

Boundary layer parameterization and climate

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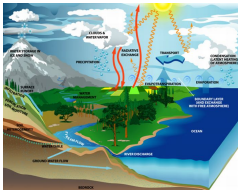
Outline

- 1 Introduction
- 2 Approaches to the parameterization of the boundary layer
 - Scale decomposition
 - Diffusive approaches and their limitations
 - Alternatives to diffusive approaches
- 3 Boundary layer parameterizations in climate models
 - Cumulus clouds and mass flux parametrisations
 - From boundary layer to deep convection
 - Tracer transport
- 4 Conclusion

Boundary layer in the climate system

The boundary layer :

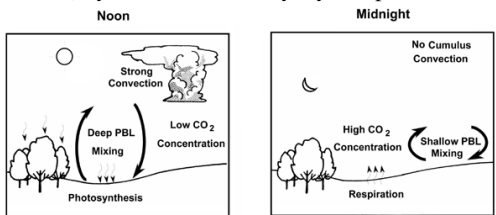
- controls energy and water exchanges with surfaces
- drives the oceanic circulation
- is associated with a large fraction of clouds



Boundary layer in the "Earth System"

Example of well indentified uncertainty source in Eart-System models.

The diurnal (seansonal) cycle of plant respiration is modulated by the diurnal (seasonal) cycle of the boundary layer depth



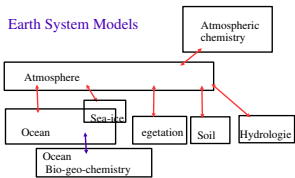
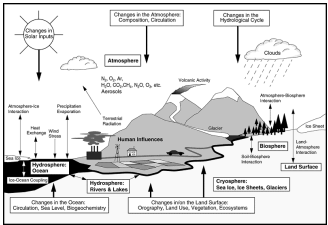
Boundary layer in the "Earth System"

Driven by the Global Change studies, climate models are more and more complex :

CO₂ cycle, CH₄, ozone chemistry, aerosols, effect of land use
⇒ coupling between atmosphere, ocean, chemistry, vegetation ...

Leading to so-called "Earth System Models".

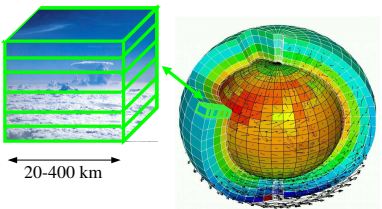
Boundary layer is central for most of those components.



Boundary layer in large scale models

Current climate models : horizontal mesh of 20 to 400 km.

Boundary layer processes are subgrid-scale ⇒ must be "parameterized"



Parameterizations

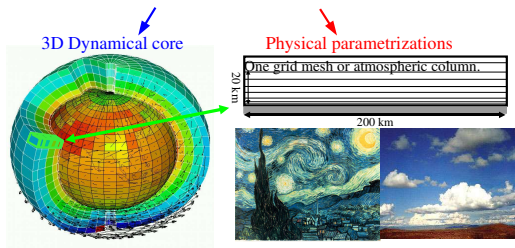
- describe the effect of subgrid-scale processes on large scale state variables
- through a set of approximate equations based on some internal variables
- must relate those internal variables to large scale variables (closure)
- closely linked to the numerical world.

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Under boundary layer approximations ($\partial/\partial x \ll \partial/\partial z$) :

$$\frac{\partial c}{\partial t} + \mathbf{v} \cdot \mathbf{grad} \, c = S_c - \frac{1}{\rho} \frac{\partial}{\partial z} \overline{w'c'}$$



\mathbf{v} and c are now the large scale variables.
 c : θ , u , v , water (vapor and others), chemical compounds ...

Diffusive or local formulations for the PBL

$$\overline{w'c'} = -K_z \frac{\partial c}{\partial z} \quad \longrightarrow \quad \frac{\partial c}{\partial t} = \frac{\partial}{\partial z} \left(K_z \frac{\partial c}{\partial z} \right)$$

- Analogy with molecular viscosity (Brownian motion \leftrightarrow turbulence)
- Down-gradient fluxes.
- Turbulence acts as a "mixing"

Scale decomposition of the conservation equation

Conservation equation | \mathbf{v} : wind field
 c : conserved quantity

Lagrangian form : $\frac{dc}{dt} = 0$

Advective form : $\frac{\partial c}{\partial t} + \mathbf{v} \cdot \mathbf{grad} \, c = 0$

Flux form : $\frac{\partial \rho c}{\partial t} + \text{div} (\rho \mathbf{v} c) = 0$

Scale decomposition
 \bar{X} : "average" or "large scale" variable
 $X' = X - \bar{X}$: turbulent fluctuation
 $\implies \overline{\mathbf{v}c} = \overline{\mathbf{v}} \bar{c} + \overline{\mathbf{v}'c'}$
 $\frac{\partial \bar{q}}{\partial t} + \overline{\mathbf{V}} \cdot \mathbf{grad} \, \bar{q} + \frac{1}{\rho} \text{div} (\rho \overline{\mathbf{v}'c'}) = 0$

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Turbulent diffusivity K_z

- Prandlt (1925) mixing length : $K_z = l|\overline{w'}|$ or $K_z = l^2 \frac{\partial ||\mathbf{v}||}{\partial z}$
- Accounting for static stability (Ex. Louis 1979)

$$K_z = f(Ri) l^2 \left| \frac{\partial \mathbf{v}}{\partial z} \right|, \quad \text{with } Ri = \frac{g}{\theta} \frac{\frac{\partial \theta}{\partial z}}{\left(\frac{\partial \mathbf{v}}{\partial z} \right)^2} \quad (1)$$

- Turbulent kinetic energy $\overline{w'^2} \simeq e = \frac{1}{2} \left[\overline{u'^2} + \overline{v'^2} + \overline{w'^2} \right]$

$$\frac{\partial e}{\partial t} = -\overline{w'u'} \frac{\partial u}{\partial z} - \overline{w'v'} \frac{\partial v}{\partial z} + \frac{g}{\theta} \overline{w'\theta'} - \frac{1}{\rho} \frac{\partial \overline{w'p'}}{\partial z} - \frac{\partial \overline{w'e}}{\partial z} - \epsilon$$

Ex : Mellor and Yamada $\overline{w'\phi'} = -K_\phi \frac{\partial \phi}{\partial z}$ with $K_\phi = l\sqrt{2e}S_\phi(Ri)$
Note : $\frac{\partial e}{\partial t} = 0$ (stationarity) $\implies K_z$ of form Eq. 1

Limitations of turbulent diffusion

Assumption leading to the diffusive approach :

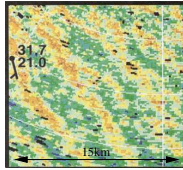
- Turbulence as a random process
- Small scale turbulence, i.e. of size $l \ll h$ with $h = \left[\frac{1}{c} \frac{\partial c}{\partial z} \right]^{-1}$

In the planetary boundary layer

- Long range vertical transport (from the bottom to PBL top)
- Organized structures



Cloud streets on North of France
(March 2009, MSG)



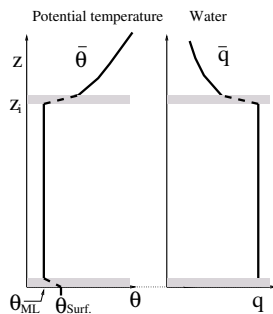
Radar echoes
dry convective
boundary layer
Florida, Hiop
Campaign
Weckwerth et al., 1997

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"Bulk" models

Constant value (or prescribed profiles) c_{ML} with discontinuities Δc at boundaries.



$$z_i \frac{\partial c_{ML}}{\partial t} = \left[\overline{w'c'}_0 - \overline{w'c'}_{z_i} \right] \quad (3)$$

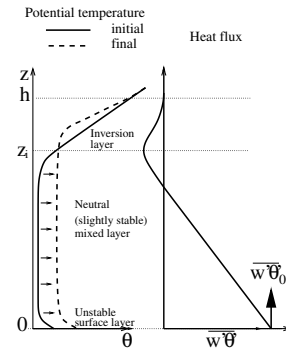
$$\text{with } \overline{w'c'}_{z_i} = -C\Delta c \quad (4)$$

Betts, Albrecht, Wang, Suarez et al 1983

Randall et al. 1992 and Lapen and Randall, 2002: Combination of bulk models with higher order closures

Limitations of turbulent diffusion

Idealized view of the dry convective boundary layer.



In the mixed layer

- Diffusive formulation

$$\overline{w'\theta'} = -K_z \frac{\partial \theta}{\partial z} = 0 \quad \text{or slightly } < 0$$

- Uniform heating by the surface

$$\frac{\partial \theta}{\partial t} \simeq \frac{\overline{w'\theta'}_0}{z_i} (\text{Cste} > 0)$$

$$\overline{w'\theta'} \simeq \frac{z - z_i}{z_i} \overline{w'\theta'}_0 > 0$$

Extension of diffusive formulations

- Introduction of a countergradient term

$$\overline{w'\theta'} = K_z \left[\Gamma - \frac{\partial \theta}{\partial z} \right] = 0 \quad \text{with } \Gamma \simeq 1K/km \quad (2)$$

Imposed countergradient Deardorf, 1966

Revisited by Troen & Mart, 1986, Holtzlag & Boville, 1993, based on a similarity approach.

- Non local mixing length (Bougeault)
- Higher order closures
 - Mellor & Yamada 1974, hierarchy at successive orders. Complex and still local.
 - Abdella & Mc Farlane, 1997, Introduce a mass flux approach to compute the 3rd order moments in a Mellor and Yamada scheme.

Transilient matrices

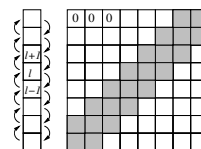
Numerical formalism (after Stull 1984)

C : Air mass exchange rate matrices between model layers

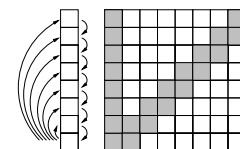
For turbulent diffusions

$$\frac{\partial c_l}{\partial t} = \frac{\partial}{\partial z} \left(K_z \frac{\partial c}{\partial z} \right) \simeq \frac{K_{l+1/2} (c_{l+1} - c_l) - K_{l-1/2} (c_l - c_{l-1})}{\delta z^2}$$

$$\Rightarrow C_{l,l+1} = K_{l+1/2} \frac{\delta t}{\delta z^2}, C_{l,l} = -(K_{l-1/2} + K_{l+1/2}) \frac{\delta t}{\delta z^2}, C_{l,m} = 0 \text{ for } |l - m| > 1$$

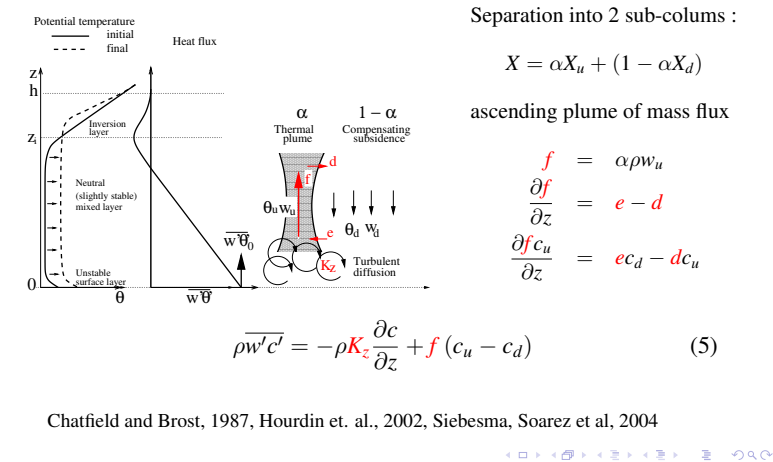


Turbulent diffusion

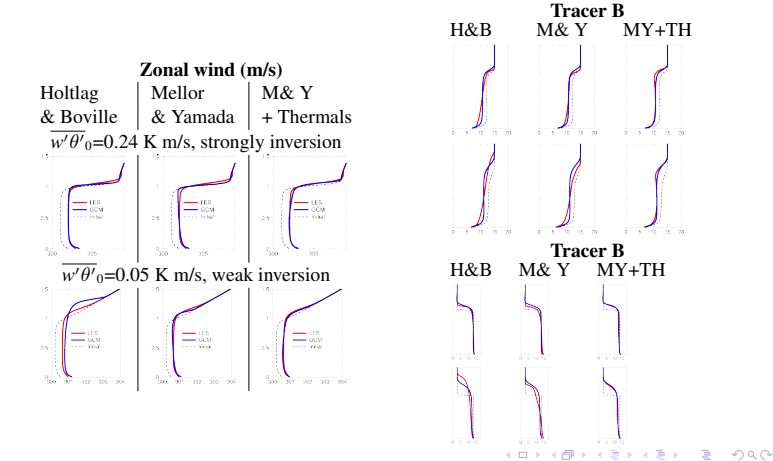


Assymmetric Convective Model of Pleim and Chang 1992

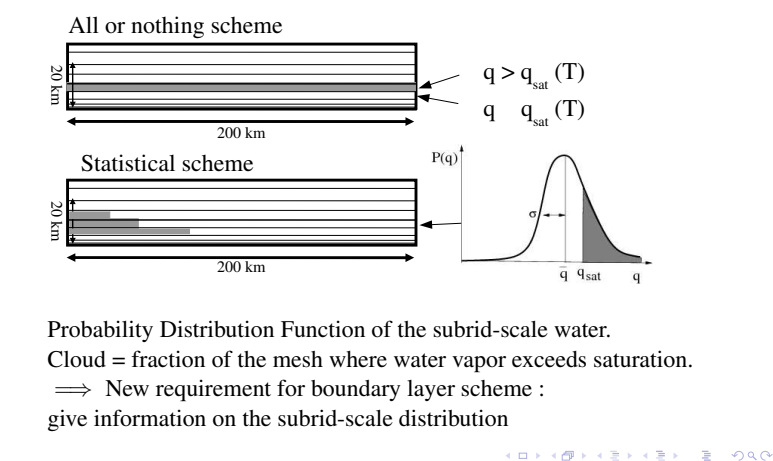
Mass flux schemes combined with turbulent diffusion



Mass flux schemes combined with turbulent diffusion

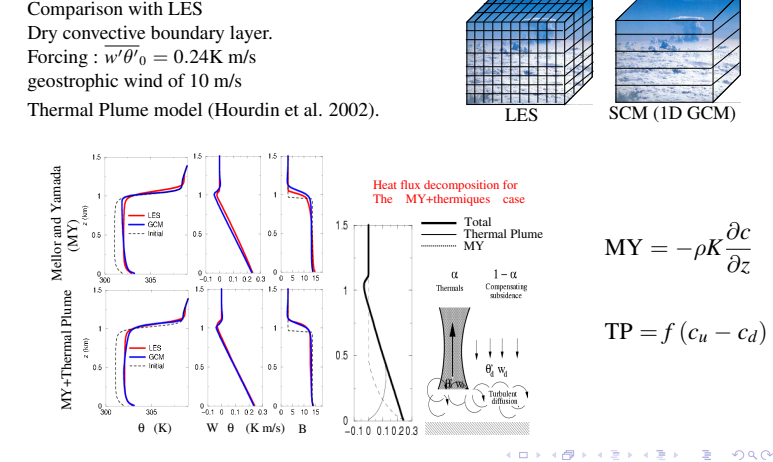


Statistical cloud schemes

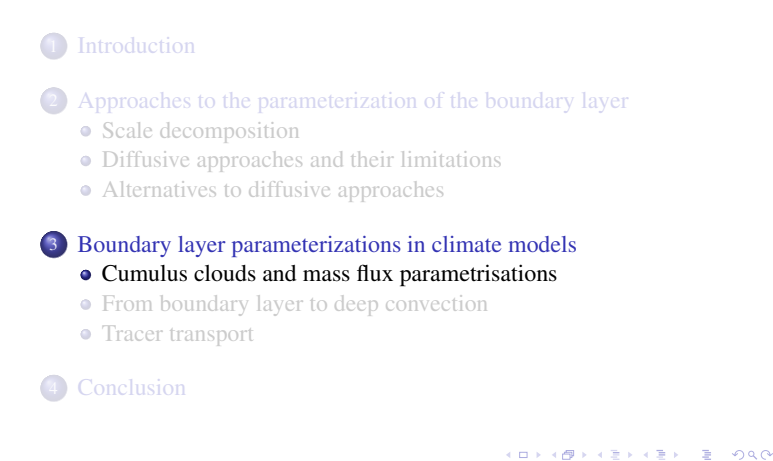


Mass flux schemes combined with turbulent diffusion

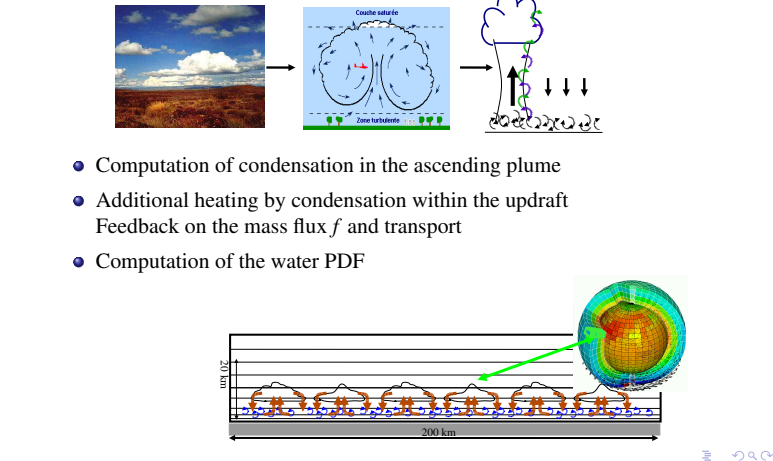
Mass flux schemes combined with turbulent diffusion



Outline



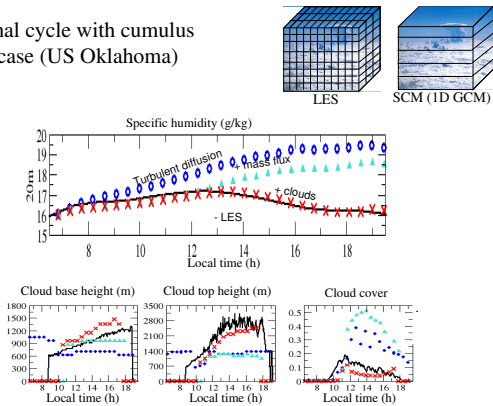
Extension of mass flux schemes to cumulus clouds



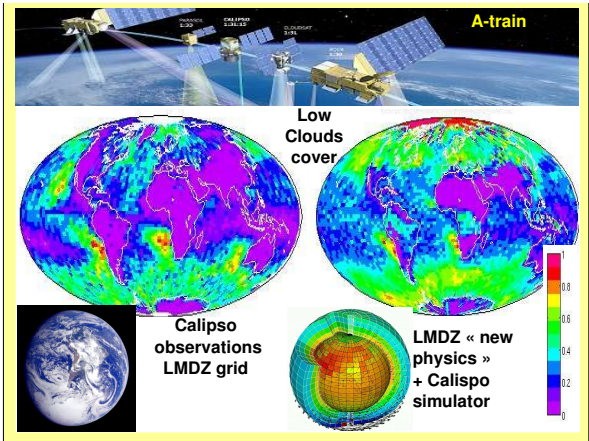
Extension of mass flux schemes to cumulus clouds

1D test of the cloudy thermal plume model

Continental diurnal cycle with cumulus
ARM EUROCS case (US Oklahoma)
Rio et al. 2008



Cloud cover and satellite observations

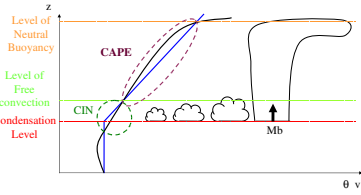


Parameterization of deep convection

Classical parameterizations :

- Mass flux schemes
- Importance of cloud phase changes and rainfall
- Controlled by instability above cloud base

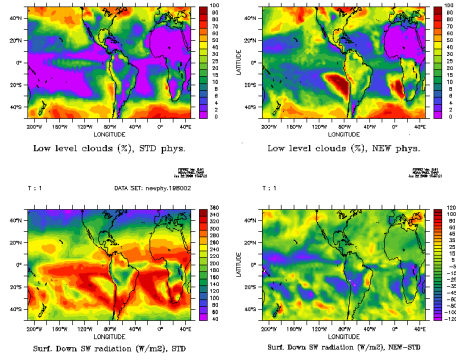
Example of the Emanuel (1991) scheme :



Trigerring :
 $B(LCL+40hPa) > |CIN|$
Closure :
 $M_B = f(CAPE)$
CAPE : Convective Available Potential Energy
CIN : Convective INhibition.

3D test of the cloudy thermal plume model

Test of the a new physical package in the LMDZ global climate model
Impact on the coverage by low clouds



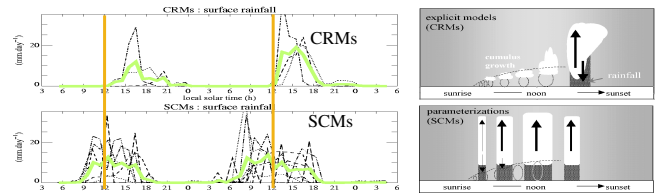
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A systematic bias of parameterized convection

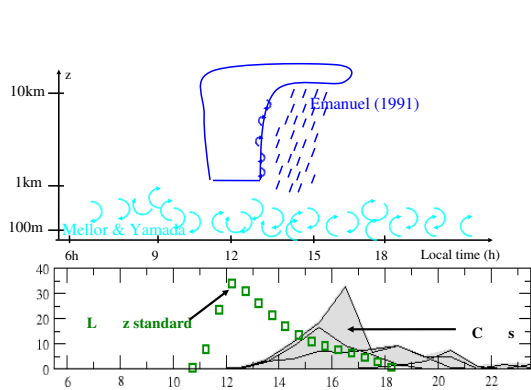
Climate models with parameterized convection tend to predict continental convection in phase with insolation, while it peaks in late afternoon in reality and in Cloud Resolving Models (mesh $\simeq 1$ km).

An idealized case of continental cycle with deep convection
ARM, Oklahoma, after Guichard et al. 2004

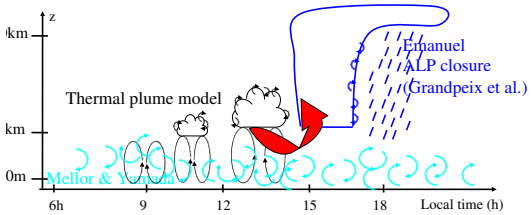


Deep convection preceded by a phase of shallow cumulus convection
Boundary layer : preconditioning and trigerring of deep convection

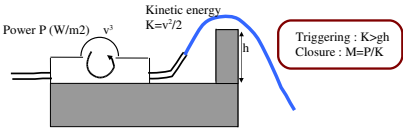
ARM case with the standard LMD SCM



Control of deep convection by sub-cloud processes



New approach (Grandpeix et al. 2009) :
Control of deep convection by sub-cloud processes.
By analogy with a nozzle above a wall of height h .

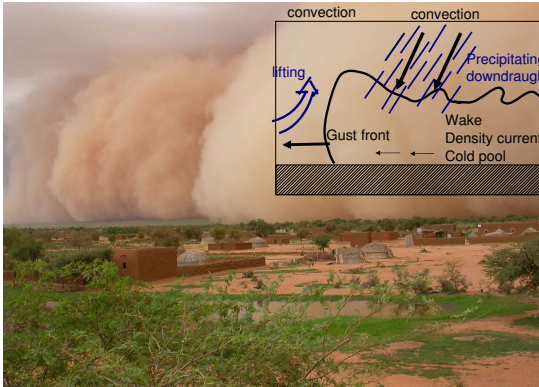


ALP closure

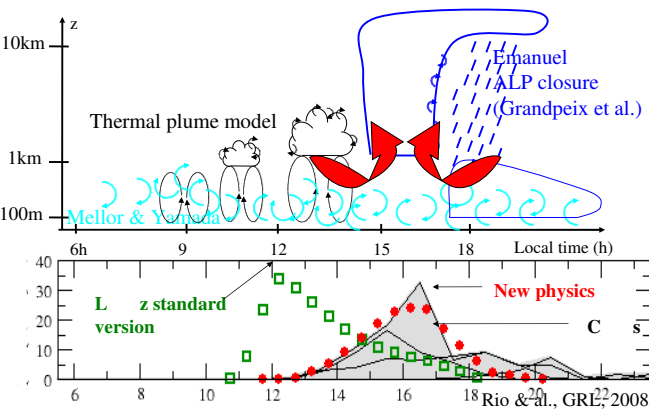
Available Lifting Energy for the convection
Scaling with w^2 .
Trigerring : $ALE > |CIN|$
Available Lifting Power for the convection
Scaling with w^3 .
Closure : $M_B = f (ALP)$

New requirements for the boundary layer scheme :
give reasonable estimates of $\overline{w'^2}$ and $\overline{w'^3}$.

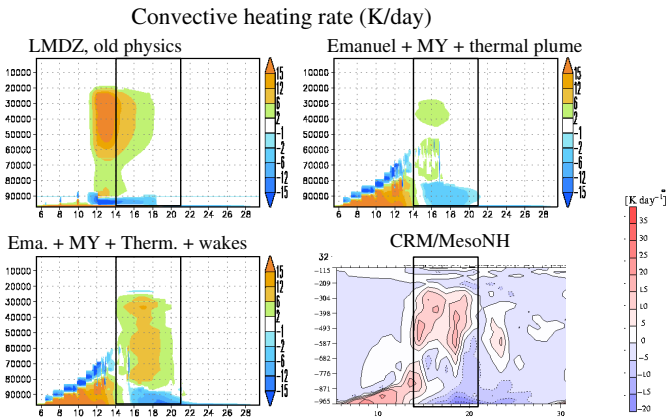
Statistical cloud schemes



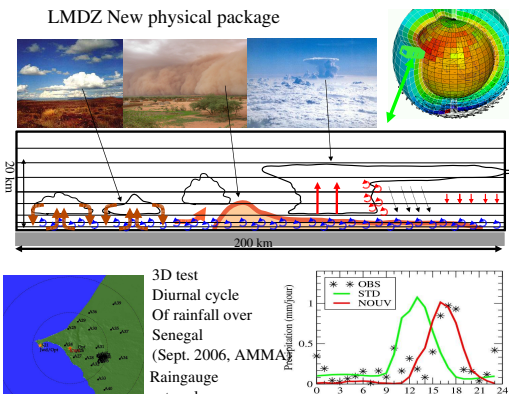
ARM case with ALP closure, thermals and wakes



ARM case with ALP closure, thermals and wakes

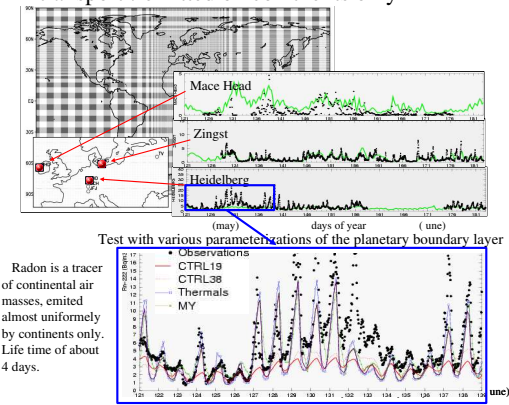


Diurnal cycle of deep convection in the 3D LMDZ GCM



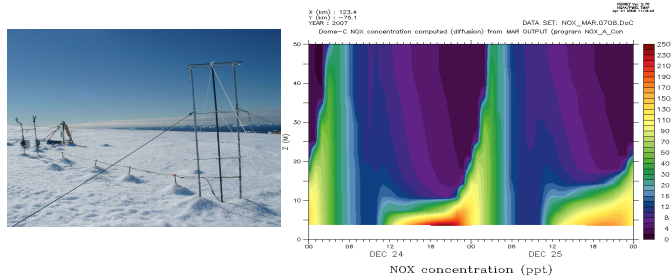
Boundary layer and transport of atmospheric tracers

Test of ²²²Rn transport : emitted on continents only



Boundary layer and transport of atmospheric tracers

NOX computation at Dome C, Antarctica
MAR Regional model



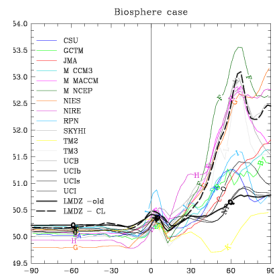
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Boundary layer and transport of atmospheric tracers

Contribution of the biosphere to the CO₂ latitudinal contrasts

Idealized seasonal cycle for surface emission (null annual mean)
GCM and transport models from the Transcom exercise
After Dargaville et al.



Concluding remarks

- Parameterization of boundary layer processes is a key issue for climate modeling and climate change studies.
- Climate models are more and more complex but the realism of the "new components" (chemistry, vegetation, ...) highly depends on the representation of atmospheric processes in general and boundary layer in particular.
- In current climate models (and still for a while), boundary layer processes must be parameterized.
- Boundary layer schemes must be valid from equator to pole, and from dry stable atmosphere to deep convection conditions.
- The "new components" put new constraints on boundary layer schemes.
- There is a large place for improvement of boundary layer parameterization.
- The combined use of a turbulent diffusion for small scales and mass flux schemes for organized structures seems a promising way.
- A hierarchy of approaches are available to improve and evaluate boundary layer parameterizations : 1D versus LES , 3D, nudged, weather forecast and climate, etc.