Representation of Cloud Related Processes in Large Scale Models

Lecture 1

Les Houches 2013

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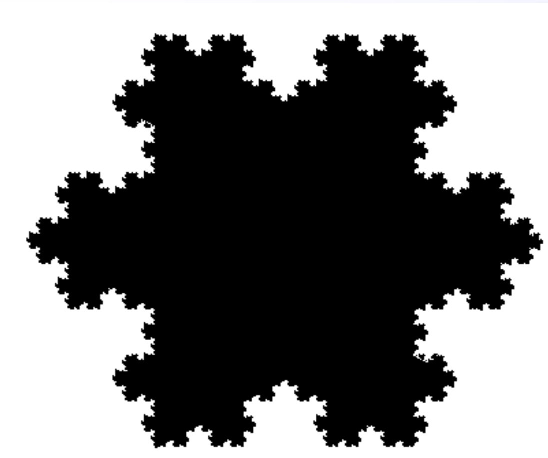
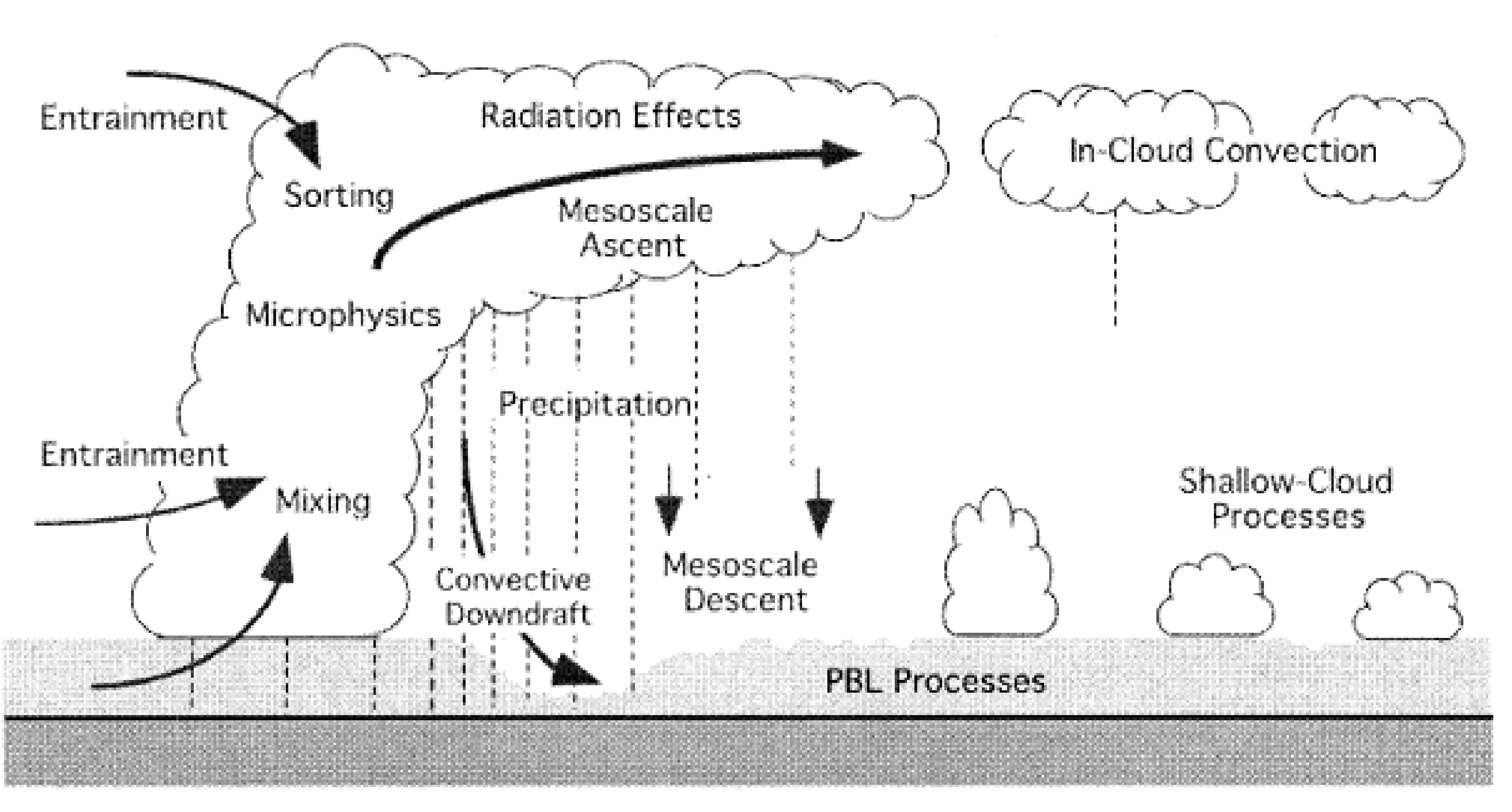


1.

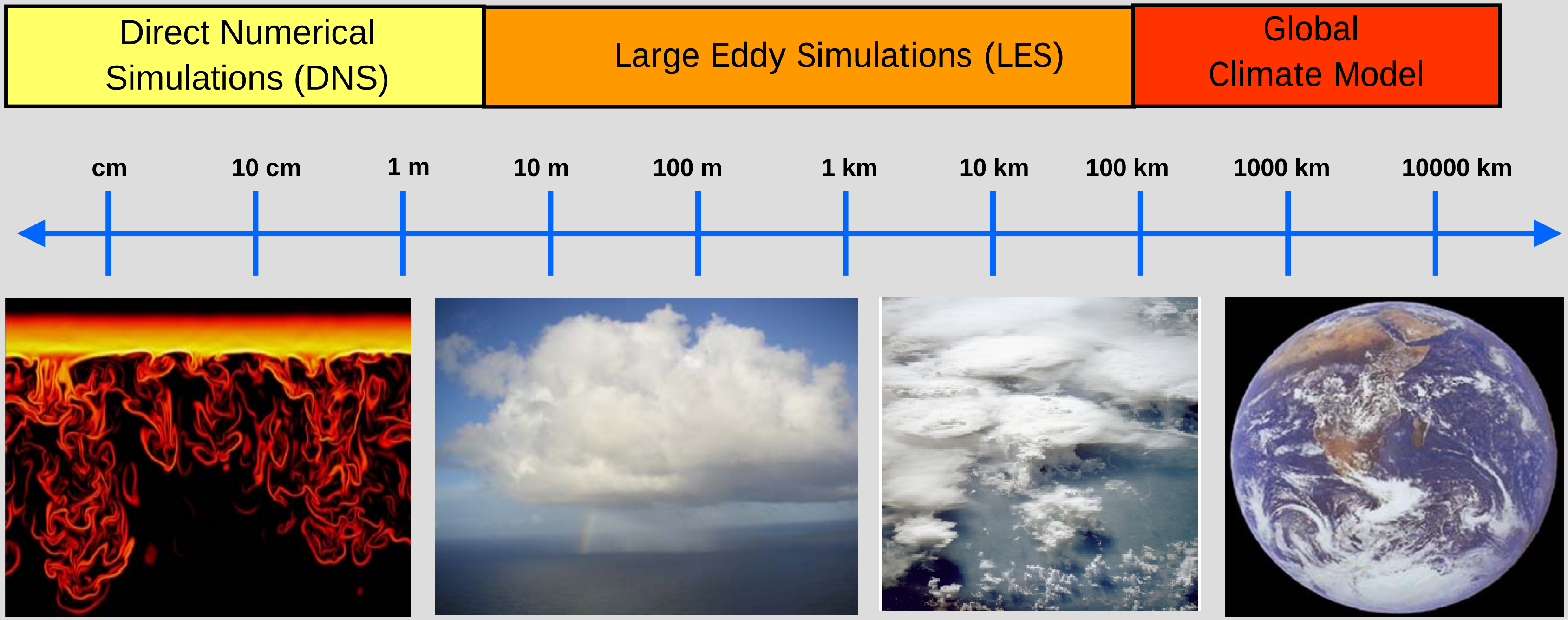
Intro

Cloud Related Processes



Arakawa 2004

Model Hierarchy



Filtered Equations for the Prognostic Variables

resolved | **subgrid**

$$\frac{\partial \bar{u}}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{u} - \bar{w}\frac{\partial \bar{u}}{\partial z} + f_c\left(v_g - \bar{v}\right)\ldots - \frac{\partial}{\partial z}\overline{u'w'}$$

$$\frac{\partial \bar{\theta}}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{\theta} - \bar{w}\frac{\partial \bar{\theta}}{\partial z}\ldots\ldots\ldots\ldots - \frac{\partial}{\partial z}\overline{w'\theta'} + \frac{\pi L}{c_p}\left(c-e\right) + Q_{rad}$$

$$\frac{\partial \bar{q}_v}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{q}_v - \bar{w}\frac{\partial \bar{q}_v}{\partial z}\ldots\ldots\ldots\ldots - \frac{\partial}{\partial z}\overline{w'q_v'}\ldots\ldots - \left(c-e\right)$$

$$\frac{\partial \bar{q}_l}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{q}_l - \bar{w}\frac{\partial \bar{q}_l}{\partial z}\ldots\ldots\ldots\ldots - \frac{\partial}{\partial z}\overline{w'q_l'}\ldots\ldots + \left(c-e\right) - G_r$$

Radiative heating

Precipitation

Large scale advection

Large scale subsidence

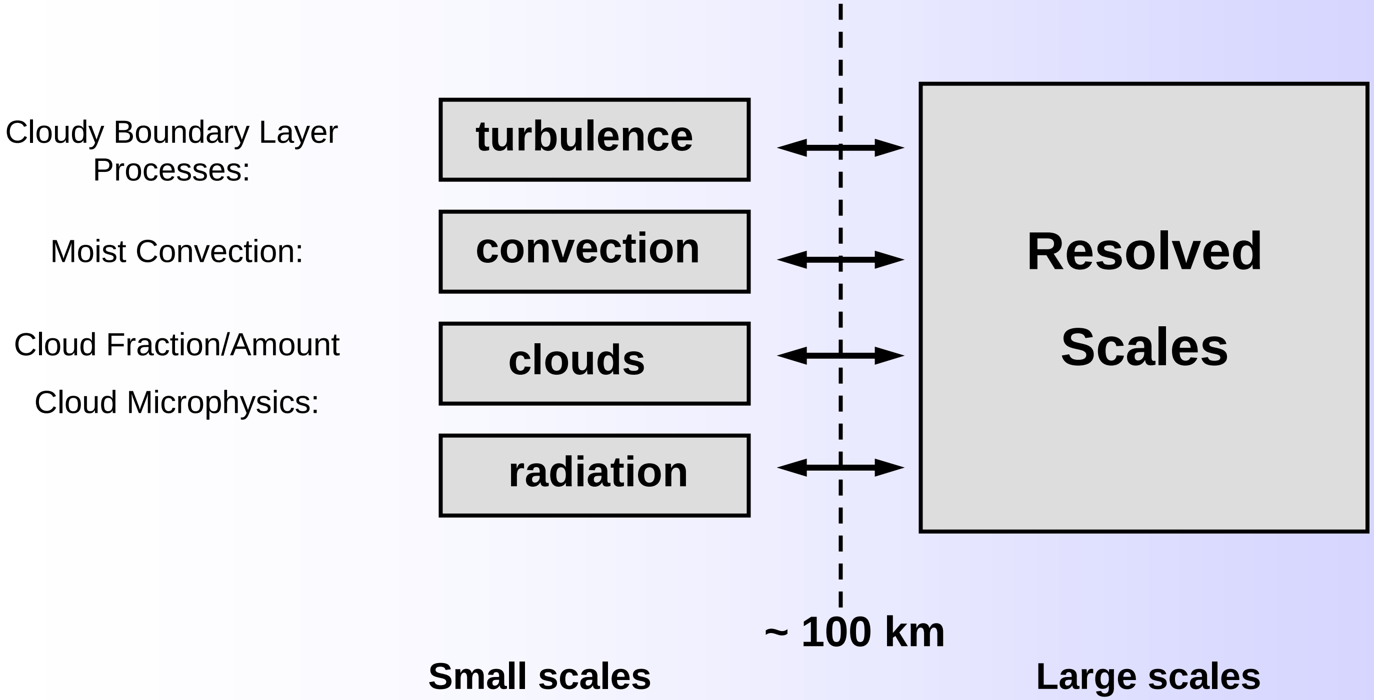
Vertical turbulent/ convective transport

Net Condensation Rate

• The effect of the sub-grid process on the large scale can only be represented statistically.

•The procedure of expressing the effect of sub-grid process is called parameterization.

•This procedure usually evolves around finding the joint pdf of (w,q,θ)

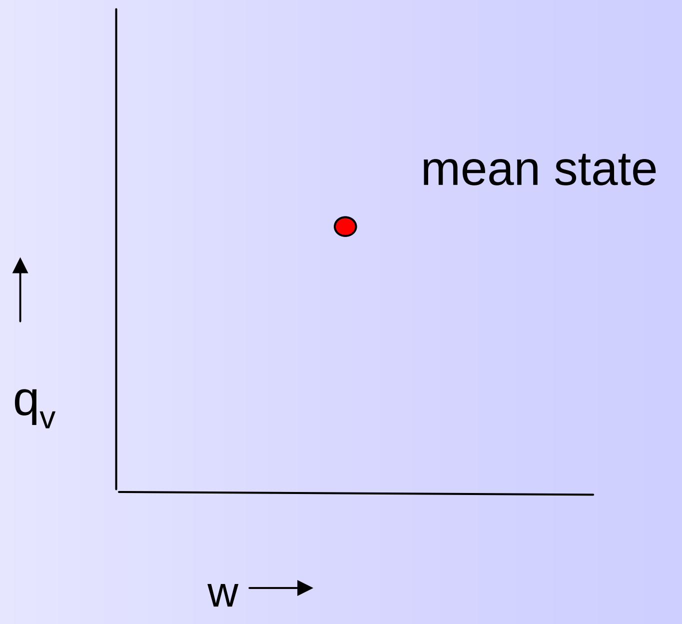


Small scales:

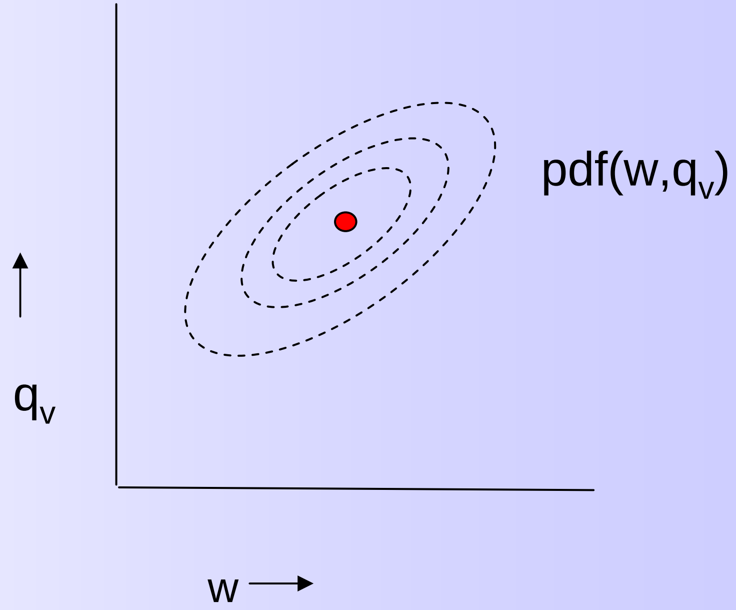
$$\overline{w'\theta'},\ \overline{\theta'^2},$$
$$\overline{w'q_t'},\ \overline{q_t'^2},$$
$$\cdots\cdots\cdots$$

Large scales:

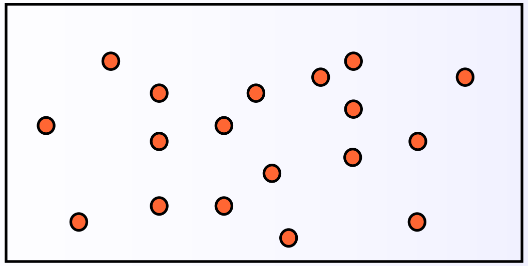
$$\overline{u}, \overline{v}, \overline{w}, \overline{q}_v, \overline{\theta}, \ldots\ldots$$


mean state
q_v
w

Impossible?



Maxwell-Boltzmann velocity equation



$$f(v) = \sqrt{\left(\frac{m}{2\pi kT}\right)^3}\; 4\pi v^2 \exp\left(-\frac{mv^2}{2kT}\right)$$

Microscopic: deterministically

Macroscopic: Statistical

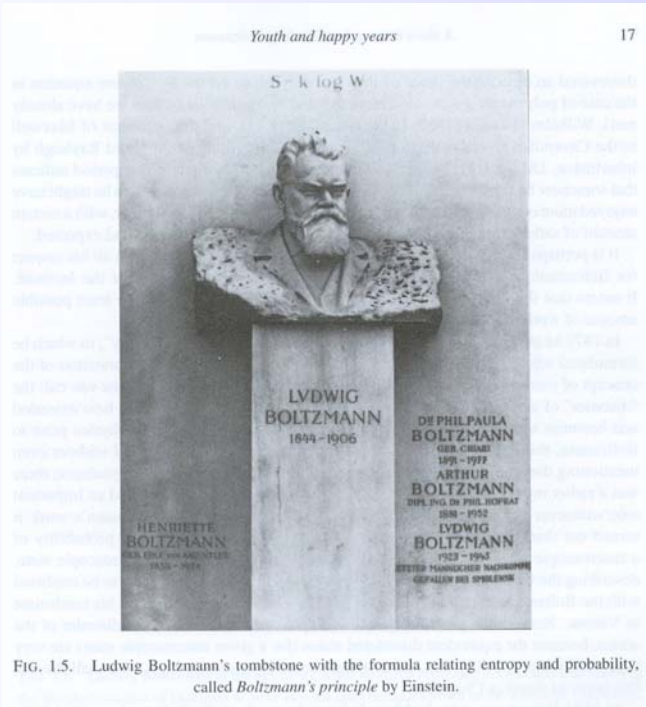

Youth and happy years 17

FIG. 1.5. Ludwig Boltzmann's tombstone with the formula relating entropy and probability, called *Boltzmann's principle* by Einstein.

Boltzmann (1844-1906)

Radiation

resolved | **subgrid**

$$\frac{\partial \bar{u}}{\partial t} = -\bar{\mathbf{v}} \cdot \nabla \bar{u} - \bar{w}\frac{\partial \bar{u}}{\partial z} + f_c\left(v_g - \bar{v}\right) \ldots - \frac{\partial}{\partial z}\overline{u'w'}$$

$$\frac{\partial \bar{\theta}}{\partial t} = -\bar{\mathbf{v}} \cdot \nabla \bar{\theta} - \bar{w}\frac{\partial \bar{\theta}}{\partial z} \ldots\ldots\ldots\ldots - \frac{\partial}{\partial z}\overline{w'\theta'} + \frac{\pi L}{c_p}(c-e) + Q_{rad}$$

Radiative heating

$$\frac{\partial \bar{q}_v}{\partial t} = -\bar{\mathbf{v}} \cdot \nabla \bar{q}_v - \bar{w}\frac{\partial \bar{q}_v}{\partial z} \ldots\ldots\ldots\ldots - \frac{\partial}{\partial z}\overline{w'q_v'} \ldots\ldots -(c-e)$$

$$\frac{\partial \bar{q}_l}{\partial t} = -\bar{\mathbf{v}} \cdot \nabla \bar{q}_l - \bar{w}\frac{\partial \bar{q}_l}{\partial z} \ldots\ldots\ldots\ldots - \frac{\partial}{\partial z}\overline{w'q_l'} \ldots\ldots +(c-e) - G_r$$

Precipitation

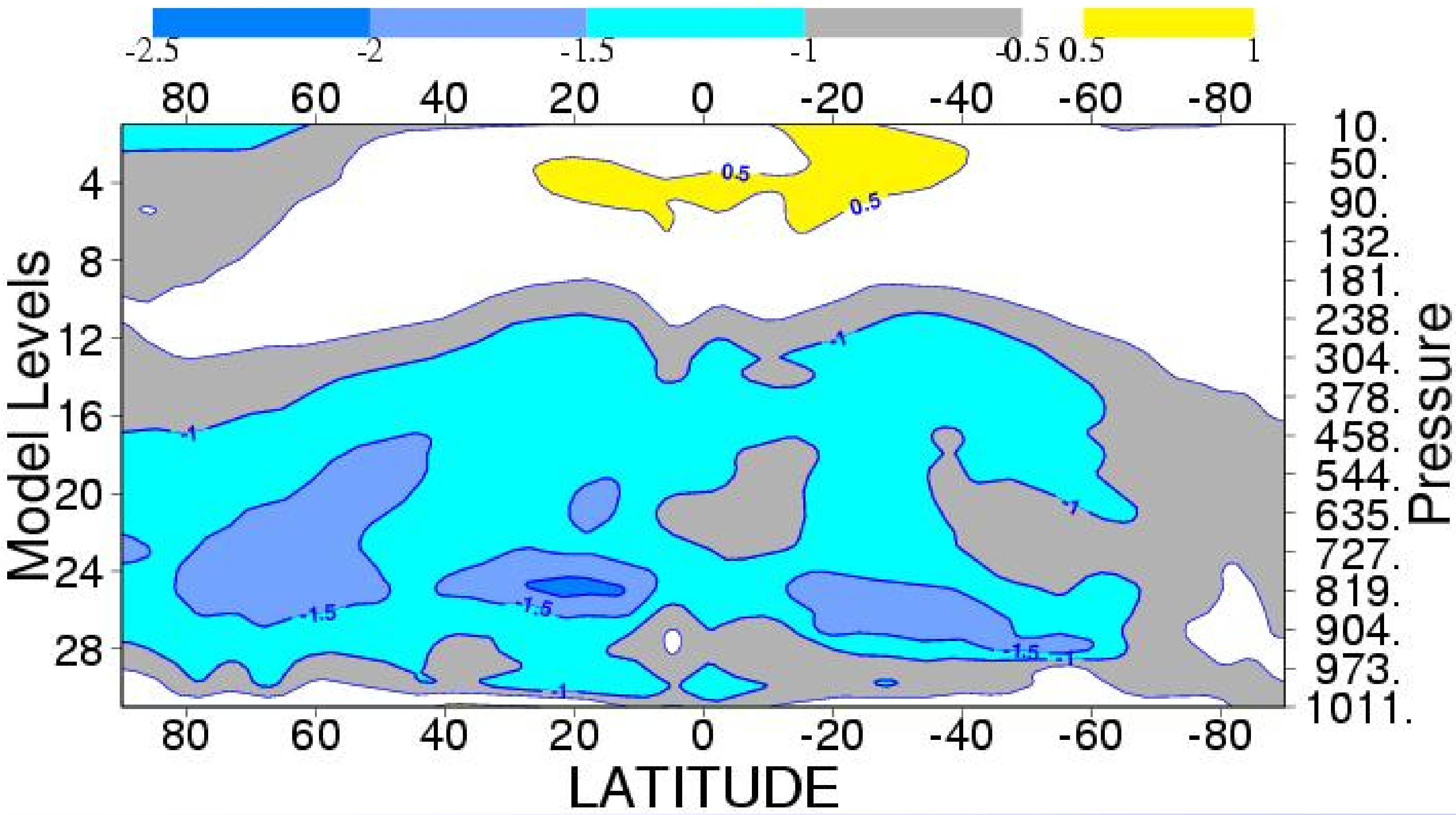
Large scale advection

Large scale subsidence

Vertical turbulent/ convective transport

Net Condensation Rate

Temperature Tendency (K/day) due to Radiation



Source: ECMWF

(Cloudy) Boundary Layer Processes

resolved | **subgrid**

$$\frac{\partial \bar{u}}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{u} - \bar{w}\frac{\partial \bar{u}}{\partial z} + f_c\left(v_g - \bar{v}\right) \;\vdots\; -\frac{\partial}{\partial z}\overline{u'w'}$$

$$\frac{\partial \bar{\theta}}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{\theta} - \bar{w}\frac{\partial \bar{\theta}}{\partial z} \ldots\ldots\ldots\ldots \vdots -\frac{\partial}{\partial z}\overline{w'\theta'} + \frac{\pi L}{c_p}\left(c-e\right) + Q_{rad}$$

Radiative heating

$$\frac{\partial \bar{q}_v}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{q}_v - \bar{w}\frac{\partial \bar{q}_v}{\partial z} \ldots\ldots\ldots\ldots \vdots -\frac{\partial}{\partial z}\overline{w'q_v'} \ldots\ldots -\left(c-e\right)$$

$$\frac{\partial \bar{q}_l}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{q}_l - \bar{w}\frac{\partial \bar{q}_l}{\partial z} \ldots\ldots\ldots\ldots \vdots -\frac{\partial}{\partial z}\overline{w'q_l'} \ldots\ldots +\left(c-e\right) - G_r$$

Precipitation

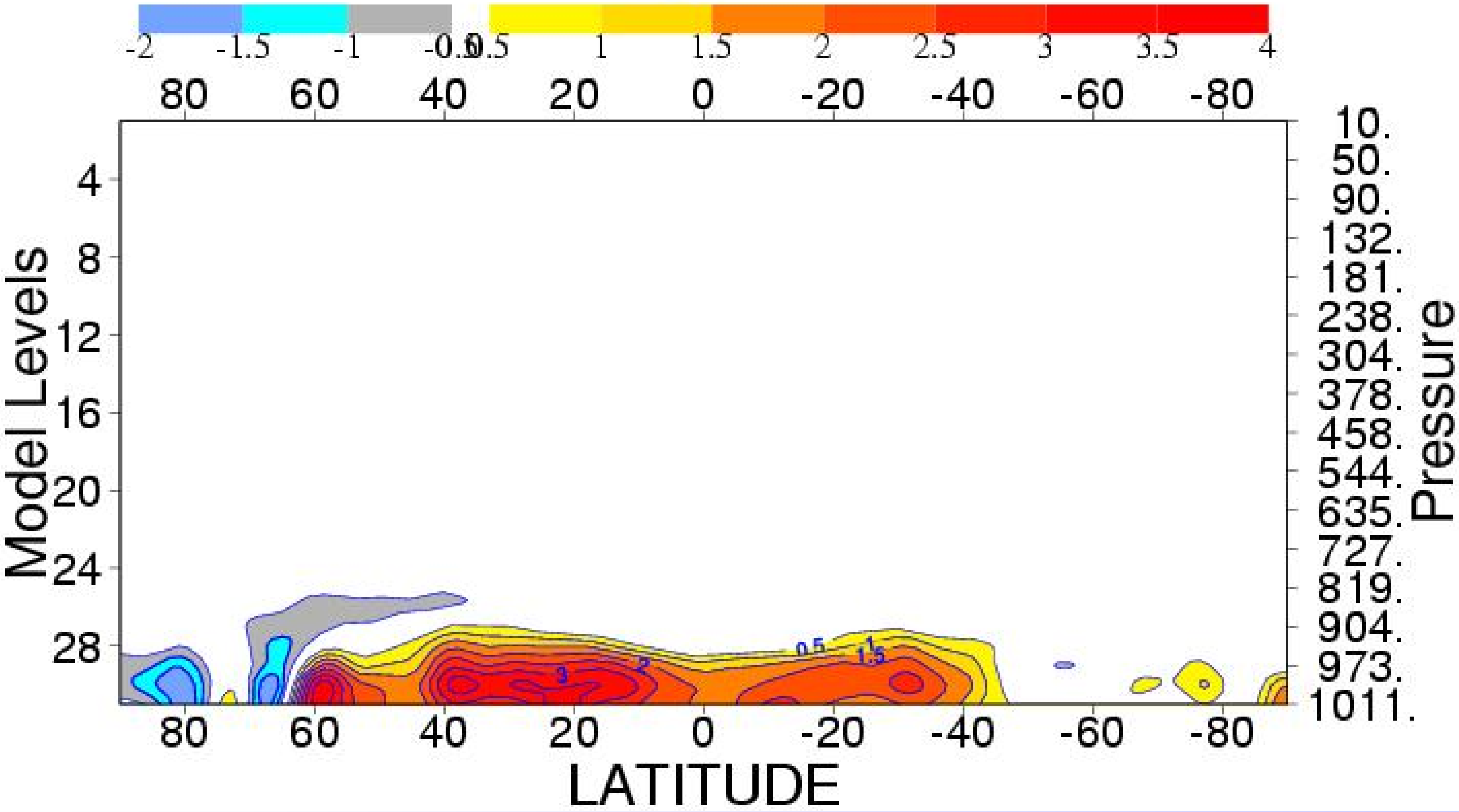
Large scale advection

Large scale subsidence

Vertical turbulent/ convective transport

Net Condensation Rate

Temperature Tendency (K/day) due to BL Turbulence



Source: ECMWF

Cumulus Convection Processes

resolved | **subgrid**

$$\frac{\partial \bar{u}}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{u} - \bar{w}\frac{\partial \bar{u}}{\partial z} + f_c\left(v_g - \bar{v}\right) \ldots - \frac{\partial}{\partial z}\overline{u'w'}$$

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$$\frac{\partial \bar{q}_v}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{q}_v - \bar{w}\frac{\partial \bar{q}_v}{\partial z} \ldots\ldots\ldots - \frac{\partial}{\partial z}\overline{w'q_v'} \ldots\ldots - (c-e)$$

$$\frac{\partial \bar{q}_l}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{q}_l - \bar{w}\frac{\partial \bar{q}_l}{\partial z} \ldots\ldots\ldots - \frac{\partial}{\partial z}\overline{w'q_l'} \ldots\ldots + (c-e) - G_r$$

Radiative heating

Precipitation

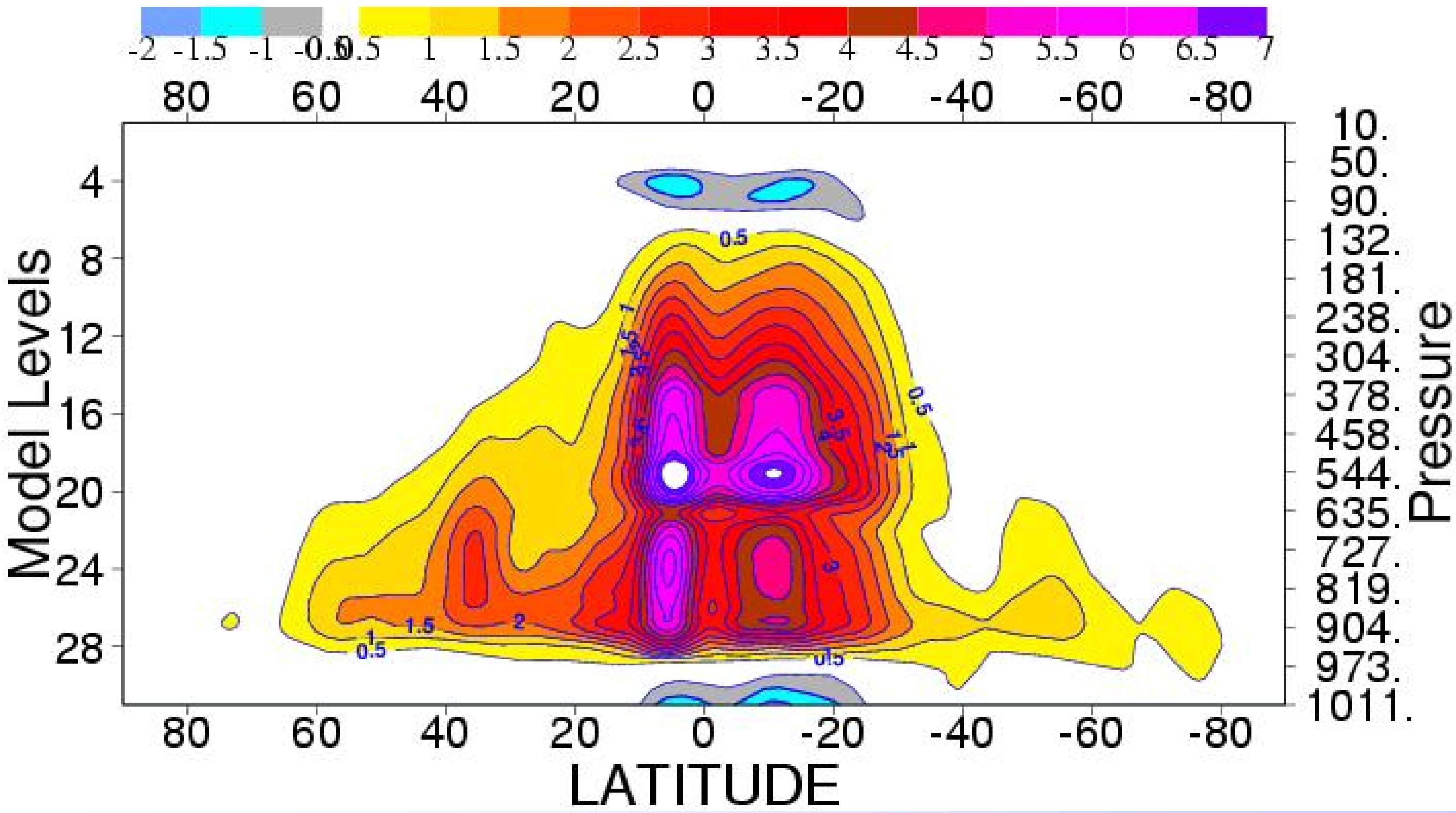
Large scale advection

Large scale subsidence

Vertical turbulent/ convective transport

Net Condensation Rate

Temperature Tendency (K/day) due to Moist Convection



Source: ECMWF

Cloud Processes

resolved | **subgrid**

$$\frac{\partial \bar{u}}{\partial t} = -\bar{\mathbf{v}}\cdot\nabla\bar{u} - \bar{w}\frac{\partial \bar{u}}{\partial z} + f_c\left(v_g - \bar{v}\right) \ldots - \frac{\partial}{\partial z}\overline{u'w'}$$

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Radiative heating

Precipitation

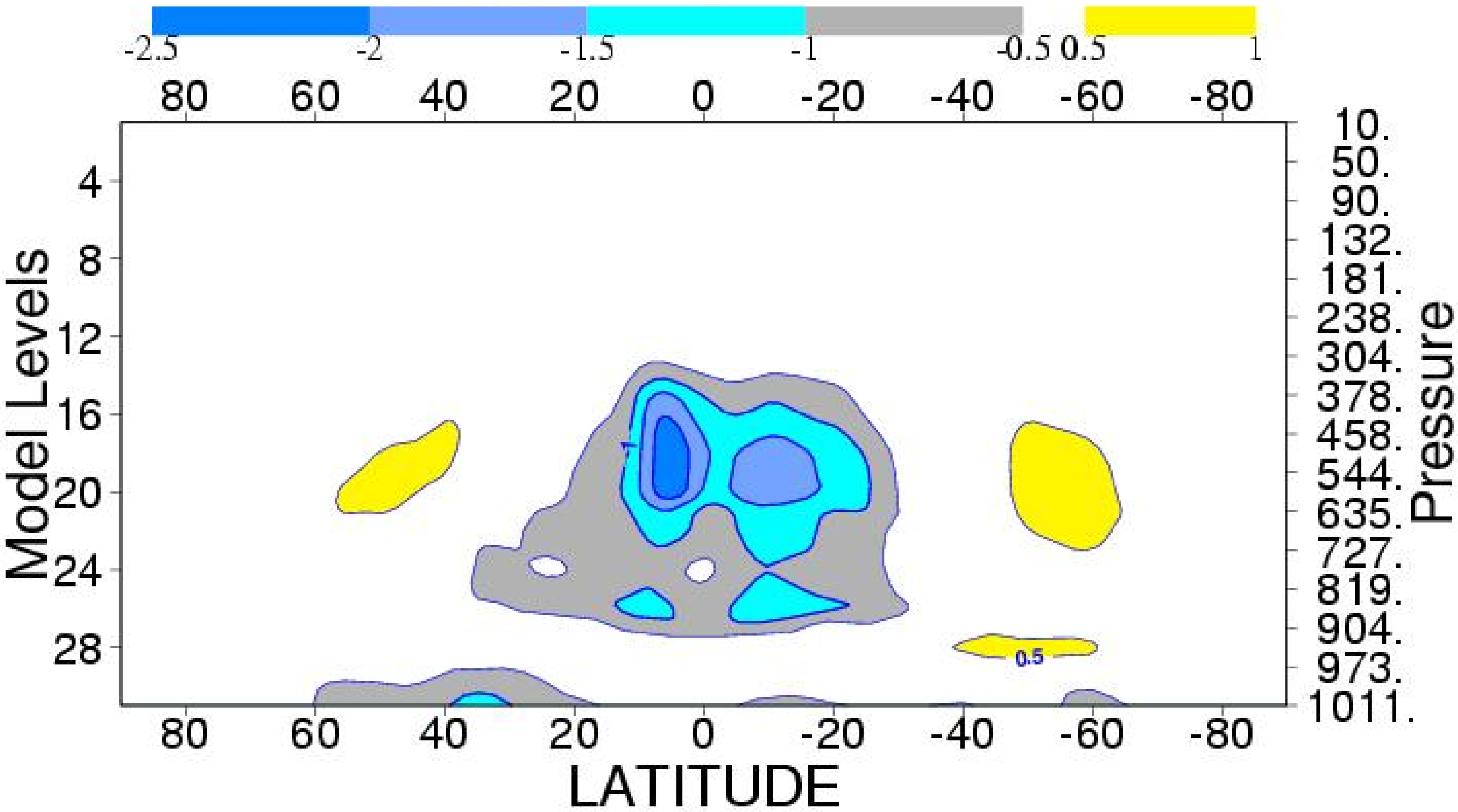
Large scale advection

Large scale subsidence

Vertical turbulent/ convective transport

Net Condensation Rate

Temperature Tendency (K/day) due to Large Scale Condensation



Source: ECMWF

Outline

- Parameterizations of the clear and well-mixed cloudy boundary layer (today)
- Parameterizations of cumulus convection (Saturday)
- Cloud Parameterizations (Monday)
- new developments (Monday)
    - Connecting parameterizations
    - Scale-aware parameterizations
    - Stochastic parametrizations

2.

Turbulence and Boundary Layer Parameterizations

The (Convective) Boundary Layer

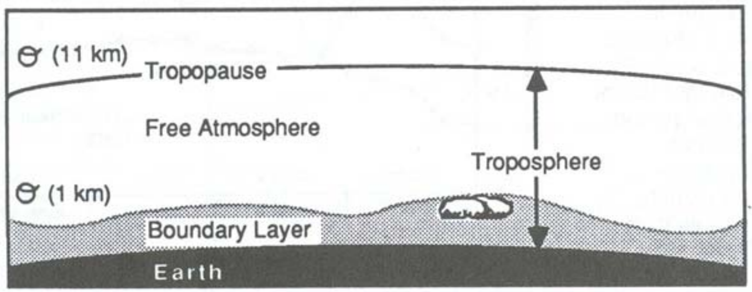


Fig. 1.1 The troposphere can be divided into two parts: a boundary layer (shaded) near the surface and the free atmosphere above it.

$\upsilon = 10^{-5} m^2 s^{-1}$

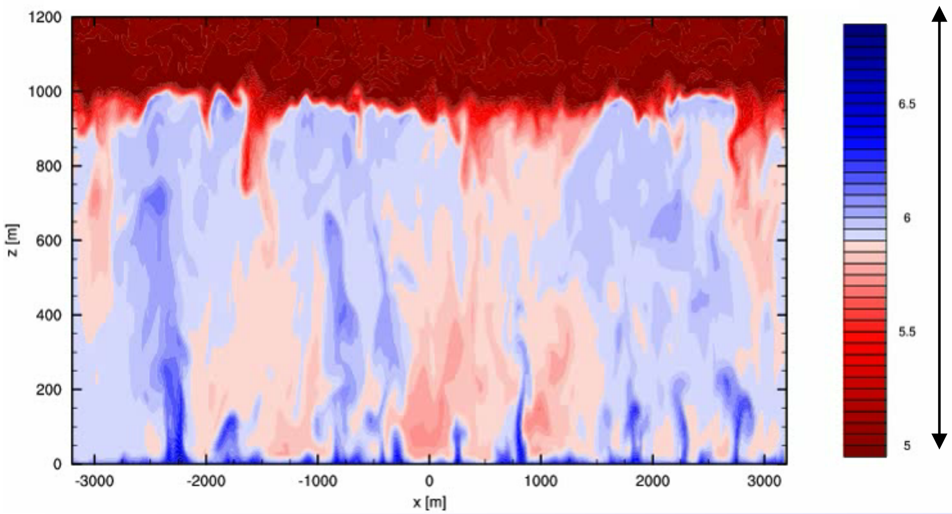
U=10m/s

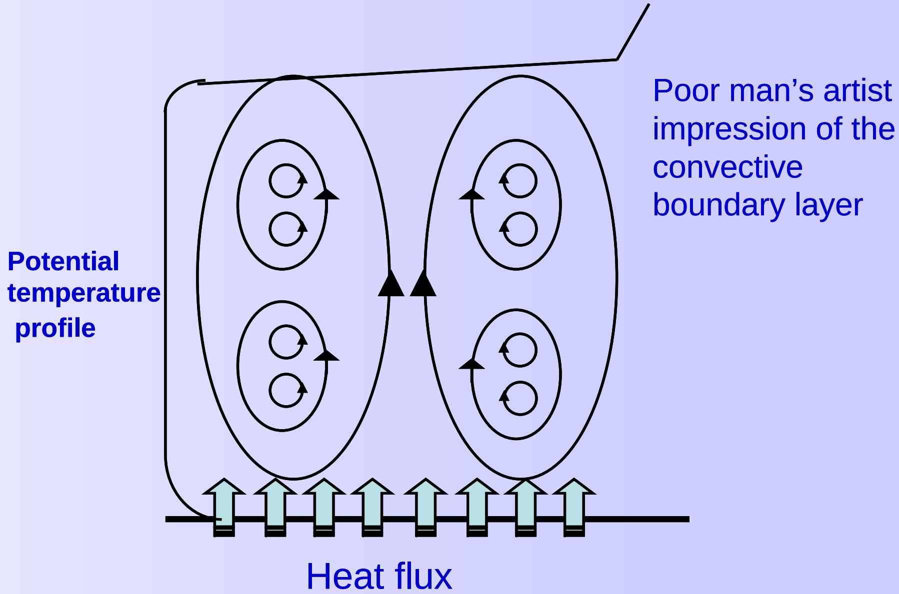
L=1000m

$$Re = \frac{UL}{\upsilon} = \frac{10000}{10^{-5}} = 10^9$$

Macrostructure dominated by non-linear advection!!

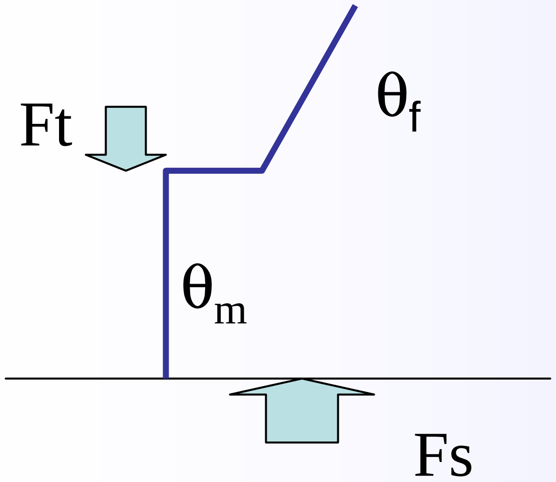
Large eddy simulation of the convective boundary layer





Mixed Layer Models

A simple mixed layer model:



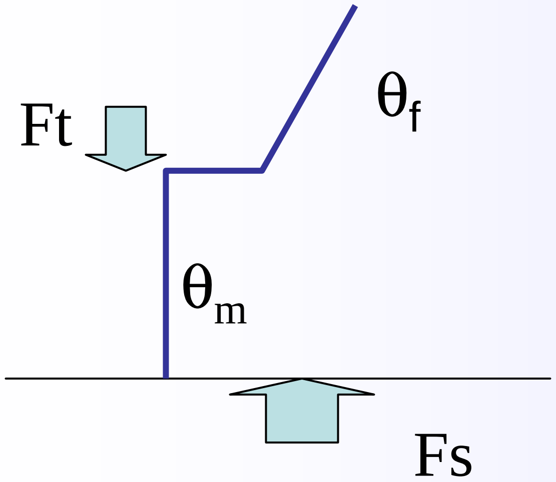
$$\frac{\partial \theta}{\partial t} = -\frac{\partial \overline{w'\theta'}}{\partial t} = \frac{-\left(F_s - F_t\right)}{h}$$

$$\frac{\partial h}{\partial t} = w_e$$

$$F_t = -\beta F_s = -w_e\left(\theta_f - \theta_m\right)$$

Mixed Layer Models

A simple mixed layer model (MLM):



$$\frac{\partial \theta}{\partial t} = -\frac{\partial \overline{w'\theta'}}{\partial t} = \frac{-\left(F_s - F_t\right)}{h}$$

$$\frac{\partial h}{\partial t} = w_e$$

$$F_t = -\beta F_s = -w_e\left(\theta_f - \theta_m\right)$$

MLM approach is too restricted. GCM's need an approach that is more general and allows for all boundary layers

Higher Order Closures (HOC)

$$\frac{\partial \overline{\phi}}{\partial t} + \ldots = -\frac{\partial}{\partial z}\overline{w'\phi'} + \ldots \quad for \quad \phi \in \{q_v, \theta, u, v\}$$

- Use Reynolds averaging to obtain prognostic equations for the subgrid fluxes:

$$\frac{\partial}{\partial t}\left(\overline{w'\varphi'}\right) = -\frac{\partial}{\partial z}\left(\overline{w'w'\varphi'}\right) + \ldots$$

- To solve equations for the second moment, we need to estimate the third-moment terms

=> <u>the closure problem</u>

- Not obvious whether higher order closures lead to more accurate results.
- Parameterization might become too less restricted

Eddy Diffusivity Approach (ED)

In ED closure the sub-grid flux is parameterized as:

$$\overline{w'\phi'} = -K \frac{\partial \overline{\phi}}{\partial z}$$

where K is the diffusivity coefficient. The mixing length approach (e.g. Taylor, Prandtl) is

$$K \approx c_\phi \, w_t \, l$$

With w_t a turbulent velocity scale and l a mixing length

Remark 1: ED is a first order closure (highest prognostic eq. is a first moment one)

Remark 2: When applying this approach turbulent mixing is approximated as diffusion:

$$\frac{\partial \overline{\phi}}{\partial t} + \ldots = -\frac{\partial}{\partial z}\overline{w'\phi'} \approx \frac{\partial}{\partial z} K \frac{\partial \phi}{\partial z}$$

Remark 3: Diffusion tends to homogenenize the field it is working on

Eddy Diffusivity Approach (ED) (cont)

Succesful for:

- Surface Layer:
  - Assume constant flux: $\overline{u'w'} \equiv -u_*^2$
  - Turbulent velocity scale $w_t \propto u_*$
  - Mixing Length $\ell \propto z$

$$\overline{w'u'} = -K \frac{\partial \overline{u}}{\partial z}$$

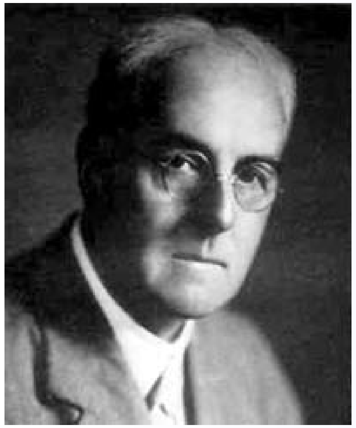
$$u_*^2 \propto u_* z \frac{\partial \overline{u}}{\partial z}$$

Logarthmic Wind Profile:

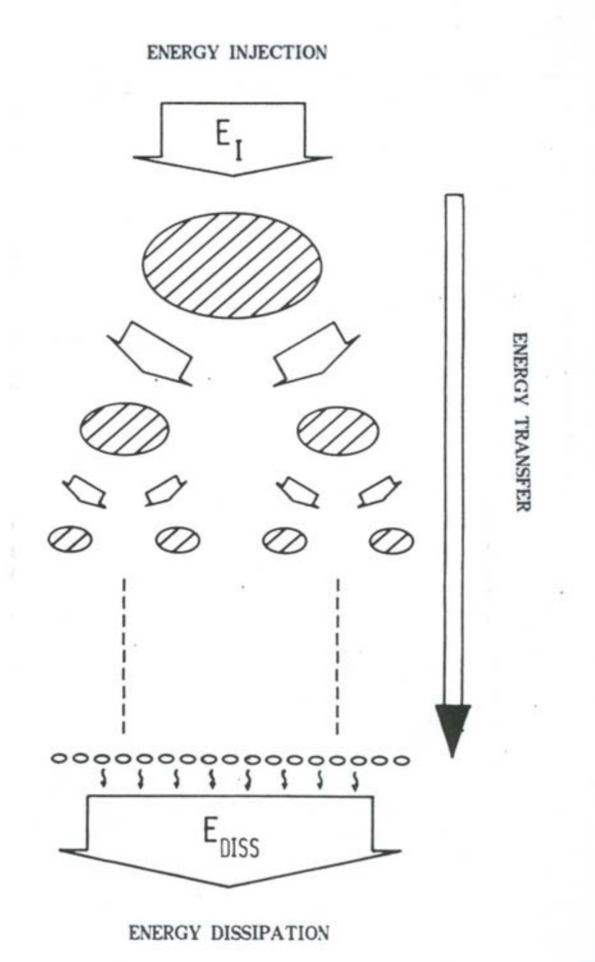
$$\overline{u} \propto u_* \ln\left(z / z_0\right)$$

But what about the rest of the boundary layer?

Energy Cascade



Richardson 1926



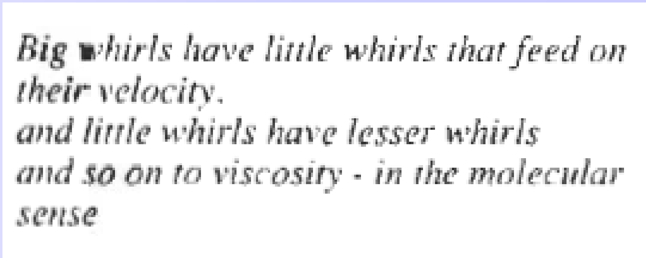
- Energy injection through buoyancy at the macroscale

$Re \rightarrow \infty$ dominated by non-linear processes

- Hence, Large eddies break up in smaller eddies that have less kinetic energy:

$$Re_{local} = \frac{UL}{\upsilon}$$

- and a lower "local" Reynold number
- until it is so small that : $Re_{local} \approx 1$
- and viscosity takes over and the eddies dissipate.

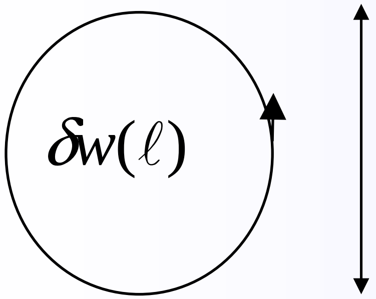


Big whirls have little whirls that feed on their velocity,
and little whirls have lesser whirls
and so on to viscosity - in the molecular sense

Kolmogorov Scaling

Kinetic Energy (per unit mass) : $$\frac{\partial e}{\partial t} = E_t - \varepsilon \approx 0$$

Dissipation rate : ε



eddy size: ℓ

eddy velocity: $\delta w(\ell)$

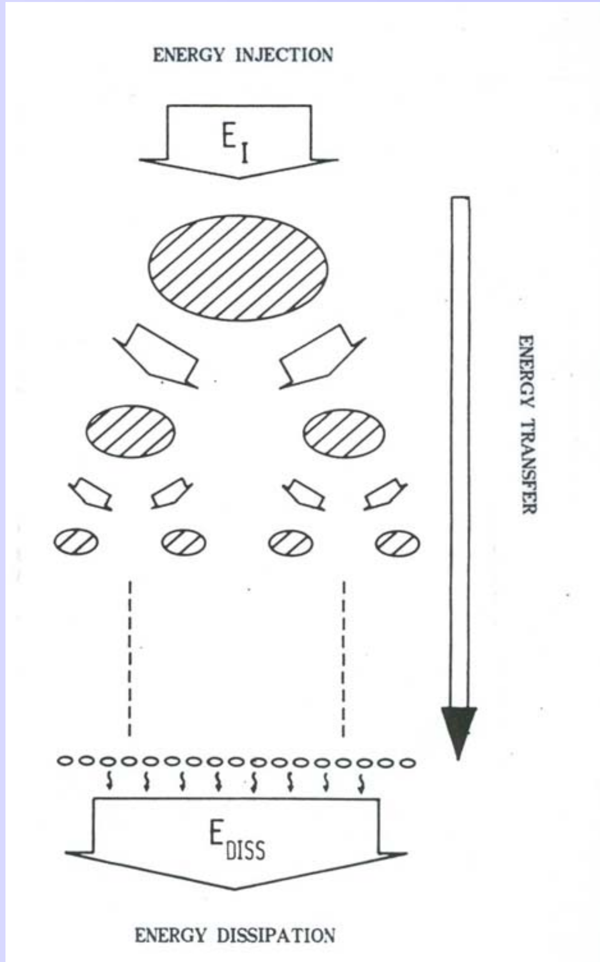
eddy turnover time: $\tau = \ell / \delta w(\ell)$

Kolmogorov Assumption:

Kinetic Energy transfer is constant
and equal to the dissipation rate

$$\frac{e(\ell)}{\tau(\ell)} \approx \frac{\delta w^2(\ell)}{\tau(\ell)} \approx \frac{\delta w^3(\ell)}{\ell} \approx \varepsilon \approx cst$$

➔ $\delta w(\ell) \sim \ell^{1/3}$



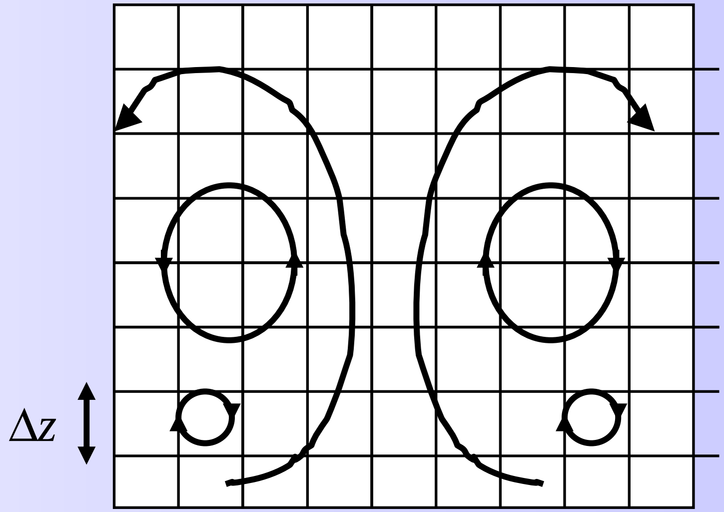
Eddy Diffusivity in Turbulent Resolving Models

$$\frac{\partial \bar{\phi}}{\partial t} + \frac{\partial \bar{w}\bar{\phi}}{\partial z} = -\frac{\partial}{\partial z}\overline{w'\phi'} \quad for \quad \phi \in \{q_v, \theta, u, v\}$$

Resolved turbulence	subgrid turbulence

$$\overline{w'\phi'} = -K\frac{\partial \bar{\phi}}{\partial z}$$

$K \approx c_\phi w_t l$ => $K \propto \Delta z^{1/3} \Delta z \propto \Delta z^{4/3}$



Remark 1:

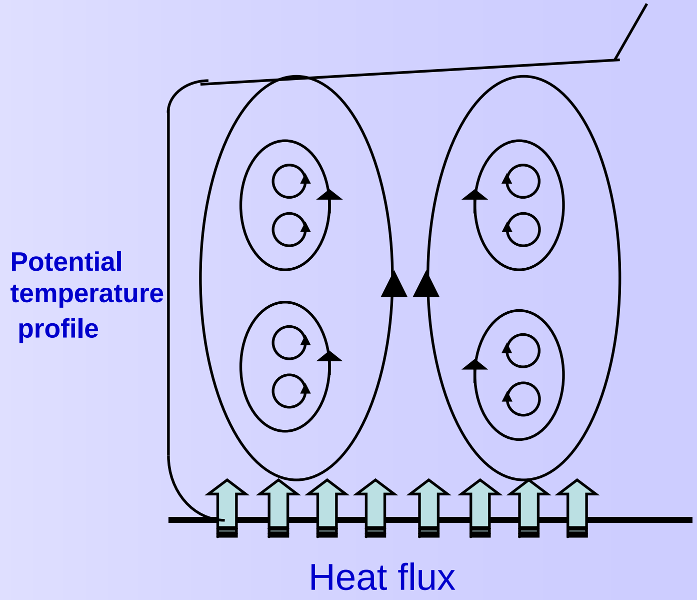
- $w_t(l)$ is the typical relative velocity of an eddy of size l
- eddy size l is related to the used resolution

Remark 2: Eddy diffusivity increase with the resolution as $\Delta z^{4/3}$ (Richardson Law)

But what if the resolution is (much) coarser than the depth of the Boundary Layer???

Eddy Diffusivity in GCMs: length scale

$$\overline{w'\phi'} = -K \frac{\partial \overline{\phi}}{\partial z} \quad \text{with} \quad K \approx c_\phi \, w_t \, l$$



Length scale l(z):

•Not well defined but loosely interpreted as the size of the dominant turbulent eddy at height z

•Many different formulations have been proposed

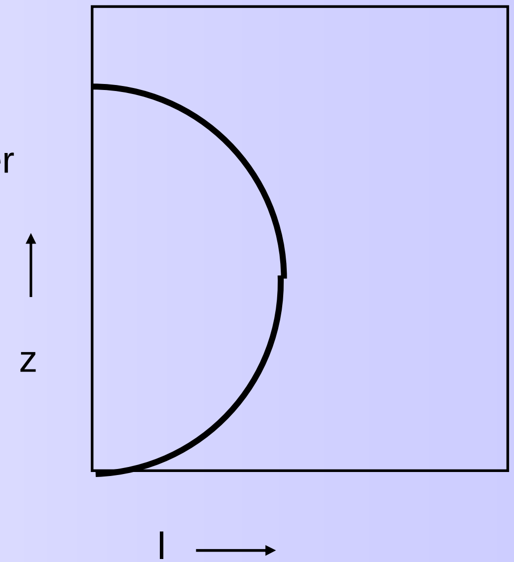
Example:

• convective boundary layer:

•small eddies near the surface and near the inversion

•Large eddies in the middle of the convective boundary layer

$$\ell \propto z\left(1 - \frac{z}{z_i}\right)^p$$



Eddy Diffusivity in GCMs: turbulent velocity scale

$$\overline{w'\phi'} = -K \frac{\partial \overline{\phi}}{\partial z} \qquad \text{with} \qquad K \approx c_\phi \, w_t \, l$$

Turbulent Kinetic Energy: $w_t = \sqrt{e} = \sqrt{\frac{1}{2}\left(\overline{u'u'} + \overline{v'v'} + \overline{w'w'}\right)}$

$$\frac{\partial \overline{e}}{\partial t} = \underbrace{-\overline{u'w'}\frac{\partial \overline{u}}{\partial z}}_{\text{shear production}} + \underbrace{\frac{g}{\theta_o}\overline{w'\theta_v'}}_{\text{buoyancy production}} \underbrace{- \frac{\partial}{\partial z}\overline{ew'} - \frac{1}{\overline{\rho}}\frac{\partial}{\partial z}\overline{w'p'}}_{\text{Transport}} \underbrace{- \varepsilon}_{\text{Dissipation}}$$

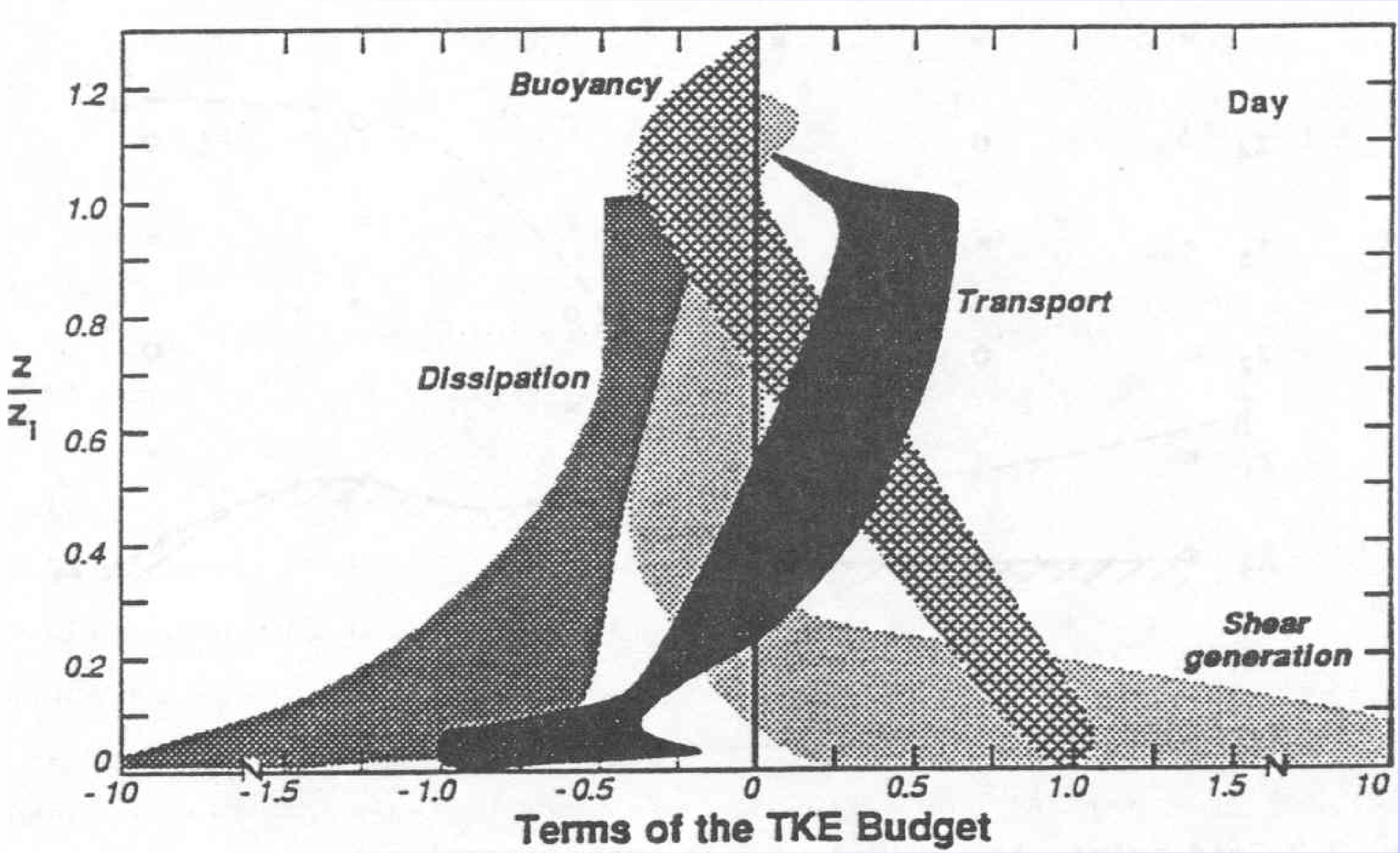
S B T D

Applying eddy diffusivity approach to all the flux terms gives:

$$\frac{\partial \overline{e}}{\partial t} = \mathrm{K}_{\mathrm{m}}\left(\frac{\partial \overline{u}}{\partial z}\right)^2 - K_h \frac{g}{\theta_o}\frac{\partial \overline{\theta}_v}{\partial z} + 2K_m \frac{\partial \overline{e}}{\partial z} - c_d \frac{e^{3/2}}{\ell}$$

$$= S + B + T - D$$

turbulent kinetic energy budget in the convective BL



From Stull : Boundary Layer Meteorology

TKE parameterizations of the BL

- The use of a TKE equation incorporates the proper driving energetics but ….

- It requires numerous parameteric choices (most notably the length scale)

- These need to be carefully calibrated to have the proper flux-profile relations in the surface layer and the proper entrainment rates at the top of the boundary layer.

- Examples : ECHAM, ARPEGE,…..

Other simpler Eddy Diffusivity (ED) formulations can be formulated in a simplified TKE framework:

Simplified Eddy Diffusivity Parameterizations (1)

Neutral and Stable BL:

$$\frac{\partial \bar{e}}{\partial t} = S + B + T - D$$

Assume a balance between production and dissipation:

$$0 \approx S + B - D$$

Richardson number

$$Ri_f \equiv \frac{\mathrm{B}}{-\mathrm{S}}$$

$Ri_f > 1$ Laminar flow

$Ri_f < 1$ Shear driven turbulence

$Ri_f < -1$ Buoyancy driven turbulence

$$\frac{D}{S} \approx 1 - Ri_f$$

Excercise: Show that this leads to an eddy diffusivity of: $K_m = \ell^2 \left| \frac{\partial}{\partial z} \right| (1 - R_i)^{1/2}$

Consistent with the original Prandtl formulation from 1925 !

Simplified Eddy Diffusivity Parameterizations (2)

Convective BL

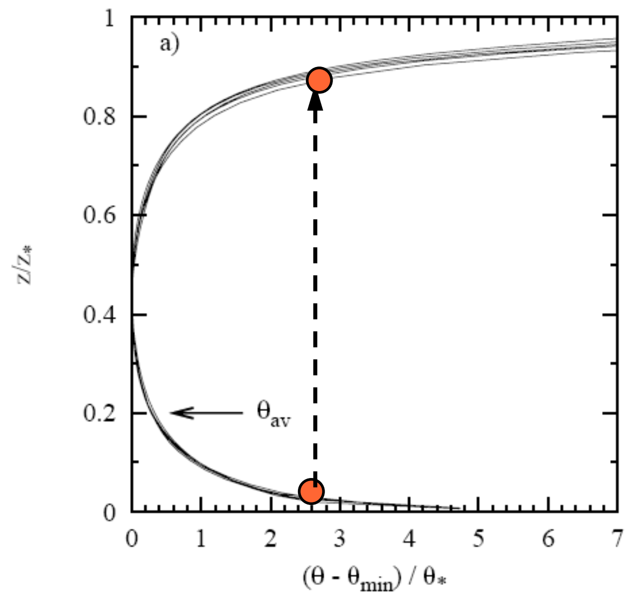
K-profile method: Simplest eddy diffusivity approach suitable for the convective BL

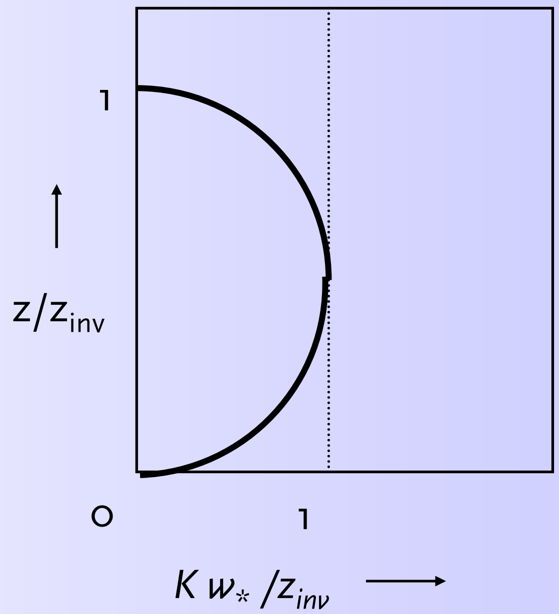
The eddy diffusivity K should forfill three constraints:

- K-profile should match surface layer similarity near zero
- K-profile should go to zero near the inversion
- Maximum value of K should be around: $K_{\max} \approx w_* z_i$

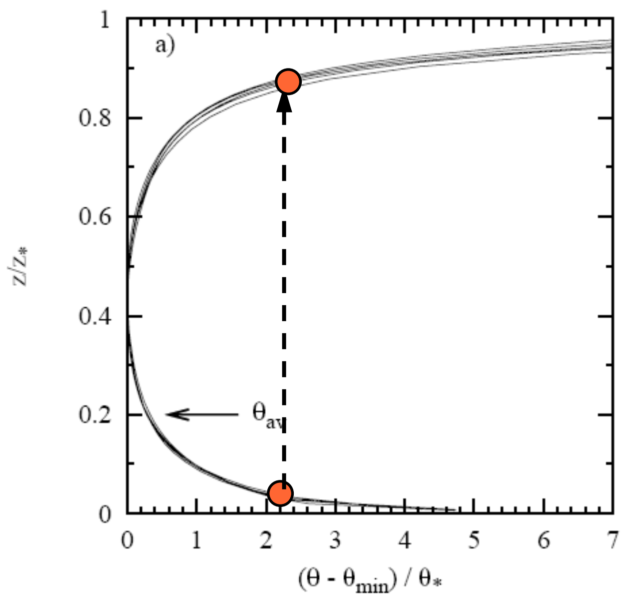
$$K_h = k\, u_*\, \phi_{h0}\, z \left(1 - \frac{z}{z_i}\right)^p$$

θ-profile in convective BL





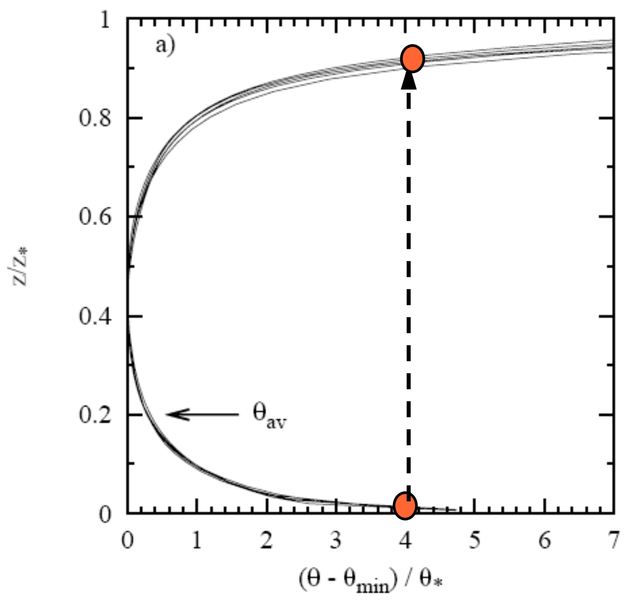
Top Entrainment



Realistic exchange of heat and moisture across the inversion (“ventilation”) is one of the most crucial tasks of the parameterized turbulent transport.

Especially for the simple K-profile method the strength of the turbulent diffusion across the inversion determines strongly on the determination of the inversion height zi

Top Entrainment



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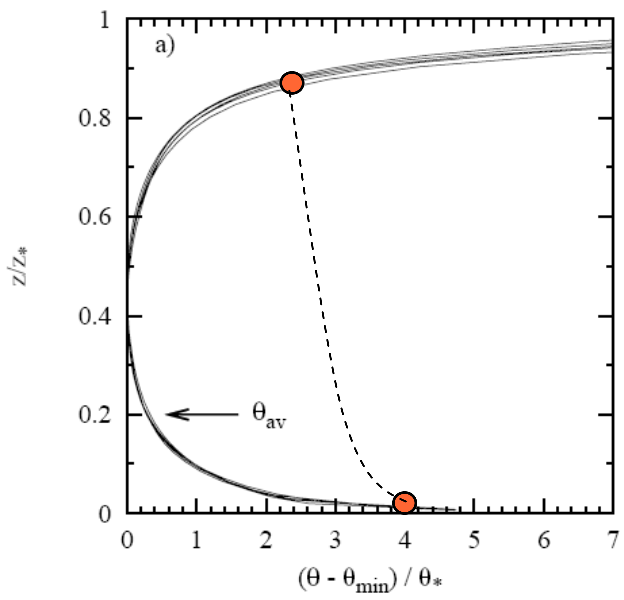
Prescribing Top Entrainment



Realistic exchange of heat and moisture across the inversion ("ventilation") is one of the most crucial tasks of the parameterized turbulent transport.

Especially for the simple K-profile method the strength of the turbulent diffusion across the inversion determines strongly on the determination of the inversion height zi

In order to constrain this, the turbulent diffusion is often prescribed according to our knowledge of the top-entrainment.:

Turbulent Flux at the top level in the pbl

$$\overline{w'\theta'_v}_{,\,entr} = -0.2\,\overline{w'\theta'}_{v,\,srf}$$

$$\overline{w'\theta'_v} = -K\frac{\partial\overline{\theta_v}}{\partial z}$$

$$\boxed{K_{top} = \frac{0.2\left(\overline{w'\theta'_v}\right)_{srf}\Delta z}{\Delta\overline{\theta}_v}}$$

Or equivalently:

$$\overline{w'\theta'}_{entr} = -w_e\Delta\theta_v \longrightarrow \boxed{K_{top} = w_e\Delta z}$$

Summary (so far)

• Virtually all NWP and Climate models use an eddy-diffusivity approach to parameterize turbulent transport in the boundary layer.

$$\overline{w'\phi'} = -K \frac{\partial \overline{\phi}}{\partial z} \qquad \text{with} \qquad K \approx c_\phi \, w_t \, l$$

• Two popular flavours:

•TKE schemes: (ECHAM, ARPEGE)

• physically well founded

• works for all regimes (convective, stable, neutral)

• many uncertain free parameters (length scale, closures in TKE etc)

• needs careful tuning for matching surface layer, top-entrainment etc…

• K-profile (with aditional Ri-formulations for stable cases) (EC-Earth, Hadgem)

•Simpler and hence more robust formulation

•Needs explicity “switching”between regimes (convective ⇔ neutral, stable).

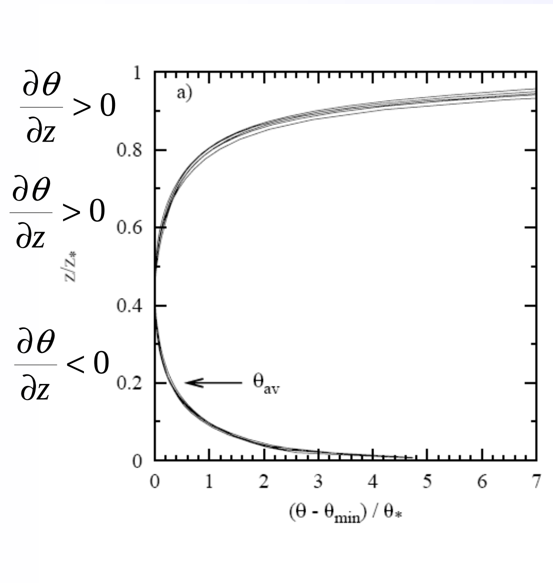
• Needs explicit treatment of top-entrainment.

3.

Properties and Shortcomings of Eddy Diffusivity Models

Does ED reproduce the internal structure of the BL?

$$\overline{w'\theta'} = -K \frac{\partial \overline{\theta}}{\partial z} \quad \Rightarrow \quad K = -\overline{w'\theta'} \Big/ \frac{\partial \overline{\theta}}{\partial z}$$



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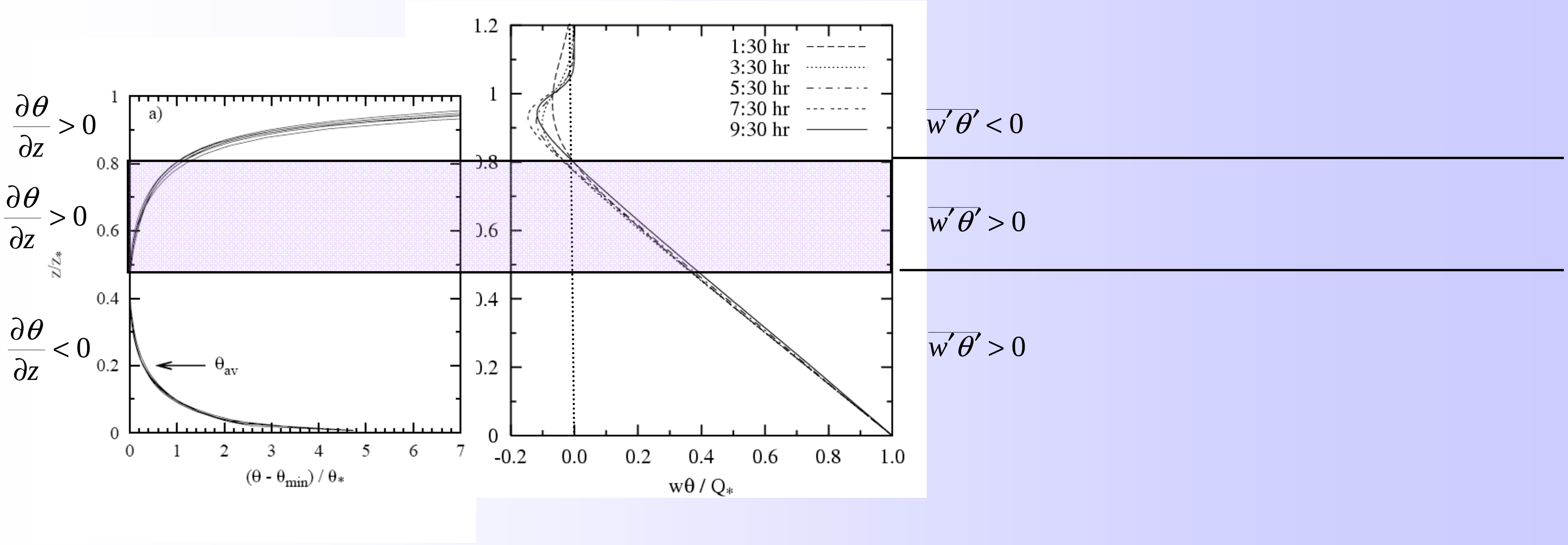

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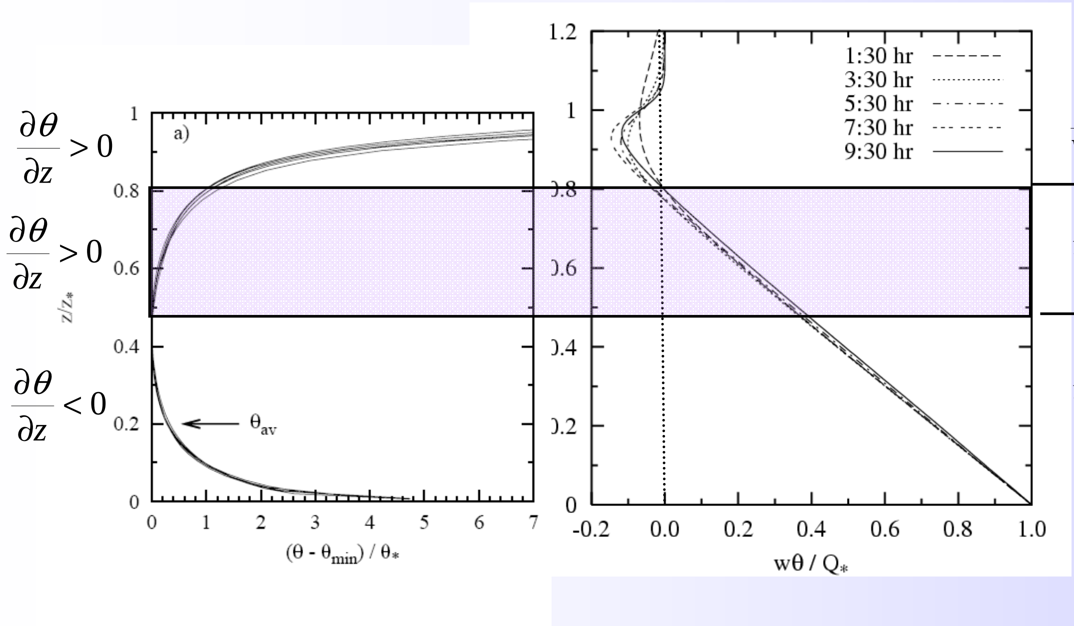


$\overline{w'\theta'} < 0$ **K>0**

$\overline{w'\theta'} > 0$ **K<0** “forbidden area”: flux works against the gradient

$\overline{w'\theta'} > 0$ **K>0**

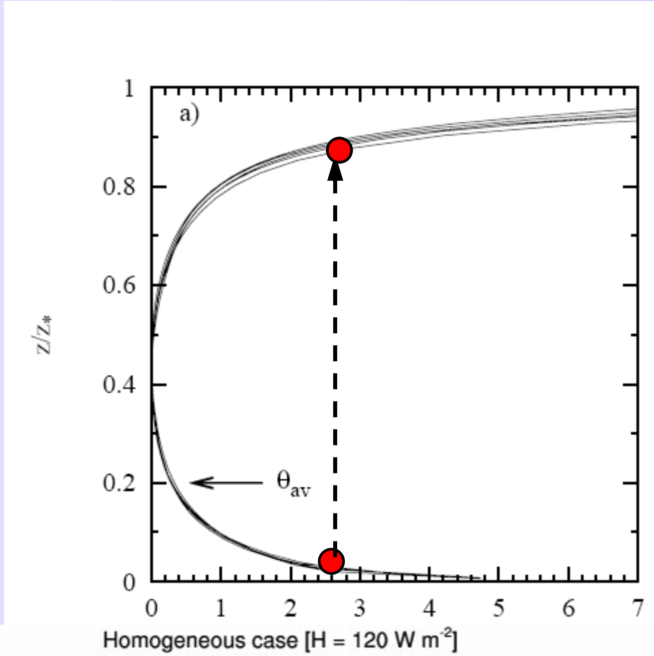
Physical Reason!

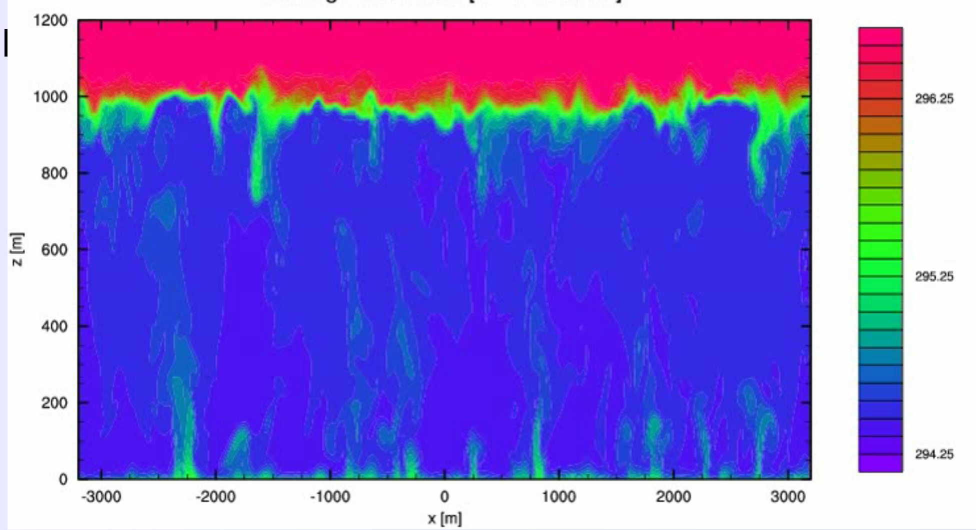
- In the convective BL undiluted parcels (thermal plumes) can rise from the surface layer all the way to the inversion.

- Convection is an inherent non-local process.

- The local gradientof the profile in the upper half of the convective BL is irrelevant to this process.

- Theories based on the local gradient (K-diffusion) fail for this part of the convective BL.



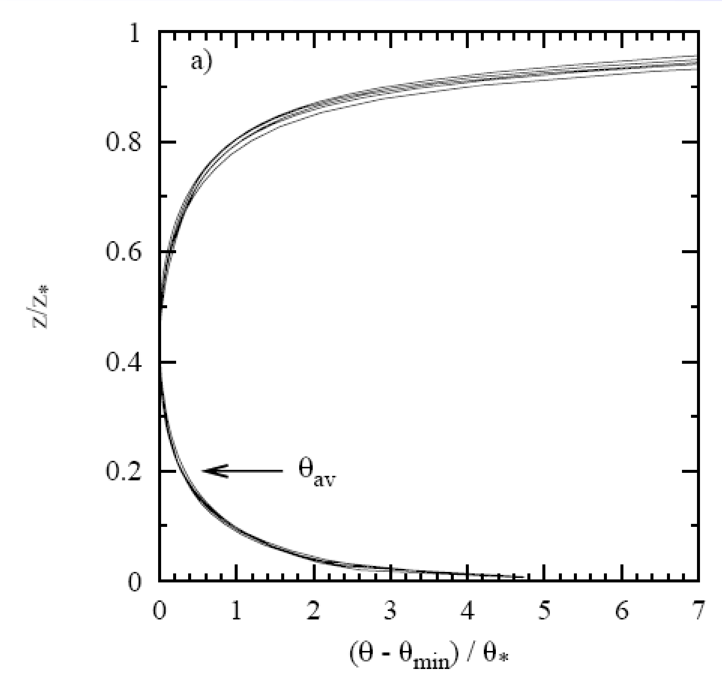


$$\frac{\partial \overline{\theta}}{\partial t} = -\frac{\partial}{\partial z} K \frac{\partial \overline{\theta}}{\partial z}$$ with a positive surface heat flux

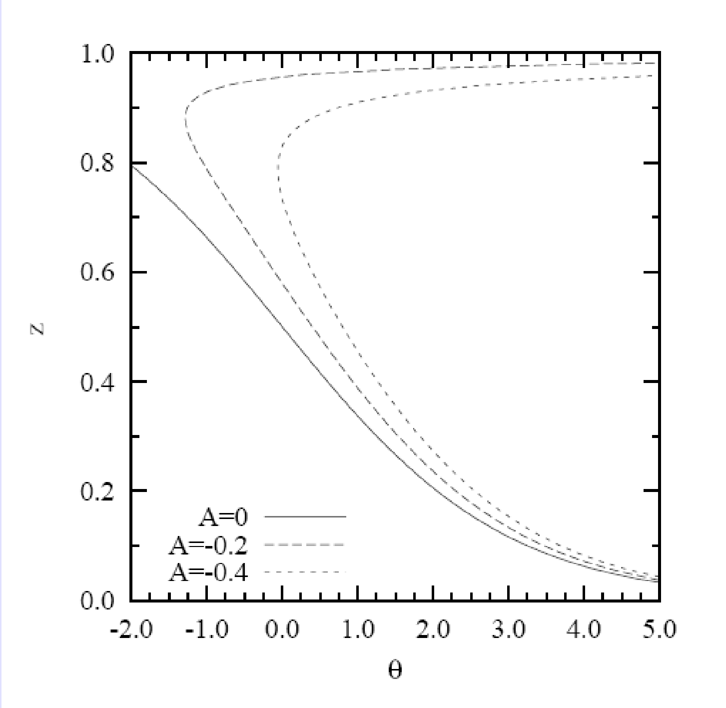
- For finite K the quasi steady steady state solutions are unstable in the whole BL.

- Only for $K \to \infty$ $\overline{\theta}$ becomes well-mixed .

LES “reality”



Eddy diffusivity quasi-steady states



"Standard " remedy

Add the socalled countergradient term:

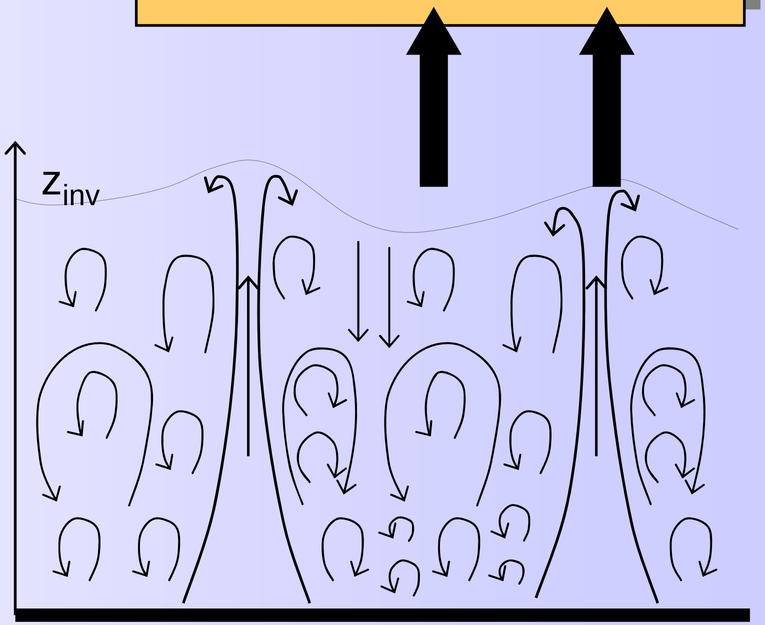
$$\overline{w'\theta'} = -K\frac{\partial\overline{\theta}}{\partial z} + \overline{w'\theta'}_{NL}$$

$$= -K\frac{\partial\overline{\theta}}{\partial z} + K\gamma$$

Long History:

Ertel	1942
Priestley	1959
Deardorff	1966,1972
Holtslag and Moeng	1991
Holtslag and Boville	1993
B. Stevens	2003

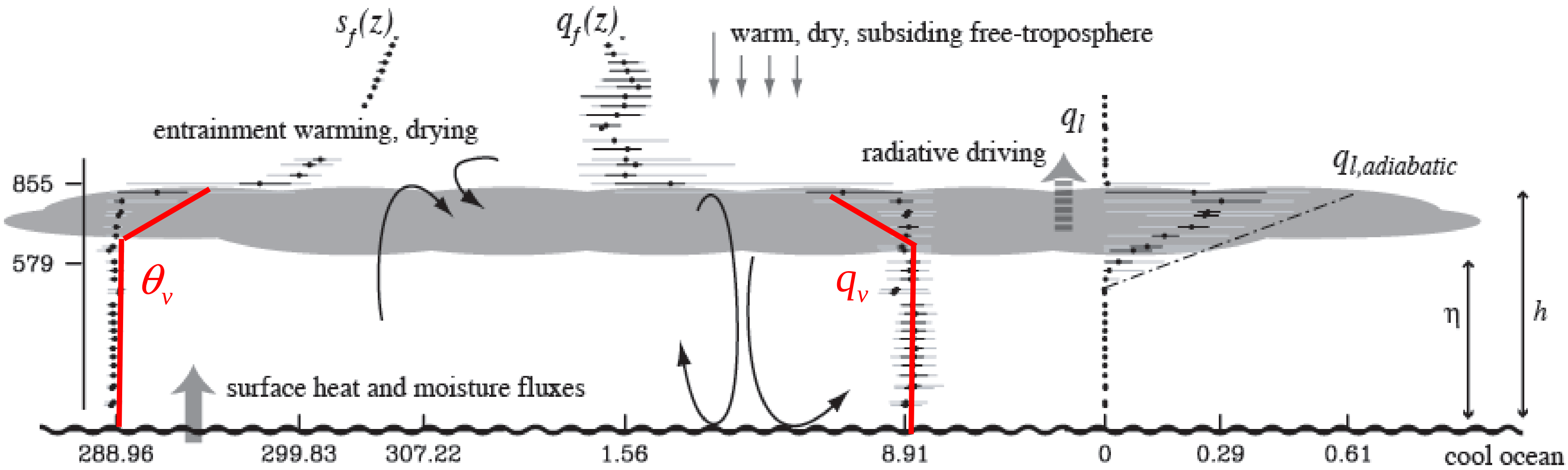
And many more…see Saturday and monday………….



4.

Extension to the well mixed Cloudy Boundary Layer

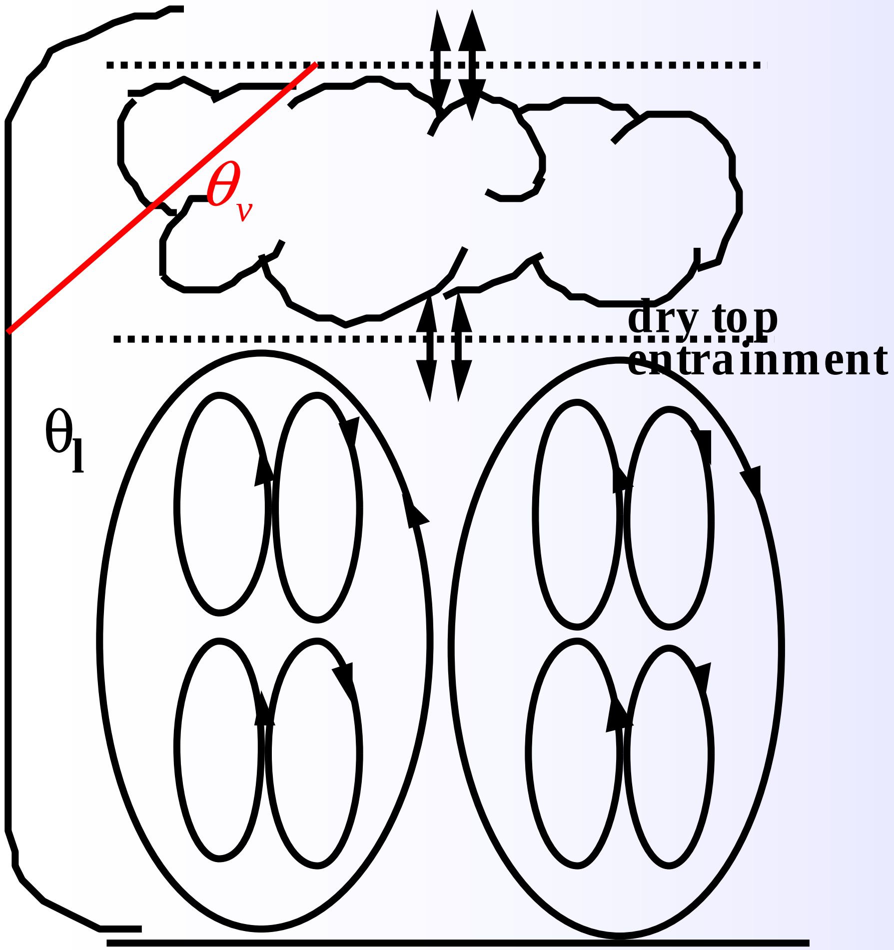
Characteristics of stratocumulus



Well mixed but only in terms of moist conserved variables: q_t,θ_l

Turbulence also driven due to the radiative cooling

$$q_t = q_v + q_l \qquad \theta_l = \theta - \frac{L}{c_p \pi} q_l$$

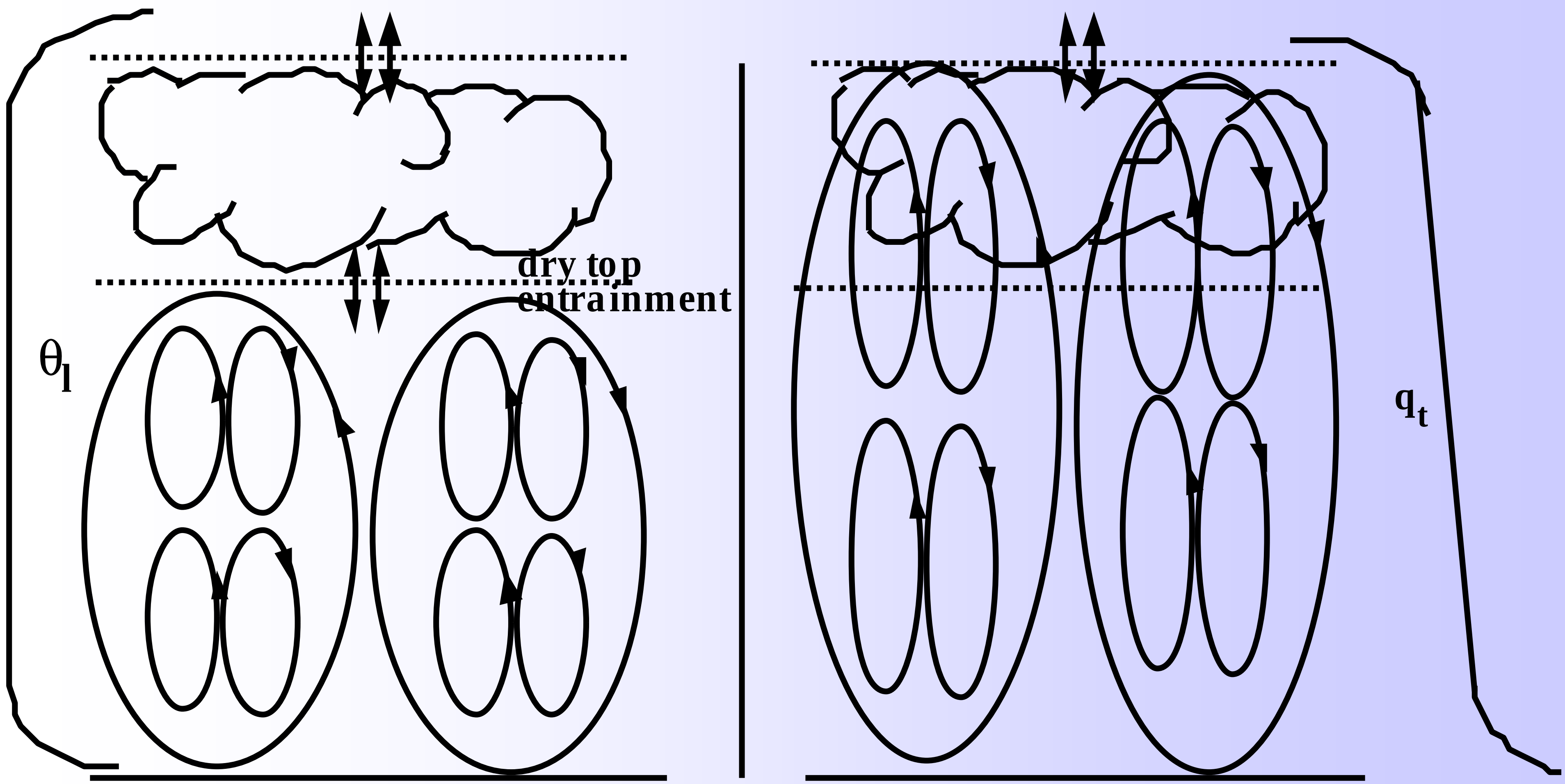


• If the formulation of the BL scheme would not modified it would mix heat and moisture only until cloud base.

• Up to 10 years ago most GCM's were in this situation. They used a socalled "dry formulation".

• This is one (of the many) reason(s) why Scu have been underestimated in many NWP and climate models.

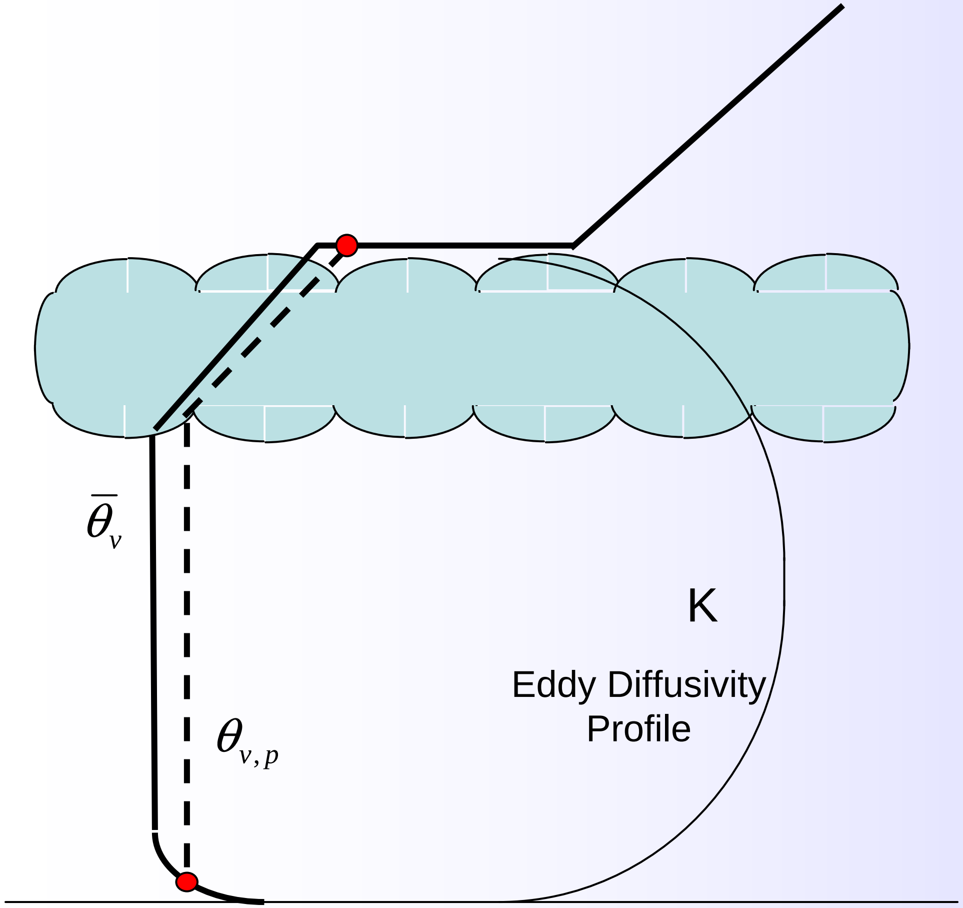
What do we need to do change in order to parameterize more realistic mixing for the Scu topped boundary layer?



Current situation

"As it should be"

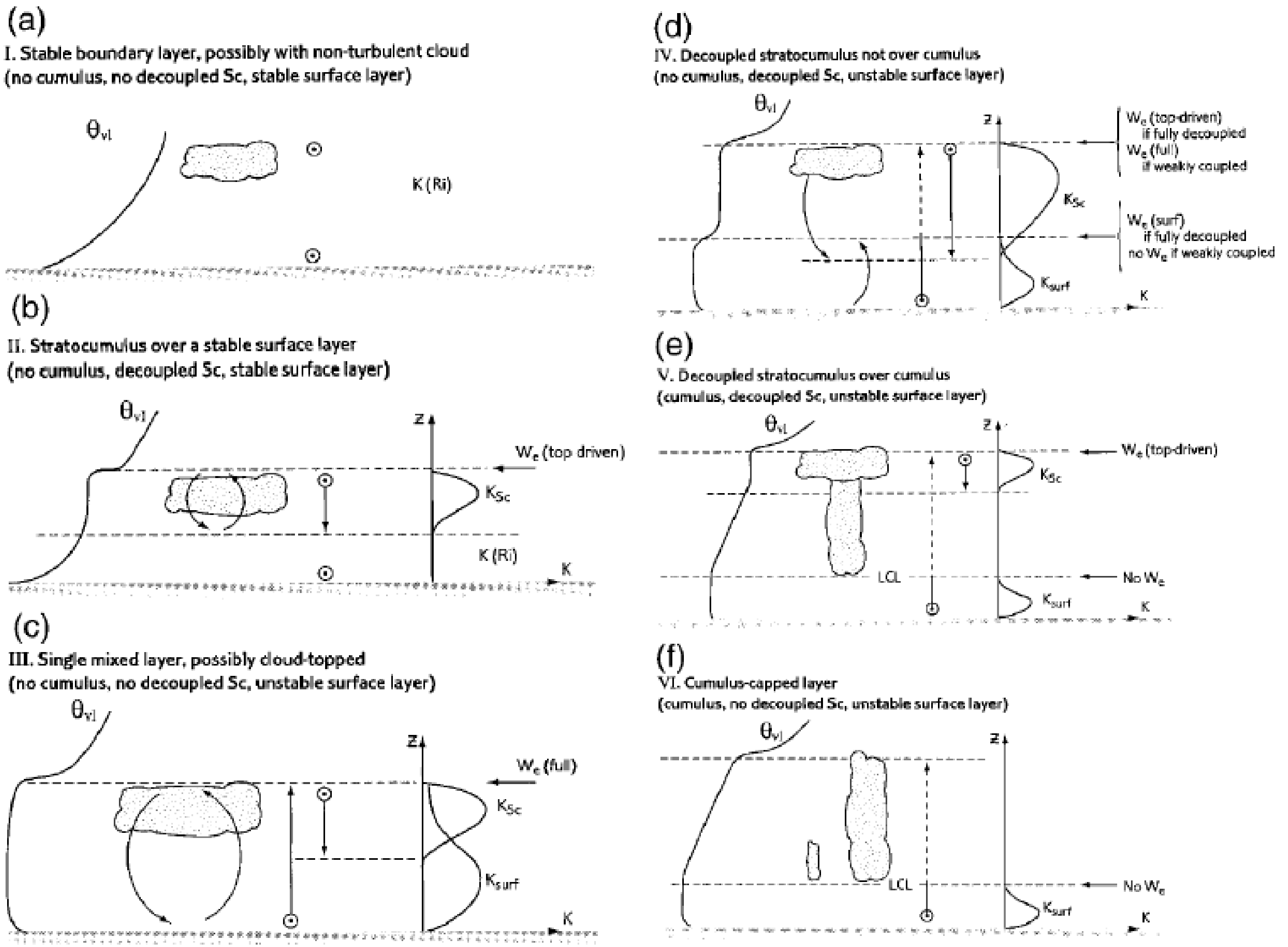
Moist K-Profile method



Required minumum modifications:

1. Allow the “test parcel” to condensate so that it can find the Scu cloud top. (at least a moist adiabat).
2. Construct a K-profile from the surface to the Scu cloud top
3. Modify the prescribed top-entrainment (see lecture de Roode)
4. Apply the Eddy Diffusivity on the moist conserved variables q_t and θ_l
5. Translate the new values of qt and θl back into qv and ql and T

Different Profiles for different regimes (Lock 2000)



Moist TKE-method

- TKE equation

$$\frac{\partial \bar{e}}{\partial t} = \frac{g}{\overline{\overline{\theta}}_v}\overline{w'\theta_v'} - \overline{u'w'}\frac{\partial \bar{u}}{\partial z} - \overline{v'w'}\frac{\partial \bar{v}}{\partial z} - \frac{\partial}{\partial z}\left(\overline{w'e'} + \frac{\overline{w'p'}}{\rho}\right) - \varepsilon$$

- Flux

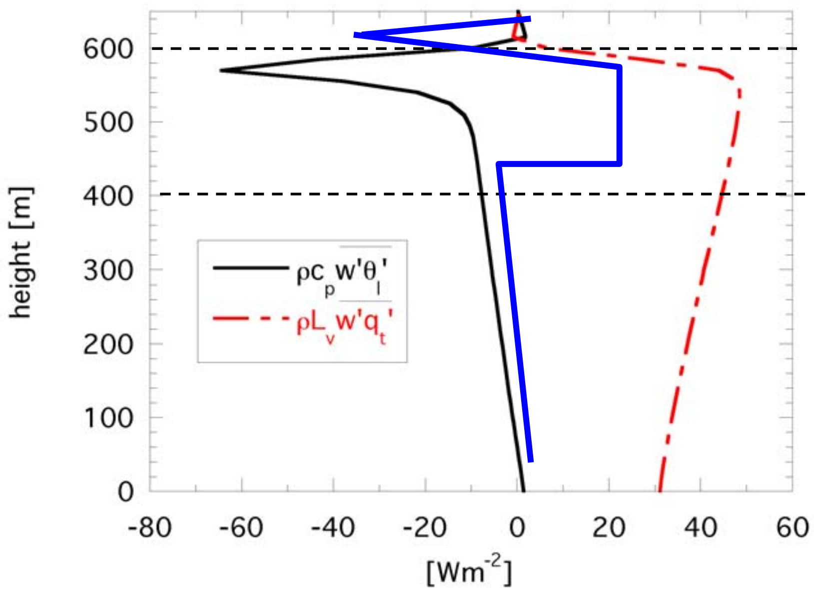
$$\overline{w'\phi'} = -c_\phi \ell \sqrt{e}\,\frac{\partial \bar{\phi}}{\partial z}$$

- length scale

$$\frac{1}{\ell} = \frac{1}{\ell_u} + \frac{1}{\ell_d}$$ (moist adiabatic testparce))

- buoyancy flux:

$$\overline{w'\theta_v'} = -c_H \sqrt{\bar{e}}\,\ell\left[\sigma\left(A_w \frac{\partial \overline{\theta}_l}{\partial z} + B_w \frac{\partial \overline{q}_t}{\partial z}\right) + (1-\sigma)\left(A_d \frac{\partial \overline{\theta}_l}{\partial z} + B_d \frac{\partial \overline{q}_t}{\partial z}\right)\right]$$



Remark 1: Note that the cloud fraction

has now entered the equations

Remark 2: If verticak resolution is high enough (100m) and the scheme is well callibrated no prescribed top-entrainment is necessary

Did it made a difference?

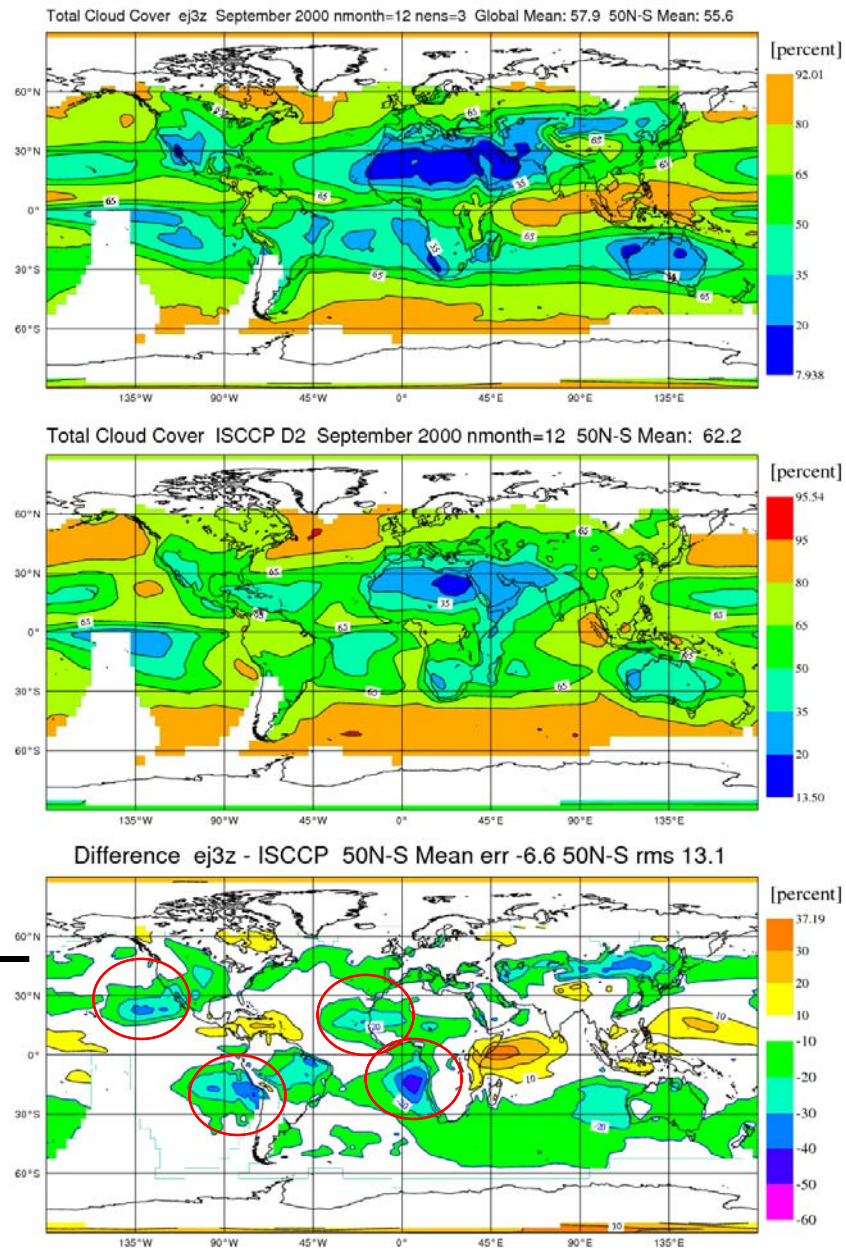
Yes, especially for those operational centres that actively participated in this process: i.e. ECMWF, Met. Office, Meteo France.

Example:

ECMWF: cloud fraction climatology

2002: underestimation of Scu

(general GCM-problem)



model - obs

Courtesy: Martin Kohler

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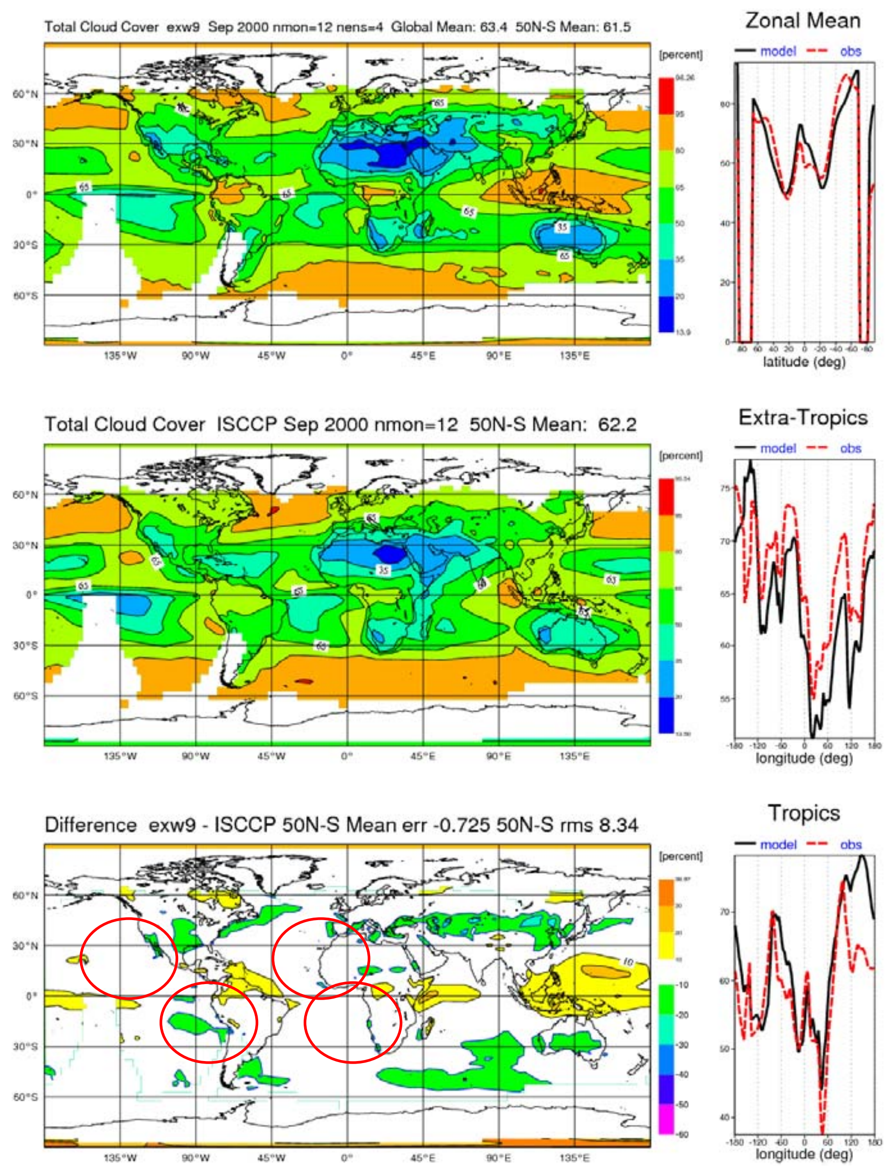


Example:

ECMWF: cloud fraction climatology

2007: Scu underestimation problem resolved.

model - obs ⟵

But more modeling centers should invest more on this!!!

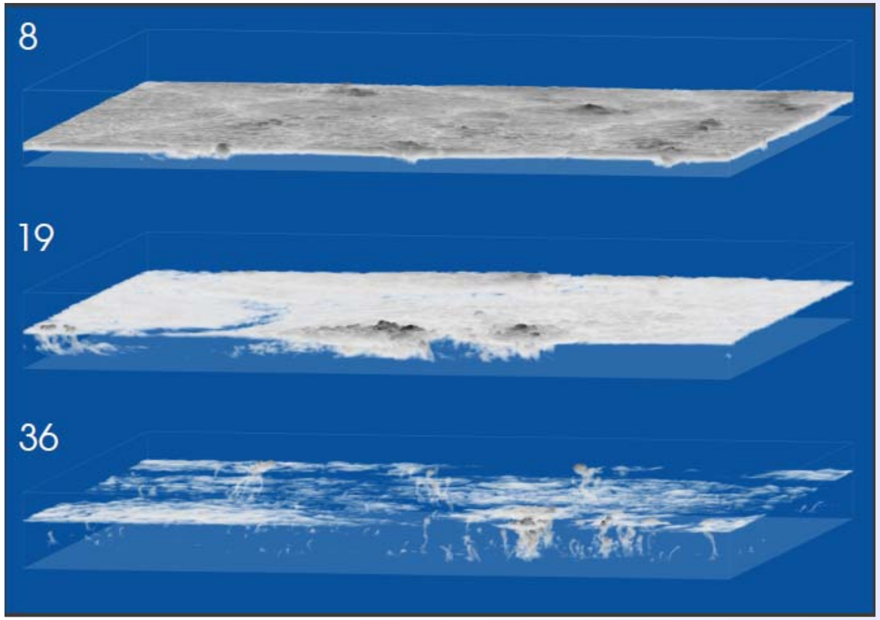
5.

Issues

Current Issues

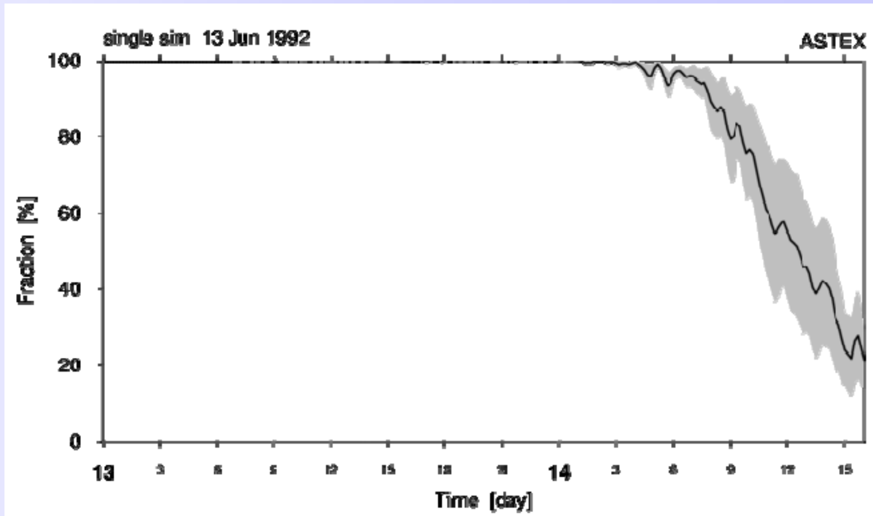
- Numerics (grid-locking, vertical resolution (sharp inversions not-resolved)
- Choice of top-entrainment parameterization.
- Drizzle
- Transition to cumulus (i.e. break-up of Scu)
- Response to perturbed climate (CGILS)

EUCLIPSE ASTEX Transition

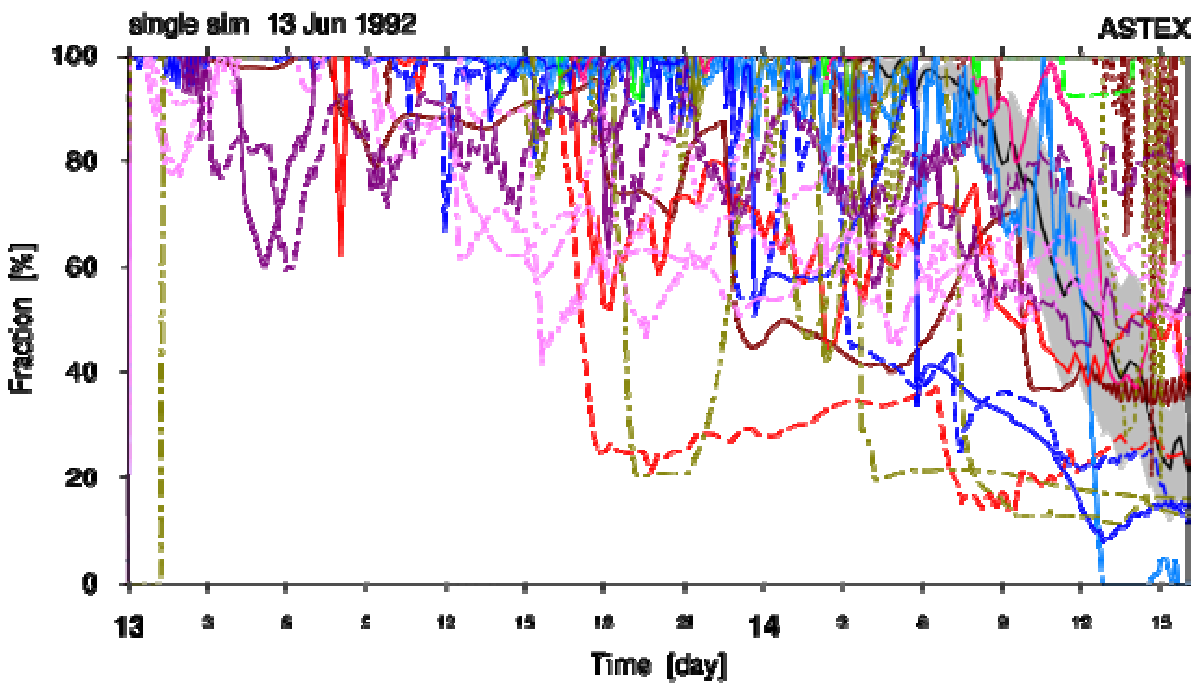


Van der Dussen et al 2013

LES



EUCLIPSE ASTEX Transition



Single Column Model versions of GCMs

Switching from PBL (moist) mixing schemes to a cumulus scheme

Scu case perturbed with +2K SST and weakened subsidence

Change in Cloud Radiative effect: