Numerical Weather Prediction
Parametrization of diabatic processes

Convection II: The parametrization

Peter Bechtold, Christian Jakob, David Gregory
(with contributions from J. Kain (NOAA/NSLL)

ECMWF

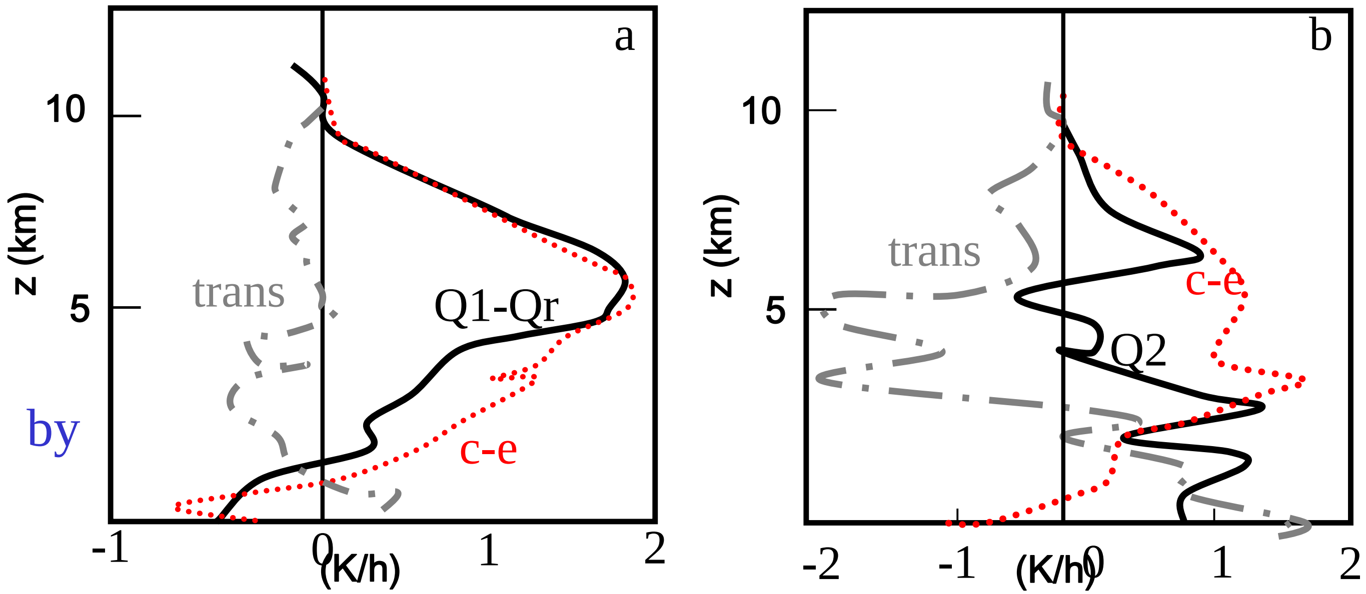
Outline

- Aims of convection parametrization
- Overview over approaches to convection parametrization
- The mass-flux approach

Task of convection parametrisation
total Q1 and Q2

To calculate the collective effects of an ensemble of convective clouds in a model column as a function of grid-scale variables. Hence parameterization needs to describe Condensation/Evaporation and Transport

$$Q_{1C} \equiv Q_1 - Q_R \equiv L(\bar{c} - \bar{e}) - \frac{\partial \overline{\omega' s'}}{\partial p}$$



Q1c is dominated by condensation term

but for Q2 the transport and condensation terms are equally important

Caniaux, Redelsperger, Lafore, JAS 1994

Task of convection parametrisation in practice this means:

Determine occurrence/localisation of convection

$\longrightarrow$ Trigger

Determine vertical distribution of heating, moistening and momentum changes

$\longrightarrow$ Cloud model

Determine the overall amount of the energy conversion, convective precipitation=heat release

$\longrightarrow$ Closure

Constraints for convection parametrization

- Physical
  - remove convective instability and produce subgrid-scale convective precipitation (heating/drying) in unsaturated model grids
  - produce a realistic mean tropical climate, coupling with microphysics
  - maintain a realistic variability on a wide range of time-scales
  - be applicable to a wide range of scales (typical 5 – 200 km) and types of convection (deep tropical, shallow, midlatitude and front/post-frontal convection)

- Computational
  - be simple and efficient for different model/forecast configurations T1279 (10-16 km), EPS, seasonal prediction T255 (80 km))

Types of convection schemes

- Schemes based on moisture budgets
  - Kuo, 1965, 1974, *J. Atmos. Sci.*
- Adjustment schemes
  - moist convective adjustement, Manabe, 1965, *Mon. Wea. Rev.*
  - penetrative adjustment scheme, Betts and Miller, 1986, *Quart. J. Roy. Met. Soc.*, Betts-Miller-Janic
- Mass-flux schemes (bulk+spectral)
  - entraining plume - spectral model, Arakawa and Schubert, 1974, Fraedrich (1973,1976), Neggers et al (2002), Cheinet (2004), *all J. Atmos. Sci.* ,
  - Entraining/detraining plume - bulk model, e.g., Bougeault, 1985, *Mon. Wea. Rev.*, Tiedtke, 1989, *Mon. Wea. Rev.; Gregory and Rowntree*, 1990, *Mon. Wea . Rev.;* Kain and Fritsch, 1990, *J. Atmos. Sci.*, Donner , 1993 *J. Atmos. Sci.;* Bechtold et al 2001, *Quart. J. Roy. Met. Soc.;* Park, *2014. J. Atmos. Sci.*
  - episodic mixing, Emanuel, 1991, *J. Atmos. Sci.*

The “Kuo” scheme closure

Closure: Convective activity is linked to large-scale moisture convergence

$$P = (1-b)\int_0^\infty \left(\frac{\partial \rho q}{\partial t}\right)_{ls} dz$$

Vertical distribution of heating and moistening: adjust grid-mean to moist adiabat

Main problem: here convection is assumed to consume water and not energy -> …. Positive feedback loop of moisture convergence, people critisized but also works

Adjustment schemes

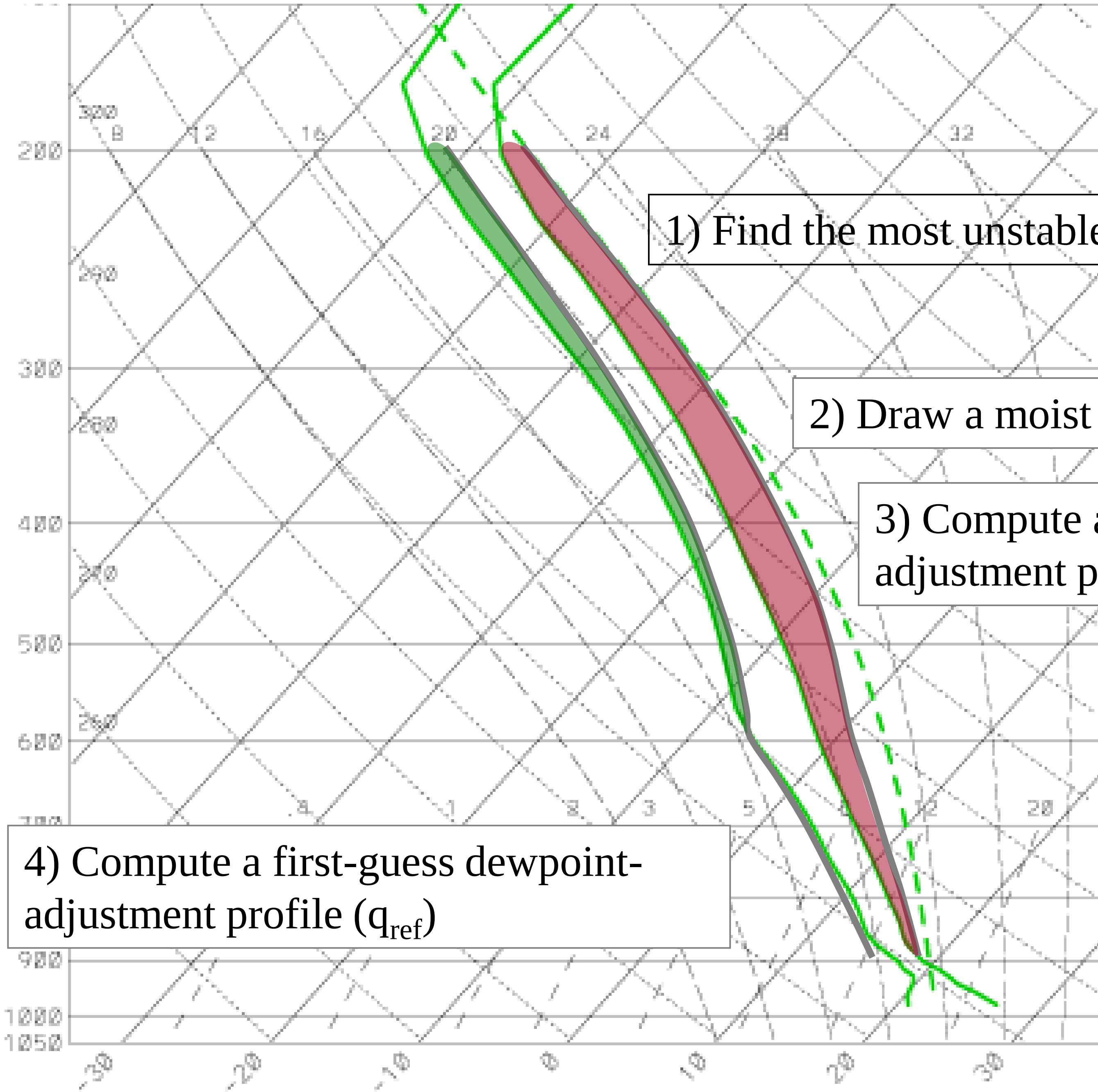
e.g. Betts and Miller, 1986, QJRMS:

When atmosphere is unstable to parcel lifted from PBL and there is a deep moist layer - adjust state back to reference profile over some time-scale, i.e.,

$$\left(\frac{\partial T}{\partial t}\right)_{conv.} = \frac{T_{ref} - T}{\tau} \qquad \left(\frac{\partial q}{\partial t}\right)_{conv.} = \frac{q_{ref} - q}{\tau}$$

T_{ref} is constructed from moist adiabat from cloud base but no universal reference profiles for q exist. However, scheme is robust and produces "smooth" fields.

Procedure followed by Betts Miller Janjić scheme…



1) Find the most unstable air in lowest ~ 200 mb

2) Draw a moist adiabat for this air

3) Compute a first-guess temperature-adjustment profile (T_{ref})

4) Compute a first-guess dewpoint-adjustment profile (q_{ref})

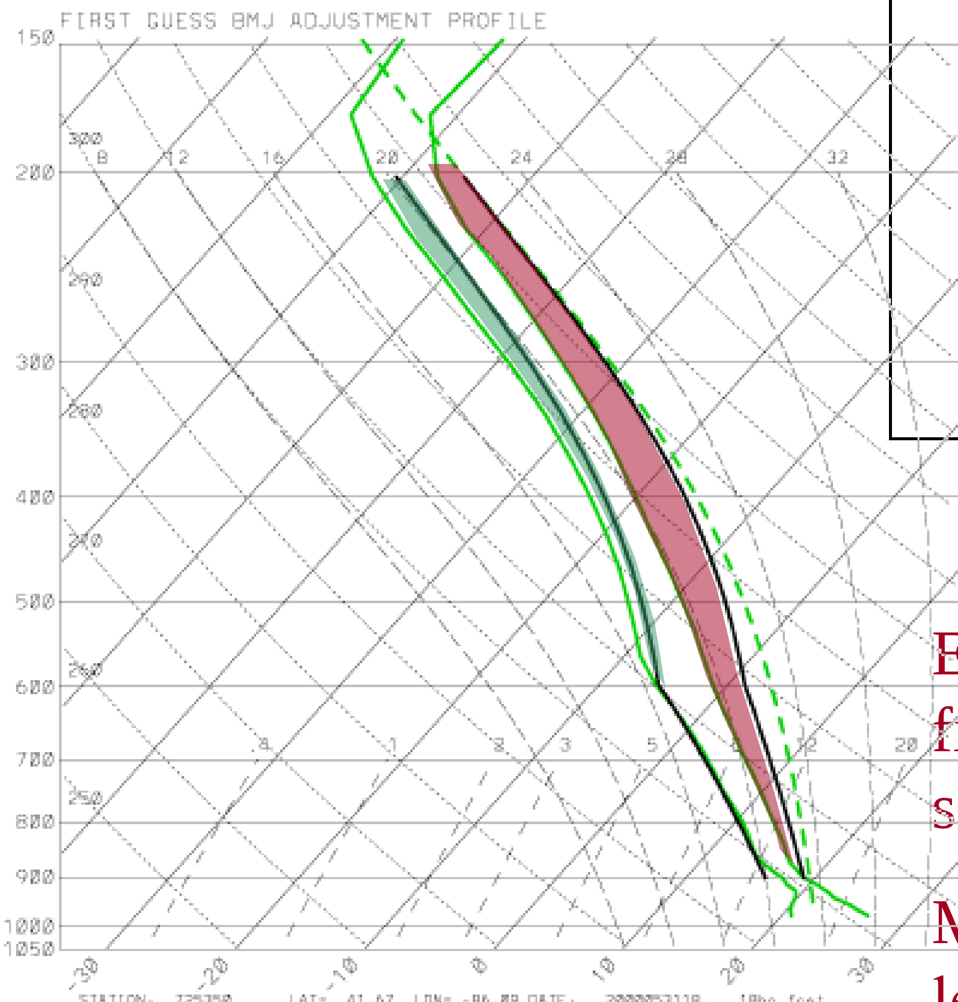
Adjustment schemes:
The Next Step is an *Enthalpy* Adjustment

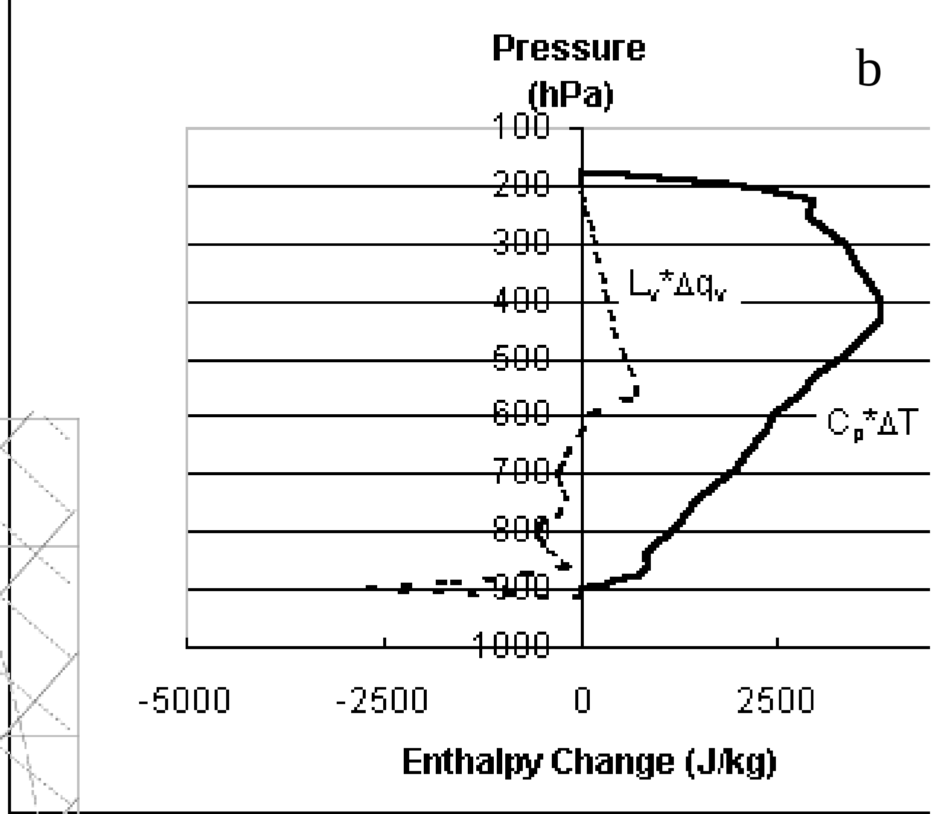
First Law of Thermodynamics:

$$dH = C_p dT + L_v dq_v$$

With Parameterized Convection, each grid-point column is treated in isolation. Total column latent heating must be directly proportional to total column drying, or ***dH = 0.***

$$\int_{P_b}^{P_t} C_p \left(T_{ref} - T\right) dp = -\int_{P_b}^{P_t} L_v (q_{vref} - q_v) dp$$





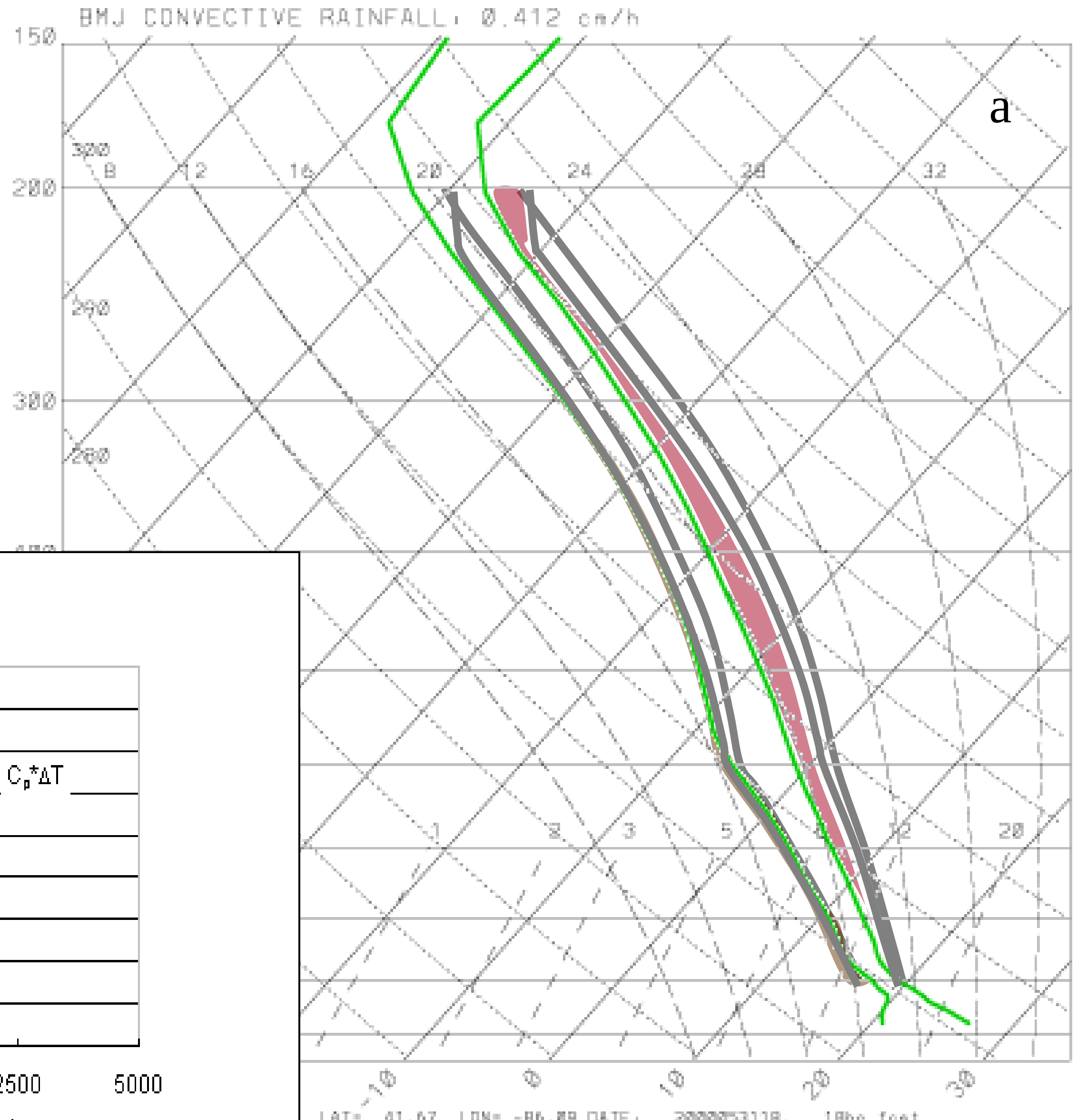
Enthalpy is *not* conserved for first-guess profiles for this sounding!

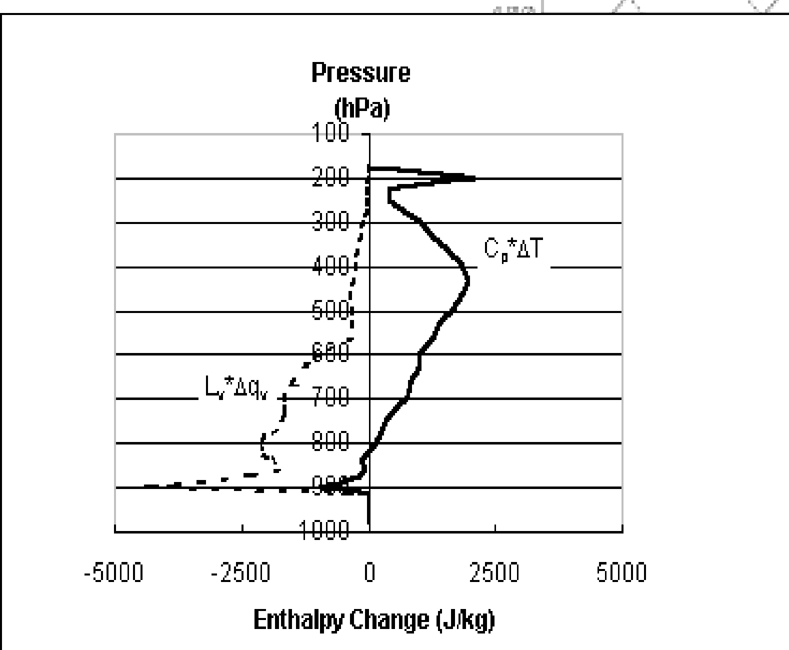
Must shift T_{ref} and q_{vref} to the left…

Imposing Enthalpy Adjustment:

b

Shift profiles to the left in order to conserve enthalpy





The mass-flux approach

$$Q_{1C} \equiv L(\bar{c} - \bar{e}) - \frac{\partial \overline{\omega' s'}}{\partial p}$$

Condensation term

Eddy transport term

Aim: Look for a simple expression of the eddy transport term

$$\overline{\omega' \Phi'} = ?$$

The mass-flux approach

Reminder:

$$\Phi = \overline{\Phi} + \Phi' \qquad \text{with} \qquad \overline{\Phi'} = 0$$

Hence

$$\begin{aligned}\overline{\omega\Phi} &= \overline{(\overline{\omega} + \omega')(\overline{\Phi} + \Phi')} \\ &= \overline{\overline{\omega}\,\overline{\Phi}} + \underbrace{\overline{\overline{\omega}\Phi'}}_{=0} + \underbrace{\overline{\omega'\overline{\Phi}}}_{=0} + \overline{\omega'\Phi'}\end{aligned}$$

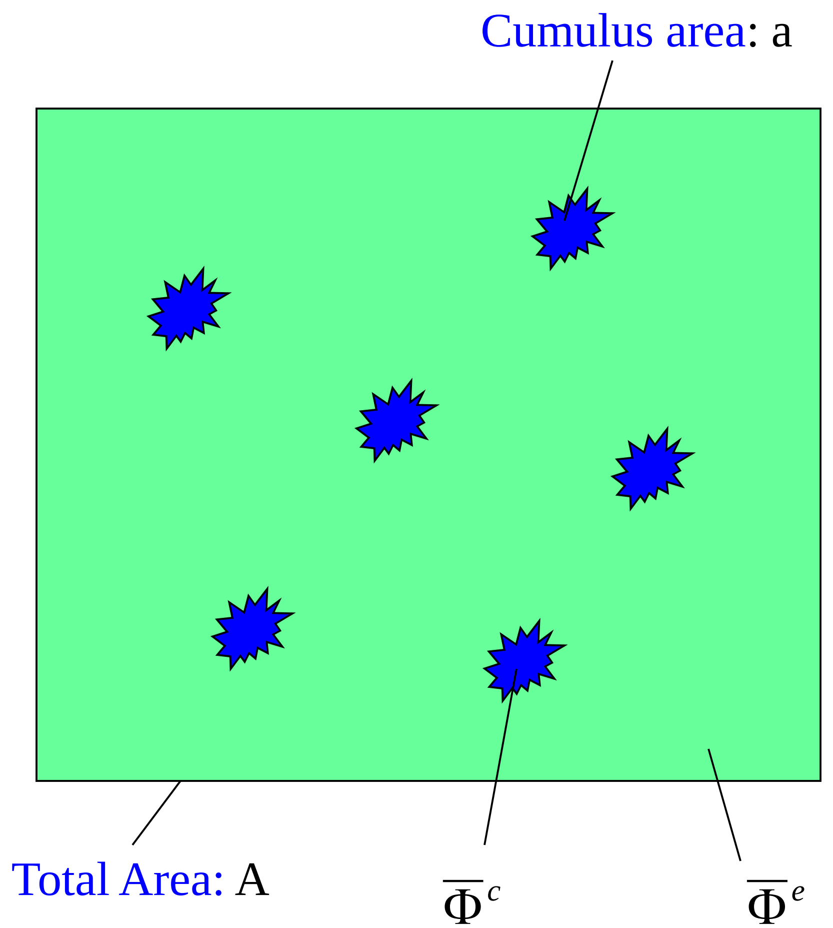
and therefore

$$\overline{\omega\Phi} = \overline{\omega}\,\overline{\Phi} + \overline{\omega'\Phi'}$$

$$\overline{\omega'\Phi'} = \overline{\omega\Phi} - \overline{\omega}\,\overline{\Phi}$$

ECMWF

The mass-flux approach:
Cloud – Environment decomposition



Fractional coverage with cumulus elements:

$$\sigma = \frac{a}{A}$$

Define area average:

$$\overline{\Phi} = \sigma \overline{\Phi}^c + (1 - \sigma)\overline{\Phi}^e$$

ECMWF

The mass-flux approach:
Cloud-Environment decomposition

With the above:

$$\overline{\omega\Phi} = \sigma\overline{\omega\Phi}^{c} + (1-\sigma)\overline{\omega\Phi}^{e}$$

Average over cumulus elements

Average over environment

$$\overline{\omega\Phi}^{c} = \bar{\omega}^{c}\bar{\Phi}^{c} + \cancel{\overline{\omega''\Phi''}^{c}}$$

and

$$\overline{\omega\Phi}^{e} = \bar{\omega}^{e}\bar{\Phi}^{e} + \cancel{\overline{\omega''\Phi''}^{e}}$$

Neglect subplume variations : (1) The top hat assumption

(see also Siebesma and Cuijpers, JAS 1995 for a discussion of the validity of the top-hat assumption)

The mass-flux approach: Derivation 1

(my prefered)

$$\overline{\omega'\Phi'} = \overline{\omega\Phi} - \bar{\omega}\bar{\Phi} = \sigma\,\overline{\omega\Phi}^{c} + \left(1-\sigma\right)\overline{\omega\Phi}^{e} - \bar{\omega}\bar{\Phi}$$

Use Reynolds averaging again for cumulus elements and environment separately:

$$= \sigma\,\overline{\omega\Phi}^{c} + \left(1-\sigma\right)\overline{\omega\Phi}^{e} - \left(\sigma\overline{\omega}^{c} + \left(1-\sigma\right)\overline{\omega}^{e}\right)\bar{\Phi}$$

top hat $$= \sigma\bar{\omega}^{c}\bar{\Phi}^{c} + \left(1-\sigma\right)\bar{\omega}^{e}\bar{\Phi}^{e} - \left(\sigma\overline{\omega}^{c} + \left(1-\sigma\right)\overline{\omega}^{e}\right)\bar{\Phi}$$

small area $$= \sigma\bar{\omega}^{c}\left(\bar{\Phi}^{c} - \bar{\Phi}\right) + \cancel{\left(1-\sigma\right)\bar{\omega}^{e}\left(\bar{\Phi}^{e} - \bar{\Phi}\right)}$$

Further simplifications : (2) The small area approximation

$$\boldsymbol{\sigma} << 1 \Rightarrow (1-\boldsymbol{\sigma}) \approx 1; \qquad \bar{\boldsymbol{\omega}}^{c} >> \bar{\boldsymbol{\omega}}^{e}$$

The mass-flux approach: Derivation 2

Then after some algebra (for your exercise) :

$$\overline{\omega'\Phi'} = \overline{\omega\Phi} - \overline{\omega}\,\overline{\Phi}$$
$$= \sigma(1-\sigma)\left(\overline{\omega}^{c} - \overline{\omega}^{e}\right)\left(\overline{\Phi}^{c} - \overline{\Phi}^{e}\right)$$

Further simplifications :

The small area approximation

$$\boldsymbol{\sigma} << 1 \Rightarrow (1-\boldsymbol{\sigma}) \approx 1; \qquad \overline{\boldsymbol{\omega}}^{c} >> \overline{\boldsymbol{\omega}}^{e}$$

The mass-flux approach

Then :

$$\overline{\omega'\Phi'} = \sigma\bar{\omega}^c\left(\bar{\Phi}^c - \bar{\Phi}^e\right)$$

Define convective mass-flux:

$$M_c = \frac{-\sigma\bar{\omega}^c}{g} = \rho\sigma\bar{w}^c$$

Then

$$\boxed{-\overline{\omega'\Phi'} = gM_c\left(\bar{\Phi}^c - \bar{\Phi}\right)}$$

The mass-flux approach

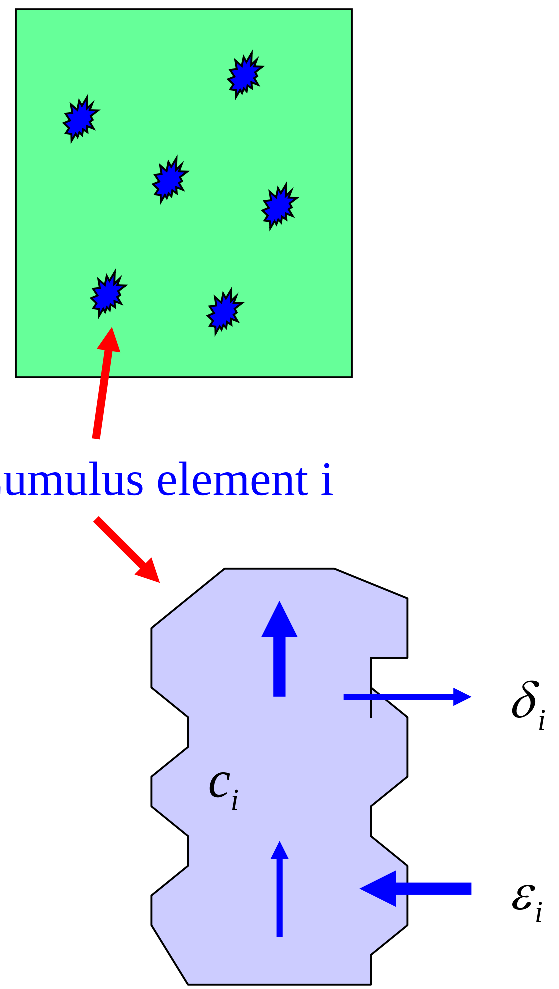
With the above we can rewrite:

$$Q_{1C} \equiv L(\bar{c} - \bar{e}) + g\,\frac{\partial\left[M_c(\bar{s}^c - \bar{s})\right]}{\partial p}$$

$$Q_2 \equiv L(\bar{c} - \bar{e}) - Lg\,\frac{\partial\left[M_c(\bar{q}^c - \bar{q})\right]}{\partial p}$$

To predict the influence of convection on the large-scale we now need to describe the convective mass-flux, the values (s, q, u, v) inside the convective elements and the condensation/evaporation term. This requires, as usual, a cloud model and a closure to determine the absolute (scaled) value of the mass flux.

Mass-flux entraining plume models



Entraining plume model

Continuity:

$$\frac{\partial \sigma_i}{\partial t} + D_i - E_i - g\frac{\partial M_i}{\partial p} = 0$$

Heat:

$$\frac{\partial(\sigma_i s_i)}{\partial t} + D_i s_i - E_i \overline{s} - g\frac{\partial(M_i s_i)}{\partial p} = Lc_i$$

Specific humidity:

$$\frac{\partial(\sigma_i q_i)}{\partial t} + D_i q_i - E_i \overline{q} - g\frac{\partial(M_i q_i)}{\partial p} = -c_i$$

Mass-flux entraining plume models
Simplifications

1. Steady state plumes, i.e., $\frac{\partial X}{\partial t} = 0$

most mass-flux convection parametrizations make that assumption, some (e.g. Gerard&Geleyn) are prognostic

2. Instead of spectral (Arakawa Schubert 1974) use one representative updraught=bulk scheme with entrainment/detrainment written as

$$\frac{1}{M}\frac{dM}{dz} = \varepsilon - \delta \Rightarrow -g\frac{\partial M_c}{\partial p} = E - D$$

ε,δ [m $^{-1}$] denote fractional entrainment/detrainment,
E,D [s $^{-1}$] entrainment/detrainment rates

Large-scale cumulus effects deduced from mass-flux models

$$-g\frac{\partial M_c}{\partial p} = E - D$$

$$-g\frac{\partial\left(M_c\overline{s}^c\right)}{\partial p} = E\overline{s} - D\overline{s}^c + Lc$$

$$\boxed{Q_{1C} \equiv L(c-e) + g\frac{\partial\left[M_c(\overline{s}^c - \overline{s})\right]}{\partial p}}$$

Flux form

Combine:

$$\boxed{Q_{1C} \equiv -gM_c\frac{\partial\overline{s}}{\partial p} + D(\overline{s}^c - \overline{s}) - Le}$$

Advective form

Large-scale cumulus effects deduced using mass-flux models

$$Q_{1C} \equiv -gM_c \frac{\partial \overline{s}}{\partial p} + D(\overline{s}^c - \overline{s}) - Le$$

Physical interpretation :

Convection affects the large scales by

Heating through compensating subsidence between cumulus elements (term 1)

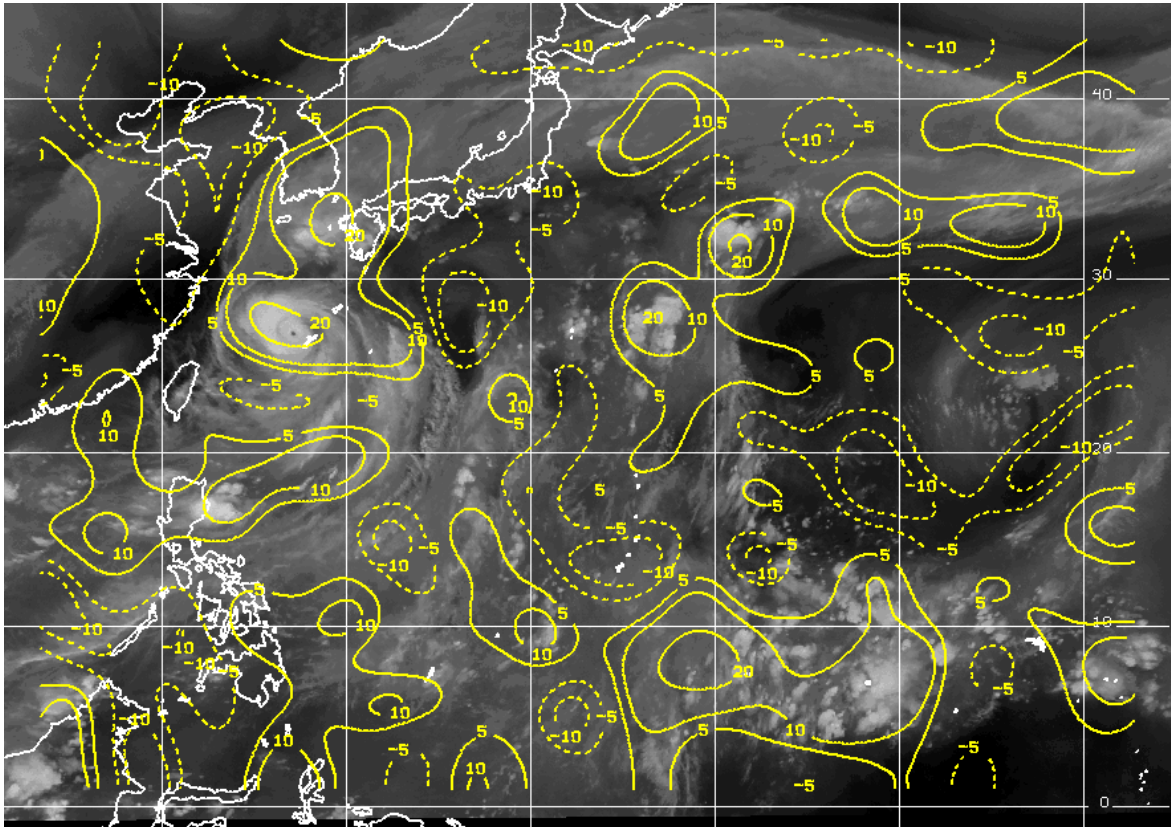
The detrainment of cloud air into the environment (term 2)

Evaporation of cloud and precipitation (term 3)

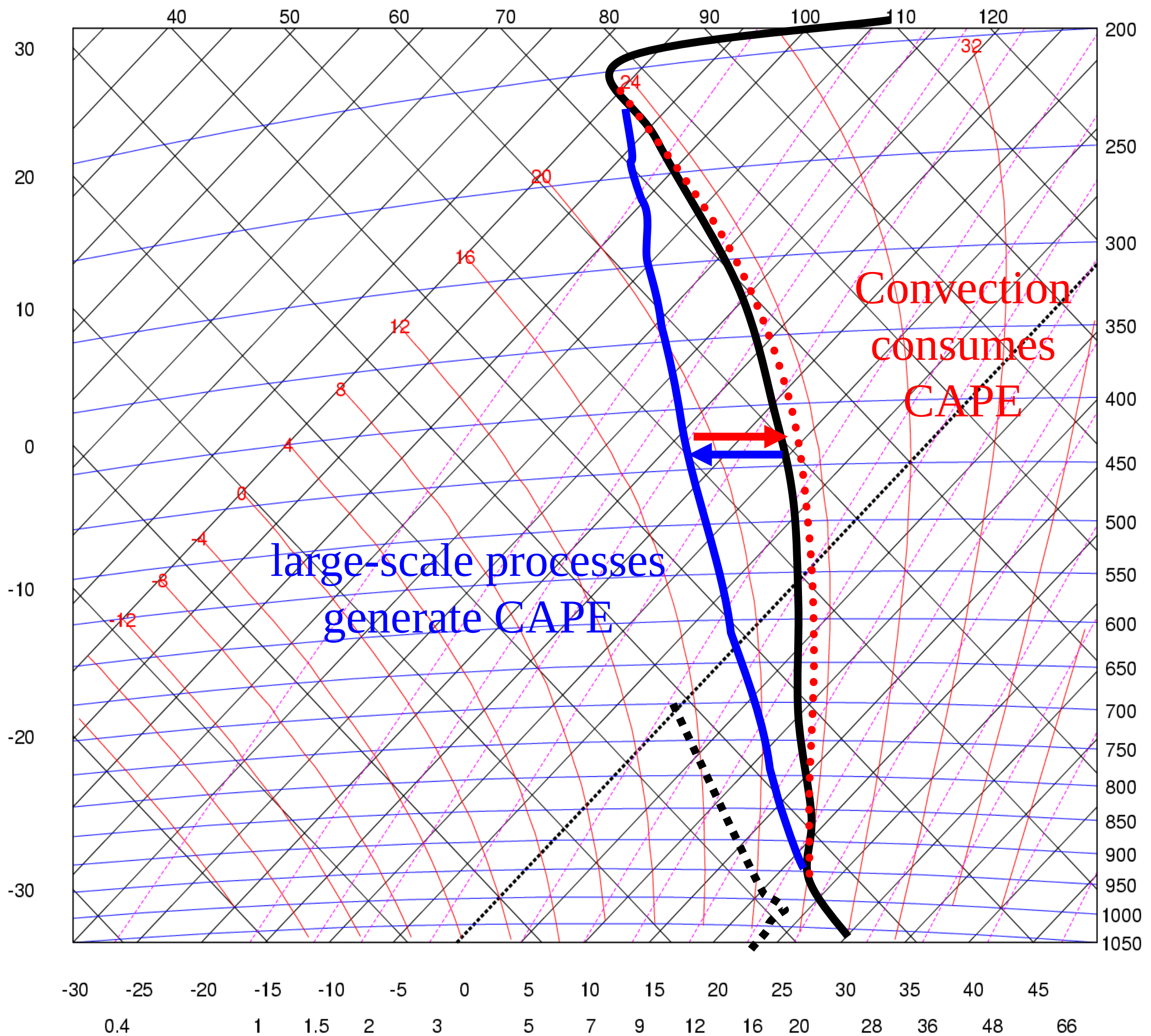
Note: In the **advective form** the condensation heating does not appear directly in Q_1. It is however the dominant term using the **flux form** and is a crucial part of the cloud model, where this heat is transformed in kinetic energy of the updrafts.

Determine mass flux change= divergence from variation of cold cloud top areas

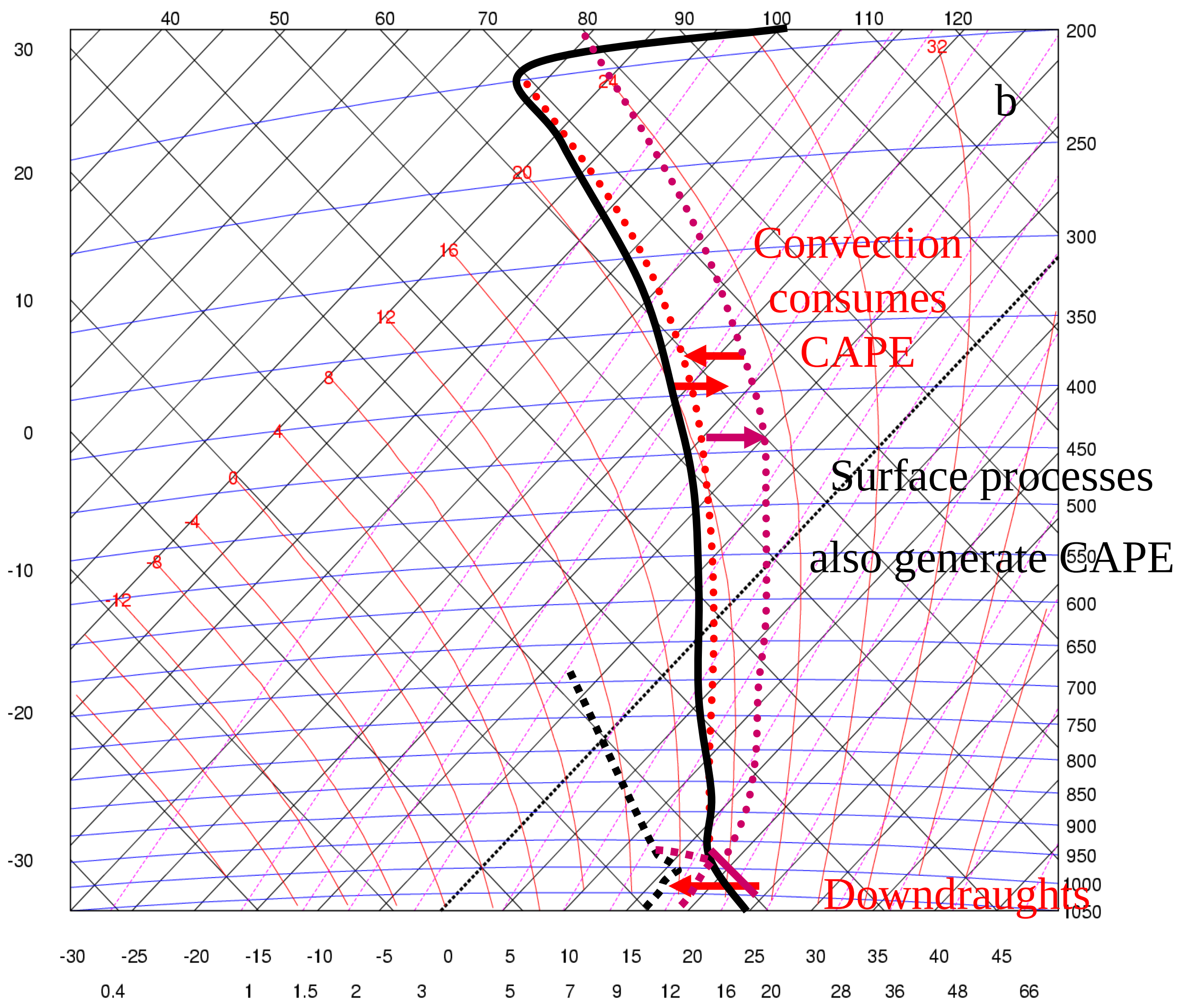
$$Div\rho\vec{U} = \lim_{Vol\to 0}\frac{1}{Vol}\iint_A \rho\vec{U}d\vec{A} = \lim_{\Delta t\to 0}\frac{1}{Vol}\frac{\Delta m}{\Delta t} \approx \rho\frac{1}{A}\frac{dA}{dt} = \frac{\partial M_c}{\partial z}$$



CAPE closure - the basic idea



CAPE closure - the basic idea



ECMWF

Summary

- Convection parametrisations need to provide a physically realistic forcing/response on the resolved model scales and need to be practical
- a number of approaches to convection parametrisation exist
- basic ingredients to present convection parametrisations are a method to trigger convection, a cloud model and a closure assumption
- the mass-flux approach has been successfully applied to both interpretation of data and convection parametrization …….

More Tricks and Tips for mass flux parametrization in Lecture III on the IFS scheme