



Turbulência Atmosférica e Parametrização da Camada Limite Planetária



Previsão Numérica de Tempo e Clima

Média de Reynolds

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

lei do gas

$$\bar{p} = \bar{\rho} R_d \bar{T}_v$$

Temperatura virtual

$$\bar{T}_v = T(1 + 0.61q_v - q_l)$$

Necessita ser parametrizado !

2nd ordem

momentum

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\delta_{i3}g + f_c \varepsilon_{ij3} \bar{u}_j - \frac{1}{\bar{\rho}} \frac{\partial \bar{P}}{\partial x_i} + \frac{\nu \partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial (\bar{u}'_i \bar{u}'_j)}{\partial x_j}$$

Advecção media

gravidade

Coriolis

Gradiente de Pressão

Estresse Viscoso

Transporte Turbulento

Eq. Continuidade

$$\frac{\partial \bar{u}_i}{\partial x_j} = 0$$

Calor

$$\frac{\partial \bar{\theta}}{\partial t} + \bar{u}_j \frac{\partial \bar{\theta}}{\partial x_j} = -\frac{1}{\bar{\rho} c_p} \frac{\partial \bar{F}_j}{\partial x_j} - \frac{\partial \bar{u}'_j \bar{\theta}'}{\partial x_j} - \frac{L_v E}{\bar{\rho} c_p}$$

Advecção media

radiação

Transporte Turbulento

Liberção de Calor Latente

Agua Total

$$\frac{\partial \bar{q}_t}{\partial t} + \bar{u}_j \frac{\partial \bar{q}_t}{\partial x_j} = \frac{S_{q_t}}{\bar{\rho}} - \frac{\partial \bar{u}'_j \bar{q}'_t}{\partial x_j}$$

Advecção media

precipitação

Transporte Turbulento



- 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**

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

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

$$\frac{\partial(\bar{q})}{\partial t} + (\bar{u}_j) \frac{\partial(\bar{q})}{\partial x_j} = - \frac{\partial(\overline{u_j' q'})}{\partial x_j} + \bar{S}$$

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



Comparações

Camada limite

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

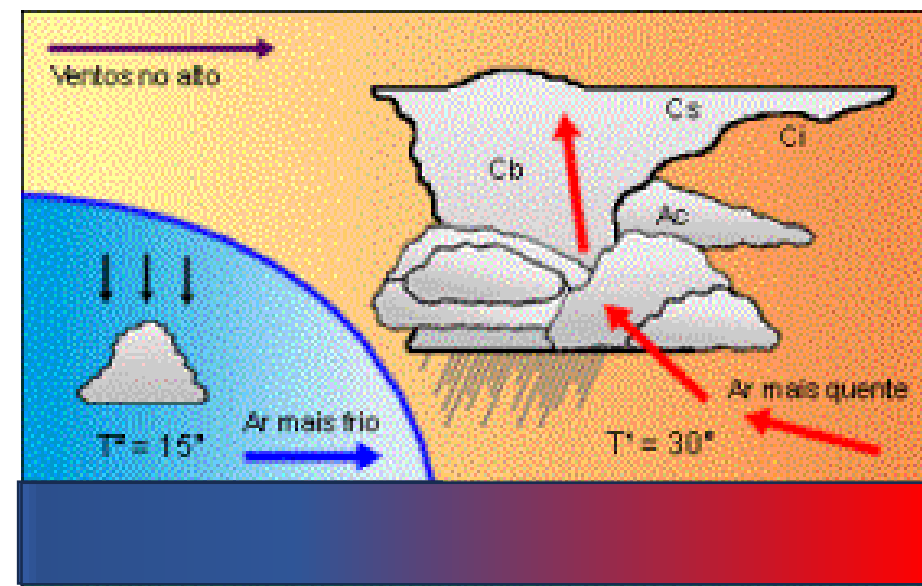
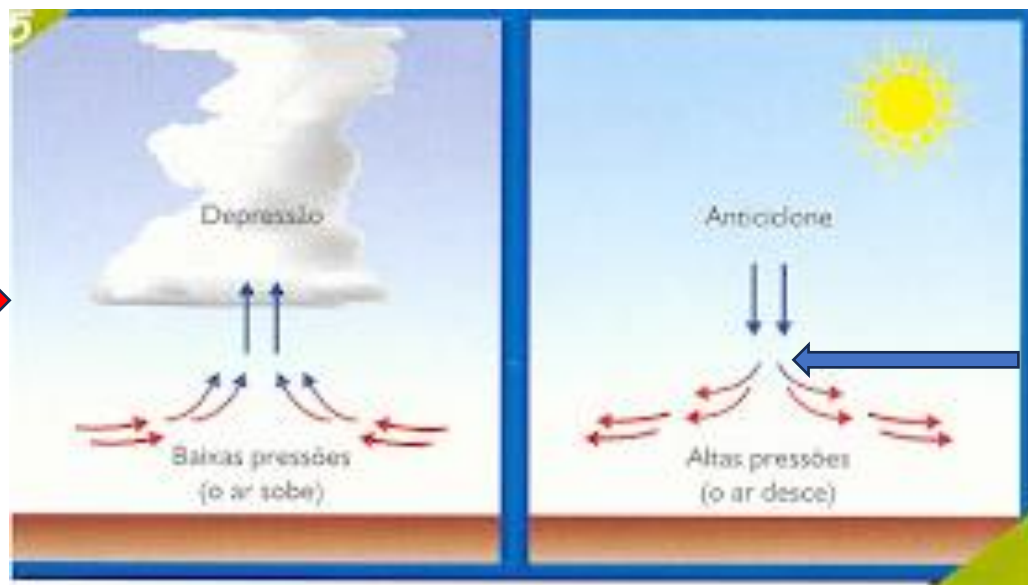
Atmosfera livre

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



Previsão Numérica de Tempo e Clima

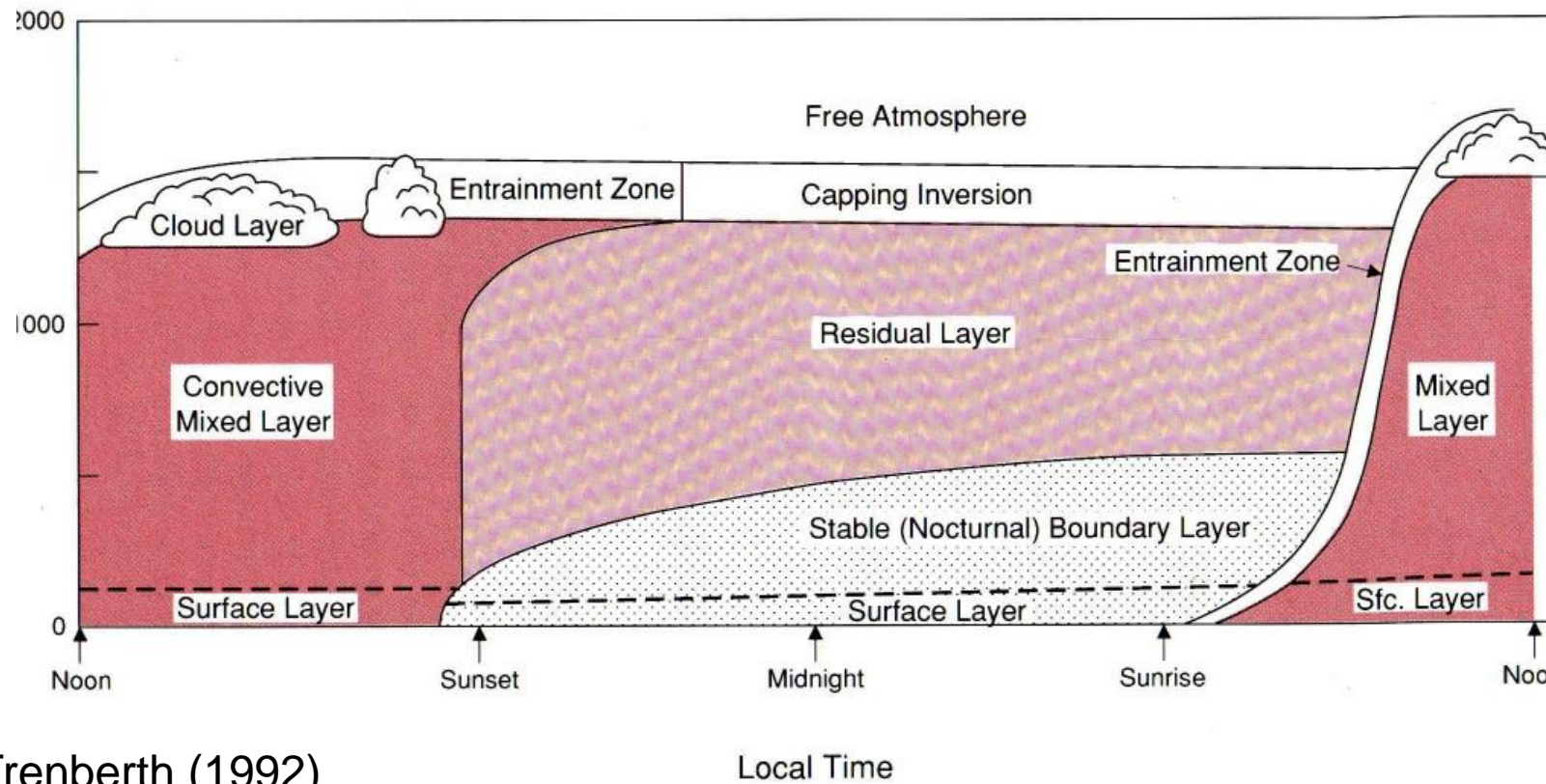
- A camada limite é **usualmente rasa em regiões de altas pressões** devido ao movimento descendente e a divergência horizontal decresce sua altura
- Em regiões de **baixa pressão a altura da camada limite é mais profunda**



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



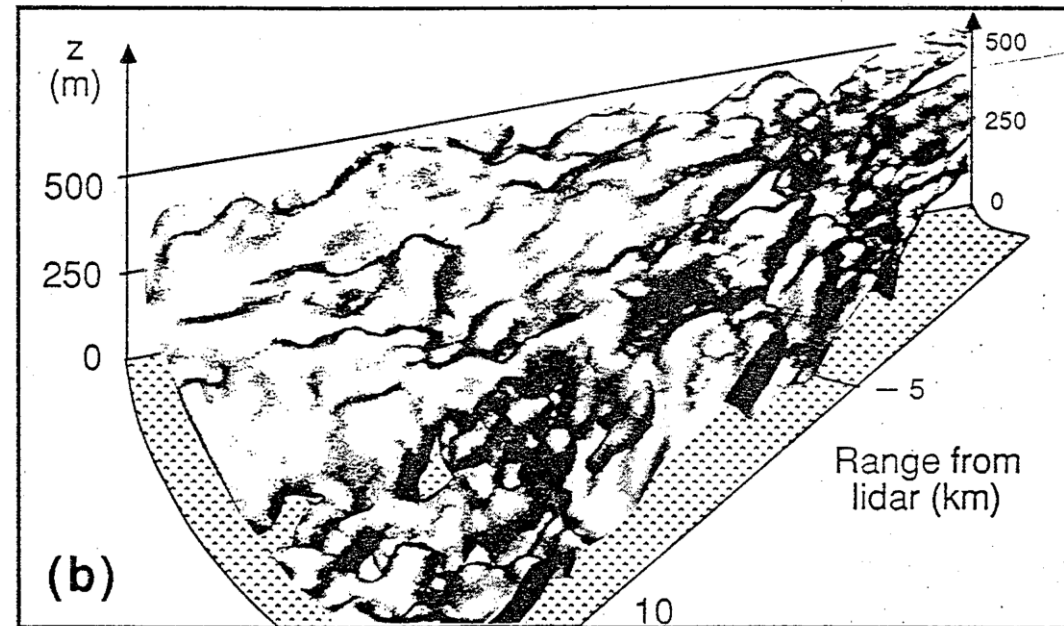
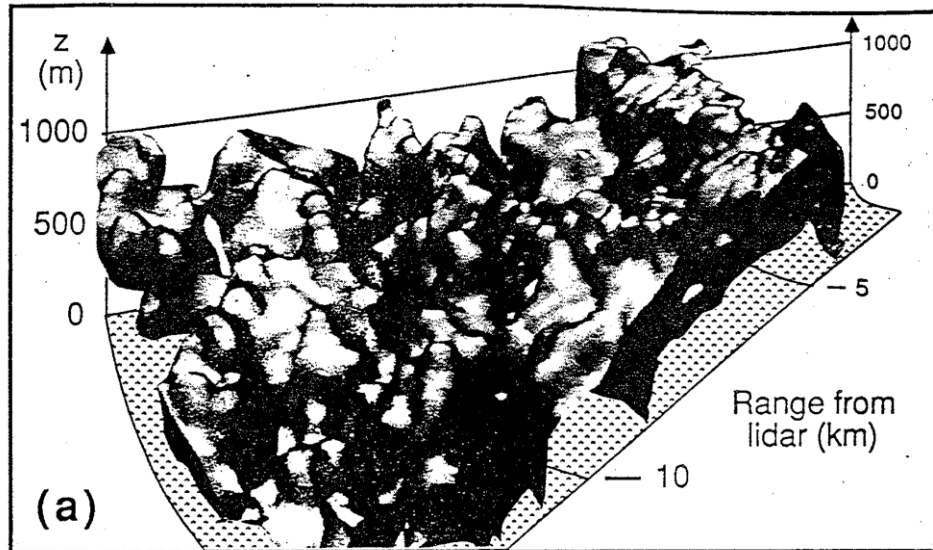
Camada Limite



Trenberth (1992)

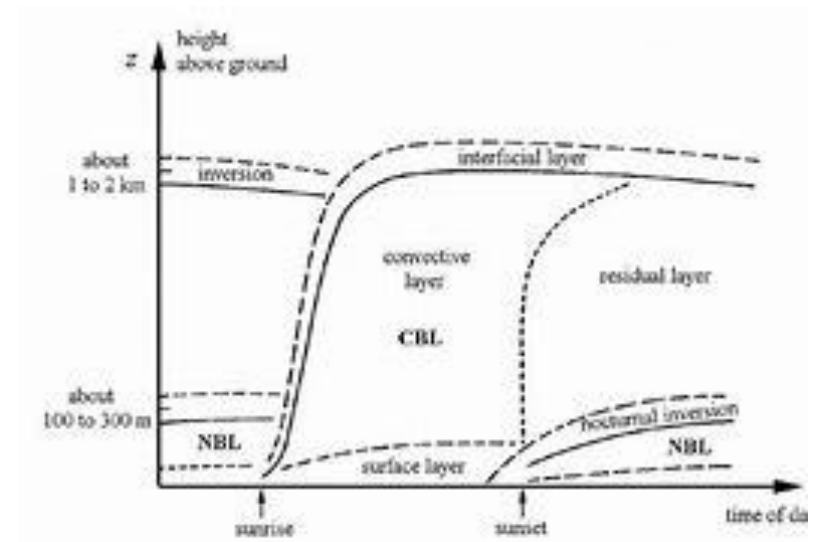
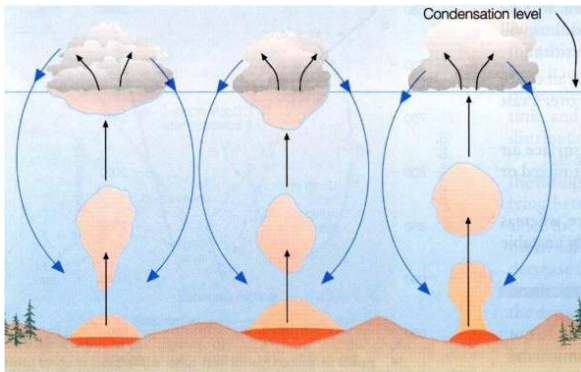


Exemplos



Camada limite

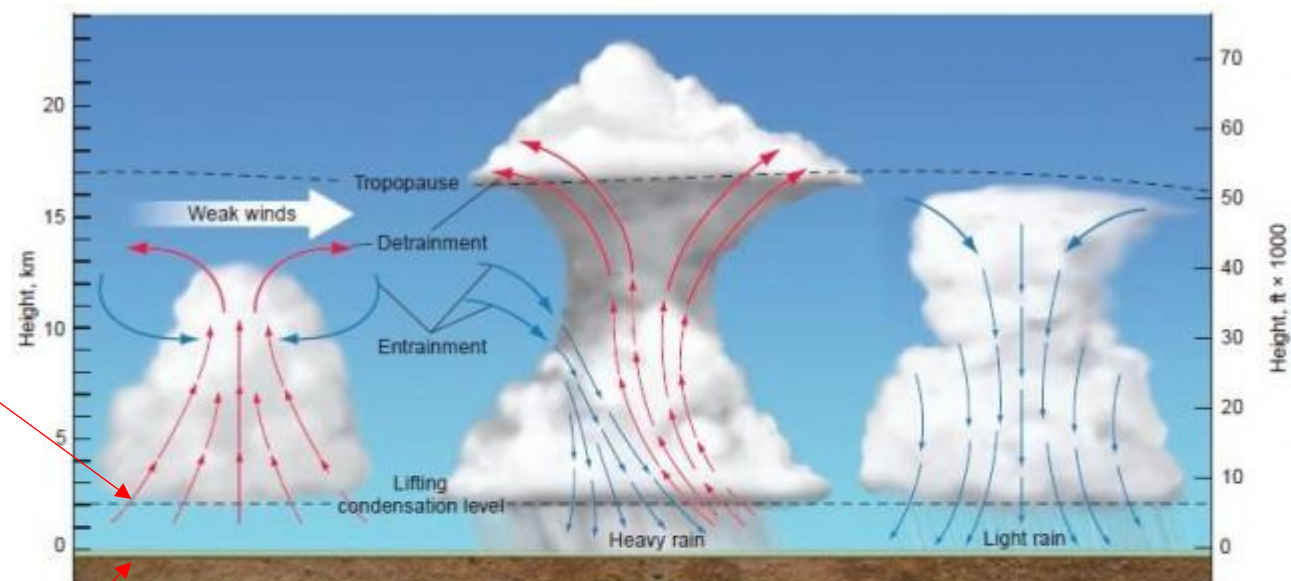
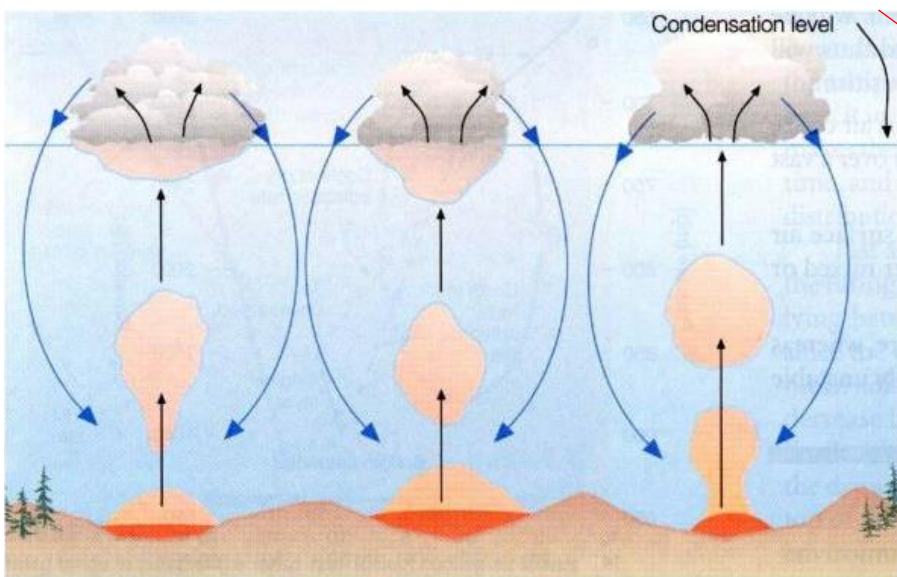
- Evolução das equações **dependem da divergência de fluxos convectivos** (calor, vapor, momentum) dirigido por **movimentos não resolvidos na vertical**



- 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.



Previsão Numérica de Tempo e Clima

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

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

$$\frac{\partial(\bar{q})}{\partial t} + (\bar{u}_j) \frac{\partial(\bar{q})}{\partial x_j} = - \frac{\partial(\overline{u_j' q'})}{\partial x_j} + \bar{S}$$



Previsão Numérica de Tempo e Clima

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

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

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

$$\begin{aligned} & \frac{\partial(\bar{u}_1)}{\partial t} + (\bar{u}_1) \frac{\partial(\bar{u}_1)}{\partial x_1} + (\bar{u}_2) \frac{\partial(\bar{u}_1)}{\partial x_2} + (\bar{u}_3) \frac{\partial(\bar{u}_1)}{\partial x_3} + \frac{1}{\rho_0} \frac{\partial(\bar{P})}{\partial x_1} + g \frac{\bar{\rho}}{\rho_0} \delta_{13} + 2\Omega \varepsilon_{111} \eta_1(\bar{u}_1) + 2\Omega \varepsilon_{121} \eta_2(\bar{u}_1) + 2\Omega \varepsilon_{131} \eta_3(\bar{u}_1) \\ & + 2\Omega \varepsilon_{112} \eta_1(\bar{u}_2) + 2\Omega \varepsilon_{122} \eta_2(\bar{u}_2) + 2\Omega \varepsilon_{132} \eta_3(\bar{u}_2) + 2\Omega \varepsilon_{113} \eta_1(\bar{u}_3) + 2\Omega \varepsilon_{123} \eta_2(\bar{u}_3) + 2\Omega \varepsilon_{133} \eta_3(\bar{u}_3) - \nu \frac{\partial^2(\bar{u}_2)}{\partial x_1^2} - \nu \frac{\partial^2(\bar{u}_2)}{\partial x_2^2} \\ & - \nu \frac{\partial^2(\bar{u}_2)}{\partial x_3^2} = - \frac{\partial(\overline{u_1' u_3'})}{\partial x_1} - \frac{\partial(\overline{u_2' u_3'})}{\partial x_2} - \frac{\partial(\overline{u_3' u_3'})}{\partial x_3} \end{aligned}$$

$$+ 2\Omega \varepsilon_{33k} \eta_3(\bar{u}_k) = 0$$

$$2\Omega \varepsilon_{313} \eta_1(\bar{u}_3) = 0$$

$$2\Omega \varepsilon_{33k} \eta_3(\bar{u}_k) = 0$$

$$\frac{\partial(\bar{u}_1)}{\partial t} + (\bar{u}_1) \frac{\partial(\bar{u}_1)}{\partial x_1} + (\bar{u}_2) \frac{\partial(\bar{u}_1)}{\partial x_2} + (\bar{u}_3) \frac{\partial(\bar{u}_1)}{\partial x_3} + \frac{1}{\rho_0} \frac{\partial(\bar{P})}{\partial x_1} - 2\Omega \eta_3(\bar{u}_2) - \nu \frac{\partial^2(\bar{u}_1)}{\partial x_1^2} - \nu \frac{\partial^2(\bar{u}_1)}{\partial x_2^2} - \nu \frac{\partial^2(\bar{u}_1)}{\partial x_3^2} = - \frac{\partial(\overline{u_1' u_1'})}{\partial x_1} - \frac{\partial(\overline{u_2' u_1'})}{\partial x_2} - \frac{\partial(\overline{u_3' u_1'})}{\partial x_3}$$



Previsão Numérica de Tempo e Clima

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

Equação governante para o escoamento zonal

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



Previsão Numérica de Tempo e Clima

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

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

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

$$\begin{aligned} & \frac{\partial(\bar{u}_2)}{\partial t} + (\bar{u}_1) \frac{\partial(\bar{u}_2)}{\partial x_1} + (\bar{u}_2) \frac{\partial(\bar{u}_2)}{\partial x_2} + (\bar{u}_3) \frac{\partial(\bar{u}_2)}{\partial x_3} + \frac{1}{\rho_0} \frac{\partial(\bar{P})}{\partial x_2} + g \frac{\bar{\rho}}{\rho_0} \delta_{23} + 2\Omega \varepsilon_{211} \eta_1(\bar{u}_1) + 2\Omega \varepsilon_{221} \eta_2(\bar{u}_1) + 2\Omega \varepsilon_{231} \eta_3(\bar{u}_1) \\ & + 2\Omega \varepsilon_{212} \eta_1(\bar{u}_2) + 2\Omega \varepsilon_{222} \eta_2(\bar{u}_2) + 2\Omega \varepsilon_{232} \eta_3(\bar{u}_2) + 2\Omega \varepsilon_{213} \eta_1(\bar{u}_3) + 2\Omega \varepsilon_{223} \eta_2(\bar{u}_3) + 2\Omega \varepsilon_{233} \eta_3(\bar{u}_3) - \nu \frac{\partial^2(\bar{u}_2)}{\partial x_1^2} - \nu \frac{\partial^2(\bar{u}_2)}{\partial x_2^2} \\ & - \nu \frac{\partial^2(\bar{u}_2)}{\partial x_3^2} = - \frac{\partial(\overline{u_1' u_2'})}{\partial x_1} - \frac{\partial(\overline{u_2' u_2'})}{\partial x_2} - \frac{\partial(\overline{u_3' u_2'})}{\partial x_3} \end{aligned}$$

$$+ 2\Omega \varepsilon_{33k} \eta_3(\bar{u}_k) = 0$$

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$$2\Omega \varepsilon_{33k} \eta_3(\bar{u}_k) = 0$$

$$\frac{\partial(\bar{u}_2)}{\partial t} + (\bar{u}_1) \frac{\partial(\bar{u}_2)}{\partial x_1} + (\bar{u}_2) \frac{\partial(\bar{u}_2)}{\partial x_2} + (\bar{u}_3) \frac{\partial(\bar{u}_2)}{\partial x_3} + \frac{1}{\rho_0} \frac{\partial(\bar{P})}{\partial x_2} + 2\Omega \eta_3(\bar{u}_1) - \nu \frac{\partial^2(\bar{u}_2)}{\partial x_1^2} - \nu \frac{\partial^2(\bar{u}_2)}{\partial x_2^2} - \nu \frac{\partial^2(\bar{u}_2)}{\partial x_3^2} = - \frac{\partial(\overline{u_1' u_2'})}{\partial x_1} - \frac{\partial(\overline{u_2' u_2'})}{\partial x_2} - \frac{\partial(\overline{u_3' u_2'})}{\partial x_3}$$



Previsão Numérica de Tempo e Clima

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

Equação governante para o escoamento Meridional

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



Previsão Numérica de Tempo e Clima

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

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



Previsão Numérica de Tempo e Clima

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

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$$\begin{aligned} & \frac{\partial(\bar{u}_3)}{\partial t} + (\bar{u}_1) \frac{\partial(\bar{u}_3)}{\partial x_1} + (\bar{u}_2) \frac{\partial(\bar{u}_3)}{\partial x_2} + (\bar{u}_3) \frac{\partial(\bar{u}_3)}{\partial x_3} + \frac{1}{\rho_0} \frac{\partial(\bar{P})}{\partial x_3} + g \frac{\bar{\rho}}{\rho_0} \delta_{33} + 2\Omega \varepsilon_{311} \eta_1(\bar{u}_1) + 2\Omega \varepsilon_{322} \eta_2(\bar{u}_2) + 2\Omega \varepsilon_{333} \eta_3(\bar{u}_3) \\ & + 2\Omega \varepsilon_{311} \eta_1(\bar{u}_1) + 2\Omega \varepsilon_{322} \eta_2(\bar{u}_2) + 2\Omega \varepsilon_{333} \eta_3(\bar{u}_3) + 2\Omega \varepsilon_{311} \eta_1(\bar{u}_1) + 2\Omega \varepsilon_{322} \eta_2(\bar{u}_2) + 2\Omega \varepsilon_{333} \eta_3(\bar{u}_3) - \nu \frac{\partial^2(\bar{u}_3)}{\partial x_1^2} - \nu \frac{\partial^2(\bar{u}_3)}{\partial x_2^2} \\ & - \nu \frac{\partial^2(\bar{u}_3)}{\partial x_3^2} = - \frac{\partial(\bar{u}_1' u_3')}{\partial x_1} - \frac{\partial(\bar{u}_2' u_3')}{\partial x_2} - \frac{\partial(\bar{u}_3' u_3')}{\partial x_3} \end{aligned}$$

$$+ 2\Omega \varepsilon_{33k} \eta_3(\bar{u}_k) = 0$$

$$2\Omega \varepsilon_{313} \eta_1(\bar{u}_3) = 0$$

$$2\Omega \varepsilon_{33k} \eta_3(\bar{u}_k) = 0$$

$$\begin{aligned} & \frac{\partial(\bar{u}_3)}{\partial t} + (\bar{u}_1) \frac{\partial(\bar{u}_3)}{\partial x_1} + (\bar{u}_2) \frac{\partial(\bar{u}_3)}{\partial x_2} + (\bar{u}_3) \frac{\partial(\bar{u}_3)}{\partial x_3} + \frac{1}{\rho_0} \frac{\partial(\bar{P})}{\partial x_3} + g \frac{\bar{\rho}}{\rho_0} \delta_{33} - \nu \frac{\partial^2(\bar{u}_3)}{\partial x_1^2} - \nu \frac{\partial^2(\bar{u}_3)}{\partial x_2^2} - \nu \frac{\partial^2(\bar{u}_3)}{\partial x_3^2} \\ & = - \frac{\partial(\bar{u}_1' u_3')}{\partial x_1} - \frac{\partial(\bar{u}_2' u_3')}{\partial x_2} - \frac{\partial(\bar{u}_3' u_3')}{\partial x_3} \end{aligned}$$



Previsão Numérica de Tempo e Clima

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

$$\begin{aligned} & \frac{\partial(\bar{u}_3)}{\partial t} + (\bar{u}_1) \frac{\partial(\bar{u}_3)}{\partial x_1} + (\bar{u}_2) \frac{\partial(\bar{u}_3)}{\partial x_2} + (\bar{u}_3) \frac{\partial(\bar{u}_3)}{\partial x_3} + \frac{1}{\rho_0} \frac{\partial(\bar{P})}{\partial x_3} + g \frac{\bar{\rho}}{\rho_0} - \nu \frac{\partial^2(\bar{u}_3)}{\partial x_1^2} - \nu \frac{\partial^2(\bar{u}_3)}{\partial x_2^2} - \nu \frac{\partial^2(\bar{u}_3)}{\partial x_3^2} \\ &= - \frac{\partial(\overline{u_1' u_3'})}{\partial x_1} - \frac{\partial(\overline{u_2' u_3'})}{\partial x_2} - \frac{\partial(\overline{u_3' u_3'})}{\partial x_3} \end{aligned}$$

Equação governante para o escoamento Vertical

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



Previsão Numérica de Tempo e Clima

Equações governantes para o escoamento atmosférico

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

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

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



Previsão Numérica de Tempo e Clima

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

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

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

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

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

$$\begin{aligned} u_3 &= w \\ x_3 &= z \\ \nu \frac{\partial^2(\bar{u}_3)}{\partial x_3^2} &\cong 0 \end{aligned}$$



- 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

$$(\bar{T}) \quad (\bar{q}) \quad (\bar{u}) \quad (\bar{v}) \quad (\bar{w})$$

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

- A CLP transfere calor, umidade e momentum

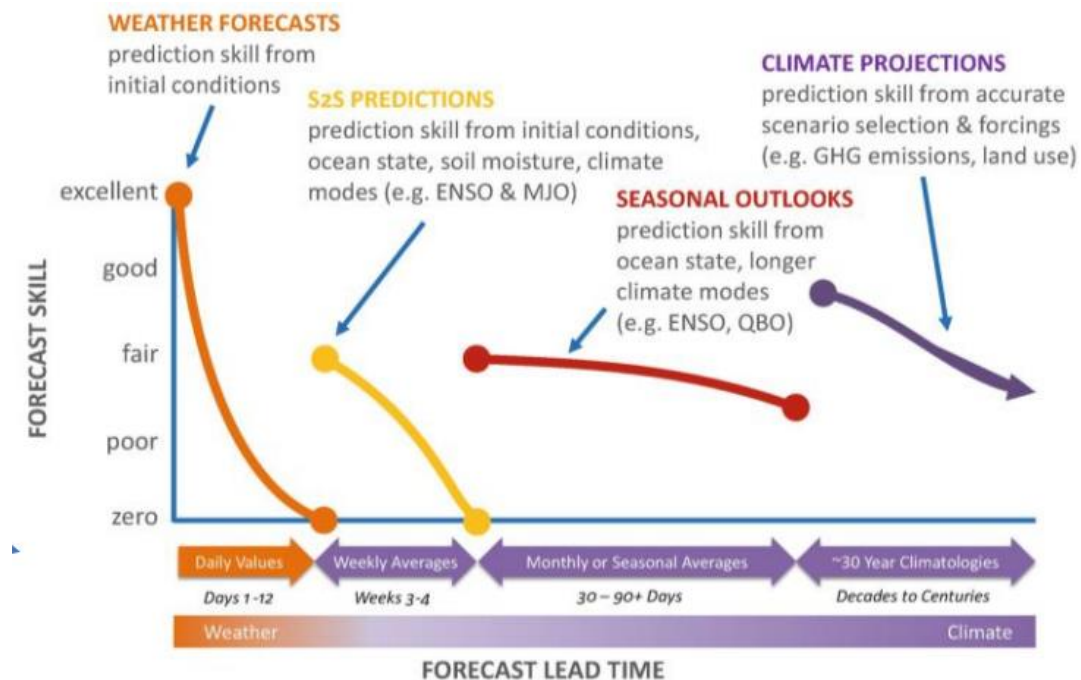
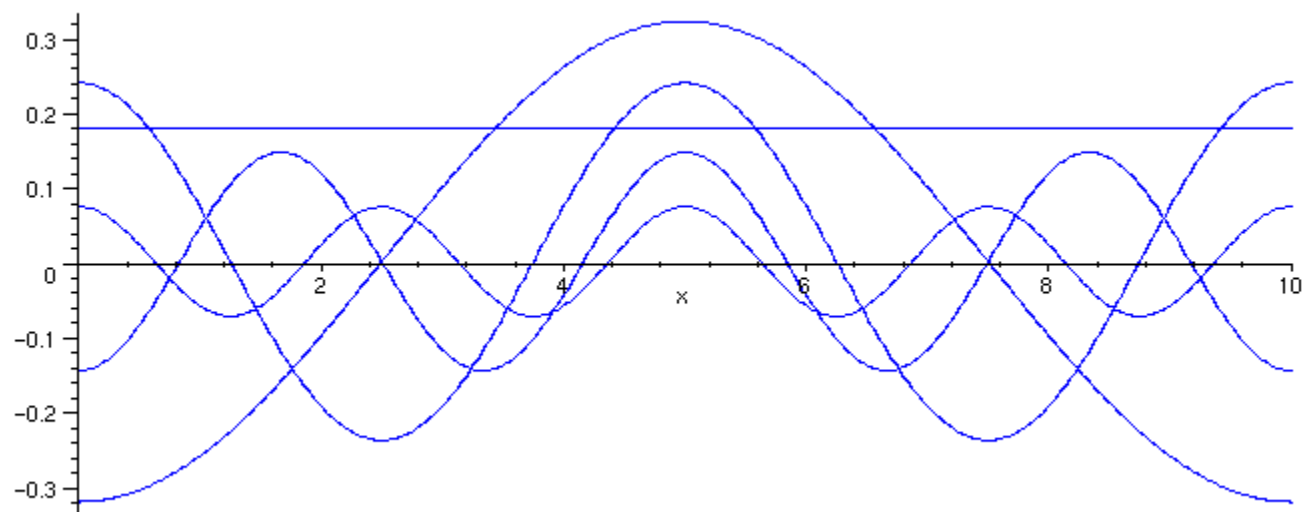
$$\frac{\partial(\overline{w'T'})}{\partial z} \quad \frac{\partial(\overline{w'q'})}{\partial z} \quad \frac{\partial(\overline{w'u'})}{\partial z} \quad \frac{\partial(\overline{w'v'})}{\partial z}$$



Previsão Numérica de Tempo e Clima



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





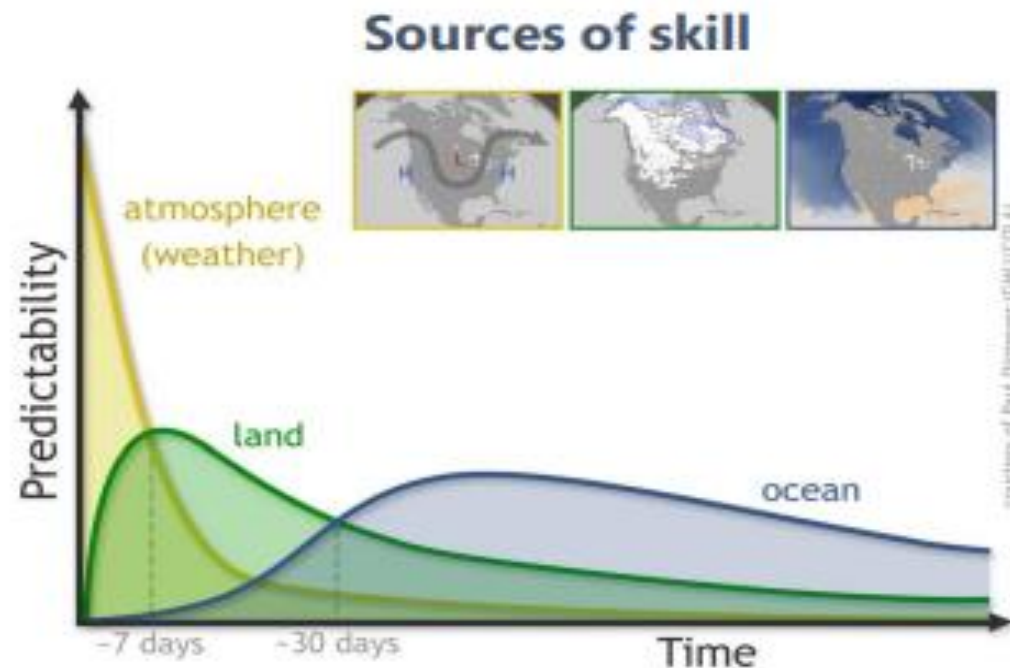
- Exemplos:
 - Em 24 horas a evapotranspiração na superfície pode incrementar o conteúdo da umidade na CLP em 25%, o qual pode ser uma fonte importante de umidade para o desenvolvimento de ciclones tropicais
 - Também, o fluxo de calor (aquecimento) superficial (principalmente em superfícies úmidas)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



Previsão Numérica de Tempo e Clima



- Fluxos superficiais são importantes no armazenamento 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** ($\sim 50\text{m}$) 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

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

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

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

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

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

$$\begin{aligned} u_3 &= w \\ x_3 &= z \\ \nu \frac{\partial^2(\bar{u}_3)}{\partial x_3^2} &\cong 0 \end{aligned}$$



Previsão Numérica de Tempo e Clima

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\delta_{i3}g + f_c \varepsilon_{ij3} \bar{u}_j - \frac{1}{\bar{\rho}} \frac{\partial \bar{P}}{\partial x_i} + \frac{\nu \partial^2 \bar{u}_i}{\partial x_j^2} - \frac{\partial (\overline{u'_i u'_j})}{\partial x_j}$$

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

$$\frac{\partial \bar{u}_i}{\partial t} = \frac{\partial \overline{u'_i u'_j}}{\partial x_j}$$

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

**Teoria do
transporte
gradiente ou
teoria K**

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



Previsão Numérica de Tempo e Clima

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

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

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

$$\frac{\partial \bar{u}_i}{\partial t} = \frac{\partial}{\partial x_j} \left(\mathbf{K}(\mathbf{z}) \frac{d\varphi}{dz} \right)$$

Desprezando a variação dos fluxos na horizontal.

$$\frac{\partial \bar{u}}{\partial t} = \mathbf{K}(\mathbf{z}) \frac{\partial}{\partial z} \left(\frac{d\varphi}{dz} \right) + \frac{\partial \mathbf{K}(\mathbf{z})}{\partial z} \left(\frac{d\varphi}{dz} \right)$$

$\mathbf{K} = \mathbf{K}(z, \text{estabilidade, nebulosidade, radiação, turbulencia, etc})$



Qual a importância numérica da PBL nos MCGAs?

**Como Parametrizar os Fluxos
Turbulentos na camada limite
superficial**



Previsão Numérica de Tempo e Clima

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

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

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

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

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

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

$$\begin{aligned} u_3 &= w \\ x_3 &= z \\ \nu \frac{\partial^2(\bar{u}_3)}{\partial x_3^2} &\cong 0 \end{aligned}$$



Previsão Numérica de Tempo e Clima

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

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

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

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

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



- 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)

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

Kinematic vertical turbulent momentum flux ($\text{m}^2 \text{s}^{-2}$) (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 ($\text{kg m}^{-2} \text{s}^{-1}$) (8.6)

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

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

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



Previsão Numérica de Tempo e Clima

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

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

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

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

$$-C\phi_{j-1}^{n+1} + (1+C)\phi_j^{n+1} = \phi_j^n$$

$$\begin{pmatrix} 1+C & 0 & 0 & 0 & 0 & 0 & -C \\ -C & 1+C & 0 & 0 & 0 & 0 & 0 \\ 0 & -C & 1+C & 0 & 0 & 0 & 0 \\ 0 & 0 & -C & 1+C & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & -C & 1+C & 0 \\ 0 & 0 & 0 & 0 & 0 & -C & 1+C \end{pmatrix} \begin{pmatrix} \phi_1^{n+1} \\ \phi_2^{n+1} \\ \phi_3^{n+1} \\ \phi_4^{n+1} \\ \vdots \\ \phi_{j-2}^{n+1} \\ \phi_{j-1}^{n+1} \end{pmatrix} = \begin{pmatrix} \phi_1^n \\ \phi_2^n \\ \phi_3^n \\ \phi_4^n \\ \vdots \\ \phi_{j-2}^n \\ \phi_{j-1}^n \end{pmatrix}$$



- A equação anterior complica a solução e adiciona termos desconhecidos
- Porém nos fornece algumas informações diagnósticas
- 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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$$\overline{w'q'_v} = \frac{E_f}{\rho_a}$$

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

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

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

$$H = \rho_a c_{pd} K_h \frac{\partial \bar{\theta}_v}{\partial z}$$

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

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



- Da mesma forma para o fluxo de umidade

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

- Onde $\mathbf{K}(\mathbf{z})$ é a difusividade turbulenta para φ



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

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

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:

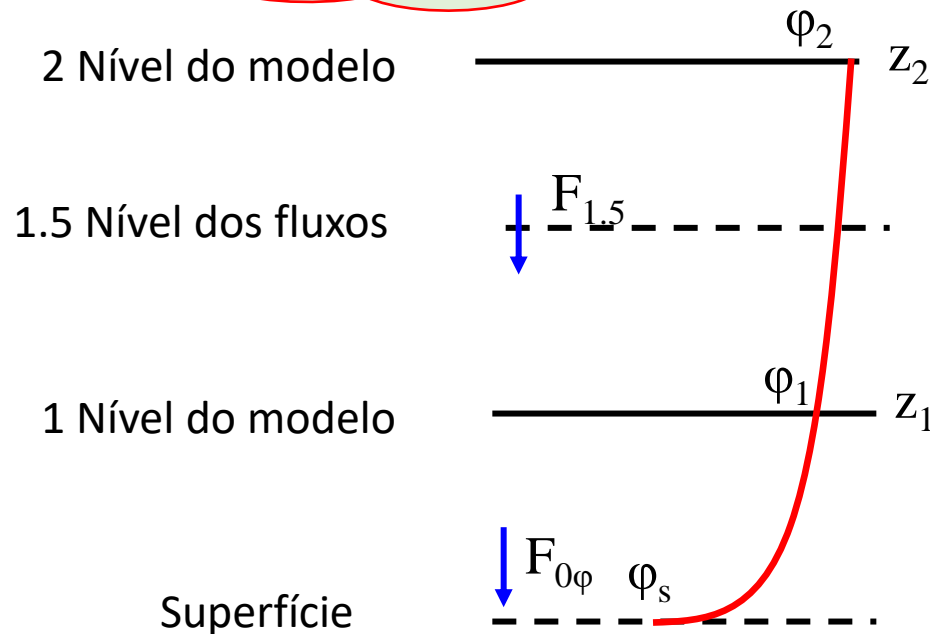
$$\varphi_1 - \varphi_s \approx \frac{F_0}{\rho} \int_{z_{0\varphi}}^{z_1} \frac{1}{K(z)} dz$$

Escoamento
neutro: $K(z) = \kappa z u_*$

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

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

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



u, v, T, q



Previsão Numérica de Tempo e Clima

Coeficientes de difusão de acordo com a similaridade MO

Conceito Básico de um modelo PBL

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

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



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

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

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



- 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



Previsão Numérica de Tempo e Clima

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

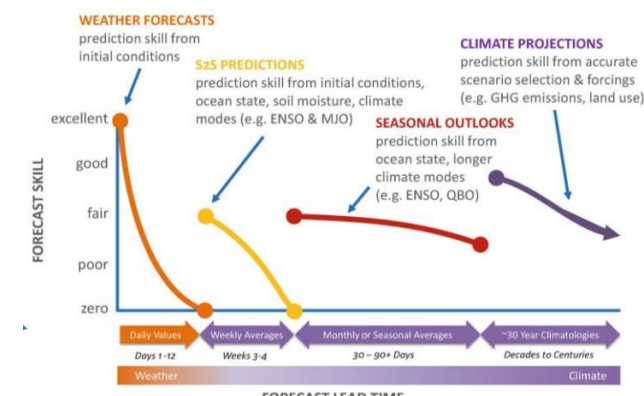
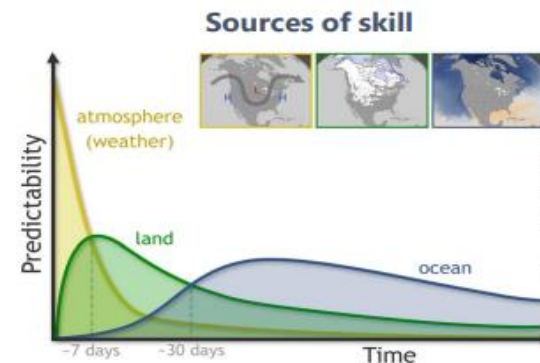
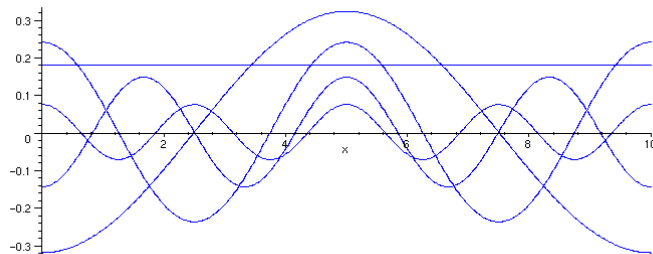
$K(z, \text{estabilidade, nebulosidade, radiação, turbulencia, etc})$

$K=K(z, \text{estabilidade, nebulosidade, radiação, turbulencia, etc})??????$

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





Desacoplamento das equações prognóstica da PBL e a Superfície

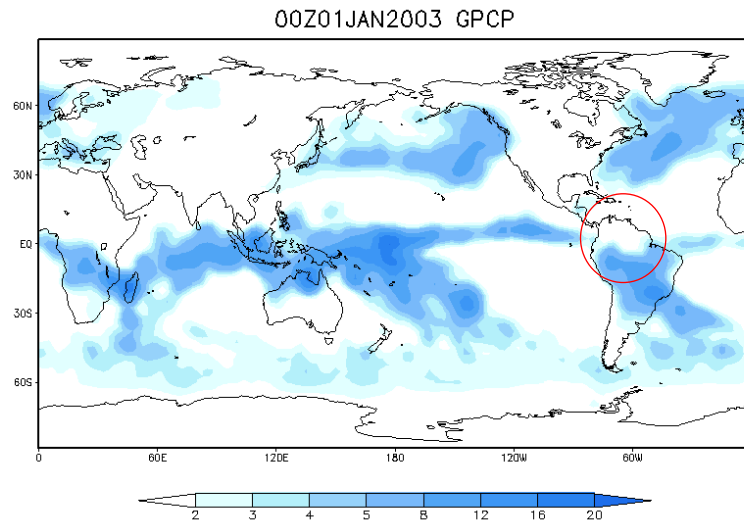


“ACOPLAMENTO” DO MCGA-CPTEC COM O IBIS “Precipitação”

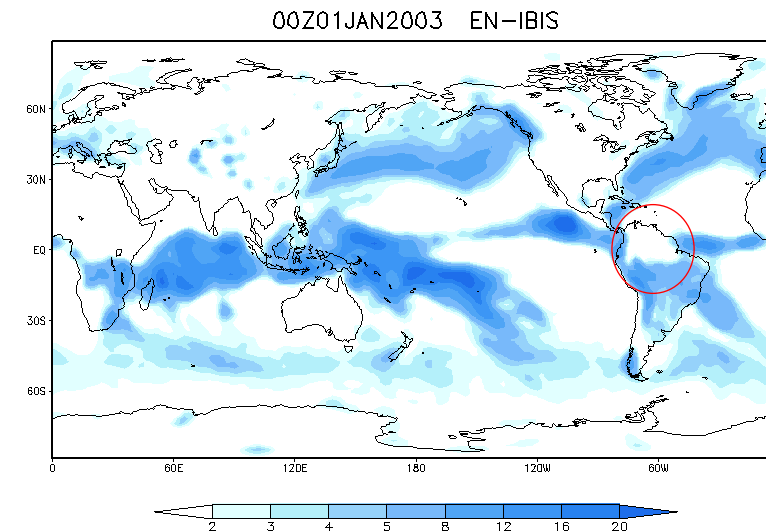
$$K_h = w_1 K_{h_{MY}} + w_2 K_{h_{TKE}} + w_3 K_{h_{HB}}$$

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

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.