A bulk model of plumes does not follow immediately from averaging over bulk plumes, but requires some extra assumptions
- Entrainment formulation is a big issue
- In bulk systems, cloud-radiation interactions have to be estimated using bulk variables
- In bulk systems, microphysics has to be calculated using bulk variables
    - This implies very simple, linearized microphysics
    - But microphysics is problematic for mass flux methods anyway, owing to non-separation of σ_i and w_i

Conclusions II

- A bulk plume is an *entraining/detraining plume* that is equivalent to *an ensemble of entraining plumes*
- A bulk system needs a "gross assumption" that $l = l_{\text{bulk}}$
  not often recognized, but relevant when detrained condensate is used as a source term for prognostic representations of stratiform cloud (for example)
- Detrained condensate from a bulk scheme is an overestimate

Bulk schemes are much more efficient, but they do have their limitations

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