Turbulência Atmosférica e Parametrização da Camada Limite Planetária

Paulo Yoshio Kubota

Previsão Numérica de Tempo e Clima

lei do gas $\bar{p} = \bar{\rho} R_d \overline{T_v}$ $\overline{T_v} = T(1+0.61q_v - q_l)$

Temperatura virtual

Necessita ser parametrizado !

2nd ordem

Média de Reynolds

$$A = \overline{A} + A'$$

momentum

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\delta_{i3} g + f_c \varepsilon_{ij3} \overline{u_j} - \frac{1}{\overline{\rho}}\frac{\partial \overline{P}}{\partial x_i} + \frac{\upsilon \partial^2 \overline{u_i}}{\partial x_j{}^2} - \frac{\partial(\overline{u_i' u_j'})}{\partial x_j}$$

Advecção media | gravidade | Coriolis | Gradiente de Pressão | Estresse Viscoso | Transporte Turbulento

Eq. Continuidade $\frac{\partial \overline{u_i}}{\partial x_j} = 0$

Calor

$$\frac{\partial \overline{\theta}}{\partial t} + \overline{u_j}\frac{\partial \overline{\theta}}{\partial x_j} = -\frac{1}{\overline{\rho} c_p}\frac{\partial \overline{F_j}}{\partial x_j} - \frac{\partial \overline{u_j' \theta'}}{\partial x_j} - \frac{L_v E}{\overline{\rho} c_p}$$

Advecção media | radiação | Transporte Turbulento | Liberação de Calor Latente

Agua Total

$$\frac{\partial \overline{q_t}}{\partial t} + \overline{u_j}\frac{\partial \overline{q_t}}{\partial x_j} = \frac{S_{q_t}}{\overline{\rho}} - \frac{\partial \overline{u_j' q_t'}}{\partial x_j}$$

Advecção media | precipitação | Transporte Turbulento

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- Região da atmosfera que é fortemente influenciada pela presença da superfície terrestre e responde em escala temporal da ordem de horas ou menos
- Importante
  - Processos na superfície são complexos
  - A camada limite é muito turbulenta

- Na camada limite o transporte horizontal é dominado pelo vento médio e na vertical pela turbulência

$$\frac{\partial(\overline{u_i})}{\partial t} + (\overline{u_j})\frac{\partial(\overline{u_i})}{\partial x_j} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_i} + g\frac{\overline{\rho}}{\rho_0}\delta_{i3} + 2\Omega\varepsilon_{ijk}\eta_j(\overline{u_k}) - \nu\frac{\partial^2(\overline{u_i})}{\partial {x_j}^2} = -\frac{\partial\left(\overline{u_j' u_i'}\right)}{\partial x_j}$$

$$\frac{\partial(\overline{T})}{\partial t} + (\overline{u_j})\frac{\partial(\overline{T})}{\partial x_j} - S_P\overline{\omega} = -\frac{\partial\left(\overline{u_j' T'}\right)}{\partial x_j} + \frac{\overline{J}}{C_p}$$

$$\frac{\partial(\overline{q})}{\partial t} + (\overline{u_j})\frac{\partial(\overline{q})}{\partial x_j} = -\frac{\partial\left(\overline{u_j' q'}\right)}{\partial x_j} + \overline{S}$$

- As variáveis (vento, temperatura umidade) e são separadas na média e perturbação (turbulência)

Comparações

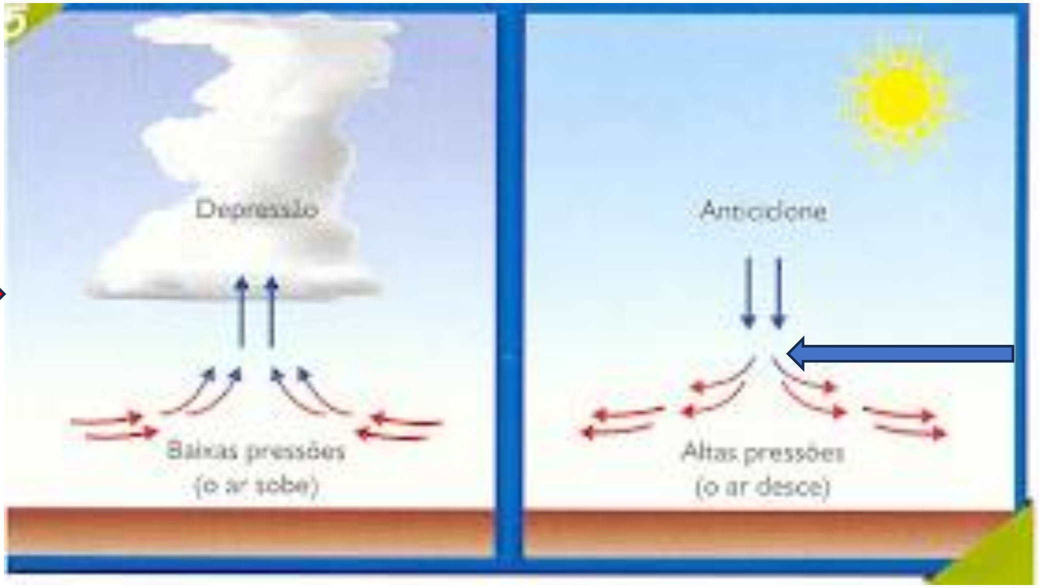
Camada limite

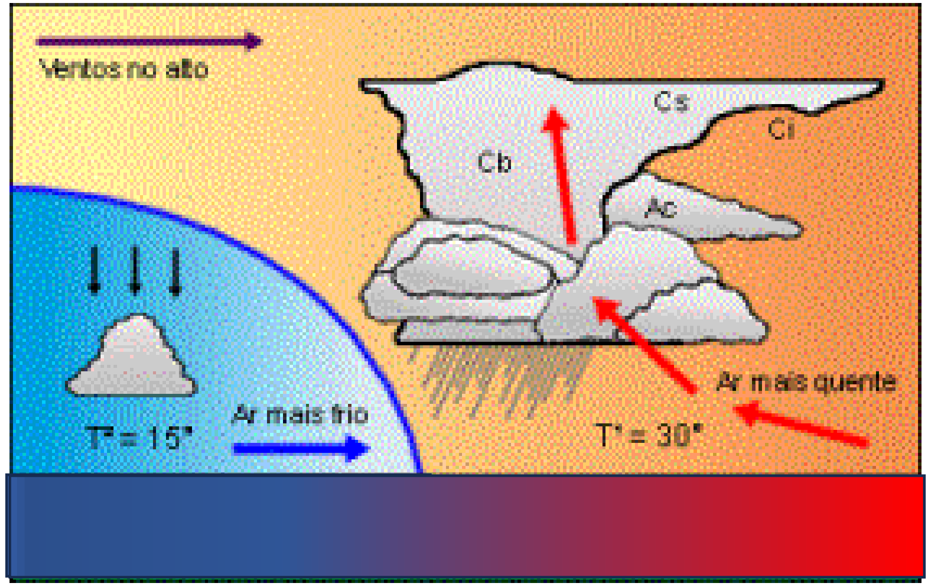
- Turbulência continua
- Forte arrastro, grande dissipação de energia
- Mistura turbulenta rápida
- Sub geostrófico
- Transporte vertical dominado pela turbulência
- Profundidade varia entre 100m e 3 km, variações diurnas

Atmosfera livre

- Em nuvens convectivas
- Pequena dissipação viscosa
- Pequena
- Ventos quase geostróficos
- Vento médio domina (cumulus)
- Menos variável 8-18 km
- variações temporais lentas

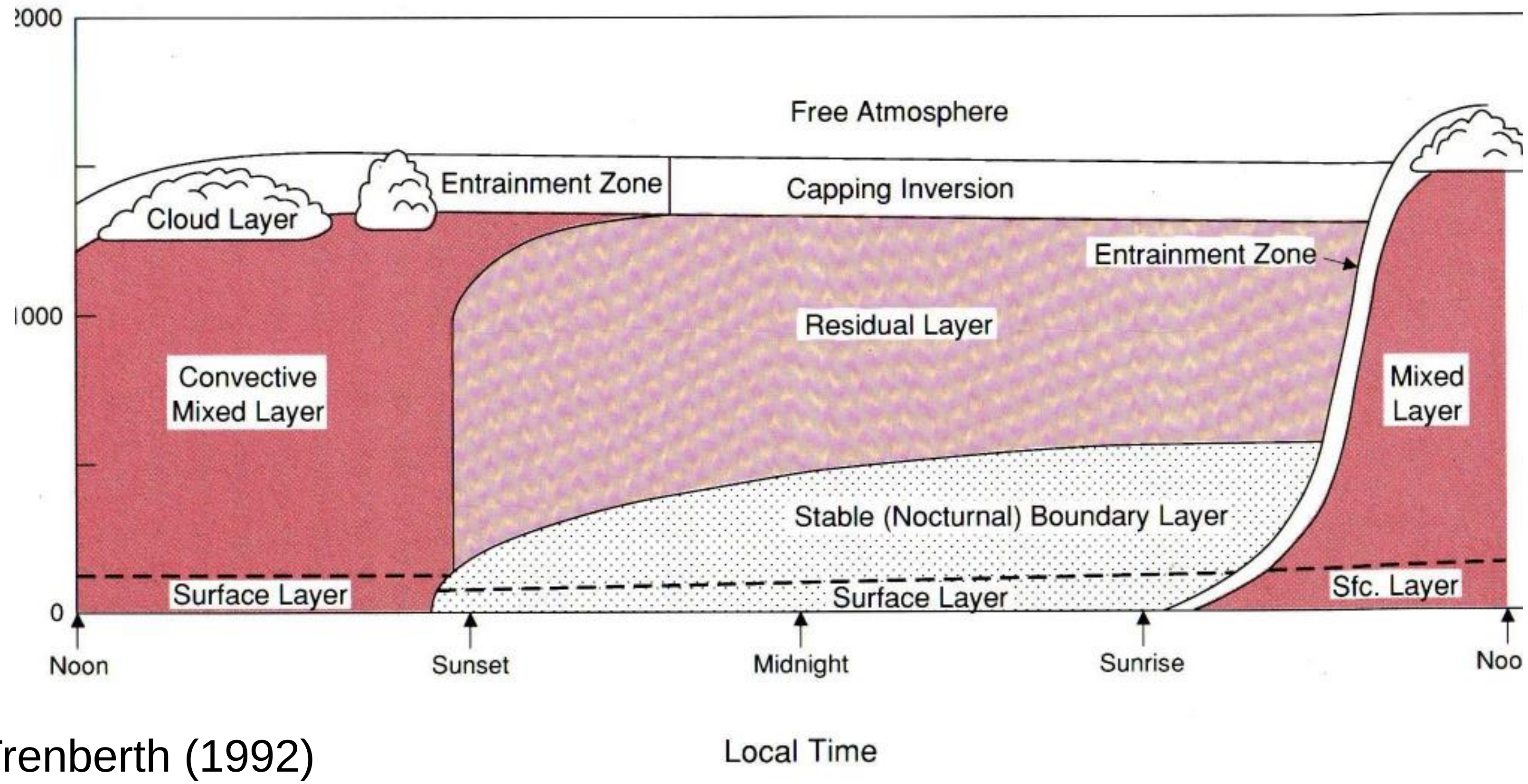
- A camada limite é usualmente rasa em regiões de altas pressões devido ao movimento descendente e a divergência horizontal decresce sua altura
- Em regiões de baixa pressão a altura da camada limite é mais profunda





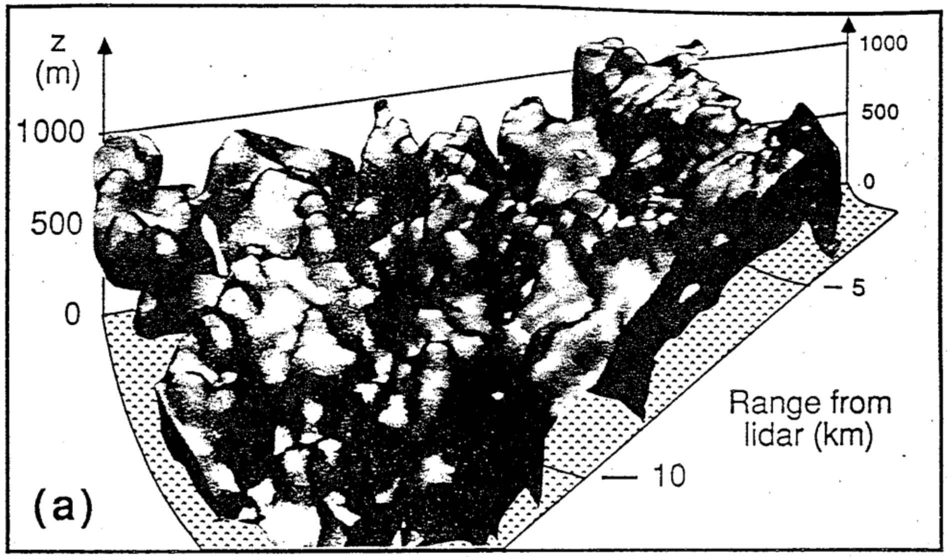
•O aquecimento superficial e o aprofundamento da camada limite é importante para a previsão

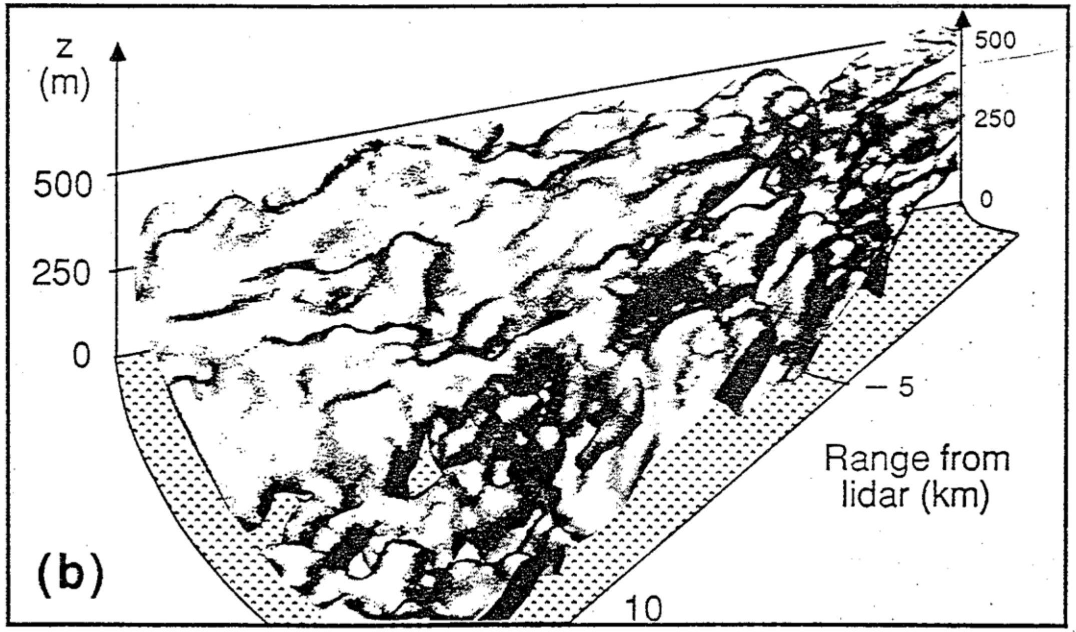
Camada Limite



Trenberth (1992)

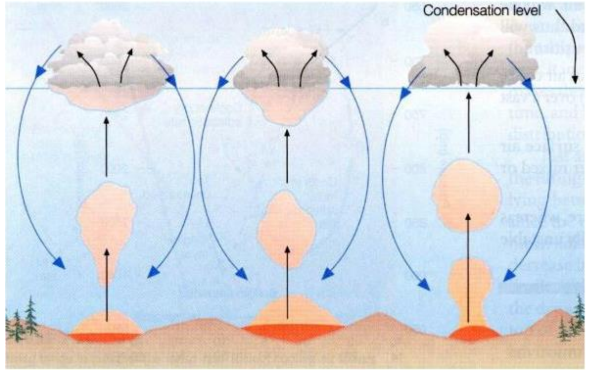
Exemplos

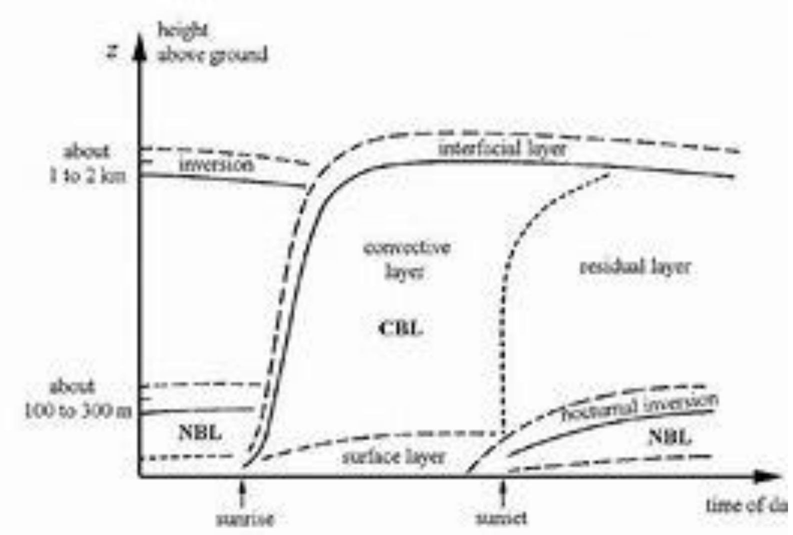

z
(m)
1000
500
0
1000
500
0
5
10
Range from
lidar (km)
(a)


z
(m)
500
250
0
500
250
0
5
10
Range from
lidar (km)
(b)

Camada limite

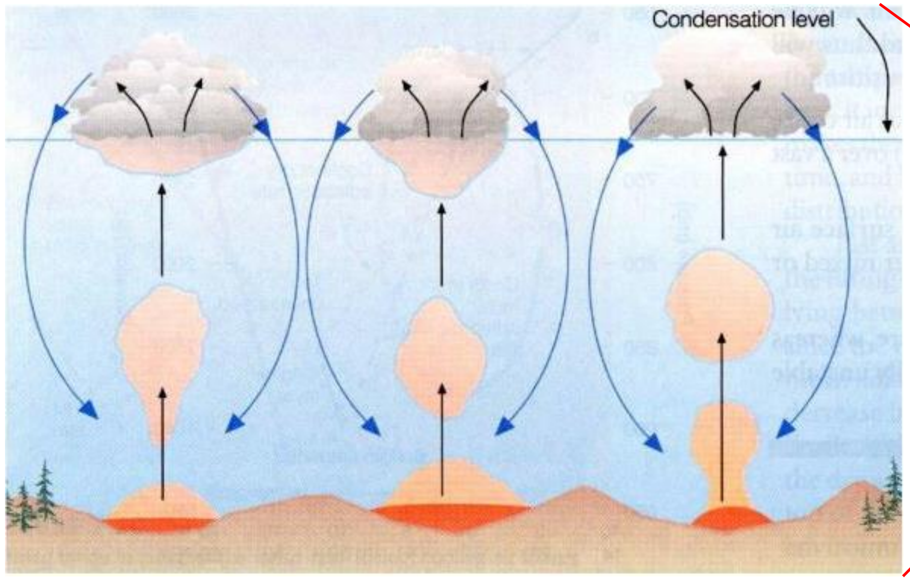
- Evolução das equações dependem da divergência de fluxos convectivos (calor, vapor, momentum) dirigido por movimentos não resolvidos na vertical

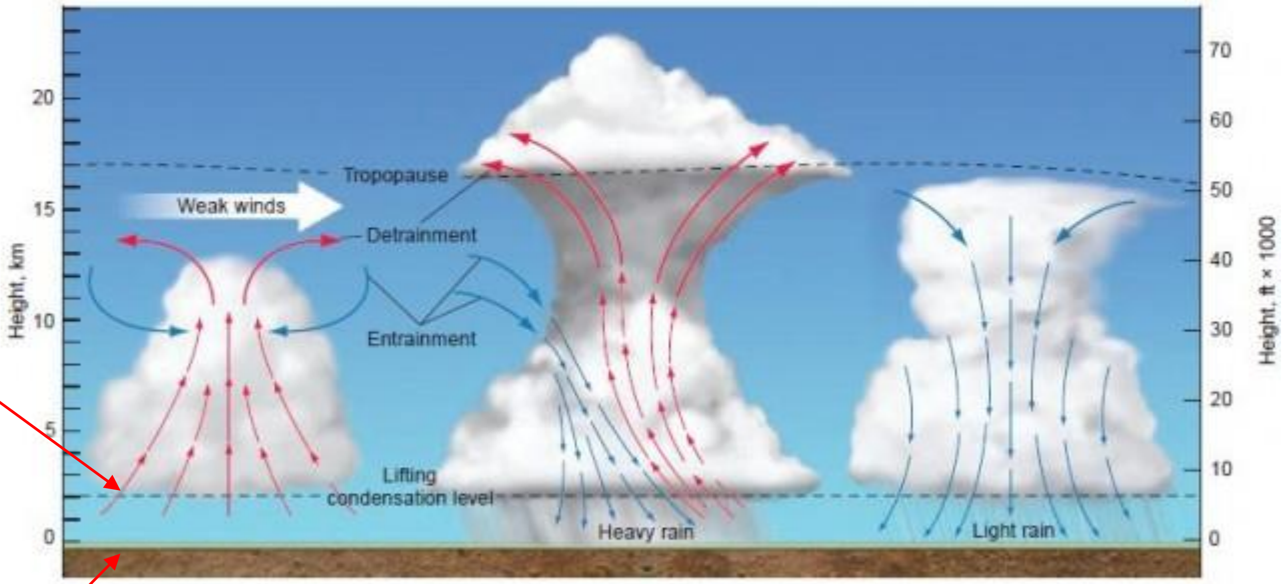




- Os processos na camada limite são parametrizados nos modelos por sua grosseira resolução vertical

- Convecção cumulus causa grandes fluxos verticais de calor e vapor na escala sub-grade (parametrizado)→ física do modelo





▲ **Cumulus stage** Vertical motions are limited by mixing with cool, dry environmental air aloft. But the mixing adds water droplets that evaporate and cool the surrounding air, creating instability.

▲ **Mature stage** In this stage, there are well-organized updrafts and downdrafts. Updrafts, which can reach as high as the tropopause, spread out to form an anvil cloud. Downdrafts are created by falling precipitation and entrainment of cooler, drier environmental air.

▲ **Dissipating stage** Dissipation occurs when cool, dry environmental air mixes into the cloud, inhibiting convection and latent heat release.

4.28 Stages in the development of an air-mass thunderstorm

The three development stages of an air-mass thunderstorm are the cumulus, mature, and dissipating stages. Each stage has characteristic vertical winds and precipitation.

$$\frac{\partial(\overline{u_i})}{\partial t} + (\overline{u_j})\frac{\partial(\overline{u_i})}{\partial x_j} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_i} + g\frac{\overline{\rho}}{\rho_0}\delta_{i3} + 2\Omega\varepsilon_{ijk}\eta_j(\overline{u_k}) - \nu\frac{\partial^2(\overline{u_i})}{\partial {x_j}^2} = -\frac{\partial\left(\overline{u_j'u_i'}\right)}{\partial x_j}$$

$$\frac{\partial(\overline{T})}{\partial t} + (\overline{u_j})\frac{\partial(\overline{T})}{\partial x_j} - S_P\overline{\omega} = -\frac{\partial\left(\overline{u_j'T'}\right)}{\partial x_j} + \frac{\overline{J}}{C_p}$$

$$\frac{\partial(\overline{q})}{\partial t} + (\overline{u_j})\frac{\partial(\overline{q})}{\partial x_j} = -\frac{\partial\left(\overline{u_j'q'}\right)}{\partial x_j} + \overline{S}$$

i = 1 e j = 1,2,3 k = 1,2,3

$$\varepsilon_{ijk} = \begin{cases} 1 & (ijk) = (123),(231),(312) \\ -1 & (ijk) = (132),(213),(321) \\ 0 & \text{else} \end{cases}$$

$$\frac{\partial(\overline{u_i})}{\partial t} + (\overline{u_j})\frac{\partial(\overline{u_i})}{\partial x_j} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_i} + g\frac{\overline{\rho}}{\rho_0}\delta_{i3} + 2\Omega\varepsilon_{ijk}\eta_j(\overline{u_k}) - \nu\frac{\partial^2(\overline{u_i})}{\partial {x_j}^2} = -\frac{\partial(\overline{u_j'u_i'})}{\partial x_j}$$

$$\frac{\partial(\overline{u_1})}{\partial t} + (\overline{u_1})\frac{\partial(\overline{u_1})}{\partial x_1} + (\overline{u_2})\frac{\partial(\overline{u_1})}{\partial x_2} + (\overline{u_3})\frac{\partial(\overline{u_1})}{\partial x_3} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_1} + g\frac{\overline{\rho}}{\rho_0}\delta_{13} + 2\Omega\varepsilon_{111}\eta_1(\overline{u_1}) + 2\Omega\varepsilon_{121}\eta_2(\overline{u_1}) + 2\Omega\varepsilon_{131}\eta_3(\overline{u_1})$$
$$+ 2\Omega\varepsilon_{112}\eta_1(\overline{u_2}) + 2\Omega\varepsilon_{122}\eta_2(\overline{u_2}) + 2\Omega\varepsilon_{132}\eta_3(\overline{u_2}) + 2\Omega\varepsilon_{113}\eta_1(\overline{u_3}) + 2\Omega\varepsilon_{123}\eta_2(\overline{u_3}) + 2\Omega\varepsilon_{133}\eta_3(\overline{u_3}) - \nu\frac{\partial^2(\overline{u_2})}{\partial {x_1}^2} - \nu\frac{\partial^2(\overline{u_2})}{\partial {x_2}^2}$$
$$- \nu\frac{\partial^2(\overline{u_2})}{\partial {x_3}^2} = -\frac{\partial(\overline{u_1'u_3'})}{\partial x_1} - \frac{\partial(\overline{u_2'u_3'})}{\partial x_2} - \frac{\partial(\overline{u_3'u_3'})}{\partial x_3}$$

$+2\Omega\varepsilon_{33k}\eta_3(\overline{u_k}) = 0$ $2\Omega\varepsilon_{313}\eta_1(\overline{u_3}) = 0$ $2\Omega\varepsilon_{33k}\eta_3(\overline{u_k}) = 0$

$$\frac{\partial(\overline{u_1})}{\partial t} + (\overline{u_1})\frac{\partial(\overline{u_1})}{\partial x_1} + (\overline{u_2})\frac{\partial(\overline{u_1})}{\partial x_2} + (\overline{u_3})\frac{\partial(\overline{u_1})}{\partial x_3} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_1} - 2\Omega\eta_3(\overline{u_2}) - \nu\frac{\partial^2(\overline{u_1})}{\partial {x_1}^2} - \nu\frac{\partial^2(\overline{u_1})}{\partial {x_2}^2} - \nu\frac{\partial^2(\overline{u_1})}{\partial {x_3}^2} = -\frac{\partial(\overline{u_1'u_1'})}{\partial x_1} - \frac{\partial(\overline{u_2'u_1'})}{\partial x_2} - \frac{\partial(\overline{u_3'u_1'})}{\partial x_3}$$

i = 3 e j = 1,2,3 k = 1,2,3

Equação governante para o escoamento zonal

$$\frac{\partial(\overline{u})}{\partial t}+(\overline{u})\frac{\partial(\overline{u})}{\partial x}+(\overline{v})\frac{\partial(\overline{u})}{\partial y}+(\overline{w})\frac{\partial(\overline{u})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x}-2\Omega\eta_3(\overline{v})-\nu\frac{\partial^2(\overline{u})}{\partial x^2}-\nu\frac{\partial^2(\overline{u})}{\partial y^2}-\nu\frac{\partial^2(\overline{u})}{\partial z^2}=-\frac{\partial(\overline{u'u'})}{\partial x}-\frac{\partial(\overline{v'u'})}{\partial y}-\frac{\partial(\overline{w'u'})}{\partial z}$$

i = 2 e j = 1,2,3 k = 1,2,3

$$\varepsilon_{ijk} = \begin{cases} 1 & (ijk) = (123),(231),(312) \\ -1 & (ijk) = (132),(213),(321) \\ 0 & \text{else} \end{cases}$$

$$\frac{\partial(\overline{u_i})}{\partial t} + (\overline{u_j})\frac{\partial(\overline{u_i})}{\partial x_j} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_i} + g\frac{\overline{\rho}}{\rho_0}\delta_{i3} + 2\Omega\varepsilon_{ijk}\eta_j(\overline{u_k}) - \nu\frac{\partial^2(\overline{u_i})}{\partial {x_j}^2} = -\frac{\partial(\overline{u_j{}'u_i{}'})}{\partial x_j}$$

$$\frac{\partial(\overline{u_2})}{\partial t} + (\overline{u_1})\frac{\partial(\overline{u_2})}{\partial x_1} + (\overline{u_2})\frac{\partial(\overline{u_2})}{\partial x_2} + (\overline{u_3})\frac{\partial(\overline{u_2})}{\partial x_3} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_2} + g\frac{\overline{\rho}}{\rho_0}\delta_{23} + 2\Omega\varepsilon_{211}\eta_1(\overline{u_1}) + 2\Omega\varepsilon_{221}\eta_2(\overline{u_1}) + 2\Omega\varepsilon_{231}\eta_3(\overline{u_1})$$
$$+ 2\Omega\varepsilon_{212}\eta_1(\overline{u_2}) + 2\Omega\varepsilon_{222}\eta_2(\overline{u_2}) + 2\Omega\varepsilon_{232}\eta_3(\overline{u_2}) + 2\Omega\varepsilon_{213}\eta_1(\overline{u_3}) + 2\Omega\varepsilon_{223}\eta_2(\overline{u_3}) + 2\Omega\varepsilon_{233}\eta_3(\overline{u_3}) - \nu\frac{\partial^2(\overline{u_2})}{\partial {x_1}^2} - \nu\frac{\partial^2(\overline{u_2})}{\partial {x_2}^2}$$
$$- \nu\frac{\partial^2(\overline{u_2})}{\partial {x_3}^2} = -\frac{\partial(\overline{u_1{}'u_2{}'})}{\partial x_1} - \frac{\partial(\overline{u_2{}'u_2{}'})}{\partial x_2} - \frac{\partial(\overline{u_3{}'u_2{}'})}{\partial x_3}$$

$$+2\Omega\varepsilon_{33k}\eta_3(\overline{u_k}) = 0 \qquad 2\Omega\varepsilon_{313}\eta_1(\overline{u_3}) = 0 \qquad 2\Omega\varepsilon_{33k}\eta_3(\overline{u_k}) = 0$$

$$\frac{\partial(\overline{u_2})}{\partial t} + (\overline{u_1})\frac{\partial(\overline{u_2})}{\partial x_1} + (\overline{u_2})\frac{\partial(\overline{u_2})}{\partial x_2} + (\overline{u_3})\frac{\partial(\overline{u_2})}{\partial x_3} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_2} + 2\Omega\eta_3(\overline{u_1}) - \nu\frac{\partial^2(\overline{u_2})}{\partial {x_1}^2} - \nu\frac{\partial^2(\overline{u_2})}{\partial {x_2}^2} - \nu\frac{\partial^2(\overline{u_2})}{\partial {x_3}^2} = -\frac{\partial(\overline{u_1{}'u_2{}'})}{\partial x_1} - \frac{\partial(\overline{u_2{}'u_2{}'})}{\partial x_2} - \frac{\partial(\overline{u_3{}'u_2{}'})}{\partial x_3}$$

$\mathrm{i} = 3 \quad \mathrm{e} \quad \mathrm{j} = 1{,}2{,}3 \quad \mathrm{k} = 1{,}2{,}3$

Equação governante para o escoamento Meridional

$$\frac{\partial(\bar{v})}{\partial t} + (\bar{u})\frac{\partial(\bar{v})}{\partial x} + (\bar{v})\frac{\partial(\bar{v})}{\partial y} + (\bar{w})\frac{\partial(\bar{v})}{\partial z} + \frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial y} + 2\Omega\eta_3(\bar{u}) - \nu\frac{\partial^2(\bar{v})}{\partial x^2} - \nu\frac{\partial^2(\bar{v})}{\partial y^2} - \nu\frac{\partial^2(v)}{\partial z^2} = -\frac{\partial(\overline{u'v'})}{\partial x} - \frac{\partial(\overline{v'v'})}{\partial y} - \frac{\partial(\overline{w'v'})}{\partial z}$$

$$\frac{\partial(\bar{u})}{\partial t}+(\bar{u})\frac{\partial(\bar{u})}{\partial x}+(\bar{v})\frac{\partial(\bar{u})}{\partial y}+(\bar{w})\frac{\partial(\bar{u})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial x}-2\Omega\eta_3(\bar{v})-\nu\frac{\partial^2(\bar{u})}{\partial x^2}-\nu\frac{\partial^2(\bar{u})}{\partial y^2}-\nu\frac{\partial^2(\bar{u})}{\partial z^2}=-\frac{\partial(\overline{u'u'})}{\partial x}-\frac{\partial(\overline{v'u'})}{\partial y}-\frac{\partial(\overline{w'u'})}{\partial z}$$

$$\frac{\partial(\bar{v})}{\partial t}+(\bar{u})\frac{\partial(\bar{v})}{\partial x}+(\bar{v})\frac{\partial(\bar{v})}{\partial y}+(\bar{w})\frac{\partial(\bar{v})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial y}+2\Omega\eta_3(\bar{u})-\nu\frac{\partial^2(\bar{v})}{\partial x^2}-\nu\frac{\partial^2(\bar{v})}{\partial y^2}-\nu\frac{\partial^2(v)}{\partial z^2}=-\frac{\partial(\overline{u'v'})}{\partial x}-\frac{\partial(\overline{v'v'})}{\partial y}-\frac{\partial(\overline{w'v'})}{\partial z}$$

i = 3 e j = 1,2,3 k = 1,2,3

$$\varepsilon_{ijk} = \begin{cases} 1 & (ijk) = (123),(231),(312) \\ -1 & (ijk) = (132),(213),(321) \\ 0 & \text{else} \end{cases}$$

$$\frac{\partial(\overline{u_i})}{\partial t} + (\overline{u_j})\frac{\partial(\overline{u_i})}{\partial x_j} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_i} + g\frac{\overline{\rho}}{\rho_0}\delta_{i3} + 2\Omega\varepsilon_{ijk}\eta_j(\overline{u_k}) - \nu\frac{\partial^2(\overline{u_i})}{\partial {x_j}^2} = -\frac{\partial(\overline{u_j' u_i'})}{\partial x_j}$$

$$\frac{\partial(\overline{u_3})}{\partial t} + (\overline{u_1})\frac{\partial(\overline{u_3})}{\partial x_1} + (\overline{u_2})\frac{\partial(\overline{u_3})}{\partial x_2} + (\overline{u_3})\frac{\partial(\overline{u_3})}{\partial x_3} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_3} + g\frac{\overline{\rho}}{\rho_0}\delta_{33} + 2\Omega\varepsilon_{311}\eta_1(\overline{u_1}) + 2\Omega\varepsilon_{322}\eta_2(\overline{u_2}) + 2\Omega\varepsilon_{333}\eta_3(\overline{u_3})$$
$$+ 2\Omega\varepsilon_{311}\eta_1(\overline{u_1}) + 2\Omega\varepsilon_{322}\eta_2(\overline{u_2}) + 2\Omega\varepsilon_{333}\eta_3(\overline{u_3}) + 2\Omega\varepsilon_{311}\eta_1(\overline{u_1}) + 2\Omega\varepsilon_{322}\eta_2(\overline{u_2}) + 2\Omega\varepsilon_{333}\eta_3(\overline{u_3}) - \nu\frac{\partial^2(\overline{u_3})}{\partial {x_1}^2} - \nu\frac{\partial^2(\overline{u_3})}{\partial {x_2}^2}$$
$$- \nu\frac{\partial^2(\overline{u_3})}{\partial {x_3}^2} = -\frac{\partial(\overline{u_1' u_3'})}{\partial x_1} - \frac{\partial(\overline{u_2' u_3'})}{\partial x_2} - \frac{\partial(\overline{u_3' u_3'})}{\partial x_3}$$

$+2\Omega\varepsilon_{33k}\eta_3(\overline{u_k}) = 0$ $2\Omega\varepsilon_{313}\eta_1(\overline{u_3}) = 0$ $2\Omega\varepsilon_{33k}\eta_3(\overline{u_k}) = 0$

$$\frac{\partial(\overline{u_3})}{\partial t} + (\overline{u_1})\frac{\partial(\overline{u_3})}{\partial x_1} + (\overline{u_2})\frac{\partial(\overline{u_3})}{\partial x_2} + (\overline{u_3})\frac{\partial(\overline{u_3})}{\partial x_3} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_3} + g\frac{\overline{\rho}}{\rho_0}\delta_{33} - \nu\frac{\partial^2(\overline{u_3})}{\partial {x_1}^2} - \nu\frac{\partial^2(\overline{u_3})}{\partial {x_2}^2} - \nu\frac{\partial^2(\overline{u_3})}{\partial {x_3}^2}$$
$$= -\frac{\partial(\overline{u_1' u_3'})}{\partial x_1} - \frac{\partial(\overline{u_2' u_3'})}{\partial x_2} - \frac{\partial(\overline{u_3' u_3'})}{\partial x_3}$$

i = 3 e j = 1,2,3 k = 3

$$\frac{\partial(\overline{u_3})}{\partial t} + (\overline{u_1})\frac{\partial(\overline{u_3})}{\partial x_1} + (\overline{u_2})\frac{\partial(\overline{u_3})}{\partial x_2} + (\overline{u_3})\frac{\partial(\overline{u_3})}{\partial x_3} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x_3} + g\frac{\overline{\rho}}{\rho_0} - \nu\frac{\partial^2(\overline{u_3})}{\partial {x_1}^2} - \nu\frac{\partial^2(\overline{u_3})}{\partial {x_2}^2} - \nu\frac{\partial^2(\overline{u_3})}{\partial {x_3}^2} = -\frac{\partial(\overline{u_1'u_3'})}{\partial x_1} - \frac{\partial(\overline{u_2'u_3'})}{\partial x_2} - \frac{\partial(\overline{u_3'u_3'})}{\partial x_3}$$

Equação governante para o escoamento Vertical

$$\frac{\partial(\overline{w})}{\partial t} + (\overline{u})\frac{\partial(\overline{w})}{\partial x} + (\overline{v})\frac{\partial(\overline{w})}{\partial y} + (\overline{w})\frac{\partial(\overline{w})}{\partial z} + \frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial z} + g\frac{\overline{\rho}}{\rho_0} - \nu\frac{\partial^2(\overline{w})}{\partial x^2} - \nu\frac{\partial^2(\overline{w})}{\partial y^2} - \nu\frac{\partial^2(\overline{w})}{\partial z^2} = -\frac{\partial(\overline{u'w'})}{\partial x} - \frac{\partial(\overline{v'w'})}{\partial y} - \frac{\partial(\overline{w'w'})}{\partial z}$$

Previsão Numérica de Tempo e Clima

Equações governantes para o escoamento atmosférico

$$\frac{\partial(\bar{u})}{\partial t}+(\bar{u})\frac{\partial(\bar{u})}{\partial x}+(\bar{v})\frac{\partial(\bar{u})}{\partial y}+(\bar{w})\frac{\partial(\bar{u})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial x}-2\Omega\eta_3(\bar{v})-\nu\frac{\partial^2(\bar{u})}{\partial x^2}-\nu\frac{\partial^2(\bar{u})}{\partial y^2}-\nu\frac{\partial^2(\bar{u})}{\partial z^2}=-\frac{\partial(\overline{u'u'})}{\partial x}-\frac{\partial(\overline{v'u'})}{\partial y}-\frac{\partial(\overline{w'u'})}{\partial z}$$

$$\frac{\partial(\bar{v})}{\partial t}+(\bar{u})\frac{\partial(\bar{v})}{\partial x}+(\bar{v})\frac{\partial(\bar{v})}{\partial y}+(\bar{w})\frac{\partial(\bar{v})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial y}+2\Omega\eta_3(\bar{u})-\nu\frac{\partial^2(\bar{v})}{\partial x^2}-\nu\frac{\partial^2(\bar{v})}{\partial y^2}-\nu\frac{\partial^2(v)}{\partial z^2}=-\frac{\partial(\overline{u'v'})}{\partial x}-\frac{\partial(\overline{v'v'})}{\partial y}-\frac{\partial(\overline{w'v'})}{\partial z}$$

$$\frac{\partial(\bar{w})}{\partial t}+(\bar{u})\frac{\partial(\bar{w})}{\partial x}+(\bar{v})\frac{\partial(\bar{w})}{\partial y}+(\bar{w})\frac{\partial(\bar{w})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial z}+g\frac{\bar{\rho}}{\rho_0}-\nu\frac{\partial^2(\bar{w})}{\partial x^2}-\nu\frac{\partial^2(\bar{w})}{\partial y^2}-\nu\frac{\partial^2(\bar{w})}{\partial z^2}=-\frac{\partial(\overline{u'w'})}{\partial x}-\frac{\partial(\overline{v'w'})}{\partial y}-\frac{\partial(\overline{w'w'})}{\partial z}$$

Previsão Numérica de Tempo e Clima

$$\frac{\partial(\overline{u})}{\partial t}+(\overline{u})\frac{\partial(\overline{u})}{\partial x}+(\overline{v})\frac{\partial(\overline{u})}{\partial y}+(\overline{w})\frac{\partial(\overline{u})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial x}-2\Omega\eta_3(\overline{v})-\nu\frac{\partial^2(\overline{u})}{\partial x^2}-\nu\frac{\partial^2(\overline{u})}{\partial y^2}-\nu\frac{\partial^2(\overline{u})}{\partial z^2}=-\frac{\partial(\overline{u'u'})}{\partial x}-\frac{\partial(\overline{v'u'})}{\partial y}-\frac{\partial(\overline{w'u'})}{\partial z}$$

$$\frac{\partial(\overline{v})}{\partial t}+(\overline{u})\frac{\partial(\overline{v})}{\partial x}+(\overline{v})\frac{\partial(\overline{v})}{\partial y}+(\overline{w})\frac{\partial(\overline{v})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial y}+2\Omega\eta_3(\overline{u})-\nu\frac{\partial^2(\overline{v})}{\partial x^2}-\nu\frac{\partial^2(\overline{v})}{\partial y^2}-\nu\frac{\partial^2(v)}{\partial z^2}=-\frac{\partial(\overline{u'v'})}{\partial x}-\frac{\partial(\overline{v'v'})}{\partial y}-\frac{\partial(\overline{w'v'})}{\partial z}$$

$$\frac{\partial(\overline{w})}{\partial t}+(\overline{u})\frac{\partial(\overline{w})}{\partial x}+(\overline{v})\frac{\partial(\overline{w})}{\partial y}+(\overline{w})\frac{\partial(\overline{w})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\overline{P})}{\partial z}+g\frac{\overline{\rho}}{\rho_0}-\nu\frac{\partial^2(\overline{w})}{\partial x^2}-\nu\frac{\partial^2(\overline{w})}{\partial y^2}-\nu\frac{\partial^2(\overline{w})}{\partial z^2}=-\frac{\partial(\overline{u'w'})}{\partial x}-\frac{\partial(\overline{v'w'})}{\partial y}-\frac{\partial(\overline{w'w'})}{\partial z}$$

$$\frac{\partial(\overline{T})}{\partial t}+(\overline{u})\frac{\partial(\overline{T})}{\partial x}+(\overline{v})\frac{\partial(\overline{T})}{\partial y}+(\overline{w})\frac{\partial(\overline{T})}{\partial z}-S_P\overline{\omega}=-\frac{\partial\left(\overline{u'T'}\right)}{\partial x}-\frac{\partial\left(\overline{v'T'}\right)}{\partial y}-\frac{\partial\left(\overline{w'T'}\right)}{\partial z}+\frac{\overline{J}}{C_p}$$

$$\frac{\partial(\overline{q})}{\partial t}+(\overline{u})\frac{\partial(\overline{q})}{\partial x}+(v)\frac{\partial(\overline{q})}{\partial y}+(\overline{w})\frac{\partial(\overline{q})}{\partial z}=-\frac{\partial(\overline{u'q'})}{\partial x}-\frac{\partial(\overline{u'q'})}{\partial y}-\frac{\partial(\overline{w'q'})}{\partial z}+\overline{S}$$

$$u_3=w$$
$$x_3=z$$
$$\nu\frac{\partial^2(\overline{u_3})}{\partial {x_3}^2}\cong 0$$

Paulo Yoshio Kubota

- Modelos de PNT/clima tem fronteiras na vertical
- Já que na atmosfera livre os termos dinâmicos nas equações para as variáveis média na grade são consideradas dominantes

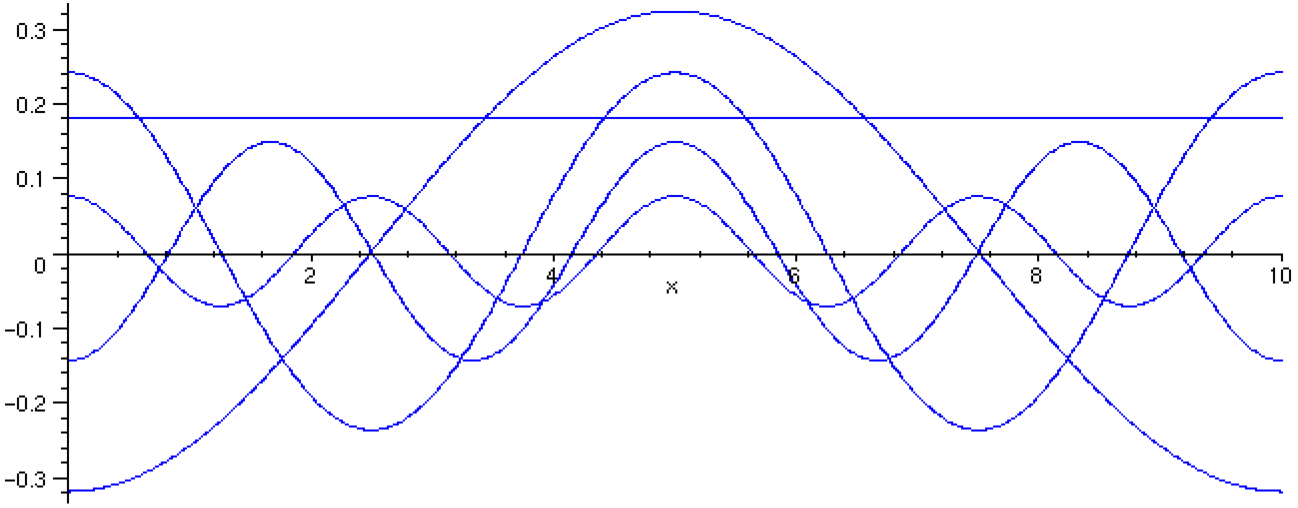
$(\overline{T})$ $(\overline{q})$ $(\overline{u})$ $(\overline{u})$ $(\overline{w})$

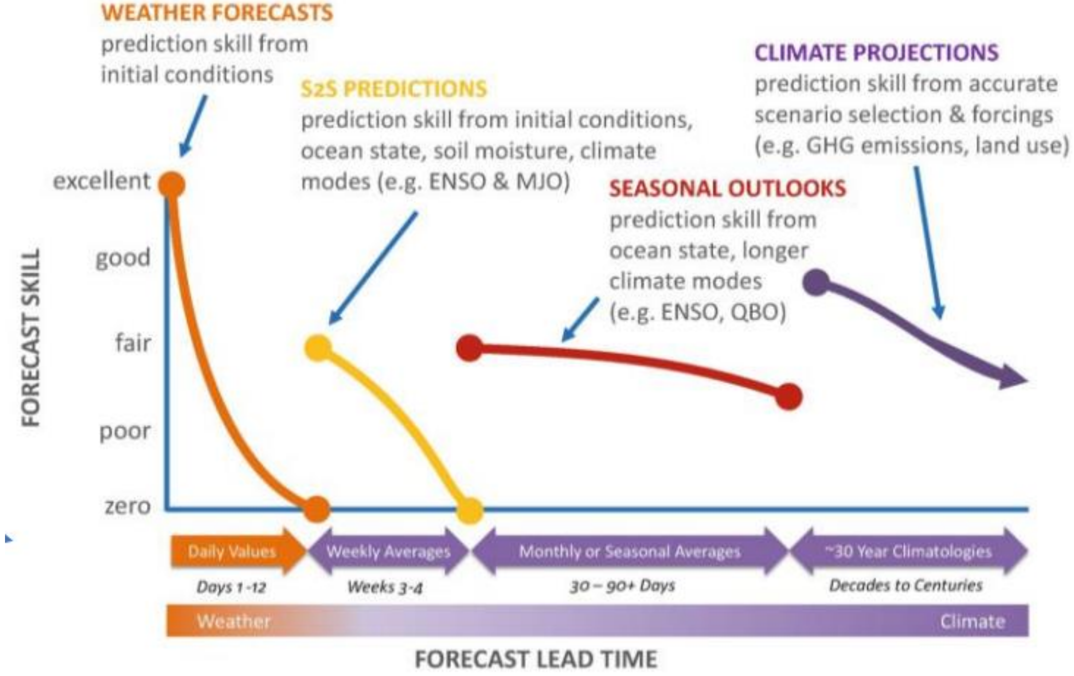
- São acopladas à superfície através de uma camada turbulenta ou camada limite planetária (CLP)

- A CLP transfere calor, umidade e momentum

$$\frac{\partial(\overline{w'T'})}{\partial z} \quad \frac{\partial(\overline{w'q'})}{\partial z} \quad \frac{\partial(\overline{w'u'})}{\partial z} \quad \frac{\partial(\overline{w'v'})}{\partial z}$$

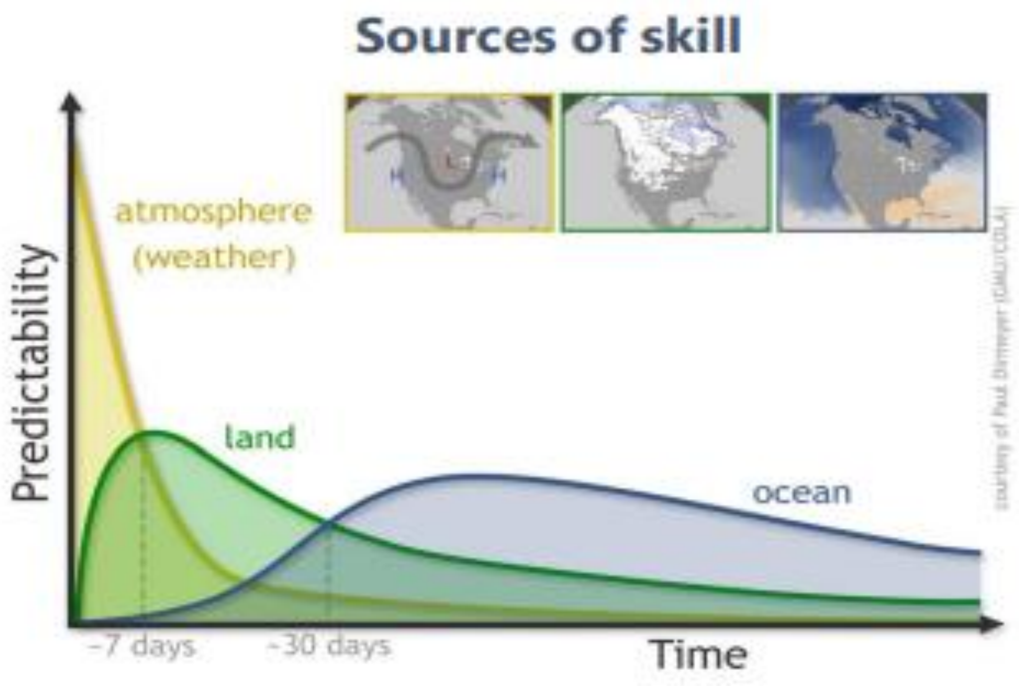
- Em outras palavras a influencia da fricção, aquecimento superficial e evaporação tem importância para previsões na escala sinótica, que aumenta com o tempo de integração (clima)





- Exemplos:
  - Em 24 horas a evapotranspiração na superfície pode incrementar o conteúdo da umidade na CLP em 25%, o qual pode ser uma fonte importante de umidade para o desenvolvimento de ciclones tropicais
  - Também, o fluxo de calor (aquecimento) superficial (principalmente em superfícies úmidas) determina a estabilidade da CLP e isto a convecção

- Fluxos superficiais são importantes no armazenagem de calor e umidade (clima) e na estabilidade (tempo e clima)
- Acredita-se que em previsões curtas é importante os prognósticos das variáveis de superfície



- Na camada atmosférica superficial (~50m) ou base da CLP os fluxos são computados comumente baseados na teoria de similaridade de Monin-Obukhov (modelos mais modernos)

- Os modelos de PNT devem calcular corretamente a redistribuição de calor e vapor por turbilhões próximos a superfície

- Esta camada tem uma profundidade que varia diurna, sazonalmente e geograficamente

- Devido a isto os modelos de PNT ***devem*** possuir suficientes níveis próximos a superfície para ***resolver a estrutura vertical da CLP***

- Muitos níveis também não é desejável, devido a que a ***complexidade da CLP não pode ser resolvida com teorias*** simples (K)
- Um modelo de CLP pode ser complexo e custoso computacionalmente
- Em modelos de PNT o mais importante é o ***intercambio de calor e umidade entre a CLP e a atmosfera livre*** que uma detalhada CLP

- A transferência acima da CLP é acompanhada por convecção cumulus e ondas de gravidade, e por velocidades verticais da larga escala

Previsão Numérica de Tempo e Clima

$$\frac{\partial(\bar{v})}{\partial t}+(\bar{u})\frac{\partial(\bar{v})}{\partial x}+(\bar{v})\frac{\partial(\bar{v})}{\partial y}+(\bar{w})\frac{\partial(\bar{v})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial y}+2\Omega\eta_3(\bar{v})-\nu\frac{\partial^2(\bar{v})}{\partial x^2}-\nu\frac{\partial^2(\bar{v})}{\partial y^2}-\nu\frac{\partial^2(v)}{\partial z^2}=-\frac{\partial(\overline{u'v'})}{\partial x}-\frac{\partial(\overline{v'v'})}{\partial y}-\frac{\partial(\overline{w'v'})}{\partial z}$$

$$\frac{\partial(\bar{u})}{\partial t}+(\bar{u})\frac{\partial(\bar{u})}{\partial x}+(\bar{v})\frac{\partial(\bar{u})}{\partial y}+(\bar{w})\frac{\partial(\bar{u})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial x}-2\Omega\eta_3(\bar{u})-\nu\frac{\partial^2(\bar{u})}{\partial x^2}-\nu\frac{\partial^2(\bar{u})}{\partial y^2}-\nu\frac{\partial^2(\bar{u})}{\partial z^2}=-\frac{\partial(\overline{u'u'})}{\partial x}-\frac{\partial(\overline{v'u'})}{\partial y}-\frac{\partial(\overline{w'u'})}{\partial z}$$

$$\frac{\partial(\bar{w})}{\partial t}+(\bar{u})\frac{\partial(\bar{w})}{\partial x}+(\bar{v})\frac{\partial(\bar{w})}{\partial y}+(\bar{w})\frac{\partial(\bar{w})}{\partial z}+\frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial z}+g\frac{\bar{\rho}}{\rho_0}-\nu\frac{\partial^2(\bar{w})}{\partial x^2}-\nu\frac{\partial^2(\bar{w})}{\partial y^2}-\nu\frac{\partial^2(\bar{w})}{\partial z^2}=-\frac{\partial(\overline{u'w'})}{\partial x}-\frac{\partial(\overline{v'w'})}{\partial y}-\frac{\partial(\overline{w'w'})}{\partial z}$$

$$\frac{\partial(\bar{T})}{\partial t}+(\bar{u})\frac{\partial(\bar{T})}{\partial x}+(\bar{v})\frac{\partial(\bar{T})}{\partial y}+(\bar{w})\frac{\partial(\bar{T})}{\partial z}-S_P\bar{\omega}=-\frac{\partial\left(\overline{u'T'}\right)}{\partial x}-\frac{\partial\left(\overline{v'T'}\right)}{\partial y}-\frac{\partial\left(\overline{w'T'}\right)}{\partial z}+\frac{\bar{J}}{C_p}$$

$$\frac{\partial(\bar{q})}{\partial t}+(\bar{u})\frac{\partial(\bar{q})}{\partial x}+(v)\frac{\partial(\bar{q})}{\partial y}+(\bar{w})\frac{\partial(\bar{q})}{\partial z}=-\frac{\partial(\overline{u'q'})}{\partial x}-\frac{\partial(\overline{u'q'})}{\partial y}-\frac{\partial(\overline{w'q'})}{\partial z}+\bar{S}$$

$$u_3=w$$

$$x_3=z$$

$$\nu\frac{\partial^2(\overline{u_3})}{\partial {x_3}^2}\cong 0$$

Paulo Yoshio Kubota

Previsão Numérica de Tempo e Clima

$$\frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\delta_{i3} g + f_c \varepsilon_{ij3} \overline{u_j} - \frac{1}{\overline{\rho}}\frac{\partial \overline{P}}{\partial x_i} + \frac{\upsilon \partial^2 \overline{u_i}}{\partial x_j{}^2} - \frac{\partial (\overline{u_i' u_j'})}{\partial x_j}$$

Como parameterizar os momentum de 2 ordem $w'\varphi'$

$$\boxed{\frac{\partial u_i}{\partial t} = \frac{\partial \overline{u_i' u_j'}}{\partial x_j}}$$

$$\overline{w'\varphi'} = K(z)\frac{d\varphi}{dz}$$

Teoria do transporte gradiente ou teoria K

Os fluxos de momento, calor ou matéria são difundidos por movimentos turbulentos dentro da camada limite.

$$\overline{w'\varphi'} = \mathrm{K(z)}\frac{d\varphi}{dz}$$

$$\frac{\partial u_i}{\partial t} = \frac{\partial \overline{u_i' u_j'}}{\partial x_j}$$

Como parameterizar os momentum de 2 ordem $w'\varphi'$

$$\frac{\partial u_i}{\partial t} = \frac{\partial}{\partial x_j}\left(\mathrm{K(z)}\frac{d\varphi}{dz}\right)$$

$$\int_{z_i}^{z_{i+1}} \frac{\partial u}{\partial t} dz = \int_{z_i}^{z_{i+1}} \frac{\partial}{\partial z}\left(\mathrm{K(z)}\frac{d\varphi}{dz}\right) dz$$

Desprezando a variação dos fluxos na horizontal.

$$\frac{\partial}{\partial t}\int_{z_i}^{z_{i+1}} u dz = \mathrm{K(z)}\left(\frac{d\varphi}{dz}\right)_{z_{i+1}} - \mathrm{K(z)}\left(\frac{d\varphi}{dz}\right)_{z_i}$$

$$\frac{\partial \bar{u}}{\partial t} = \mathrm{K(z)}\frac{\partial}{\partial z}\left(\frac{d\varphi}{dz}\right)_{z_{i+1}} - \mathrm{K(z)}\frac{\partial}{\partial z}\left(\frac{d\varphi}{dz}\right)_{z_i}$$

K=K(z, estabilidade, nebulosidade, radiação, turbulencia, etc)

Qual a importância numérica da PBL nos MCGAs?

Como Parametrizar os Fluxos Turbulentos na camada limite superficial

$$\overline{w'\varphi'} = K(z)\frac{d\varphi}{dz}$$

$$\frac{\partial(\bar{u})}{\partial t} + (\bar{u})\frac{\partial(\bar{u})}{\partial x} + (\bar{v})\frac{\partial(\bar{u})}{\partial y} + (\bar{w})\frac{\partial(\bar{u})}{\partial z} + \frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial x} - 2\Omega\eta_3(\bar{v}) - \nu\frac{\partial^2(\bar{u})}{\partial x^2} - \nu\frac{\partial^2(\bar{u})}{\partial y^2} - \nu\frac{\partial^2(\bar{u})}{\partial z^2} = -\frac{\partial(\overline{u'u'})}{\partial x} - \frac{\partial(\overline{v'u'})}{\partial y} - K(z)\frac{\partial^2\bar{u}}{\partial^2 z}$$

$$\frac{\partial(\bar{v})}{\partial t} + (\bar{u})\frac{\partial(\bar{v})}{\partial x} + (\bar{v})\frac{\partial(\bar{v})}{\partial y} + (\bar{w})\frac{\partial(\bar{v})}{\partial z} + \frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial y} + 2\Omega\eta_3(\bar{u}) - \nu\frac{\partial^2(\bar{v})}{\partial x^2} - \nu\frac{\partial^2(\bar{v})}{\partial y^2} - \nu\frac{\partial^2(v)}{\partial z^2} = -\frac{\partial(\overline{u'v'})}{\partial x} - \frac{\partial(\overline{v'v'})}{\partial y} - K(z)\frac{\partial^2\bar{v}}{\partial^2 z}$$

$$\frac{\partial(\bar{w})}{\partial t} + (\bar{u})\frac{\partial(\bar{w})}{\partial x} + (\bar{v})\frac{\partial(\bar{w})}{\partial y} + (\bar{w})\frac{\partial(\bar{w})}{\partial z} + \frac{1}{\rho_0}\frac{\partial(\bar{P})}{\partial z} + g\frac{\bar{\rho}}{\rho_0} - \nu\frac{\partial^2(\bar{w})}{\partial x^2} - \nu\frac{\partial^2(\bar{w})}{\partial y^2} - \nu\frac{\partial^2(\bar{w})}{\partial z^2} = -\frac{\partial(\overline{u'w'})}{\partial x} - \frac{\partial(\overline{v'w'})}{\partial y} - K(z)\frac{\partial(\bar{w})}{\partial z}$$

$$\frac{\partial(\bar{T})}{\partial t} + (\bar{u})\frac{\partial(\bar{T})}{\partial x} + (\bar{v})\frac{\partial(\bar{T})}{\partial y} + (\bar{w})\frac{\partial(\bar{T})}{\partial z} - S_P\bar{\omega} = -\frac{\partial\left(\overline{u'T'}\right)}{\partial x} - \frac{\partial\left(\overline{v'T'}\right)}{\partial y} - K(z)\frac{\partial^2\bar{T}}{\partial^2 z} + \frac{\bar{J}}{C_p}$$

$$\frac{\partial(\bar{q})}{\partial t} + (\bar{u})\frac{\partial(\bar{q})}{\partial x} + (v)\frac{\partial(\bar{q})}{\partial y} + (\bar{w})\frac{\partial(\bar{q})}{\partial z} = -\frac{\partial(\overline{u'q'})}{\partial x} - \frac{\partial(\overline{u'q'})}{\partial y} - K(z)\frac{\partial^2\bar{q}}{\partial^2 z} + \bar{S}$$

$$u_3 = w$$

$$x_3 = z$$

$$\nu\frac{\partial^2(\bar{u}_3)}{\partial {x_3}^2} \cong 0$$

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$$\frac{\partial(\overline{u})}{\partial t} = -\mathrm{K(z)}\,\frac{\partial^2\overline{u}}{\partial^2 z}$$

$$\frac{\partial(\overline{v})}{\partial t} = -\mathrm{K(z)}\,\frac{\partial^2\overline{v}}{\partial^2 z}$$

$$\frac{\partial(\overline{T})}{\partial t} = -\mathrm{K(z)}\,\frac{\partial^2\overline{T}}{\partial^2 z}$$

$$\frac{\partial(\overline{q})}{\partial t} = -\mathrm{K(z)}\,\frac{\partial^2\overline{q}}{\partial^2 z}$$

$$\overline{w'\varphi'} = \mathrm{K(z)}\frac{d\varphi}{dz}$$

- Teoria K
  - Assume-se um equilíbrio entre os fluxos verticais de sub-grade e a estrutura vertical na grade, ***os fluxos horizontais na sub-grade são desprezíveis***
  - Isto permite o **tratamento da CLP de forma 1-D** (somente estrutura vertical)

Magnitude of Reynolds stress at ground surface (8.2)

$$|\tau_z| = \rho_a\left[\left(\overline{w'u'}\right)^2 + \left(\overline{w'v'}\right)^2\right]^{1/2}$$

Kinematic vertical turbulent momentum flux ($m^2\ s^{-2}$) (8.3)

$$\overline{w'u'} = -\frac{\tau_{zx}}{\rho_a}$$

$$\overline{w'v'} = -\frac{\tau_{zy}}{\rho_a}$$

Vertical turbulent sensible-heat flux ($W\ m^{-2}$) (8.4)

$$H_f = \rho_a c_{p,d}\overline{w'\theta_v'}$$

Kinematic vert. turbulent sensible-heat flux ($m\ K\ s^{-1}$) (8.5)

$$\overline{w'\theta_v'} = \frac{H_f}{\rho_a c_{p,d}}$$

Vertical turbulent water vapor flux ($kg\ m^{-2}\ s^{-1}$) (8.6)

$$E_f = \rho_a\overline{w'q_v'}$$

Kinematic vert. turbulent moisture flux ($m\ kg\ s^{-1}\ kg^{-1}$) (8.7)

$$\overline{w'q_v'} = \frac{E_f}{\rho_a}$$

$$\frac{\partial(\overline{u})}{\partial t} = -K(z)\,\frac{\partial^2\overline{u}}{\partial^2 z}$$

$$\frac{\partial(\overline{v})}{\partial t} = -K(z)\,\frac{\partial^2\overline{v}}{\partial^2 z}$$

$$\frac{\partial(\overline{T})}{\partial t} = -K(z)\,\frac{\partial^2\overline{T}}{\partial^2 z}$$

$$\frac{\partial(\overline{q})}{\partial t} = -K(z)\,\frac{\partial^2\overline{q}}{\partial^2 z}$$

$$\frac{\partial\bar{u}}{\partial t} = K(z)\,\frac{\partial}{\partial z}\left(\frac{d\varphi}{dz}\right)_{z_{i+1}} - K(z)\,\frac{\partial}{\partial z}\left(\frac{d\varphi}{dz}\right)_{z_i}$$

$$-C\varnothing_{j-1}^{n+1} + (1 + C)\varnothing_j^{n+1} = \varnothing_j^n$$

$$\begin{pmatrix} 1+C & 0 & 0 & 0 & 0 & 0 & -C \\ -C & 1+C & 0 & 0 & 0 & 0 & 0 \\ 0 & -C & 1+C & 0 & 0 & 0 & 0 \\ 0 & 0 & -C & 1+C & 0 & 0 & 0 \\ \ddots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\ 0 & 0 & 0 & 0 & -C & 1+C & 0 \\ 0 & 0 & 0 & 0 & 0 & -C & 1+C \end{pmatrix} \begin{pmatrix} \varnothing_1^{n+1} \\ \varnothing_2^{n+1} \\ \varnothing_3^{n+1} \\ \varnothing_4^{n+1} \\ \vdots \\ \varnothing_{j-2}^{n+1} \\ \varnothing_{j-1}^{n+1} \end{pmatrix} = \begin{pmatrix} \varnothing_1^{n} \\ \varnothing_2^{n} \\ \varnothing_3^{n} \\ \varnothing_4^{n} \\ \vdots \\ \varnothing_{j-2}^{n} \\ \varnothing_{j-1}^{n} \end{pmatrix}$$

- A equação anterior complica a solução e adiciona termos desconhecidos

- Porém nos fornece algumas informações diagnosticas

- Suposição no problema de fechamento: ***relação linear fluxo-gradiente ou teoria K***

- Assume-se que o gradiente médio (temperatura ou umidade) dirige o fluxo turbulento (calor ou umedecimento)

Magnitude of Reynolds stress at ground surface (8.2)

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$$E_f = \rho_a\overline{w'q'_v}$$

Kinematic vert. turbulent moisture flux ($m\ kg\ s^{-1}\ kg^{-1}$) (8.7)

$$\overline{w'q'_v} = \frac{E_f}{\rho_a}$$

$$H = \rho_a c_{pd}\overline{w'\theta_v{}'}$$

$$\mathrm{Ef} = \rho_a L_v \overline{w'q'}$$

$$\overline{w'\varphi'} = \mathbf{K(z)}\frac{d\varphi}{dz}$$

$$H = \rho_a c_{pd} K_h \frac{\partial\overline{\theta_v}}{\partial z}$$

$$\mathrm{Ef} = \rho_a L_v K_q \frac{\partial\bar{q}}{\partial z}$$

- Onde $K_H(z)$, m^2s^{-1} é a **difusividade turbulenta para calor**, γ_d é o lapse rate adiabático

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- Da mesma forma para o fluxo de umidade

$$\overline{w'\varphi'} = \mathbf{K(z)}\frac{d\varphi}{dz}$$

- Onde **K(z)** é a difusividade turbulenta para φ

Como parameterizar os momentum de 2 ordem $w'\varphi'$ na CL Superficial

$$F=\rho K(z)\frac{d\varphi}{dz} \qquad (F=\overline{w'\varphi'})$$

Calcular $K(z_{1.5})$???

Formulação em diferenças finitas

$$F_{1.5} = \rho K(z_{1.5}) \frac{\varphi_2-\varphi_1}{z_2-z_1}$$

Integral da camada superfície :

$$\varphi_1 - \varphi_s = \int_{z_{0\varphi}}^{z_1} \frac{F_{0\varphi}}{\rho K(z)} dz$$

Camada de fluxo constante:

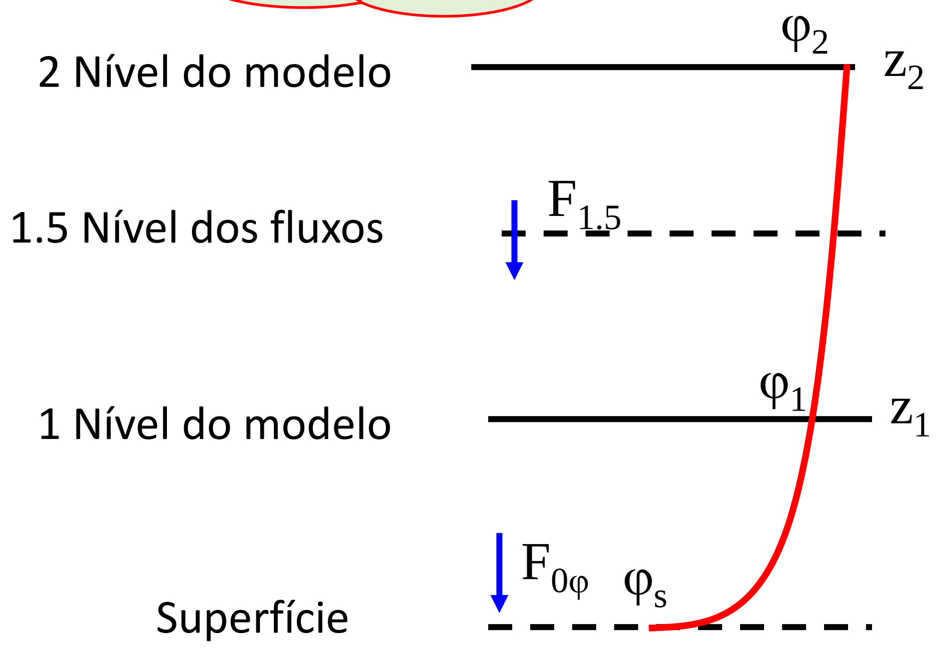
$$\varphi_1 - \varphi_s \approx \frac{F_0}{\rho} \int_{z_{0\varphi}}^{z_1} \frac{1}{K(z)} dz$$

Escoamento neutro:

$$K(z) = \kappa z u_*$$

$$\varphi_1 - \varphi_s \approx \frac{F_{0\varphi}}{\rho\kappa u_*} \int_{z_{0\varphi}}^{z_1} \frac{dz}{z} \quad \Rightarrow \quad \varphi_1 - \varphi_s = \frac{F_{0\varphi}}{\rho\kappa u_*} \ln\left(\frac{z_1}{z_{0\varphi}}\right)$$

u,v,T,q



κ : Von Karman constant (0.4)
u_* : Friction velocity
ρ : Density

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Coeficientes de difusão de acordo com a similaridade MO

Conceito Básico de um modelo PBL

$$K_M = \frac{1}{\phi_m^2} l^2 \left|\frac{\partial U}{\partial z}\right| \qquad K_H = \frac{1}{\phi_m \phi_h} l^2 \left|\frac{\partial U}{\partial z}\right|$$

Calcular $K(z_{1.5})$???

Usando a relação entre R_i e $\frac{z}{L}$

$$R_i = \frac{g}{\theta_v} \frac{\frac{\partial \theta_v}{\partial z}}{\left|\frac{\partial U}{\partial z}\right|^2} = \frac{g}{\theta_v} \frac{z\theta_* \phi_h}{u_*^2 \phi_m^2} = \frac{z}{\kappa L} \frac{\phi_h}{\phi_m^2}$$

$$\frac{1}{\phi_m^2} = \frac{\kappa L}{z\,\phi_h} R_i$$

$$\frac{1}{\phi_m \phi_h} = \frac{\phi_m}{\phi_h^2} \frac{\kappa L}{z} R_i$$

Resolver para $\frac{z}{L} = \xi$

$$K_M = l^2 \left|\frac{dU}{dz}\right| f_M(R_i) \qquad K_H = l^2 \left|\frac{dU}{dz}\right| f_H(R_i)$$

Como parameterizar os momentum de 2 ordem $\overline{w'\varphi'}$, K_M, K_H

Kubota

- Existe também a camada da superfície atmosférica nos 50 m próximos a superfície da CLP

- O movimento vertical e a mistura é limitado pela proximidade da superfície

- Os gradientes verticais do vento, temperatura e umidade são muitos grandes

- Monin e Obuhkov estabeleceram uma teoria empírica da CS

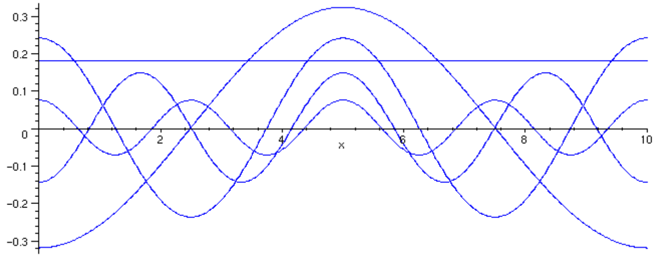
- Determinada pelos fluxos turbulentos de momentum e calor que a atravessam

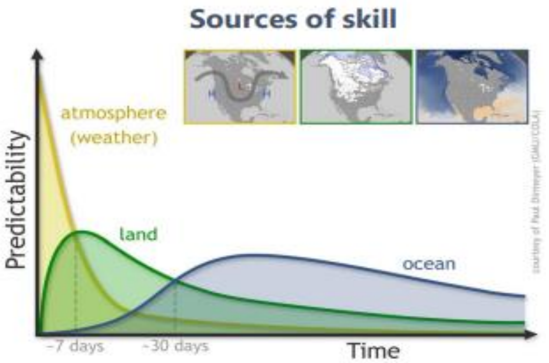
O problema da parametrização de camada limite planetária é determinar como será feita a difusão a cada instante do tempo

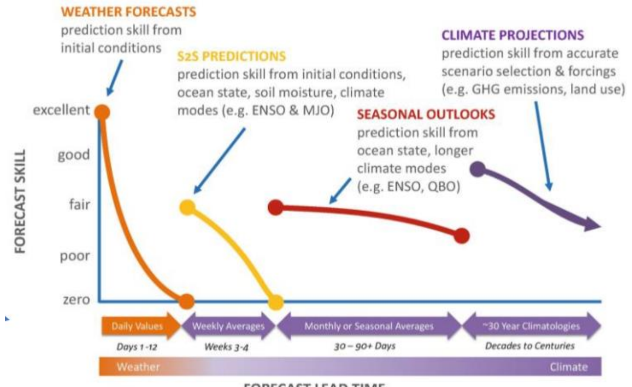
K(z, estabilidade, nebulosidade, radiação, turbulencia, etc)

K=K(z, estabilidade, nebulosidade, radiação, turbulencia, etc)??????
Precisa saber todos os fenômenos físicos que afetam o perfil vertical de de
K_M, K_H

Como parameterizar os momentum de 2 ordem $w'\varphi'$, K_M, K_H





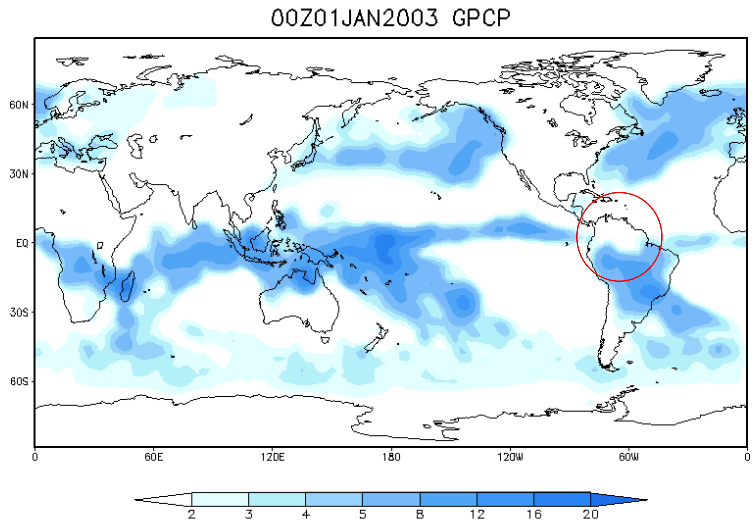


"ACOPLAMENTO" DO MCGA-CPTEC COM O IBIS
"Precipitação"

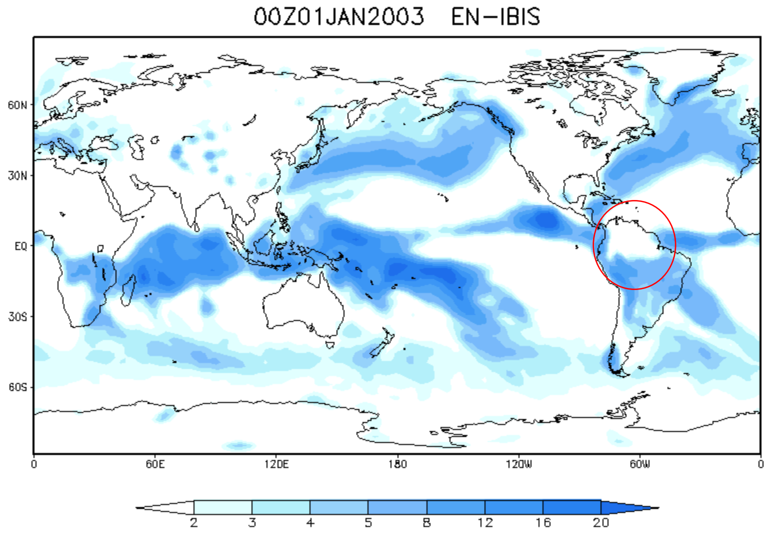
$$\boxed{K_h = w_1 K_{h_{MY}} + w_2 K_{h_{TKE}} + w_3 K_{h_{HB}}}$$

$$\boxed{K_m = w_1 K_{m_{MY}} + w_2 K_{m_{TKE}} + w_3 K_{m_{HB}}}$$

Observado GPCP



Simulação com o mesmo peso para cada coeficiente de difusão



Norte da AMAZ.:sul

NE:super.

Referências

- Stull, R. B., 1988: An Introduction to Boundary Layer Meteorology. Kluwer Academic, 666 pp.
- Chapter 5 of Holton, J. R., 1992: An Introduction to Dynamic Meteorology. Academic Press, New York, 511 pp.