Numerical Weather Prediction
Parameterization of diabatic processes

Convection III: The IFS scheme

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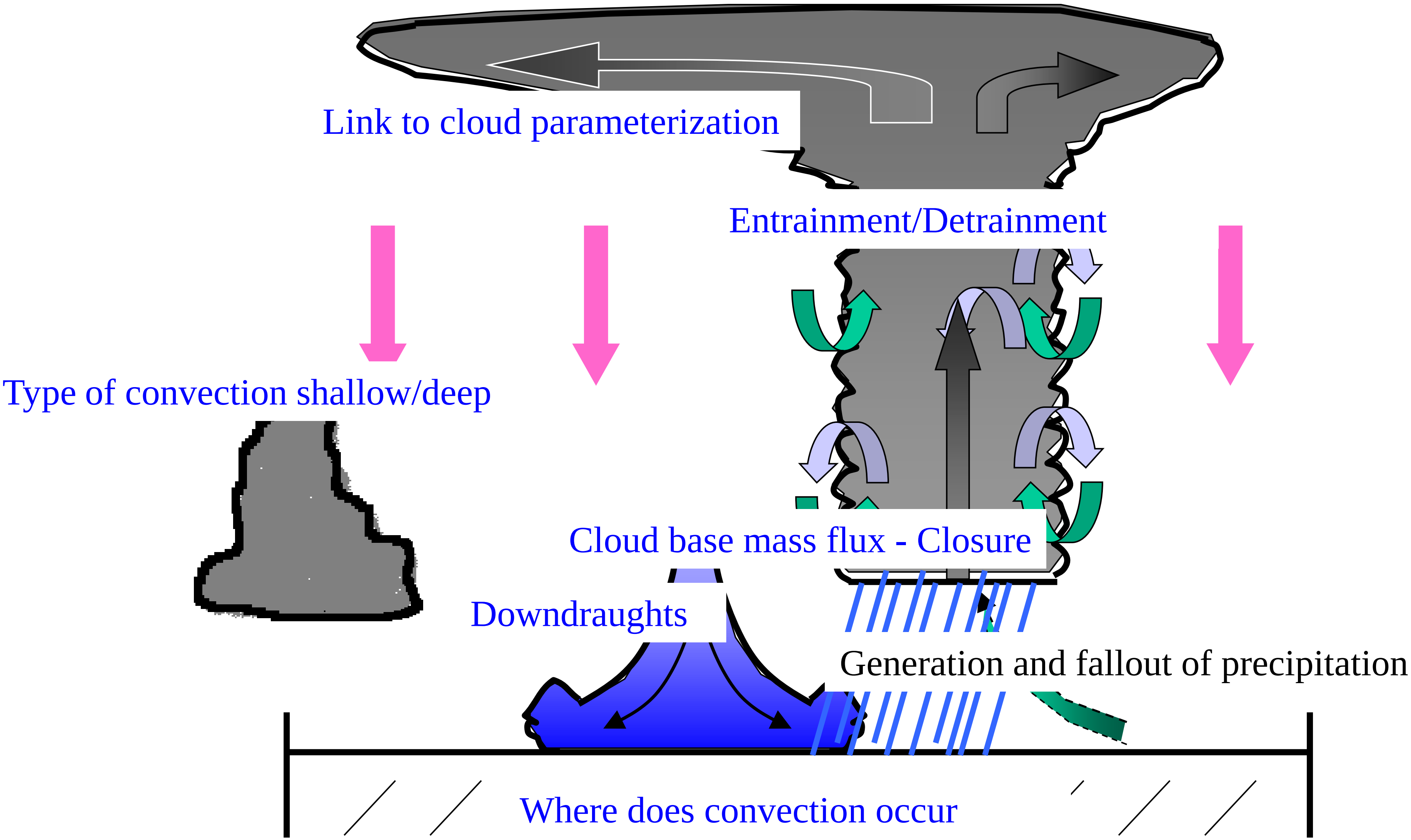
A bulk mass flux scheme
What needs to be considered



Basic Features

- Bulk mass-flux scheme
- Entraining/detraining plume cloud model
- 3 types of convection: deep, shallow and mid-level - mutually exclusive
- saturated downdraughts
- simple microphysics scheme
- closure dependent on type of convection
  - deep: CAPE adjustment
  - shallow: PBL equilibrium
- strong link to cloud parameterization - convection provides source for cloud condensate

Large-scale budget equations:
$M=\rho w$; $M_u>0$; $M_d<0$

Heat (dry static energy):

Prec. evaporation in downdraughts

Freezing of condensate in updraughts

$$\left(\frac{\partial s}{\partial t}\right)_{cu} = g\frac{\partial}{\partial p}\left[M_u s_u + M_d s_d - (M_u + M_d)\bar{s}\right] + L(c_u - e_d - e_{subcld}) - L_f(M - F)$$

Mass-flux transport in up- and downdraughts

condensation in updraughts

Prec. evaporation below cloud base

Melting of precipitation

Humidity:

$$\left(\frac{\partial q}{\partial t}\right)_{cu} = g\frac{\partial}{\partial p}\left[M_u q_u + M_d q_d - (M_u + M_d)\bar{q}\right] - (c_u - e_d - e_{subcld})$$

Large-scale budget equations

Momentum:

$$\left(\frac{\partial u}{\partial t}\right)_{cu} = g\frac{\partial}{\partial p}\left[M_u u_u + M_d u_d - (M_u + M_d)\overline{u}\right]$$

$$\left(\frac{\partial v}{\partial t}\right)_{cu} = g\frac{\partial}{\partial p}\left[M_u v_u + M_d v_d - (M_u + M_d)\overline{v}\right]$$

Cloud condensate:

$$\left(\frac{\partial l}{\partial t}\right)_{cu} = D_u l_u$$

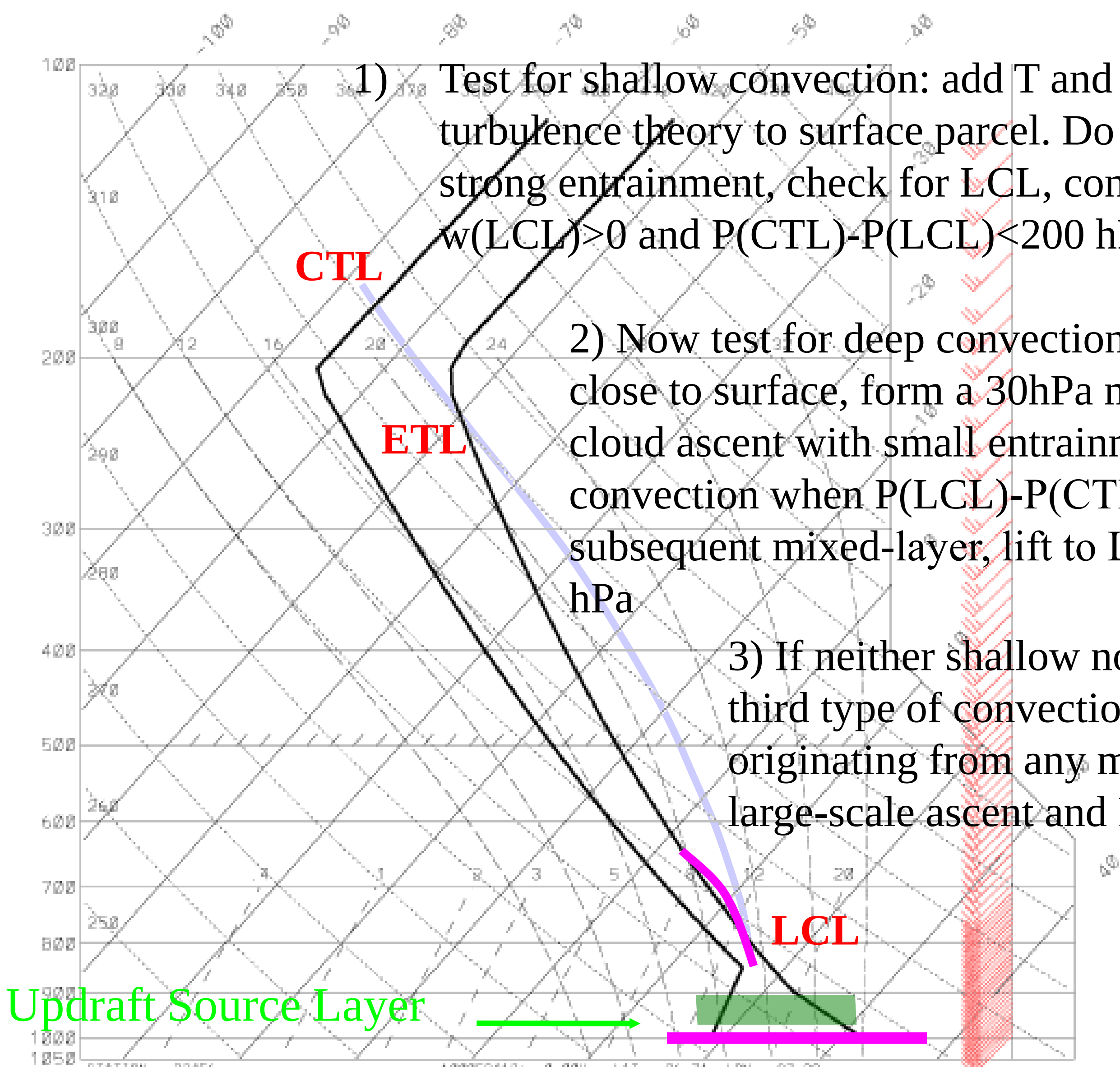
Nota: These tendency equations have been written in flux form which by definition is conservative (not in advective form!!). It can be solved either explicitly (just apply vertical discretisation) or implicitly (see later).

Occurrence of convection:
make a first-guess parcel ascent

1) Test for shallow convection: add T and q perturbation based on turbulence theory to surface parcel. Do ascent with w-equation and strong entrainment, check for LCL, continue ascent until w<0. If w(LCL)>0 and P(CTL)-P(LCL)<200 hPa : shallow convection

2) Now test for deep convection with similar procedure. Start close to surface, form a 30hPa mixed-layer, lift to LCL, do cloud ascent with small entrainment+water fallout. Deep convection when P(LCL)-P(CTL)>200 hPa. If not …. test subsequent mixed-layer, lift to LCL etc. … and so on until 300 hPa

3) If neither shallow nor deep convection is found a third type of convection – “midlevel” – is activated, originating from any model level below 10 km if large-scale ascent and RH>80%.



Cloud model equations – updraughts

E and D are positive by definition

Mass (Continuity)

$$-g\frac{\partial M_u}{\partial p} = E_u - D_u$$

Heat

$$-g\frac{\partial M_u s_u}{\partial p} = E_u\bar{s} - D_u s_u + Lc_u$$

Humidity

$$-g\frac{\partial M_u q_u}{\partial p} = E_u\bar{q} - D_u q_u - c_u$$

Liquid+Ice

$$-g\frac{\partial M_u l_u}{\partial p} = -D_u l_u + c_u - G_{P,u}$$

Precip

$$-g\frac{\partial M_u r_u}{\partial p} = -D_u r_u + G_{P,u} - Sfout$$

Momentum

$$-g\frac{\partial M_u u_u}{\partial p} = E_u\bar{u} - D_u u_u \qquad -g\frac{\partial M_u v_u}{\partial p} = E_u\bar{v} - D_u v_u$$

Kinetic Energy (vertical velocity) – use height coordinates

$$\frac{\partial K_u}{\partial z} = -\frac{E_u}{M_u}(1+\beta C_d)2K_u + \frac{1}{f(1+\gamma)}g\frac{T_{v,u}-\bar{T}_v}{\bar{T}_v}, \qquad K_u = \frac{w_u^2}{2}$$

Downdraughts

1. Find level of free sinking (LFS)

   highest model level for which an equal saturated mixture of cloud and environmental air becomes negatively buoyant

2. Closure

$$M_{d,LFS} = -\alpha M_{u,b} \qquad \alpha = 0.3$$

Cloud model equations – downdraughts

E and D are defined positive

$$g\frac{\partial M_d}{\partial p} = E_d - D_d$$

Mass

$$g\frac{\partial M_d s_d}{\partial p} = E_d \bar{s} - D_d s_d + Le_d$$

Heat

$$g\frac{\partial M_d q_d}{\partial p} = E_d \bar{q} - D_d q_d + e_d$$

Humidity

$$\left.\begin{aligned} g\frac{\partial M_d u_d}{\partial p} &= E_d \bar{u} - D_d u_d \\ g\frac{\partial M_d v_d}{\partial p} &= E_d \bar{v} - D_d v_d \end{aligned}\right\}$$

Momentum

Entrainment/Detrainment (1)

$$-g\frac{\partial M_u}{\partial p} = E_u - D_u = \frac{M_u}{\rho}\left(\varepsilon - \delta\right) = \frac{M_u}{\rho}\left(\varepsilon_{turb} - \delta_{turb} - \delta_{org}\right)$$

ε and δ are generally given in units (m^{-1})

$$\varepsilon = \underbrace{c_1\left(1.3 - RH\right)}_{buoy>0} F_\varepsilon; \quad RH = \frac{\bar{q}}{\bar{q}_s}; \quad \delta_{turb} = c_2$$

$$c_1 = 1.75\times10^{-3} m^{-1}; c_2 = 0.75\times10^{-4} m^{-1};$$

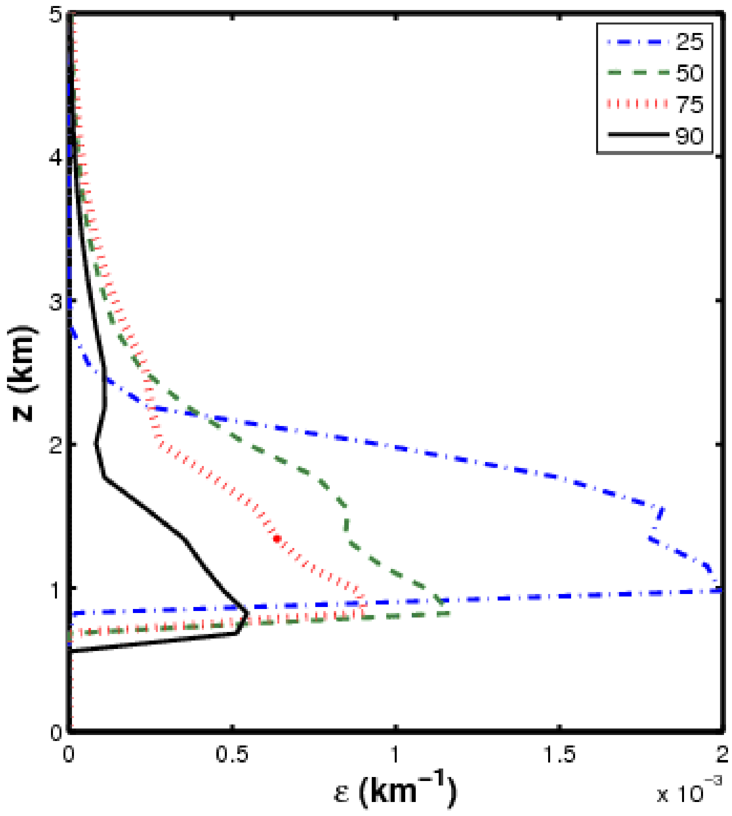
$$F_\varepsilon = \left(\frac{\bar{q}_s}{\bar{q}_{s\,base}}\right)^3$$

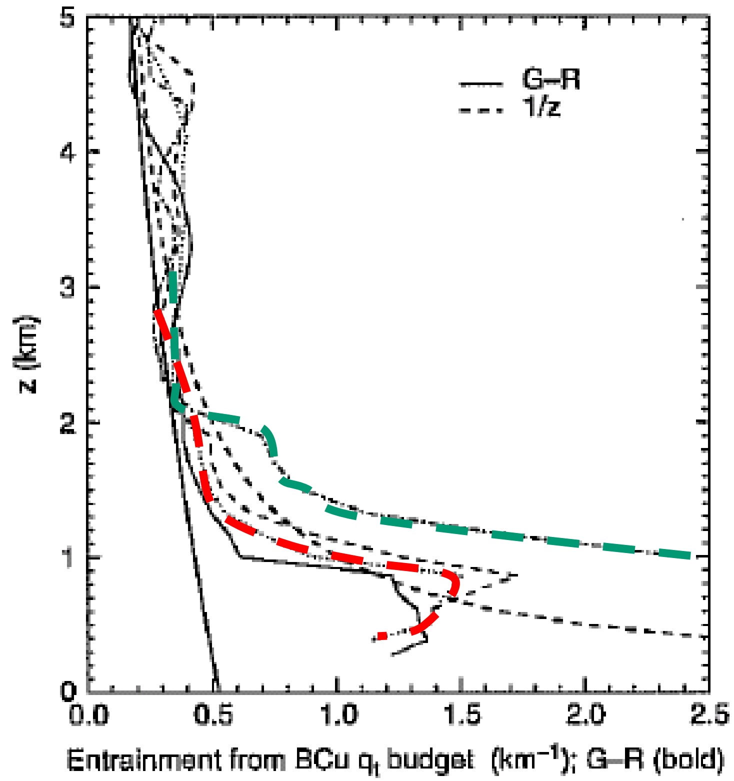
Constants

Scaling function to mimick a cloud ensemble

Entrainment/Detrainment (2)

Entrainment formulation looks so simple $\varepsilon = 1.8\times10^{-3}\,(1.3-RH)f(p)$ so how does it compare to LES colours denote different values of RH





Derbyshire et al. (2011)

Looks good: Note that shallow convective entrainment is typically a factor of 2 larger than that for deep convection

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Entrainment/Detrainment (3)

Organized detrainment:

Only when negative buoyancy (updraught kinetic energy K decreases with height), compute mass flux at level z+Δz with following relation:

$$\longrightarrow \quad \frac{M_u(z)}{M_u(z+\Delta z)} \approx \alpha(RH)\sqrt{\frac{K_u(z)}{K_u(z+\Delta z)}}$$

with

$$K_u = \frac{w_u^2}{2}$$

Precipitation

Liquid+solid precipitation fluxes:

$$P^{rain}(p) = \int_{Ptop}^{P} (G^{rain} - e_{down}^{rain} - e_{subcld}^{rain} + Melt)dp / g$$

$$P^{snow}(p) = \int_{Ptop}^{P} (G^{snow} - e_{down}^{snow} - e_{subcld}^{snow} - Melt)dp / g$$

Where P^{rain} and P^{snow} are the fluxes of precip in form of rain and snow at pressure level p. G^{rain} and G^{snow} are the conversion rates from cloud water into rain and cloud ice into snow. Evaporation occurs in the downdraughts e_{down}, and below cloud base e_{subcld}, *Melt* denotes melting of snow.

Generation of precipitation in updraughts

$$\rho G_{P,u} = M_u \frac{c_0}{w_u} l_u \left[1 - e^{-\left(\frac{l_u}{l_{crit}}\right)^2} \right]$$

Simple representation of Bergeron process included in c_0 and l_{crit}

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Precipitation

Fallout of precipitation from updraughts

$$\rho S_{fallout} = M_u \frac{V_{prec}}{w_u \Delta z} r_u$$

$$V_{prec,rain} = 5.32 r_u^{0.2} \qquad V_{prec,ice} = 2.66 r_u^{0.2}$$

Evaporation of precipitation

1. Precipitation evaporates to keep downdraughts saturated
2. Precipitation evaporates below cloud base

$$e_{subcld} = \sigma \alpha_1 \left(RH\, q_s - \bar{q} \right) \left(\frac{\sqrt{p/p_{surf}}}{\alpha_2} \frac{\bar{P}}{\sigma} \right)^{\alpha_3}, \quad \text{assume a cloud fraction } \sigma = 0.05$$

Closure - Deep convection

$$CAPE = g\int_{cloud}\frac{T_{v,u}-\overline{T}_v}{\overline{T}_v}dz \approx g\int_{cloud}\frac{\theta_{e,u}-\overline{\theta}_{esat}}{\overline{\theta}_{esat}}dz$$

Use instead density scaling, time derivative then relates to mass flux:

$$PCAPE = -\int_{Pbase}^{Ptop}\frac{T_{v,u}-\overline{T}_v}{\overline{T}_v}dp$$

$$\frac{\partial PCAPE}{\partial t} \approx \underbrace{-\int_{Pbase}^{Ptop}\frac{1}{\overline{T}_v}\frac{\partial \overline{T}_v}{\partial t}dp}_{LS+Cu} \underbrace{-\int_{Pbase}^{Ptop}\frac{1}{\overline{T}_v}\frac{\partial T_{v,u}}{\partial t}dp + \left.\frac{T_{v,u}-\overline{T}_v}{\overline{T}_v}\right|_{base}\frac{\partial p_{base}}{\partial t}}_{BL+Cu} =$$

$$= \left.\frac{\partial PCAPE}{\partial t}\right|_{LS} + \left.\frac{\partial PCAPE}{\partial t}\right|_{BL} + \left.\frac{\partial PCAPE}{\partial t}\right|_{Cu=shal+deep}$$

this is a prognostic CAPE closure: now try to determine the different terms and try to achieve balance $\partial PCAPE/\partial t \;\square\; \partial PCAPE/\partial t|_{cu}, \partial PCAPE/\partial t|_{LS}$

Closure - Deep convection

1 $$\left.\frac{\partial PCAPE}{\partial t}\right|_{cu,1} = -\frac{PCAPE - PCAPE_{BL}}{\tau}; \qquad \tau = \frac{H}{\overline{w}_u}$$

2 $$\left.\frac{\partial PCAPE}{\partial t}\right|_{cu,2} = \int_{Pbase}^{Ptop} \frac{1}{\overline{T}_v} \left.\frac{\partial \overline{T}_v}{\partial t}\right|_{cu} dp = -\int_{zbase}^{ztop} \frac{g}{\overline{T}_v} M \left(\frac{\partial \overline{T}_v}{\partial z} + \frac{g}{c_p}\right) dz$$

$$= -\frac{M_{u,b}}{M^*_{u,b}} \int_{zbase}^{ztop} \frac{g}{\overline{T}_v} M^* \left(\frac{\partial \overline{T}_v}{\partial z} + \frac{g}{c_p}\right) dz$$

Nota: all the trick is in the $PCAPE_{BL}$ term=PCAPE not available to deep convection but used for boundary-layer mixing (see Bechtold et al. 2014).

If $PCAPE_{BL}$=0 then wrong diurnal cycle over land!

Closure - Deep convection

Solve now for the cloud base mass flux by equating 1 and 2

$$M_{u,b} = M^*_{u,b} \frac{PCAPE - PCAPE_{BL}}{\tau} \frac{1}{\int\limits_{cloud} M^* \frac{g}{\overline{T}_v} \frac{\partial \overline{T}_v}{\partial z} dz}; \qquad M_{u,b} \geq 0$$

$$PCAPE_{BL} = -\tau_{BL} \frac{1}{T^*} \int\limits_{psurf}^{pbase} \left. \frac{\partial \overline{T}_v}{\partial t} \right|_{BL} dp$$

$M^* = M_u + M_d$ Mass flux from the updraught/downdraught computation

$M^*_{u,b}$ initial updraught mass flux at base, set proportional to 0.1Δp

$PCAPE_{bl}$ contains the boundary-layer tendencies due to surface heat fluxes, radiation and advection

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Closure - Shallow convection

Based on PBL equilibrium : what goes in must go out - including downdraughts

$$\int_{psurf}^{pbase} \frac{\partial \bar{h}}{\partial t} dp = 0$$

$$\int_{0}^{cbase} \left[g \left. \frac{\partial \left(\overline{w'h'} \right)}{\partial p} \right|_{cu} + \left(\frac{\partial \bar{h}}{\partial t} \right)_{turb} + \left(\frac{\partial \bar{h}}{\partial t} \right)_{dyn} + \left(\frac{\partial \bar{h}}{\partial t} \right)_{rad} \right] dp = 0$$

$$\bar{\rho} \left(\overline{w'h'} \right)_{cu,b} = M_{u,b} \left(h_u - \varepsilon h_d - (1-\varepsilon)\bar{h} \right)_{base} ; \quad \varepsilon = M_u / M_d ;$$

Assume 0 convective flux at surface, then it follows for cloud base flux

$$M_{u,b} = \frac{ -\frac{1}{g} \int_{psurf}^{pbase} \left[\left(\frac{\partial \bar{h}}{\partial t} \right)_{turb} + \left(\frac{\partial \bar{h}}{\partial t} \right)_{dyn} + \left(\frac{\partial \bar{h}}{\partial t} \right)_{rad} \right] dp }{ \left(h_u - \varepsilon h_d - (1-\varepsilon)\bar{h} \right)_{cbase} }$$

Closure - Midlevel convection

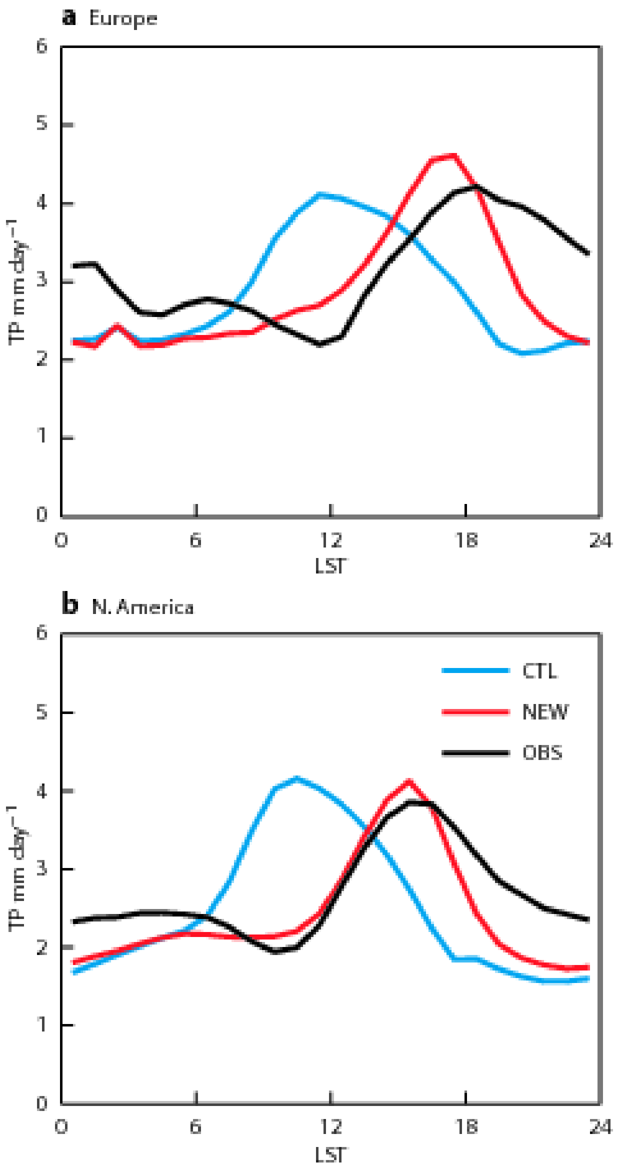
Roots of clouds originate outside PBL

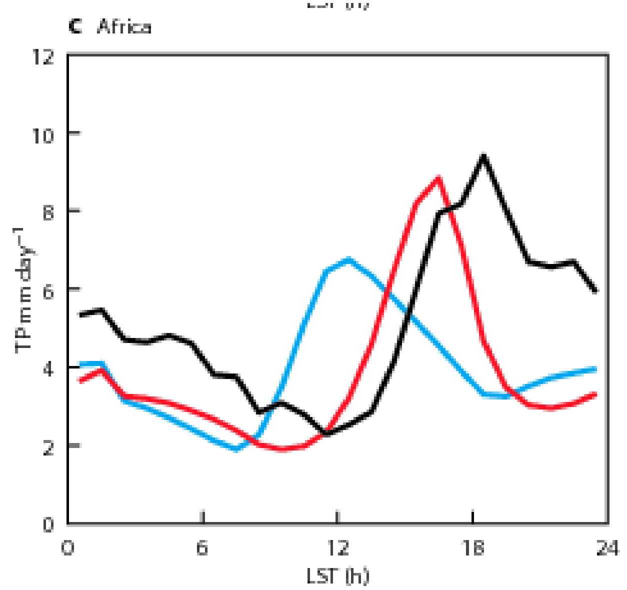
assume midlevel convection exists if there is large-scale ascent, RH>80% and there is a convectively unstable layer

Closure:

$$M_{u,b} = \rho \overline{w}_b$$

Impact of closure on diurnal cycle
JJA 2011-2012 against Radar





Obs radar

NEW=with PCAPEBbl term

Bechtold et al., 2014, J. Atmos. Sci.
ECMWF Newsletter No 136 Summer 2013

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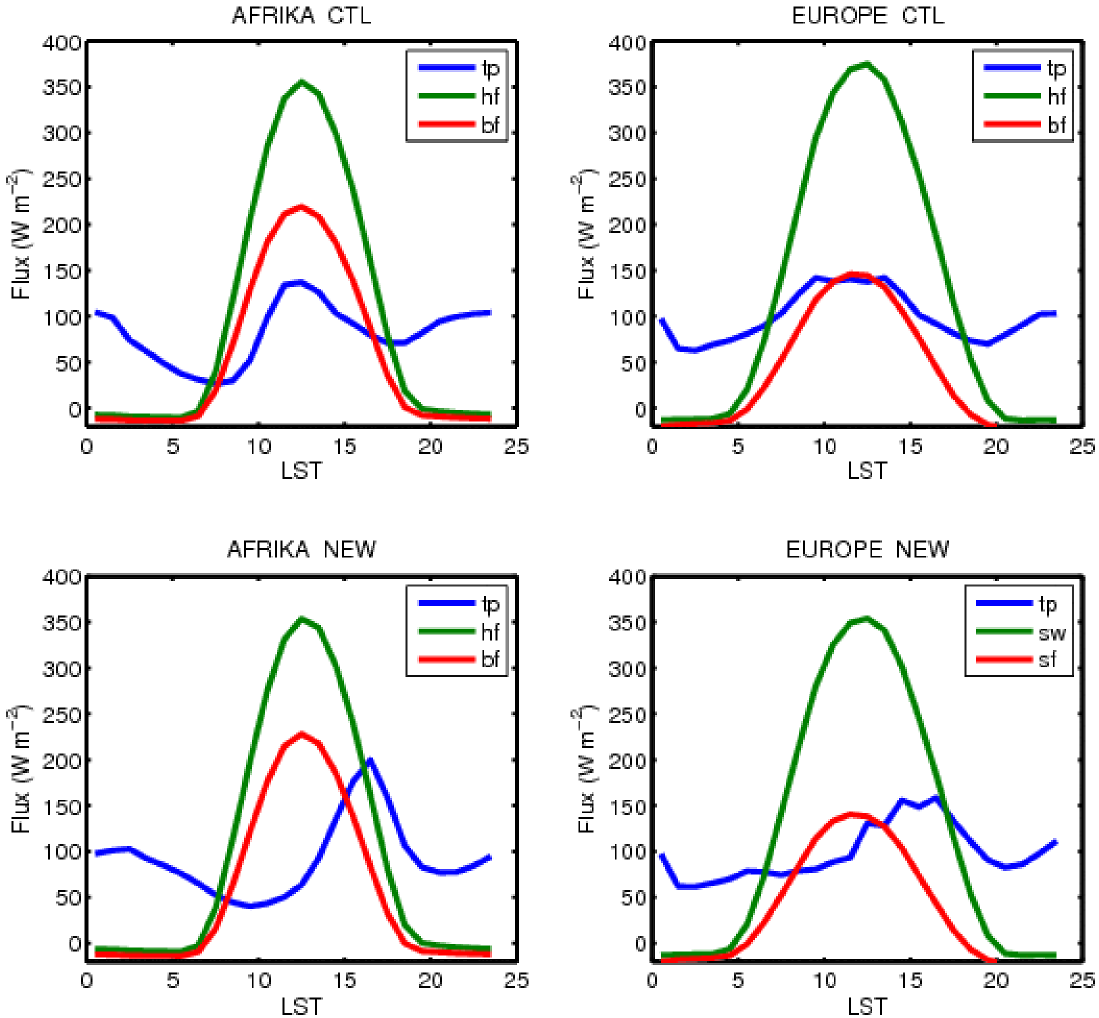
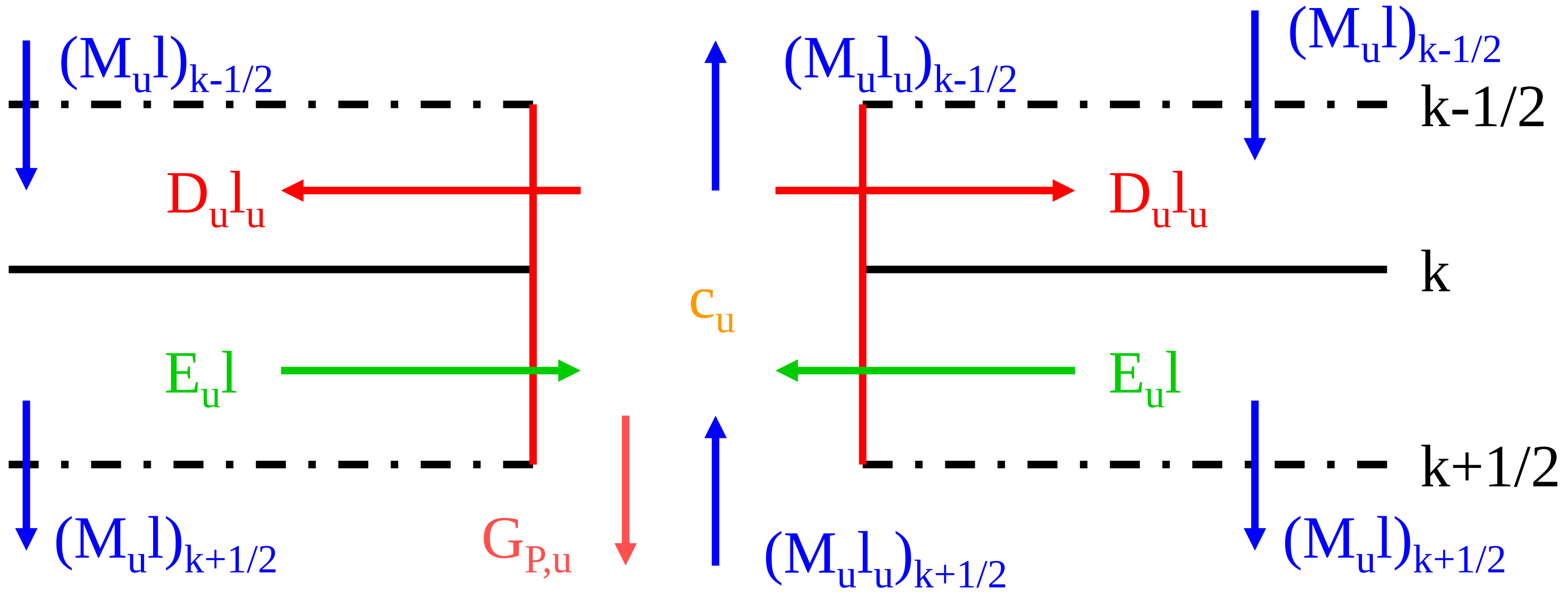
How does diurnal convective precipitation scale?



TP=total precipitation HF=surface enthalpy flux BF=surface buoyancy flux
NOTE: in NEW = revised diurnal cycle surface daytime precipitation scales as the surface buoyancy flux

Vertical Discretisation

Fluxes on half-levels, state variable and tendencies on full levels



Numerics: solving Tendency advection equation explicit solution

$$\left.\frac{\partial \bar{\psi}}{\partial t}\right|_{conv} = g\frac{\partial}{\partial p}\left[M^u(\psi^u - \bar{\psi})\right] + S;$$

if $\psi = T,q$ $\quad S = \frac{\partial}{\partial p}\mathrm{Pr}$

Use vertical discretisation with fluxes on half levels (*k+1/2*), and tendencies on full levels *k*, so that

$$\Delta p = P_{k+1/2} - P_{k-1/2}$$

$$\left.\frac{\partial \bar{\psi}_k}{\partial t}\right|_{conv} = \frac{g}{\Delta p}\left[M^u_{k+1/2}\psi^u_{k+1/2} - M^u_{k-1/2}\psi^u_{k-1/2} - M^u_{k+1/2}\bar{\psi}_{k+1/2} + M^u_{k-1/2}\bar{\psi}_{k-1/2}\right] + S_k$$

In order to obtain a better and more stable "upstream" solution ("compensating subsidence", use shifted half-level values to obtain:

$$\bar{\psi}_{k-1/2} = \bar{\psi}_{k-1}$$

$$\left.\frac{\partial \bar{\psi}_k}{\partial t}\right|_{conv} = \frac{g}{\Delta p}\left[M^u_{k+1/2}\psi^u_{k+1/2} - M^u_{k-1/2}\psi^u_{k-1/2} - M^u_{k+1/2}\bar{\psi}_{k} + M^u_{k-1/2}\bar{\psi}_{k-1}\right] + S$$

Numerics: implicit solution

$$\left.\frac{\partial \bar{\psi}}{\partial t}\right|_{conv} = g\frac{\partial}{\partial p}\left[M^u(\psi^u - \bar{\psi})\right] + S;$$

if $\psi = T,q$ $\quad S = \frac{\partial}{\partial p}\mathrm{Pr}$

Use temporal discretisation with $\bar{\psi}$ on RHS taken at future time $\bar{\psi}^{n+1}$ and not at current time $\bar{\psi}^{n}$

$$\Delta p = P_{k+1/2} - P_{k-1/2}$$

For "upstream" discretisation as before one obtains: $\quad \bar{\psi}_{k\text{-}1/2} = \bar{\psi}_{k\text{-}1}$

$$\bar{\psi}_k^{n+1} - \bar{\psi}_k^n = g\frac{\Delta t}{\Delta p}\left[M^u_{k+1/2}\psi^u_{k+1/2} - M^u_{k-1/2}\psi^u_{k-1/2} - M^u_{k+1/2}\bar{\psi}_k^{n+1} + M^u_{k-1/2}\bar{\psi}_{k-1}^{n+1}\right] + \Delta t S_k^n$$

$$(1 + M^u_{k+1/2})\bar{\psi}_k^{n+1} - M^u_{k-1/2}\bar{\psi}_{k-1}^{n+1} = g\frac{\Delta t}{\Delta p}\left[M^u_{k+1/2}\psi^u_{k+1/2} - M^u_{k-1/2}\psi^u_{k-1/2}\right] + \Delta t S_k^n$$

→ Only bi-diagonal linear system, and tendency is obtained as

$$\left.\frac{\partial \bar{\psi}_k}{\partial t}\right|_{conv} = \frac{\bar{\psi}_k^{n+1} - \bar{\psi}_k^n}{\Delta t}$$

Numerics: Semi Lagrangien advection

$$\frac{\partial \overline{\psi}}{\partial t} = -gM^{u}\frac{\partial \overline{\psi}}{\partial p} + D(\psi^{u} - \overline{\psi});$$

$$\frac{d\overline{\psi}}{dt} = \frac{\partial \overline{\psi}}{\partial t} + M^{u}g\frac{\partial \overline{\psi}}{\partial p} = -\frac{g}{\Delta p}\left[D^{u}(\psi^{u} - \overline{\psi})\right];$$

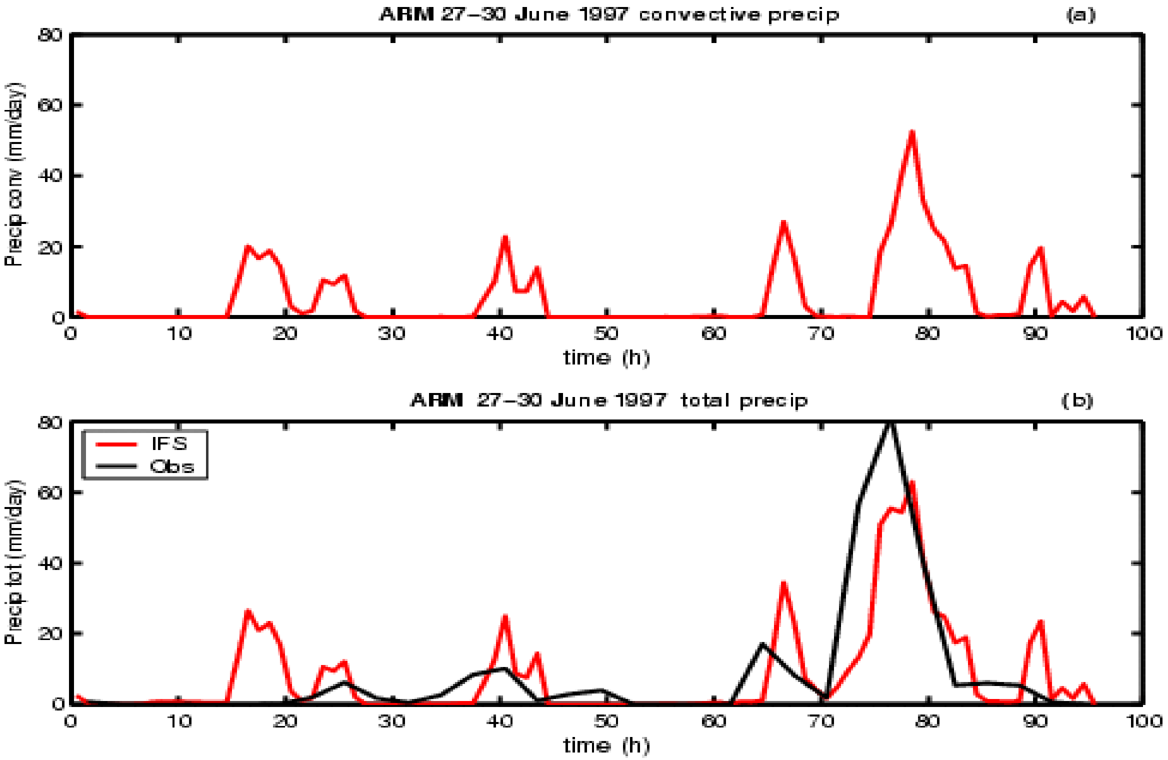
Advection velocity

$$\left.\frac{\partial \overline{\psi}}{\partial t}\right|_{conv} = \frac{\overline{\psi}_{dep} - \overline{\psi}}{\Delta t} - \frac{g}{\Delta p}\left[D^{u}(\psi^{u} - \overline{\psi})\right];$$

$$\overline{\psi}_{dep} = \overline{\psi}_{(P - M^{u}g\Delta t)}$$

Tracer transport experiments Single-column simulations (SCM)

Surface precipitation; continental convection during ARM



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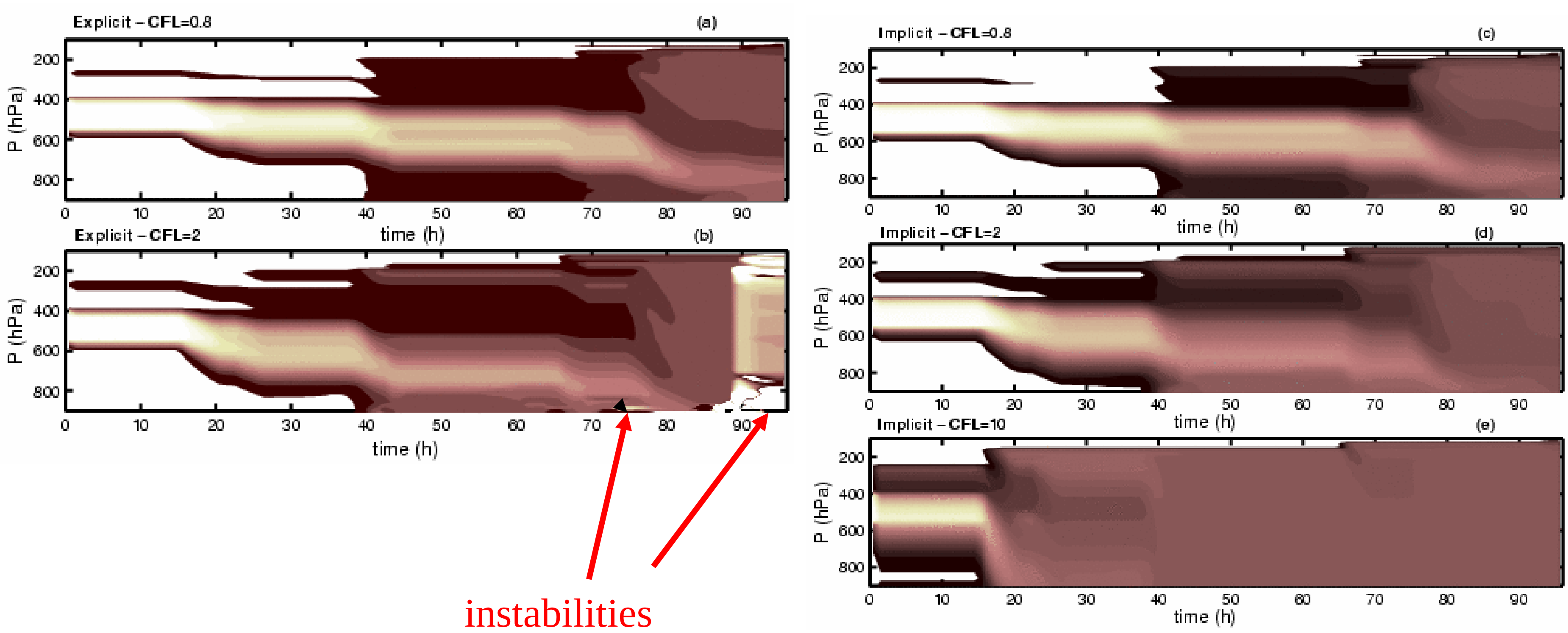
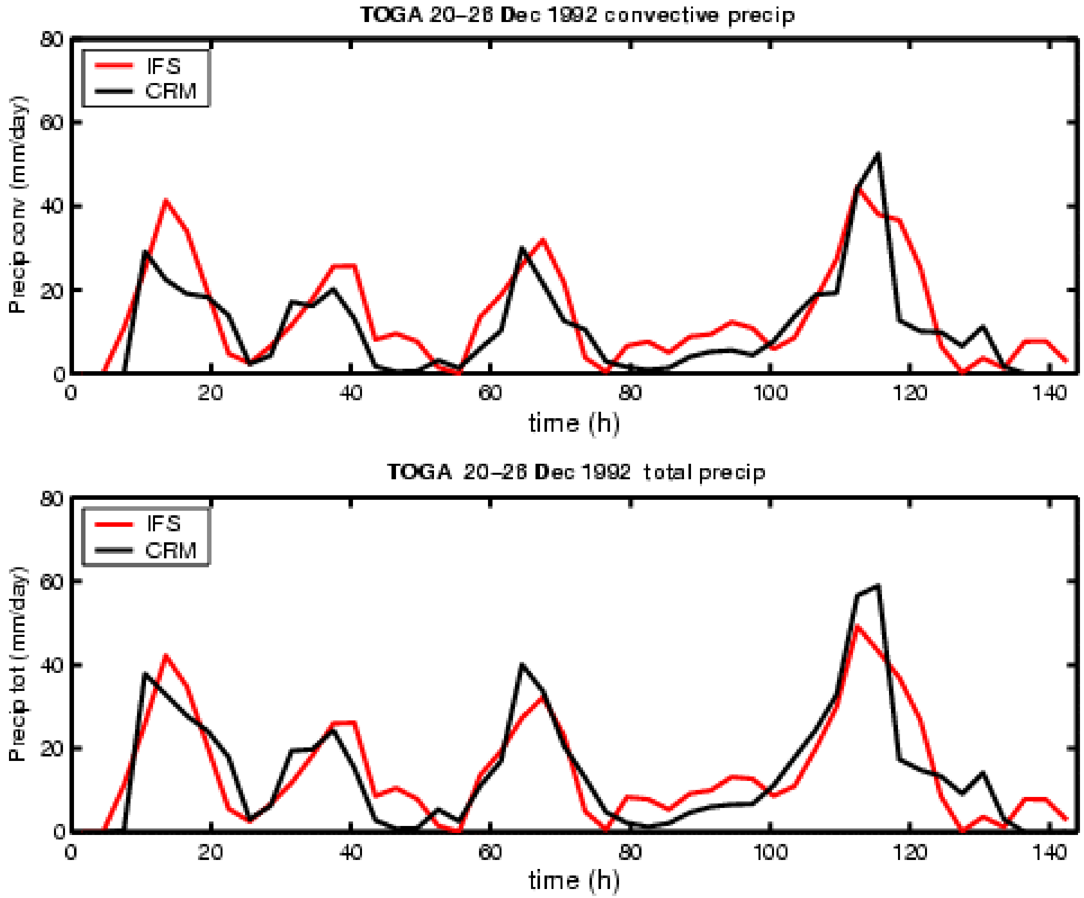
Tracer transport in SCM
Stability in implicit and explicit advection



- Implicit solution is stable.
- If mass fluxes increases, mass flux scheme behaves like a diffusion scheme: well-mixed tracer in short time

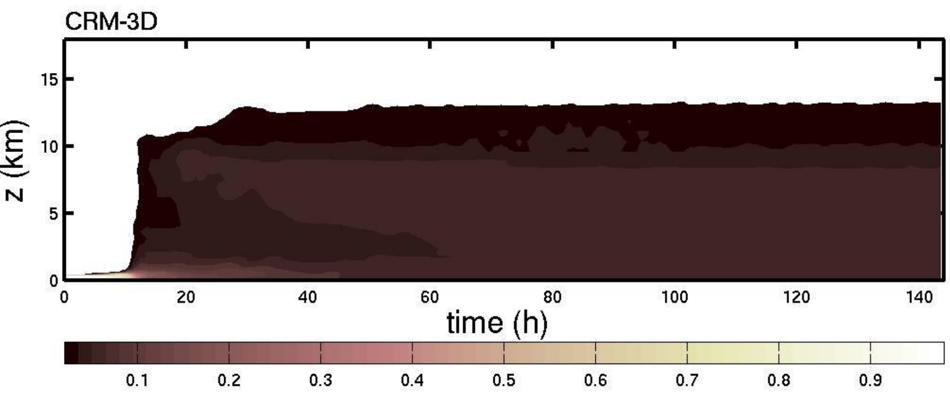
Tracer transport experiments (2)
Single-column model against CRM

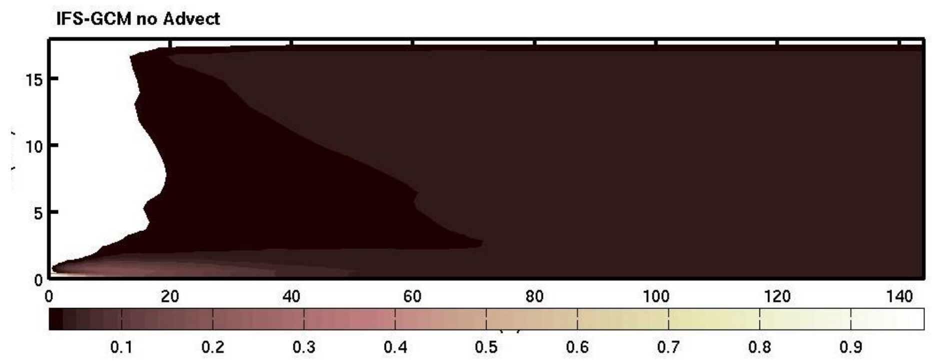
Surface precipitation; tropical oceanic convection during TOGA-COARE

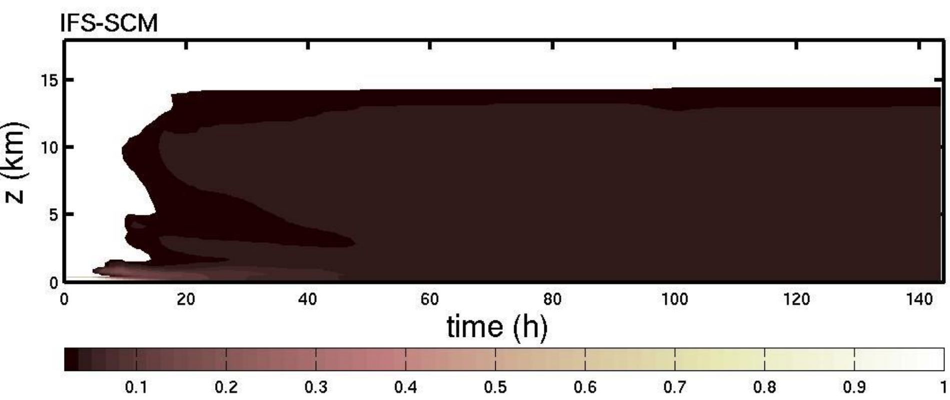


Tracer transport
SCM and global model against CRM

1. Boundary-layer Tracer



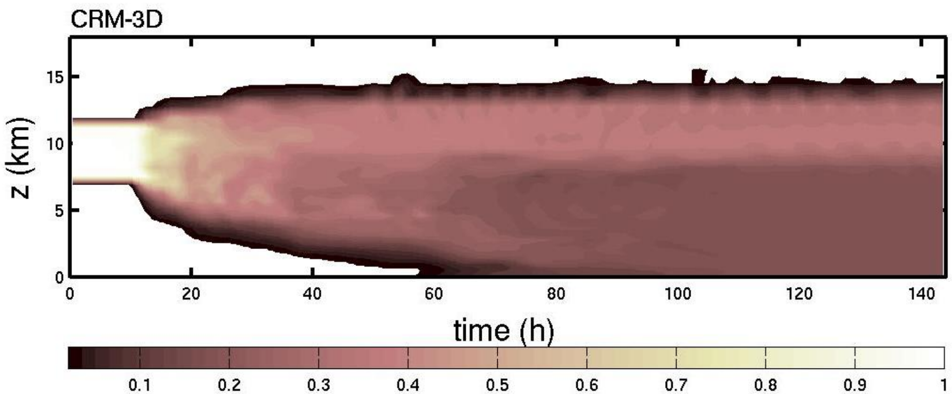


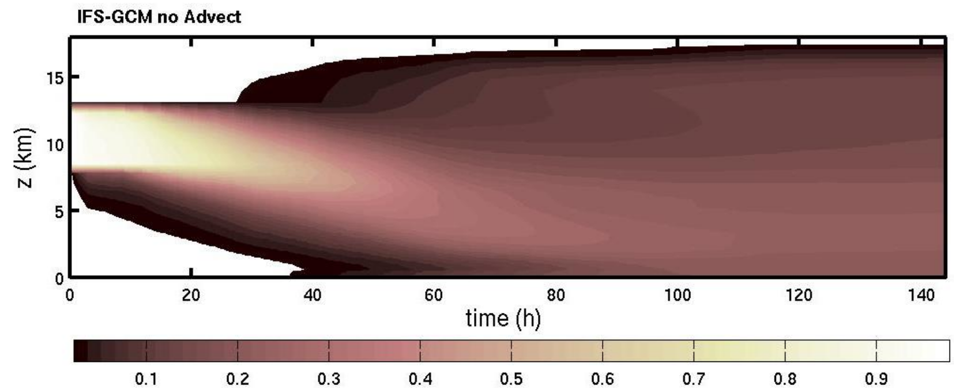


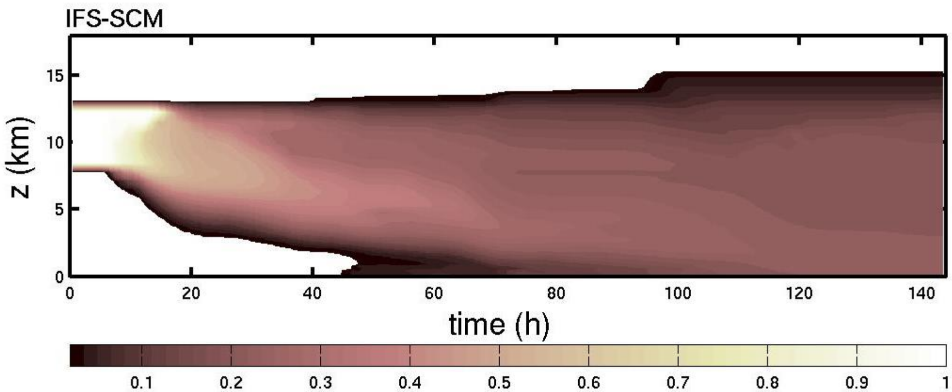
- Boundary-layer tracer is quickly transported up to tropopause
- Forced SCM and CRM simulations compare reasonably well
- In GCM tropopause higher, normal, as forcing in other runs had errors in upper troposphere

Tracer transport
SCM and global model against CRM

2. Mid-tropospheric Tracer







- Mid-tropospheric tracer is transported upward by convective draughts, but also slowly subsides due to cumulus induced environmental subsidence
- IFS SCM (convection parameterization) diffuses tracer somewhat more than CRM

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