

Parameterization of Convection in ECMWF

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- Cumulus convection is parameterized by a mass flux scheme which was originally described by *Tiedke* (1989).

- The scheme considers deep, shallow and mid-level convection.

- Cumulus clouds are assumed to be embedded in large-scale environment, have a common cloud base but different heights of tops due to different sizes with different entrainment and detrainment rates.

- The large-scale equations for heat moisture and momentum,

$$\frac{\partial \overline{s}}{\partial t} + \overline{V} \cdot \nabla \overline{s} + \overline{w} \frac{\partial \overline{s}}{\partial z} = -\frac{1}{\rho} \frac{\partial}{\partial z} \left(\overline{\rho} \overline{w' s'} \right) + L \left(\overline{c} - \overline{e} \right) + \overline{Q}_R$$

$$\frac{\partial \overline{q}}{\partial t} + \overline{V} \cdot \nabla \overline{q} + \overline{w} \frac{\partial \overline{q}}{\partial z} = -\frac{1}{\rho} \frac{\partial}{\partial z} \left(\overline{\rho} \overline{w' q'} \right) - \left(\overline{c} - \overline{e} \right)$$

$$\frac{\partial \overline{V}}{\partial t} + \overline{V} \cdot \nabla \overline{V} + \overline{w} \frac{\partial \overline{V}}{\partial z} = -\frac{1}{\rho} \frac{\partial}{\partial z} \left(\overline{\rho} \overline{w' V'} \right) - \frac{1}{\rho} \nabla \overline{p} + \overline{X}$$

- The eddy transports,

$$\overline{\rho}\left(\overline{w'x'}\right)_{cu} = \overline{\rho}\sum_i a_{ui}\left(w_{ui}-\overline{w}\right)\left(x_{ui}-\overline{x}\right) + \overline{\rho}\sum_i a_{ui}\left(w_{di}-\overline{w}\right)\left(x_{di}-\overline{x}\right) +$$

$$+\overline{\rho}\left(1-\sum_i\left(a_{ui}+a_{di}\right)\right)\left(\tilde{w}-\overline{w}\right)\left(\tilde{x}-\overline{x}\right)$$

- Convective mass fluxes,

$$M_{ui} = \overline{\rho}a_{ui}\left(w_{ui}-\overline{w}\right) \qquad M_{di} = \overline{\rho}a_{di}\left(w_{di}-\overline{w}\right)$$

- The contributions from cumulus convection to the large-scale budget equations of heat moisture and momentum,

$$\left(\frac{\partial \bar{s}}{\partial t}\right)_{cu} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left[M_{up}s_{up} + M_d s_d - \left(M_{up} + M_d\right)\bar{s}\right]$$
$$+ L\left(c_{up} - e_d - \tilde{e}_{scl}\right) - \left(L_{subl} - L_{vap}\right)\left(\mathcal{M} - \mathcal{F}\right)$$

$$\left(\frac{\partial \bar{q}}{\partial t}\right)_{cu} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left[M_{up}q_{up} + M_d q_d - \left(M_{up} + M_d\right)\bar{q}\right]$$
$$+ \left(c_{up} - e_d - \tilde{e}_{scl}\right)$$

- Where c_{up} and e_d are the condensation/sublimation in the updrafts and the evaporation in the downdrafts, $s_{up,}$ $s_{d,}$ $q_{d,}$ $u_{up,}$ $u_{d,}$ v_{up} and v_d are the weighted averages of the dry static energy ($\bar{s}$), the specific humidity ($\bar{q}$), and the horizontal wind components ($\bar{u}$ and $\bar{v}$) from all updrafts and downdrafts within a grid box.

$$\left(\frac{\partial \bar{u}}{\partial t}\right)_{cu} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left[M_{up}u_{up} + M_d u_d - \left(M_{up} + M_d\right)\bar{u}\right]$$

$$\left(\frac{\partial \bar{v}}{\partial t}\right)_{cu} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left[M_{up}v_{up} + M_d v_d - \left(M_{up} + M_d\right)\bar{v}\right]$$

$$P^{rain}(z) = \int_z^{\infty}\left(G^{rain} - e_d^{rain} - \tilde{e}_{scl}^{rain} + \mathcal{M}\right)\rho\, dz$$

$$P^{snow}(z) = \int_z^{\infty}\left(G^{snow} - e_d^{snow} - \tilde{e}_{scl}^{rain} - \mathcal{M}\right)\rho\, dz$$

where $P^{rain}(z)$ and $P^{snow}(z)$ are the fluxes of precipitation in the forms of rain and snow at height z. G^{rain} and G^{snow} are the conversion rates from cloud water into rain and cloud ice snow. The evaporation of precipitation in the downdrafts $e_{d,}$ and below cloud base $e_{scl,}$ have been split into water and ice components

The Cloud model

Cumulus updrafts - the updraft of the cloud ensemble is assumed to be in steady state.

$$\frac{\partial M_{up}}{\partial z} = E_{up} - D_{up}$$

$$\frac{\partial M_{up} s_{up}}{\partial z} = E_{up}\bar{s} - D_{up} s_{up} + L\bar{c}_{up} \qquad \frac{\partial M_{up} q_{up}}{\partial z} = E_{up}\bar{q} - D_{up} q_{up} - \bar{c}_{up}$$

$$\frac{\partial M_{up} l_{up}}{\partial z} = -D_{up} l_{up} + \bar{c}_{up} - \bar{G} \qquad \frac{\partial M_{up} r_{up}}{\partial z} = -D_{up} l_{up} + \bar{G} - \bar{S}_{fallout}$$

$$\frac{\partial M_{up} u_{up}}{\partial z} = E_{up}\bar{u} - D_{up} u_{up} \qquad \frac{\partial M_{up} v_{up}}{\partial z} = E_{up}\bar{v} - D_{up} v_{up}$$

- The conversion from water/ice to rain/snow is parameterized as,

$$\Delta G = M_{up} \frac{c_0}{0.75 w_p} l_{up} \left[1 - \exp\left\{ -\left(l_{up} / l_{crit} \right)^2 \right\} \right]$$

where c_0=*1x10*$^{-3}$*s*$^{-1}$ and l_{crit}=*0.5x10*$^{-3}$*g/kg.* w_p is the updraft vertical velocity and is limited to a maximum value of 10 m/s.

- Fallout of rain water/snow is parameterized as,

$$\Delta S_{fallout} = M_{up} \frac{V}{w_{up} \Delta z} r_{up}$$

where Δz is the model layer depth. The terminal velocity is parameterized as,

$$V = 5.23 r_{up}^{0.2}$$

- Entrainment of mass into convective plumes is assumed to occur through
  - turbulence exchange of mass through the cloud edges;
  - organized inflow associated with large-scale convergence.

$$E_{up} = E_{up}^{(1)} + E_{up}^{(2)}$$

- Detrainment is assumed to occur through
  - turbulent exchange;
  - organized outflow at cloud top.

$$D_{up} = D_{up}^{(1)} + D_{up}^{(2)}$$

Turbulent Entrainment and Detrainment Rates

- Turbulent entrainment and detrainment are parameterized as,

$$E_{up}^{(1)} = \varepsilon_{up}^{(1)} M_{up} \qquad D_{up}^{(1)} = \delta_{up}^{(1)} M_{up}$$

where the fractional entrainment/detrainment rates depend inversely on cloud radii in the updrafts,

$$\varepsilon_{up}^{(1)} = \frac{0.2}{R_{up}} \qquad \delta_{up}^{(1)} = \frac{0.2}{R_{up}}$$

$$\varepsilon_{up}^{(1)} = \delta_{up}^{(1)} = \begin{cases} 1 \times 10^{-4} \text{ m}^{-1} & \text{for penetrative and mid-level convergence} \\ & \text{in the presence of large-scale flow convergence} \\ 3 \times 10^{-4} \text{ m}^{-1} & \text{for shallow convection in supressed conditions} \end{cases}$$

- In order to take into account enhanced turbulence in the lower part of the clouds, the fractional rates are increased in the lowest 150hPa of the cloud in the case of deep and shallow convection. The enhancement factor varies linearly from 4 at cloud base to 1 at 150hPa above cloud base.

Organized Entrainment and Detrainment

- Organized entrainment is applied to deep and mid-level convection.

- Organized detrainment is estimated from the vertical variation of the updraft vertical velocity $w_{up,}$ which is estimated from the budget equation for the updraft kinetic energy,

$$\frac{\partial K_{up}}{\partial z} = -\frac{\varepsilon_{up}}{M_{up}}(1+\lambda C_d)2K_{up} + \frac{1}{f(1+\lambda)} g \frac{T_{v,up} - \bar{T}_v}{\bar{T}_v}$$

$K_{up} = \frac{w_{up}^2}{2}$ the updraft kinetic energy;

ε_{up} is a mixing coefficient which is equal to the entrainment mass flux (E_{up}) or the detrainment mass flux (D_{up}) if this is larger;

λ (=0.5) is the virtual mass coefficient;

the factor *f* (=2) is introduced because the flow is highly turbulent;

C_d is the drag coefficient

The cloud base value of the updraft velocity is chosen as 1m/s.

- ***Downdrafts***-are considered to be associated with convective precipitation from the updrafts and originate from cloud air influenced by the injection of environmental air.

- The Level of Free Sinking (LFS) is assumed to be the highest model level (below the level of minimum moist static energy) where a mixture of equal parts of cloud and saturated environmental air at the wet-bulb temperature becomes negative buoyant with respect to the environmental air.

- The downdraft mass flux is assumed to be directly proportional to the upward mass flux.

- The mass flux at the LFS is specified from the updraft mass flux at the cloud base as,

$$\left(M_{down}\right)_{LFS} = \eta\left(M_{up}\right)_{base} \qquad \text{with} \quad \eta = -0.3$$

- The vertical distribution of downdraft mass flux, dry static energy, moisture and horizontal momentum below the LFS are determined by entraining/detraining plume equations similar to those for the updraft,

$$-\frac{\partial M_d}{\partial z} = E_d - D_d$$

$$-\frac{\partial M_d s_d}{\partial z} = E_d \bar{s} - D_d s_d + L\bar{c}_d + L\bar{e}_d$$

$$-\frac{\partial M_d q_d}{\partial z} = E_d \bar{q} - D_d q_d - \bar{e}_d$$

$$\frac{\partial M_d u_d}{\partial z} = E_d \bar{u} - D_d u_d$$

$$\frac{\partial M_d v_d}{\partial z} = E_d \bar{v} - D_d v_d$$

Turbulent Entrainment and Detrainment

- For turbulent mixing,

$$\varepsilon_d^{(1)} = \delta_d^{(1)} = 2 \times 10^{-4}\ m^{-1}$$

Organized Entrainment and Detrainment

- Organized entrainment for the downdraft is based upon a formulation suggested by Nordeng (1994),

$$\varepsilon_d^{(2)} = \frac{\left[g \frac{T_{v,d} - T_d r_d - \bar{T}_v}{\bar{T}_v} \right]}{\left(w_d^{LFS}\right)^2 - \int_{z_{LFS}}^{z} \left[g \frac{T_{v,d} - T_d r_d - \bar{T}_v}{\bar{T}_v} \right] dz}$$

where w_d^{LFS} is the vertical velocity in the downdraft at the LFS (set to 1m/s).

- The scheme has no explicit rain water equation for the downdraft and so r_d is estimated by,

$$r_d = \frac{\sum_{k=1}^{NLEV} r_{up}^k M_{up}^k}{M_{up}^k}$$

- Organized detrainment from downdraft occurs when either the downdraft becomes positively buoyant or approaches the surface. If the downdraft remains negatively buoyant until it reaches the surface then the mass flux is decreased linearly over the bottom three model levels for L31and L50 versions. In L60 version the downdraft is detrained over the lowest seven model levels, maintaining an outflow depth of about 50hPa. However if a downdraft becomes positively buoyant during its descent, it is detrained over one level, except where this occurs at cloud base, when the downdraft fluxes are decreased linearly (deep convection) or quadratically (mid-level convection) to zero at the surface.

Convective Types

- In using a bulk mass flux scheme, as opposed to a scheme which considers an ensemble of convective clouds (Arakawa and Schubert), some determination of convective cloud type must be made so that appropriate choices can be made for the cloud properties.

- Firstly it must be determined if the profile can support convection from the surface layer. If on carrying out an undilute ascent from the surface layer a cloud base is found where the parcel buoyancy is greater than -0.5K, then either deep or mid-level convection is initiated. If no such cloud base is found then higher levels of the model are tested for a buoyant layer, mid-level convection being initiated from the lowest such level.

- If the cloud depth exceeds 200 hPa then deep convection is assumed, shallow convection if not.

Deep Convection

- The cloud base mass flux for deep convection is estimated from assuming that convection acts to reduce the CAPE towards zero over a specified time scale τ,

$$\frac{\partial CAPE}{\partial t} = -\frac{CAPE}{\tau} = \int_{z_{base}}^{z_t} \frac{g}{\overline{T}_v}\left(\frac{\partial \overline{T}_v}{\partial t}\right)^{cum} dz - \int_{z_{base}}^{z_t} M_{cld}\frac{g}{\overline{T}_v}\left(\frac{\partial \overline{T}_v}{\partial t}\right) dz$$

- ***CAPE*** is estimated from the parcel ascent incorporating the effects of water loading,

$$CAPE = \int g\left(\frac{T_{v,up} - \overline{T}_v}{\overline{T}_v} - l_{up}\right) dz$$

- The adjustment time scale τ is rather arbitrary '*but experience suggests that to prevent grid-scale saturation it must be such that* $M_{cld} \Delta t < \overline{w}$, *where* $\overline{w}$ *is the grid-scale vertical velocity'.* For resolutions of the deterministic forecast (T_L319) $\tau = 1400s$, close the time step of the model at this resolution (~1200s), implying that convection acts to produce zero ***CAPE*** at each time step.

Shallow Convection

- This type of convection seems to be effectively controlled by sub-cloud layer turbulence (typical examples are trade-wind cumuli under a subsidence inversion, convection occurring in the ridge region of tropical easterly waves and daytime convection over land).

- The mass flux at cloud base is based on the moist static energy budget,

$$\left[M_{up}\left(h_{up}-\bar{h}\right)\right]_{base}=\int_{0}^{B}\left[\overline{V}\cdot\nabla\bar{h}+\bar{w}\frac{\partial\bar{h}}{\partial z}+c_p\left(\frac{\partial\bar{T}}{\partial t}\right)_{rad}+\frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho\overline{w'h'}\right)_{rad}\right]dz$$

- The moisture supply to the shallow cumulus is largely through surface evaporation as the contributions from large-scale convergence are either small or even negative, such as in the undisturbed trades where dry air is transported downward to lower levels.

- No organized entrainment is applied to shallow convection. As turbulent entrainment and detrainment rates are equal, the mass flux remains constant with height until reducing at the cloud top by organized detrainment.

Mid-level Convection

- Mid-level convection - convective cells which have their roots not in the boundary layer but originates at levels above the boundary layer (often occur at rain bands at warm fronts and in the warm sectors of extratropical cyclones). This cells are formed by the lifting of low level air until it becomes saturated and the primary moisture source for the clouds is from low-level large-scale convergence. Often a low-level temperature inversion exists that inhibits convection from starting freely from the surface; therefore convection seems to be initiated by lifting low-level air dynamically to the level of free convection. This occurs often in connection with mesoscale circulations which might be related to conditionally symmetric instability.

- The parameterization scheme assumes that convection is activated when there is a large-scale ascent, the environmental air is sufficiently moist (i.e. the relative humidity exceeds 80%) and convectively unstable layer exists above. The free convection level is determined by lifting a parcel of environmental temperature and moisture content adiabatically, allowing for condensational heating, and then check for buoyancy.

- The upward mass flux is set equal to the vertical mass transport by large scale flow at that level.

Momentum Transports

- Studies have shown that for deep convection momentum transports are overestimated by the plum models unless the effects of cloud scale horizontal pressure gradients are included. For unorganised convection the effects of the pressure gradients are to adjust the in-cloud winds towards those of large-scale flow. This can be represented by an enhanced turbulent entrainment rate in the cloud momentum equations. To ensure mass continuity the turbulent detrainment rate is also increased by an equivalent amount. As the air entrained as detrained have different properties and this adjust the in-cloud wind back towards large-scale value.

- Hence for deep and mid-level convection the turbulent entrainment and detrainment rates used in updraft momentum equations are,

$$\lambda_{up}^{k,(1),(u,v)} = \lambda_{up}^{k,(1)} + \Box\Box_{up}^{(1)}$$

$$\lambda_{up}^{k,(1),(u,v)} = \lambda_{up}^{k,(1)} + \Box\Box_{up}^{(1)}$$

When $\lambda_{up}^{k,(1)} > 0$ (below the mid-level of the cloud) $\Box = 2$, while if $\lambda_{up}^{k,(1)} = 0$ (in the upper part of the cloud) then $\Box = 3$.

- For shallow convection and downdrafts it is assumed that the effects of pressure gradient term can be neglected and no enhancement of the entrainment rates in the momentum equations is applied. This formulation limits the momentum transports to be downgradient. Upgradient transports by highly organized convective systems (e.g. African squall lines) are not captured by this method.

- The definition of the horizontal wind in the updraft and downdraft at cloud base and LFS is not well known. For the updraft the value at cloud base is set to an average of the large-scale winds over the depth of the sub-cloud layer. For the downdraft the initial values at the LFS are set equal to the average values of the winds in the updraft and those of the large-scale flow.