Boundary layer parameterization and climate

Frédéric Hourdin

June 23, 2009

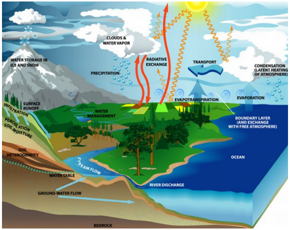
Outline

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

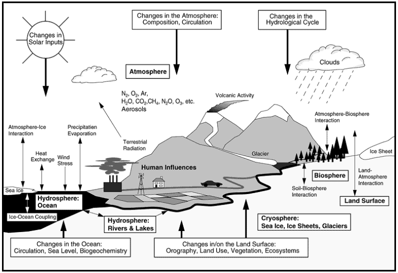
The boundary layer :

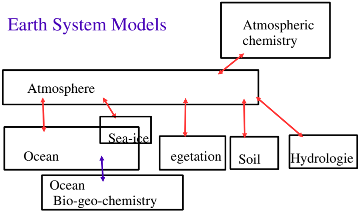
- controls energy and water exchanges with surfaces
- drives the oceanic circulation
- is associated with a large fraction of clouds



Boundary layer in the "Earth System"

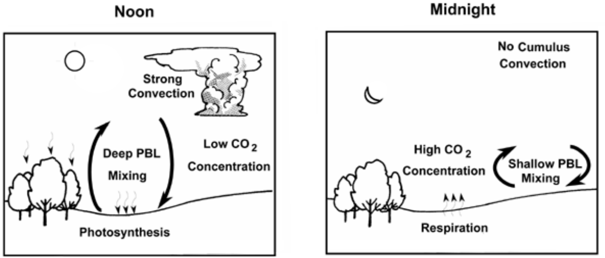
Driven by the Global Change studies, climate models are more and more complex :
CO_2 cycle, CH_4, ozone chemistry, aerosols, effect of land use
$\Longrightarrow$ coupling between atmosphere, ocean, chemistry, vegetation ...
Leading to so-called "Earth System Models".
Boundary layer is central for most of those components.





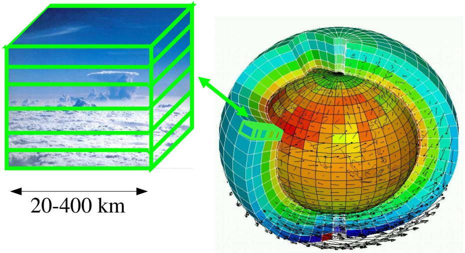
Boundary layer in the "Earth System"

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 large scale models

Current climate models : horizontal mesh of 20 to 400 km.
Boundary layer processes are subgrid-scale $\Longrightarrow$ 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.

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

Scale decomposition of the conservation equation

Conservation equation

$\mathbf{v}$: wind field
c : conserved quantity

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

Advective form : $$\frac{\partial c}{\partial t} + \mathbf{vgrad}c = 0$$

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

Scale decomposition

$\overline{X}$: "average" or "large scale" variable
$X' = X - \overline{X}$: turbulent fluctuation

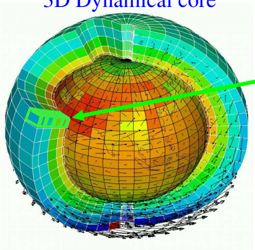
$$\Longrightarrow \overline{\mathbf{v}c} = \overline{\mathbf{v}}\,\overline{c} + \overline{\mathbf{v}'c'}$$

$$\frac{\partial \overline{q}}{\partial t} + \overline{V}.\mathbf{grad}\,\overline{q} + \frac{1}{\rho}\text{div}\left(\overline{\rho \mathbf{v}'c'}\right) = 0$$

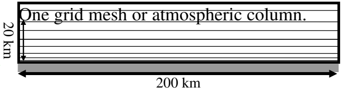
Under boundary layer approximations $(\partial/\partial x << \partial/\partial z)$:

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

3D Dynamical core



Physical parametrizations



v and c are now the large scale variables.

c : θ, u, v, water (vapor and others), chemical compounds ...

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

Diffusive or local formulations for the PBL

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

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

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)

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

- 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

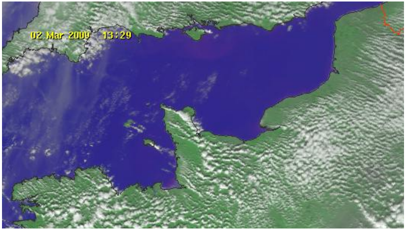
Limitations of turbulent diffusion

Assumption leading to the diffusive approach :

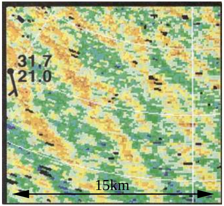
- Turbulence as a random process
- Small scale turbulence, i.e. of size $l << h$ with $h = \left[\frac{1}{c}\frac{\partial c}{\partial z}\right]^{-1}$

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)

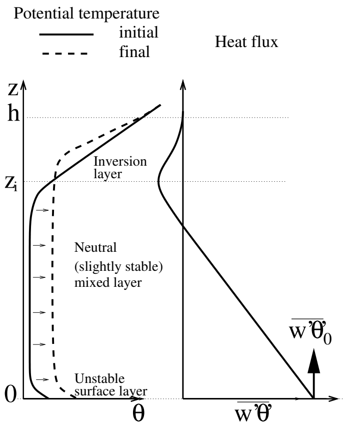


Radar echoes dry convective boundary layer Florida, Hiop Campaign

Weckwerth et al., 1997

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

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

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

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

Extension of diffusive formulations

- **Introduction of a countergradient term**

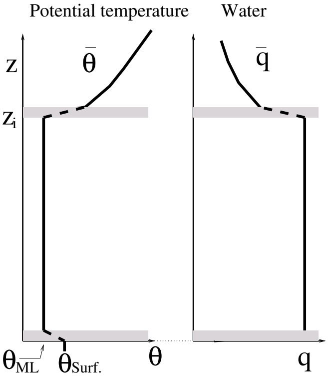
$$\overline{w'\theta'} = K_z \left[\Gamma - \frac{\partial \theta}{\partial z} \right] = 0 \quad \text{with } \Gamma \simeq 1K/km \qquad (2)$$

  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.

"Bulk" models

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



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

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

Betts, Albrecht, Wang, Suarez et al 1983

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

Transilient matrices

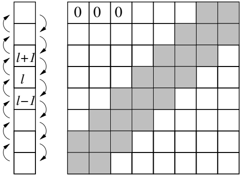
Numerical formalism (after Stull 1984)

C : Air mass exchange rate matrices between model layers

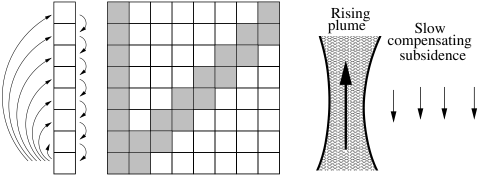
For turbulent diffusions

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

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

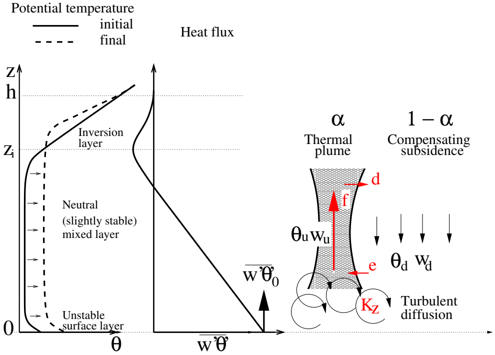


Turbulent diffusion



Assymetric Convective Model of Pleim and Chang 1992

Mass flux schemes combined with turbulent diffusion



Separation into 2 sub-colums :

$$X = \alpha X_u + (1 - \alpha X_d)$$

ascending plume of mass flux

$$f = \alpha \rho w_u$$

$$\frac{\partial f}{\partial z} = e - d$$

$$\frac{\partial f c_u}{\partial z} = e c_d - d c_u$$

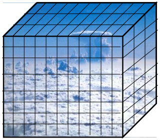
$$\rho \overline{w'c'} = -\rho K_z \frac{\partial c}{\partial z} + f\,(c_u - c_d) \qquad (5)$$

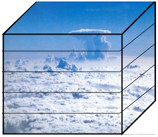
Chatfield and Brost, 1987, Hourdin et. al., 2002, Siebesma, Soarez et al, 2004

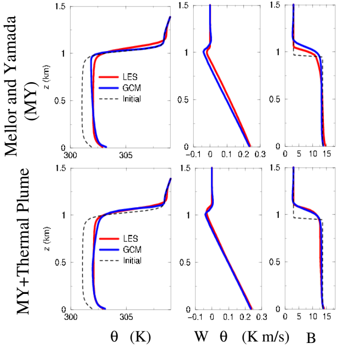
Mass flux schemes combined with turbulent diffusion

Comparison with LES
Dry convective boundary layer.
Forcing : $\overline{w'\theta'}_0 = 0.24$K m/s
geostrophic wind of 10 m/s

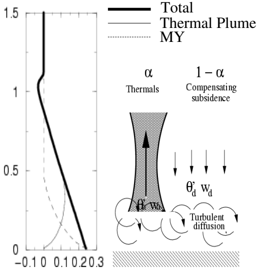
Thermal Plume model (Hourdin et al. 2002).


LES


SCM (1D GCM)



Heat flux decomposition for
The MY+thermiques case



$$MY = -\rho K \frac{\partial c}{\partial z}$$

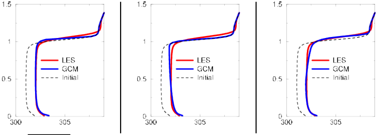
$$TP = f\left(c_u - c_d\right)$$

Mass flux schemes combined with turbulent diffusion

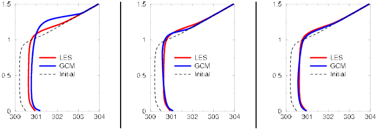
Zonal wind (m/s)

Holtlag & Boville	Mellor & Yamada	M& Y + Thermals

$\overline{w'\theta'}_0$=0.24 K m/s, strongly inversion

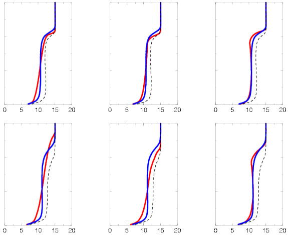


$\overline{w'\theta'}_0$=0.05 K m/s, weak inversion



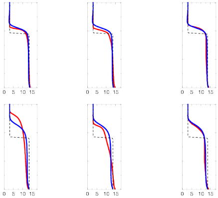
Tracer B

H&B M& Y MY+TH



Tracer B

H&B M& Y MY+TH



Outline

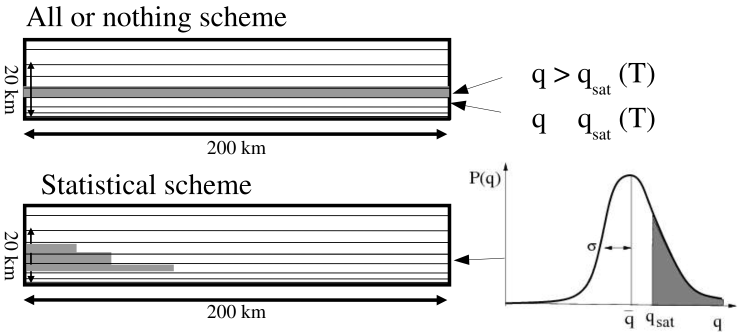
1 Introduction

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

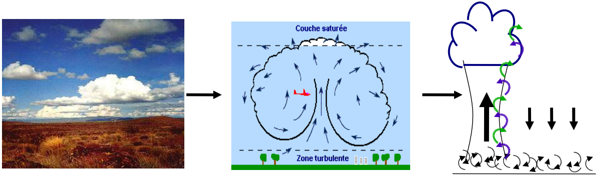
4 Conclusion

Statistical cloud schemes

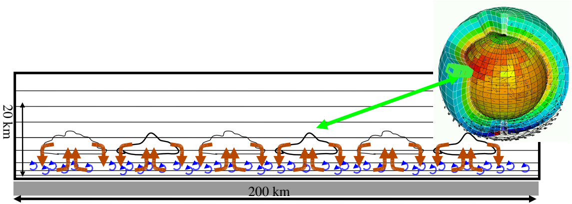


Probability Distribution Function of the subrid-scale water.
Cloud = fraction of the mesh where water vapor exceeds saturation.
$\Longrightarrow$ New requirement for boundary layer scheme :
give information on the subrid-scale distribution

Extension of mass flux schemes to cumulus clouds

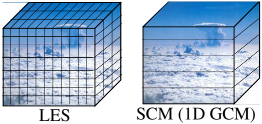


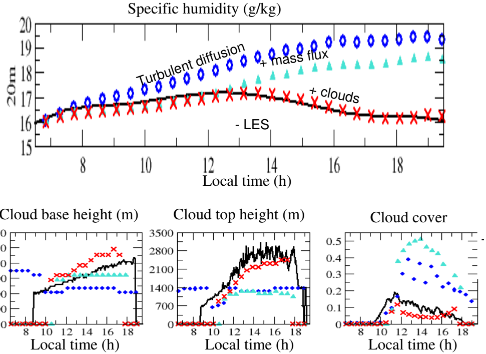
- Computation of condensation in the ascending plume
- Additional heating by condensation within the updraft
  Feedback on the mass flux f and transport
- Computation of the water PDF



1D test of the cloudy thermal plume model

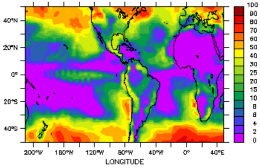
Continental diurnal cycle with cumulus
ARM EUROCS case (US Oklahoma)
Rio et al. 2008



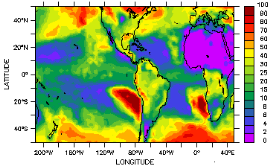


3D test of the cloudy thermal plume model

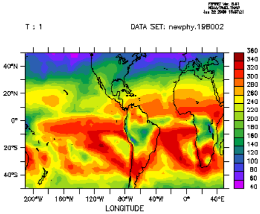
Test of the a new physical package in the LMDZ global climate model
Impact on the coverage by low clouds



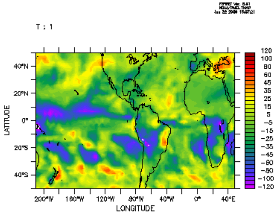
Low level clouds (%), STD phys.



Low level clouds (%), NEW phys.

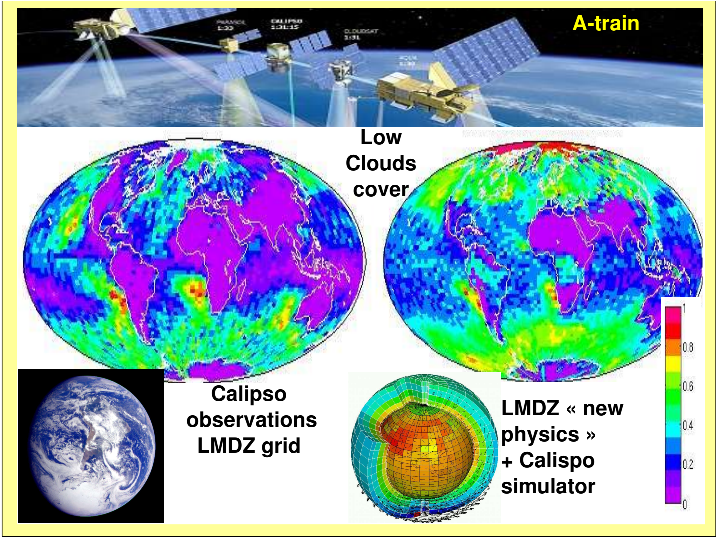


Surf. Down SW radiation (W/m2), STD



Surf. Down SW radiation (W/m2), NEW−STD

Cloud cover and satelite observations



Outline

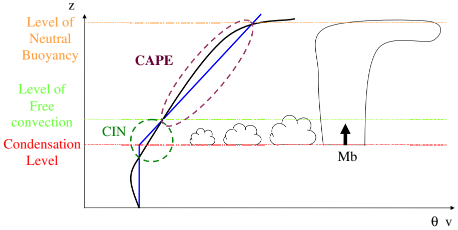
1. Introduction
2. Approaches to the parameterization of the boundary layer
   - Scale decomposition
   - Diffusive approaches and their limitations
   - Alternatives to diffusive approaches
3. Boundary layer parameterizations in climate models
   - Cumulus clouds and mass flux parametrisations
   -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

Parameterization of deep convection

Classical parameterizations :

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

Example of the Emanuel (1991) scheme :



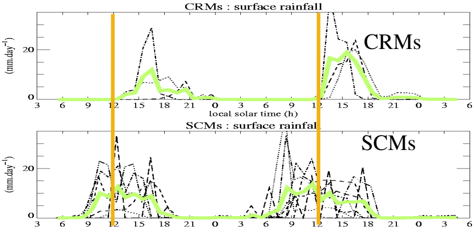
Trigerring :
B (LCL+40hPa) > |CIN|
Closure :
M_B = f(CAPE))

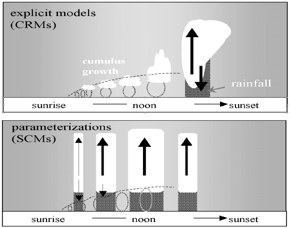
CAPE : Convective Available Potential Energy
CIN : Convective INhibition.

A systematic biais 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

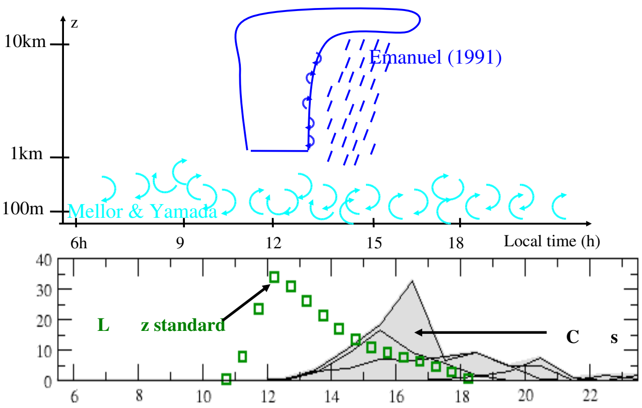




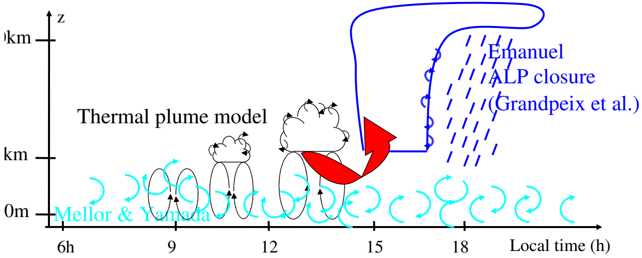
Deep convection preceeded by a phase of shallow cumulus convection

Boundary layer : preconditioning and trigerring of deep convection

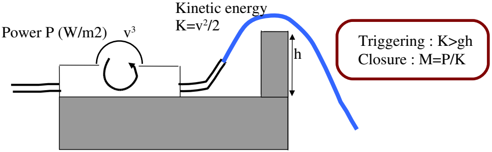
ARM case with the standard LMD SCM



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*.



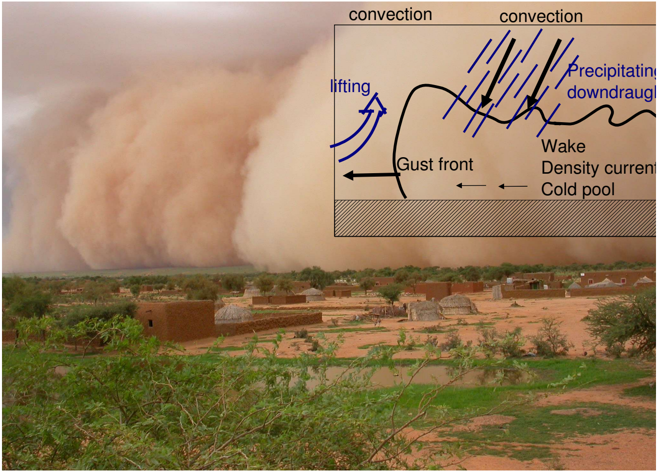
ALP closure

Avaliable Lifting Energy for the convection
Scaling with w^2.
Trigerring : ALE > |CIN|

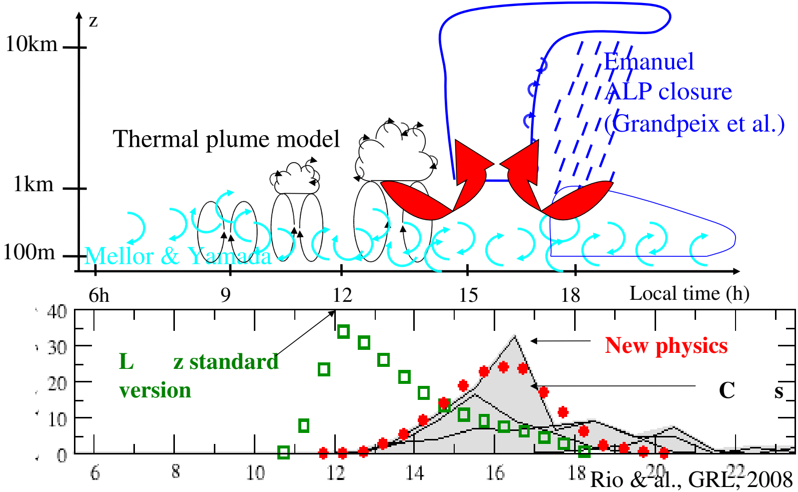
Avaliable Lifting Power for the convection
Scaling with w^3.
Closure : $M_B = f\,(ALP)$

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

Statistical cloud schemes



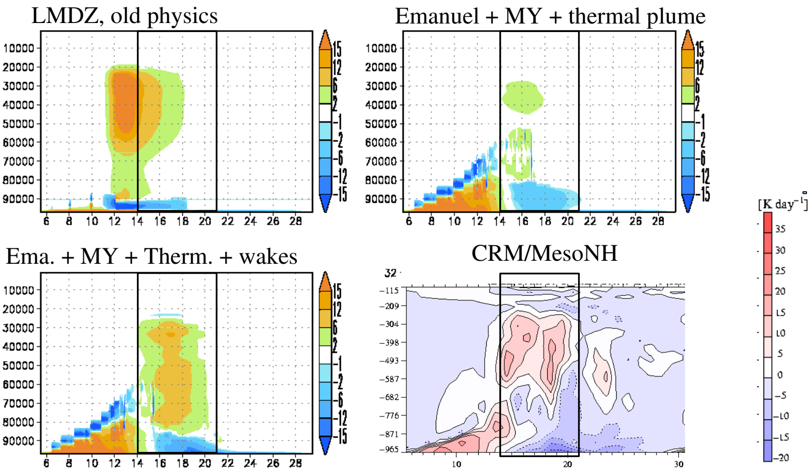
ARM case with ALP closure, thermals and wakes



Rio & al., GRL, 2008

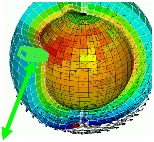
ARM case with ALP closure, thermals and wakes

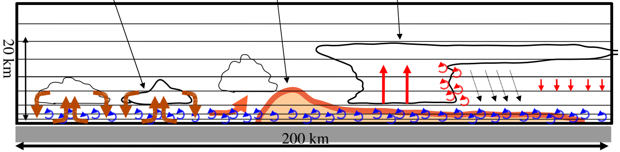
Convective heating rate (K/day)

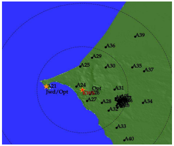


Diurnal cycle of deep convection in the 3D LMDZ GCM

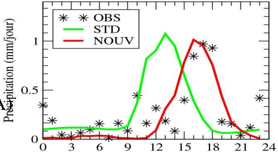
LMDZ New physical package







3D test
Diurnal cycle
Of rainfall over
Senegal
(Sept. 2006, AMMA)
Raingauge

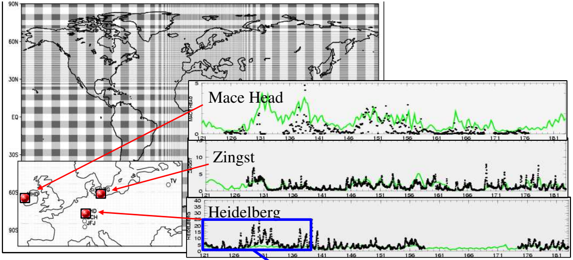


Outline

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 and transport of atmospheric tracers

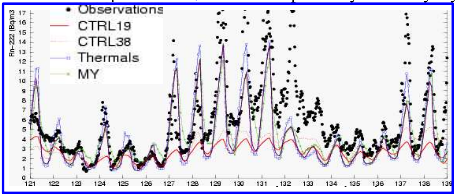
Test of ^{222}Rn transport : emitted on conitnents only



(may) days of year (une)

Test with various parameterizations of the planetary boundary layer

Radon is a tracer of continental air masses, emited almost uniformely by continents only. Life time of about 4 days.

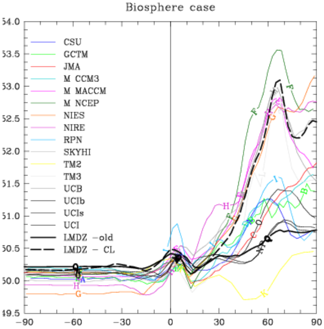


une)

Boundary layer and transport of atmospheric tracers

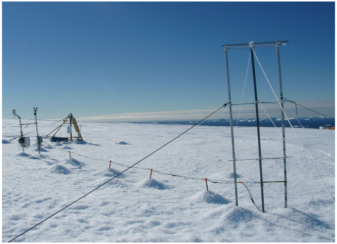
Contribution of the biosphere to the CO_2 latitudinal contrasts

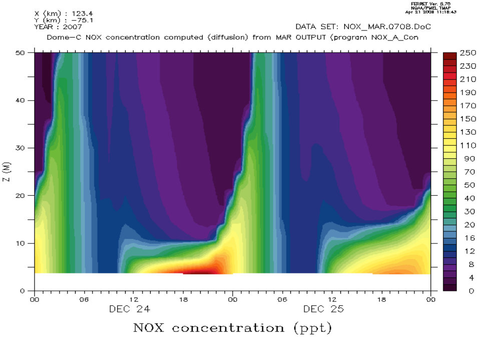
Idealized seasonal cycle for surface emission (null annual mean)
GCM and transport models from the Transcom exercize
After Dargaville et al.



Boundary layer and transport of atmospheric tracers

NOX computation at Dome C, Antartica
MAR Regional model





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 promizing way.
- A hierarchy of approaches are available to improve and evaluate boundary layer parameterizations : 1D versus LES , 3D, nudged, weather forecast and climate, etc.