Feedback and Sensitivity in Climate

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Outline

1. Boundary layer processes in climate
   - Boundary layer as a boundary condition
   - Boundary layer and clouds
   - Boundary layer in the "Earth Systemp"
2. Approaches to the parametrization of the boundary layer
   - Scale decomposition
   - Diffusive approaches and their limitations
   - Alternatives to diffusive approaches
3. Boundary layer, clouds and convection
   - Could schemes in climate models
   - Cumulus clouds and mass flux parametrisations
   - Boundary layer and deep convection

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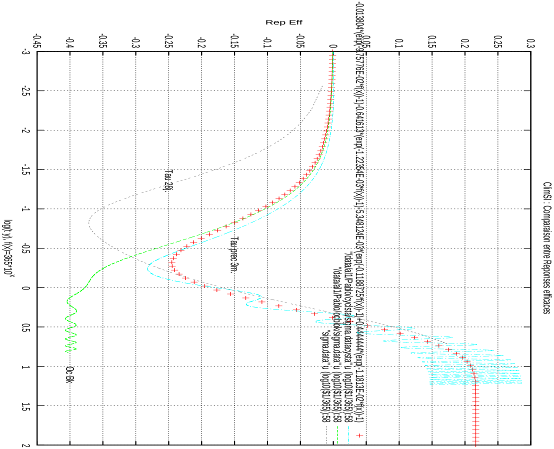

Figure: ClimSI WV feedback model responses.

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Scale decomposition of the conservation equation

Conservation equation

$\mathbf{v}$: wind field

c : conserved quantity $(dc/dt = 0)$,

$$\textbf{Advective form :} \quad \frac{\partial c}{\partial t} + \mathbf{vgrad}c = 0 \qquad (1)$$

$$\textbf{Flux form :} \quad \frac{\partial \rho c}{\partial t} + \mathrm{div}\,(\rho \mathbf{v} c) = 0 \qquad (2)$$

Scale decomposition

$\overline{X}$: "average" or "large scale" variable

$X' = X - \overline{X}$: turbulent fluctuation

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

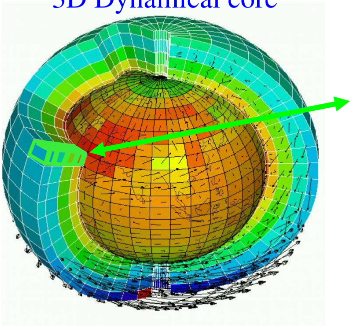
$$\frac{\partial \overline{q}}{\partial t} + \overline{V}.\mathbf{grad}\;\overline{q} + \frac{1}{\rho}\mathrm{div}\left(\overline{\rho \mathbf{v}'c'}\right) = 0 \qquad (3)$$

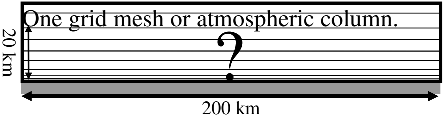
Under boundary layer approximations $(\partial/\partial x << \partial/\partial z)$:

$$\frac{\partial c}{\partial t} + \mathbf{v.grad}\ c = S_c + \frac{1}{\rho}\frac{\partial}{\partial z}\overline{w'c'} \qquad (4)$$

3D Dynamical core

Physical parametrizations





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

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Diffusive or local formulations for the PBL

$$\overline{w'c'} = -K_z \frac{\partial c}{\partial z} \qquad \longrightarrow \qquad \frac{\partial c}{\partial t} = \frac{\partial}{\partial z}\left(K_z \frac{\partial c}{\partial z}\right) \tag{5}$$

- Analogy with molecular viscosity.
- 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)

$$K_z = f(Ri) l^2 \left| \frac{\partial \mathbf{v}}{\partial z} \right|, \qquad \text{with } Ri = \frac{g}{\theta} \frac{\frac{\partial \theta}{\partial z}}{\left(\frac{\partial \mathbf{v}}{\partial z}\right)^2} \quad (6)$$

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

$$\frac{\partial e}{\partial t} = -\overline{w'u'}\frac{\partial u}{\partial z} - \overline{w'v'}\frac{\partial v}{\partial z} - -\frac{g}{\theta}\overline{w'\theta'} - \frac{1}{\rho}\frac{\partial \overline{w'p'}}{\partial z} - \frac{\partial \overline{w'e}}{\partial z} - \epsilon \quad (7)$$

Ex : Mellor and Yamada $\overline{w'\phi'} = -K_\phi \frac{\partial \phi}{\partial z}$ with $K_\phi = l\sqrt{2e} S_\phi(Ri)$
Note : Imposing $\frac{\partial e}{\partial t}$ gives a coefficient of the form Eq. 6

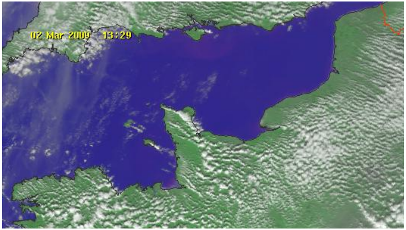
Limitations of turbulent diffusion

Diffusive approach :

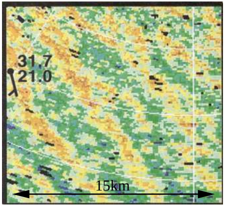
- Random process
- Small scale turbulence of size $l << h$ with $h = \left[\frac{1}{c}\frac{\partial c}{\partial z}\right]^{-1}$

Real turbulence

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



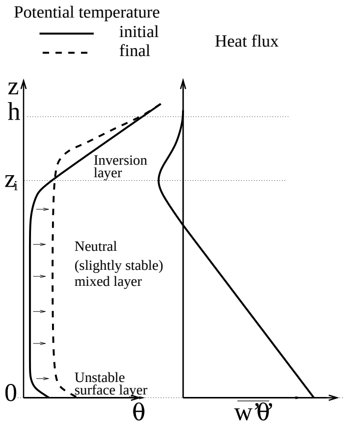
Cloud streets on North of France (March 2009, MSG)



Radar echoes in a dry convective boundary layer

Limitations of turbulent diffusion

Idealized view of the dry convective boundary layer.



In the mixed layer

- Diffusive formulation

$$\overline{w'\theta'} = -K_z \frac{\partial \theta}{\partial z} = 0 \quad \text{or slightly} < 0 \tag{8}$$

- Uniform heating by the surface

$$\frac{\partial \theta}{\partial t} \simeq \frac{\overline{w'\theta'}_0}{z_i} (\text{Cste} > 0) \tag{9}$$

$$\overline{w'\theta'} \simeq \frac{z - z_i}{z_i} \overline{w'\theta'}_0 > 0 \tag{10}$$

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Extension of diffusive formulations

- **Introduction of a countergradient term**

$$\overline{w'\theta'} = -K_z \left[\Gamma - \frac{\partial\theta}{\partial z}\right] = 0 \quad \text{with } \Gamma \simeq -1K/km \qquad (11)$$

  Imposed countergradient Deardorf, 1966
  Revisited by Troen & Mart, 1986, Holtzlag & Boville, 1993, based on a similarity approach.

- **Higher order closures**
  Abdella & Mc Farlane, 1997, Randall et al., 1992, Lapen & Ransall, 2002

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