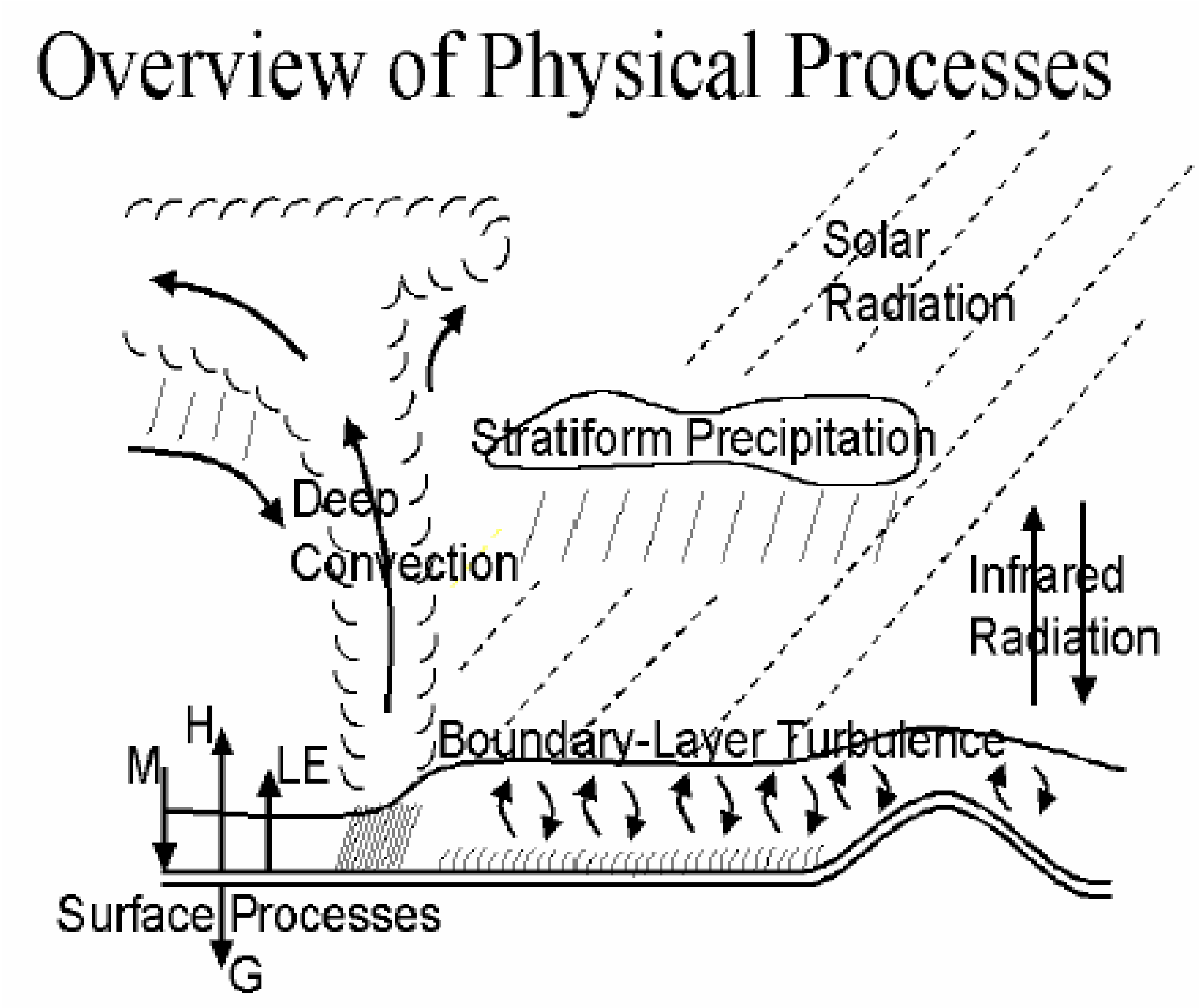
Parameterizations in CMC NWP Models



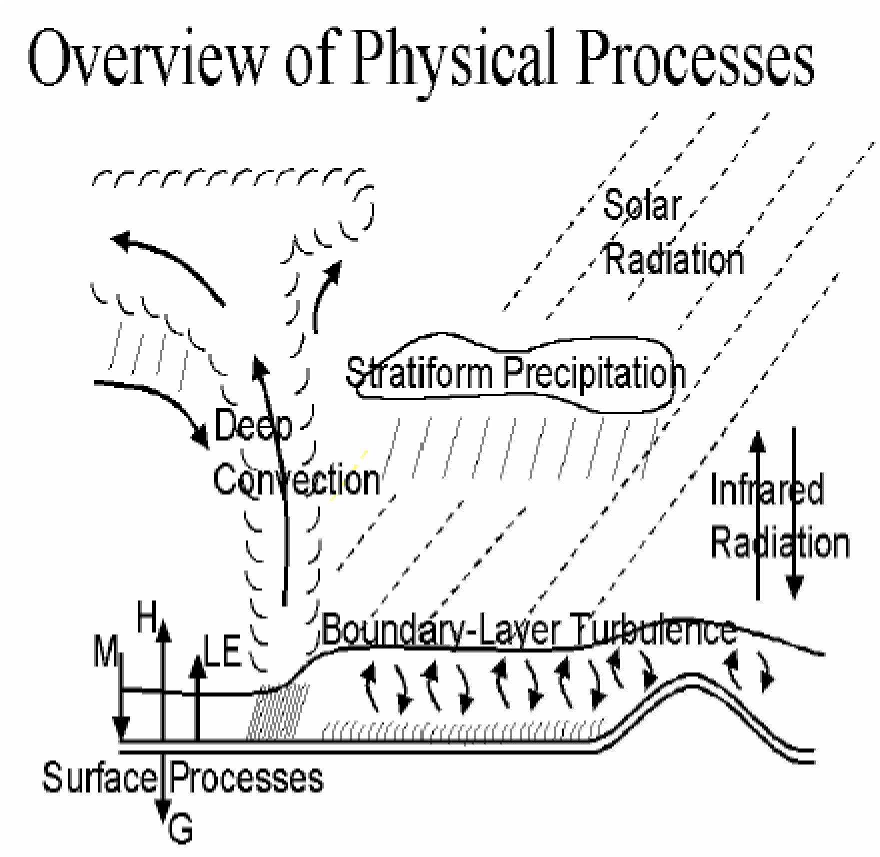
(from Physical Parameterizations in Canadian Operational Models, S. Bélair)

"The Regional Atmospheric Modeling System (RAMS) is used to investigate model sensitivity and the summer climate of North America… **The surface boundary forcing is the dominant factor in generating atmospheric variability** and exerts greater control on the model as the influence of lateral boundary conditions diminish. The sensitivity to surface forcing is also influenced by the model parameterizations."

"INVESTIGATION OF THE SUMMER CLIMATE OF NORTH AMERICA: A REGIONAL ATMOSPHERIC MODELING STUDY". Ph.D. dissertation, C. L. Castro, Department of Atmospheric Science
Colorado State University, Fort Collins, CO 80523, Fall 2005

(however, here we shall focus on convective parameterization rather than parameterization of surface forcing, which is covered --- without much detail --- in course notes)

Parameterizations in CMC NWP Models



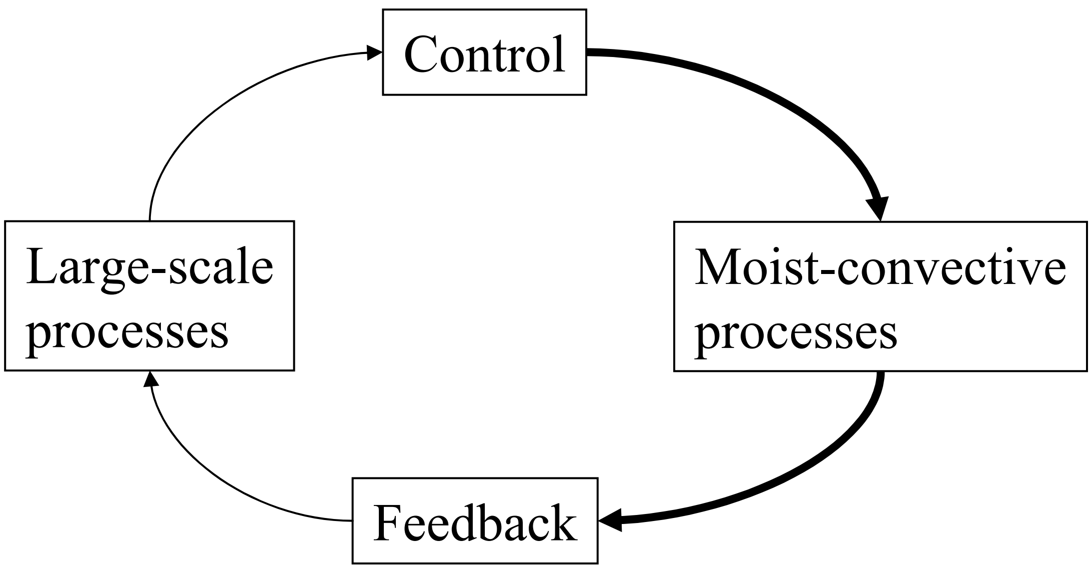
(from Physical Parameterizations in Canadian Operational Models, S. Bélair)

Molinari [1] defines mesoscale models as hydrostatic models with $10 \leq \Delta x \leq 50$ km

Thus both the global (33 km) and Regional (15 km) runs of CMC's Global Multiscale Environmental NWP model are mesoscale models

"At a grid spacing of 10 km, the grid scale approaches the preferred scale for instability of convection in nature." (Molinari, [1]) Most individual clouds are sub-grid scale: must formulate the statistical behaviour and collective effects of subgrid-scale clouds in terms of prognostic variables of grid scale (paraphrased from Arakawa, [1])

Wish for : universal formulation (impossible), valid over some well-defined range of grid lengths Δx. But in practice there are “schemes for large scale models”, and “schemes for mesoscale models” [1]



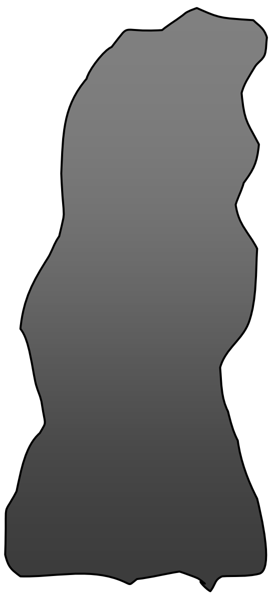
From Arakawa; formulation of the path connected by heavy curves is the purpose of “cumulus parameterization”

Use of Primitive Equation models in NWP has made parametrization of the role of convection essential: for otherwise the lapse rate may become unstable during a numerical forecast, and intense (and false) synoptic scale vertical velocities can develop and ruin the large-scale forecast (Simard and Girard, CMC)…

Control

- stratification
- convergent flow
- vertical motion
- humidity

Convective parameterization is an important challenge. The subject does not lend itself to tidy mathematical or numerical formulations – the schemes and the papers describing them tend to be bitsy, and barely recognizable as fluid mechanics. Problem for mesoscale models has been called “muddy” and “not well posed” [1]



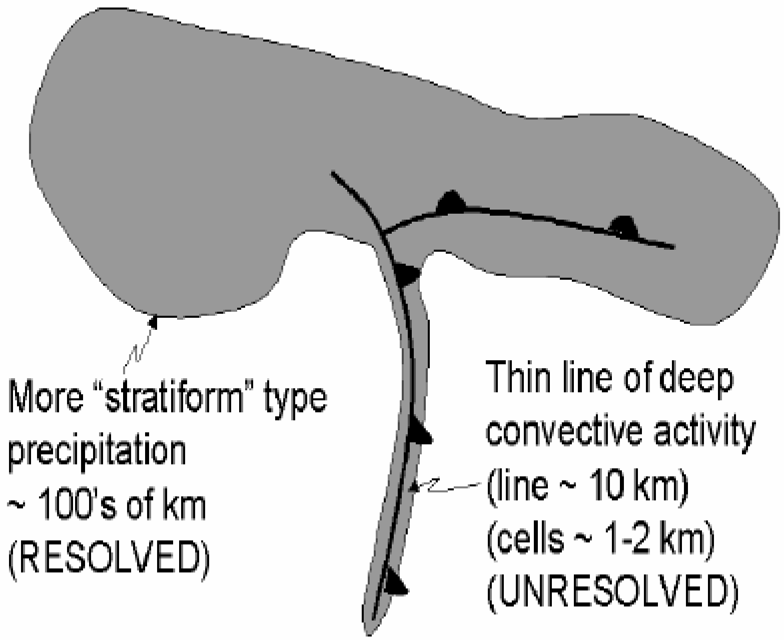
“The premise underlying all physical parameterization is that some aspect of the microscale chaotic process is in statistical equilibrium with the macroscale system” (Emanuel, [1])

Convective parameterization “requires in principle a spectral gap between scales being parameterized and scales being resolved on the grid” [1]… Challenge to uphold a meaningful distinction between (and avoid double counting of) parameterized and resolved condensation.

Feedback

- Subsidence (compensates cloud updraft)
- Detrainment (mixing) of cloud air with environment
- Evaporation of falling precip

Resolvable versus unresolvable cloud & precip



… but while correcting unstable model lapse rates is a compelling reason in and of itself, obviously sub-grid cloud needs to be accounted for - and is essential if we wish to have quantitative NWP guidance on precip & severe weather

Arakawa's Classiification of schemes (Many models include >1 scheme)

• large scale condensation – condensation assumed to occur when air is supersaturated on the grid scale

• moist-convective adjustment (eg. Manabe et al., [3]) – moist convection assumed to occur where air is conditionally (or absolutely) unstable and supersaturated, at grid scale. Temperature and humidity are adjusted (non-locally) to saturated, moist adiabatic state, subject to energy being conserved in sum across the cloud layer… criticism: *requires* grid scale saturation before invokes subgrid moist convection. Many refinements (eg. Betts and Miller, [6])

• cloud-model schemes (prototype, Kuo, [4]). Kuo scheme was extensively used in large scale models (ie. *not* mesoscale) and is considered covered in some detail in notes. States Emanuel [1]: "one of the earliest and most enduringly popular schemes… convection is assumed to consume water at the rate it is supplied by the macrofluid system… violates causality… convection is *not* caused by the macroscale water supply."

> "What we eventually need... is a unified cloud parameterization, covering deep, shallow, high, low, cumuliform, and stratiform clouds with and without mesoscale organizations" (Arakawa, p15, [1])

"Over the past three decades, significant effort has been devoted to improving our understanding of the interaction between cumulus convection and larger-scale circulations and to modeling such interaction in various approaches of cumulus parameterization. Despite these efforts, a general theory of cumulus parameterization does not exist, and no one single scheme is found to outperform other schemes consistently in a wide range of weather situations." (Kuo et al., [5])

Anthes (1977) noted that "imperfectly represented cloud processes may interact with the larger-scale model flow in unrealistic ways that are not permitted with the simpler (convective) adjustment schemes"

Dry Convection

Consider a model layer $z_B - z_T$ that is unsaturated $(q < q_*)$ but unstable $(\Gamma > \Gamma_d)$. Adjust the virtual temperature (but lets drop the subscript v) temperature by $\delta T(z)$ throughout the layer to obtain a revised neutral lapse rate $\Gamma = \Gamma_d$ subject to the constraint

$$\int_{z_B}^{z_T} \rho c_p \delta T(z)\, dz = 0 \qquad (10.1)$$

Non-convective large scale condensation

Prior to the application of the adjustment scheme the model layer is super-saturated (specific humidity $q > q_*$) but stable ($\Gamma < \Gamma_d$).

Adjust both T and q by amounts $\delta T(z)$, $\delta q(z)$ subject to the constraints

$$\begin{aligned} -L\,\rho\,\delta\,q(z) &= \rho\,c_p\,\delta T(z), \quad (\delta T > 0) \\ q(z) + \delta q(z) &= q_*(T + \delta T, p) \end{aligned} \tag{10.2}$$

Here there is no vertical energy transport (thus "non-convective" local condensation) so energy is locally exchanged between latent and sensible form.

Moist convection

The layer is super-saturated ($q > q_*$) and unstable ($\Gamma > \Gamma_m$). Readjust to obtain (saturated) neutrality $\Gamma = \Gamma_m$ such that:

$$\begin{aligned} -\int_{z_B}^{z^T} L\,\rho\,\delta\,q(z)\,dz &= \int_{z_B}^{z^T} \rho\,c_p\,\delta T(z)\,dz \\ q(z) + \delta q(z) &= q_*(T + \delta T, p) \end{aligned} \tag{10.3}$$

This is solved numerically by successive approximations. When condensation occurs, the resulting precipitation is

$$P\,[\mathrm{kg\ m^{-2}}] = -\int_{z_B}^{z^T} \rho\,\delta q(z)\,dz \tag{10.4}$$

and the latent heat is released instantly to the layer.

Kuo cloud model scheme (deep convection scheme)

• classic scheme universally employed for models with gridlength order 100 km or more; problematic at modern resolution (**has been replaced in GEM** by “Kain-Fritsch scheme”)

• cumulus convection exists only in the presence of deep, conditionally unstable layer in which there is net moisture convergence

• moisture supply = large-scale convergent advection of vapour + surface evap’n

• scheme vertically redistributes water and releases latent heat due to condensation

• simplistic computation of cloud location and state: lift a surface parcel along dry adiabat to LCL; above the LCL, ascent continues along a moist-adiabat slightly modified by entrainment. The top of the cloud layer is the level of non-buoyancy

• scheme computes cloud fraction (“μ”) in the column over the grid square; remixes model layers; produces precipitation

Kuo cloud model scheme

Cloud Occurrence

It is assumed that cumulus convection always occurs[2] in "deep" (quantify?) layers having the potential to support convection: specifically, layers of conditionally (or unconditionally) unstable stratification over areas of mean low-level convergence.

Kuo cloud model scheme

If μ is the fractional area of sky that is covered by deep cumulus clouds, then the temperature at level z after the dissolution of the cloud (mixing) will be

$$T(z) = \widetilde{T}(z) + \mu\left(T_c(z) - \widetilde{T}(z)\right) \tag{10.5}$$

where $\widetilde{T}$ is the environmental temperature prior to this mixing-in of the cloud air and $T_c(z)$ is the temperature in the cloud.

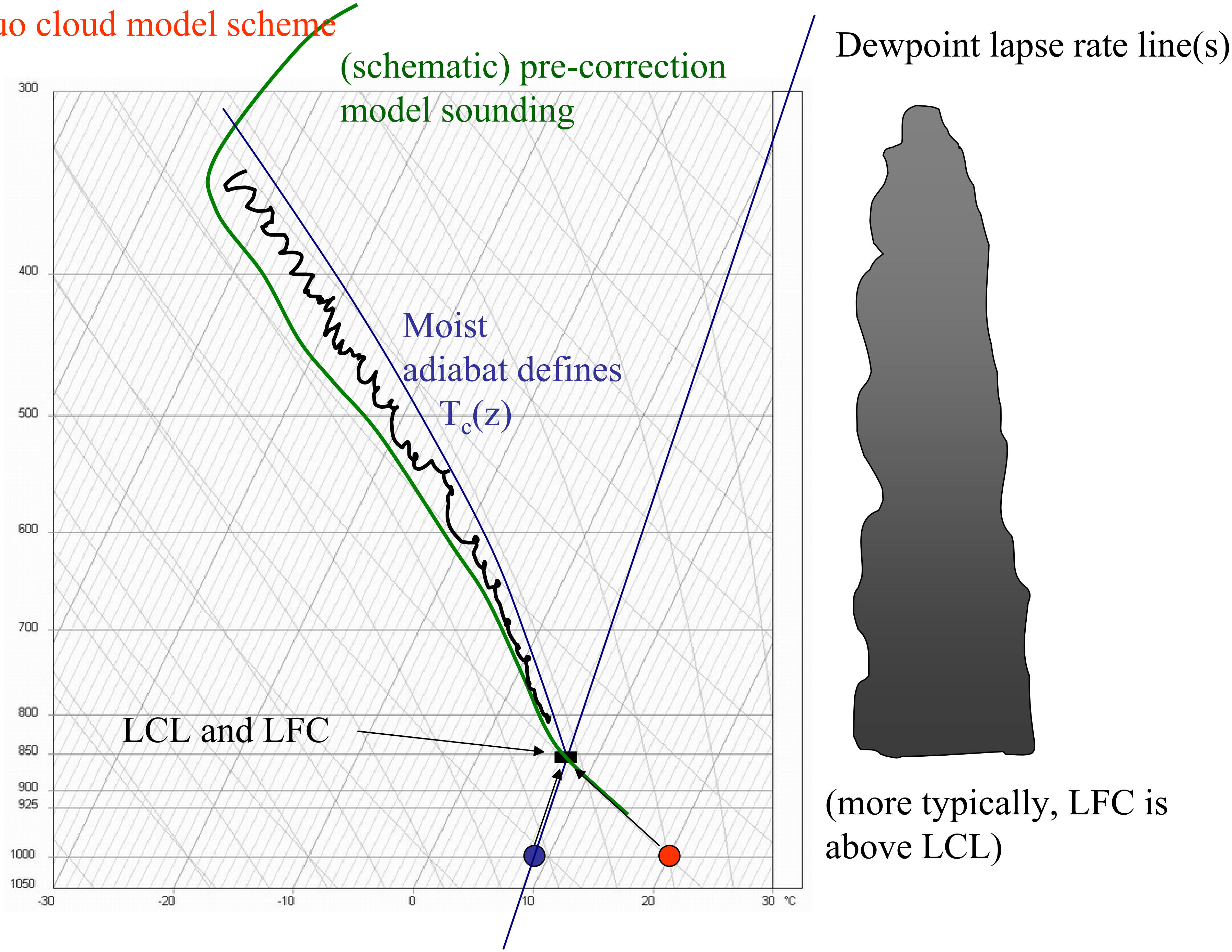
Thus need to diagnose μ and $T_c(z)$ for each grid column over which deep convection is inferred to be occurring

Kuo cloud model scheme

Cloud Location and Properties

Cloud base (z_B) is presumed to be the lifting condensation level (LCL) of surface air (in the CMC Spectral Model, the LCL is computed by assuming a parcel from the surface arrives at the top of boundary layer carrying the height-average properties of the boudary-layer, ie. boundary-layer mean temperature and humidity). The in-cloud vertical distribution of temperature $T_c(z)$ and specific humidity $q_c = q_*(T_c)$ are presumed moist adiabatic (the profiles of T_c and q_c for the presumed cloud are therefore readily calculated). Cloud top (z_T) occurs where this moist adiabat from the lifting condensation level crosses the environmental "sounding" (presumably the latter is estimated from the model predictions prior to application of the scheme). Complete mixing (cloud dissolution) of the cloud, level-by-level, with the environment is assumed.

Kuo cloud model scheme



Moisture Supply

Kuo cloud model scheme

The total rate [kg m^{-2} s^{-1}] at which water vapour becomes available to the vertical column above unit ground area is

$$M_t = - \int_0^\infty \nabla_H \bullet \left(\rho \, q \, \vec{V}_H \right) \, dz + E_0 \qquad (10.6)$$

where E_0 is the surface evaporation rate (the subscript 'H' indicates the horizontal components only are retained). Kuo speaks of "control of the water vapour supply (for tropical storms) by the low level mean flow field," presumably meaning that both vapour density and the flow convergence are numerically largest near the ground/ocean (maximum cross-isobar flow). When we multiply M_t by a time interval Δt (the model timestep) we have an amount $M_t \Delta t$ of vapour (per unit ground area) available to make (and therefore "used" by the model to make) cloud columns from environmental air.

Moisture Needed

Kuo cloud model scheme

In order to form a cloud column spanning $(z_B - z_T)$ it is assumed we raise the temperature from environmental temperature T_e (in practise given by the model output $\widetilde{T}$ *before* application of the cloud parameterisation scheme) to T_c (known, see above) by condensing water vapour (it is also assumed that all this condensed water is precipitated out); the amount of water vapour needed per unit ground area is easily calculated as

$$W_1\,[\mathrm{kg\ m^{-2}}] = \frac{\rho c_p}{L} \int_{z_B}^{z_T} \left(T_c(z) - \widetilde{T}(z)\right)\, dz \tag{10.7}$$

and is to be drawn from the "accession flux" M_t. In addition to this "condensing part," there is a non-condensing "humidification part," that raises the humidity of the cloud column $(z_B - z_T)$ to saturation,

$$W_2\,[\mathrm{kg\ m^{-2}}] = \int_{z_B}^{z_T} \rho\ (q_c - \widetilde{q})\ dz \tag{10.8}$$

This is also readily calculated, and likewise to be drawn from the accession flux

Fractional sky cover

The dimensionless ratio

$$\mu = \frac{M_t\,\Delta t}{W_1 + W_2} \tag{10.9}$$

is the ratio of the amount of vapour available (the supply) to the amount of vapour needed for cloud formation, over timestep Δt. If the timestep is sufficiently small, we can ensure $\mu < 1$ (moisture supply $M_t \Delta t$ too small

relative to the required moisture for the cloud column); then μ can be considered as "the fractional area of the sky that is covered by newly formed cumulus cloud as a result of the accession of moisture by advection and by evaporation from below." And μ can be used in the above-suggested manner to correct the forecast. However Kuo suggested that μ be interpreted only "somewhat figuratively" as the fractional cloud cover; and he argued that even if Δt is sufficiently large that μ exceeds 1, the correction procedure is still valid.

Fritsch and Chappell* ([8]) mesoscale cloud model scheme ($\Delta x \leq 20$ km)

What “causes” deep convection?

* precursor to Kain & Fritsch scheme

- moisture accession (a la Kuo) ?

- low level frictional convergence?

- CAPE?...

Fritsch & Chappell note:

• “studies by (others) indicate that frictional pumping is neither a necessary** nor a sufficient cause for the occurrence of cumulus convection”

• thermals are stronger and larger when low-level convergence is present

**since friction always occurs in the real world, how can one *know* it isn’t necessary? Maybe by virtue of modelling studies… in which one could turn off friction. But anyway, its totally obvious that one could have intense buoyancy driven convection with no *mean* motion near the lower boundary

Fritsch and Chappell (ctd…)

• "moist convection only occurs when air is forced to its LFC by low-level convergence, air mass overrunning, or when low-level heating and mixing remove any stable layers suppressing moist convection (ie. when potential buoyant energy becomes available)"

Fritsch and Chappell scheme (ctd.)

- each grid column isolated from all others

- assumes deep convection the dominant cloud form

- recognizes convection responds not only to the rate at which the large scale is generating buoyant energy, but also to the buoyant energy generated and stored prior to the onset of deep convection

- designed to simulate a vertical rearrangement of mass that allows the (model) atmosphere to eliminate CAPE, through three vertical transport mechanisms: moist convective updraft, moist convective downdraft, and a dry branch (ascent or descent) all occurring locally (within the grid cell)

- precip efficiency is (empirically) related to wind shear across the cloud depth

- parameterization "capable of generating convectively driven mesoscale pressure systems"

$$\frac{\partial T}{\partial t} = \left(\frac{\partial T}{\partial t}\right)_{dyn} + \left(\frac{\partial T}{\partial t}\right)_{conv}$$

before action of scheme

After action of scheme

$$\left(\frac{\partial T}{\partial t}\right)_{conv} = \frac{T - \hat{T}}{\tau_c}$$

• "convective parameterization problem is to determine $\hat{T}$ and τ_c

• timescale τ_c for removal of CAPE is computed as Δx / U (U the mean environmental horiz speed over cloud depth), but limited to the range 30-60 min

Kain & Fritsch ([9]); see also Kain ([10]), Bechtold et al.([2])

• "magnitude of convective heating and drying effects (ie. *condensation releasing latent heat plus precipitation removing moisture to elsewhere*) on scales less than 50 km is much more strongly correlated with local convective available potential energy (CAPE) than with the large-scale rate of destabilization or moisture convergence" (whereas eg. Kuo scheme predicates existence of deep convection on moisture convergence)

• as model resolution is increased more of the stratiform component of precipitation associated with convective systems is explicitly resolved

• as the horizontal resolution in larger scale models approaches the scale of individual convective clouds, greater flexibility in these models' parameterization of subgrid scale convection will be necessary to represent disparate convective environments faithfully

Scheme entails:

• trigger
• mass flux formulation
• closure

Used now for both shallow and deep convection in some models

Trigger function

- identify "updraft source layers" (USL's), ie. potential source layers for clouds

  - model layers from surface to depth 60 hPa are mixed** to define T, T_d

  - undilute ascent to LCL. Implied parcel T_{LCL} is augmented by an empirical correction

$$\delta T = k\left[w_g - c(z)\right]^{1/3}$$ (formulation differs in Bechtold et al.)

where w_g is resolved vertical velocity, c(z) a threshold value of order 2 cm s^{-1} depending on the height of the LCL. Rationale: "convective development is favoured by background vertical motion"

  - if $T_{LCL} + \delta T < T_{ENV}\left(z_{LCL}\right)$ this parcel eliminated… whereas

** note deviation from later-described updraft formulation

Trigger function (ctd…)

• if $$T_{LCL} + \delta T \geq T_{ENV}\left(z_{LCL}\right)$$

parcel is "candidate for deep convection" and is lifted (including effects of entrainment, detrainment and water loading ← cloud model).

• if parcel vertical velocity remains positive over depth that exceeds a "specified minimum cloud depth (typically 3-4 km) deep convection is activated** using this USL"… otherwise

• "base of the potential USL is moved up one level and process repeated" and continues until 1st suitable USL is found or search has moved above lowest 300 hPa of atmosphere

** where used for shallow convection, this restriction revised

Mass flux equations

$$\left.\frac{\partial \overline{\psi}}{\partial t}\right|_{conv} = -\frac{\partial}{\partial z}\overline{w'\psi'}$$

$$= \frac{1}{\rho_r A}\left[\frac{\partial}{\partial z}\left\{\left(M^u + M^d\right)\overline{\psi}\right\} - \left(\varepsilon^u - \varepsilon^d\right)\overline{\psi} + \delta^u \psi^u + \delta^d \psi^d\right]$$

- A grid cell area, $\overline{\psi}$ resolved (mean) value over the grid cell
- ρ_r reference density
- $M^{u,d} = \rho_r w^{u,d} A$ mass flux [kg s^{-1}], w vertical velocity
- ε entrainment rate [kg m^{-1} s^{-1}]
- δ detrainment rate

The needed properties supplied by a "one dimensional entraining/detraining plume model" (ODEDP)

A few definitions:

• Virtual temperature: temperature of a dry parcel having same pressure and density as the given sample whose temperature and specific humidity are T,q :

$$T_v = T\left(1 + 0.61q\right)$$

• Virtual potential temperature θ_v : virtual temperature of a parcel subjected to unsaturated adiabatic compression from its actual pressure p to a reference pressure

• **Virtual potential temperature θ_v is conserved (invariant) along a dry adiabat**

• Equivalent temperature: temperature a moist parcel would attain if all latent heat were converted to sensible heat (not same as virtual temp.)

$$T_e = T + e/\gamma$$

(e the vapour pressure, γ the psychrometric constant)

• Equivalent potential temperature: θ_e … resultant temperature if parcel having temp T_e and pressure p is compressed adiabatically to reference pressure

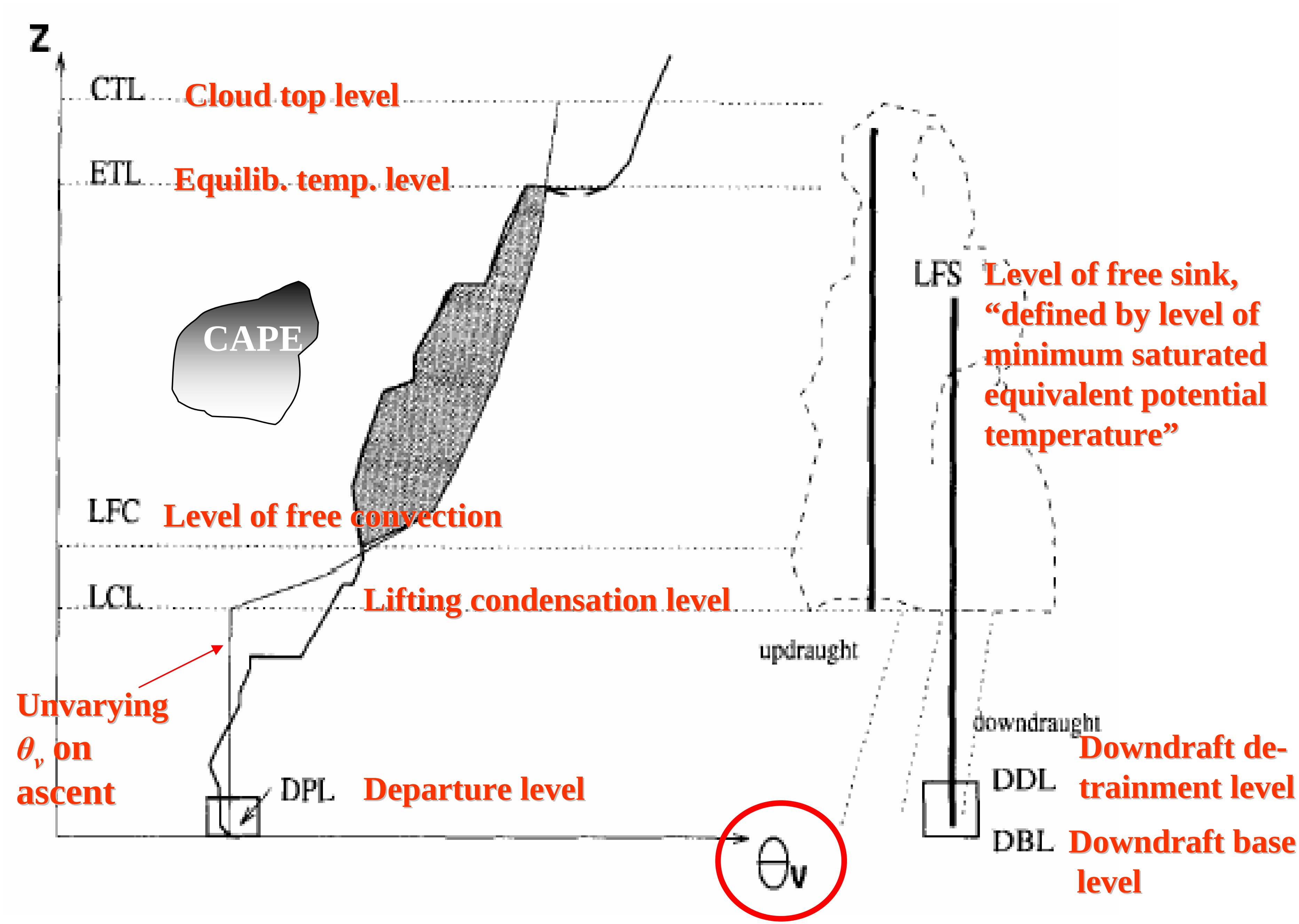


Fig. 1 of Bechtold et al. [2].

Cloud model: the updraft

Once a suitable departure level DPL (or updraft source level USL) defined:

- updraft originates at DPL, entrains environmental air while within the ABL, then undergoes "undilute ascent" to the LCL… then

- $$M^u(LCL) = \rho_r \, w_{LCL} \, \pi R_0^2$$

  w_{LCL}= 1 m s^{-1}

  R_0 = 1500 m (deep convection)
  = 50 m (shallow convection)

- $$M^{u,k+1} - M^{u,k} = \varepsilon^u - \delta^u$$

  (change in updraft mass flux: r.h.s. values are avg for layer)

- $$\varepsilon^u = c_{etr} \; M^u \; \frac{\Delta z}{R_0} \; f_\varepsilon$$

  $$\delta^u = c_{etr} \; M^u \; \frac{\Delta z}{R_0} \; f_\delta$$

  (c_{etr}=0.2, the f ' s are "fractional entrainment/detrainment rates defined in [9])

Cloud model: the downdraft

- downdraft originates at level of free sink (LFS), identified as level of minimum environmental saturated equivalent potential temperature

- $$M^{d}(LFS) = -\left(1 - \mathrm{Pr}_{eff}\right) M^{u}(LCL)$$

  Pr_{eff} the precipitation efficiency, an empirical function of wind shear across the cloud layer and of cloud base height

- $$M^{d,k} - M^{d,k+1} = \varepsilon^{d} > 0$$ (change in downdraft mass flux: detrainment set to zero, except in 60 mb layer DDL-DBL)

- a vast number of other details of the model and its implementation are involved

References

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[6] Betts and Miller, 1986. *A new convective adjustment scheme. Part II…*Quart. J.R. Meteorol. Soc., Vol. 112, 693-709

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Ctd…

[8] Fritsch and Chappell, 1980. *Numerical prediction of convectively driven mesoscale pressure systems. Part I: Convective parameterization.* J. Atmos. Sci., Vol. 37, 1722-1733

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