MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

Turbulence parameterization review

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2nd WCRP Summer School on Climate Model
Development:
Scale aware parameterization for representing sub-grid scale processes
January 22nd - 31st, 2018
Cachoeira Paulista - SP, Brazil
CPTEC - INPE

Research interest

Haroldo F. de Campos Velho (LAC-INPE)

Senior Researcher / Scientific computing

RESEARCH FIELDS:

- Scientific computing and Inverse problems
- Data science and data assimilation:

  New method: based on neural network

- Atmospheric turbulence parameterization:

  Some results: Taylor's approach for turbulence in clouds

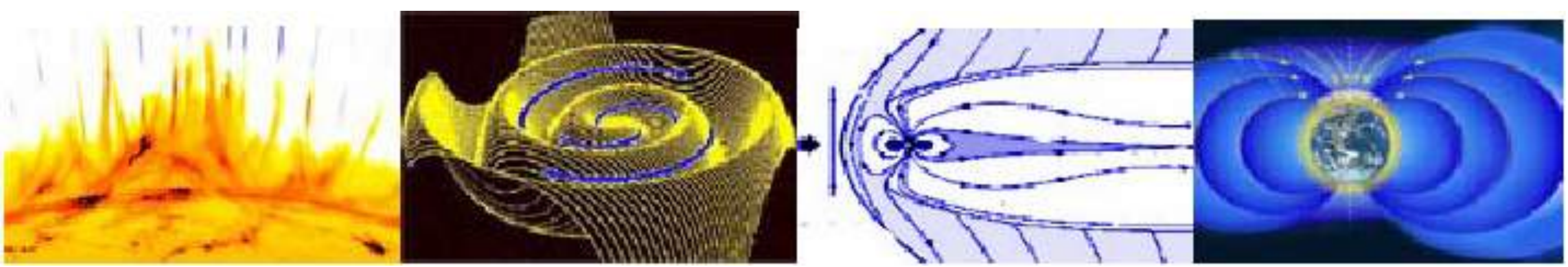
  New model for convective boundary layer growth

  Cosmological evolution as turbulent-like dynamics

Applications: space weather

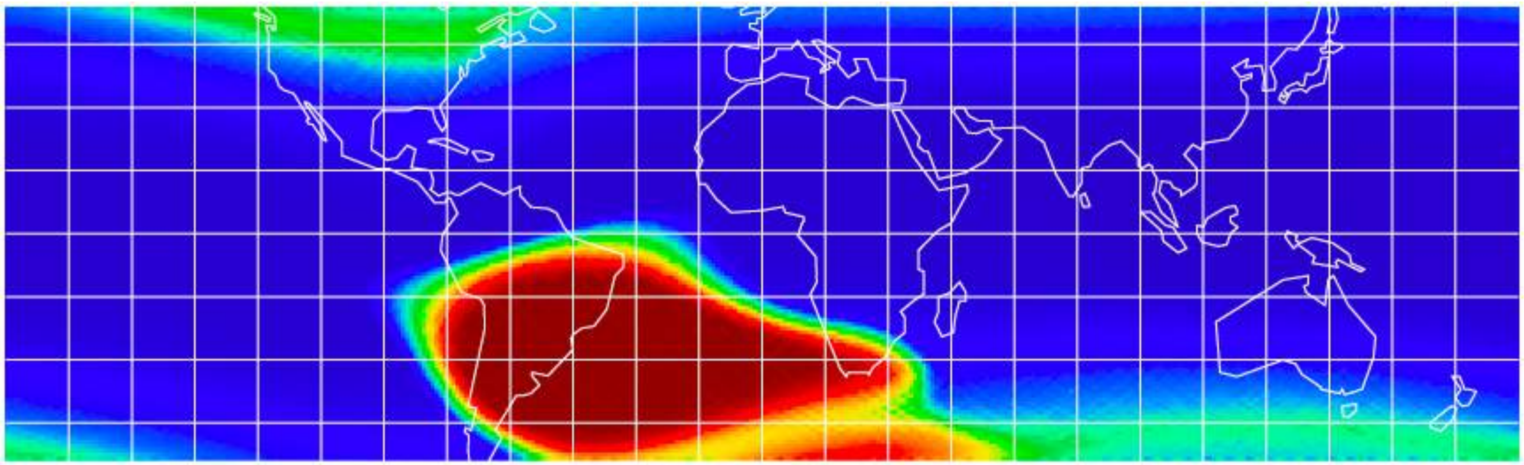
Sun-Earth interaction:

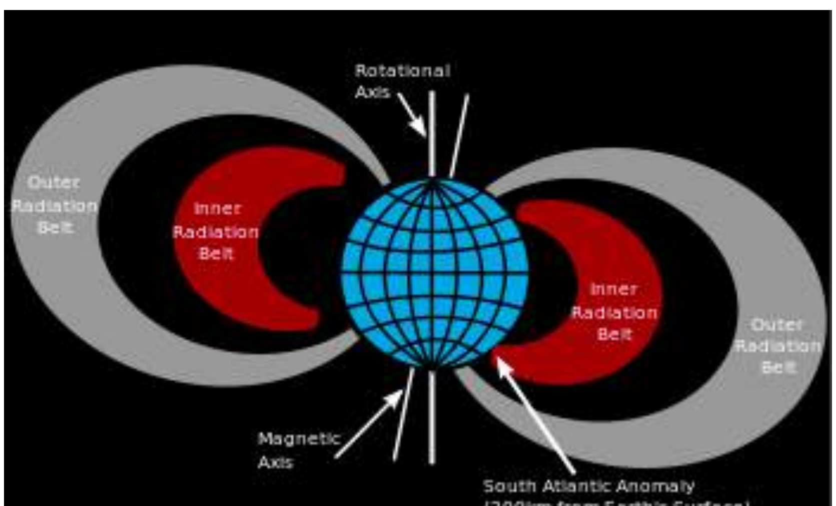
Sun activity	Propagation	Impact on magnetosphere	Perturbing ionosphere



Applications: space weather

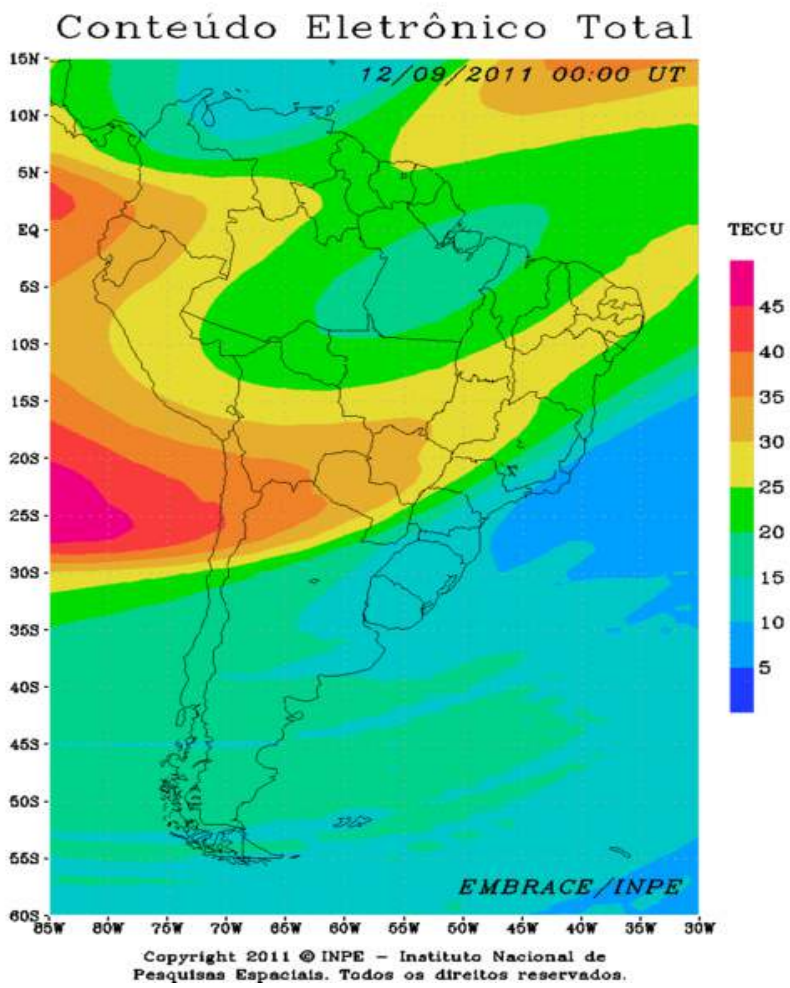
SAA: South Atlantic Anomaly





Figures from the wikipedia

Applications: space weather



Prediction 24 h:

SUPIM model

TEC: Total Electronic Content

SUPIM: Space weather prediction

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 54 (2014) 22–36

Advances in Space Research
(a COSPAR publication)

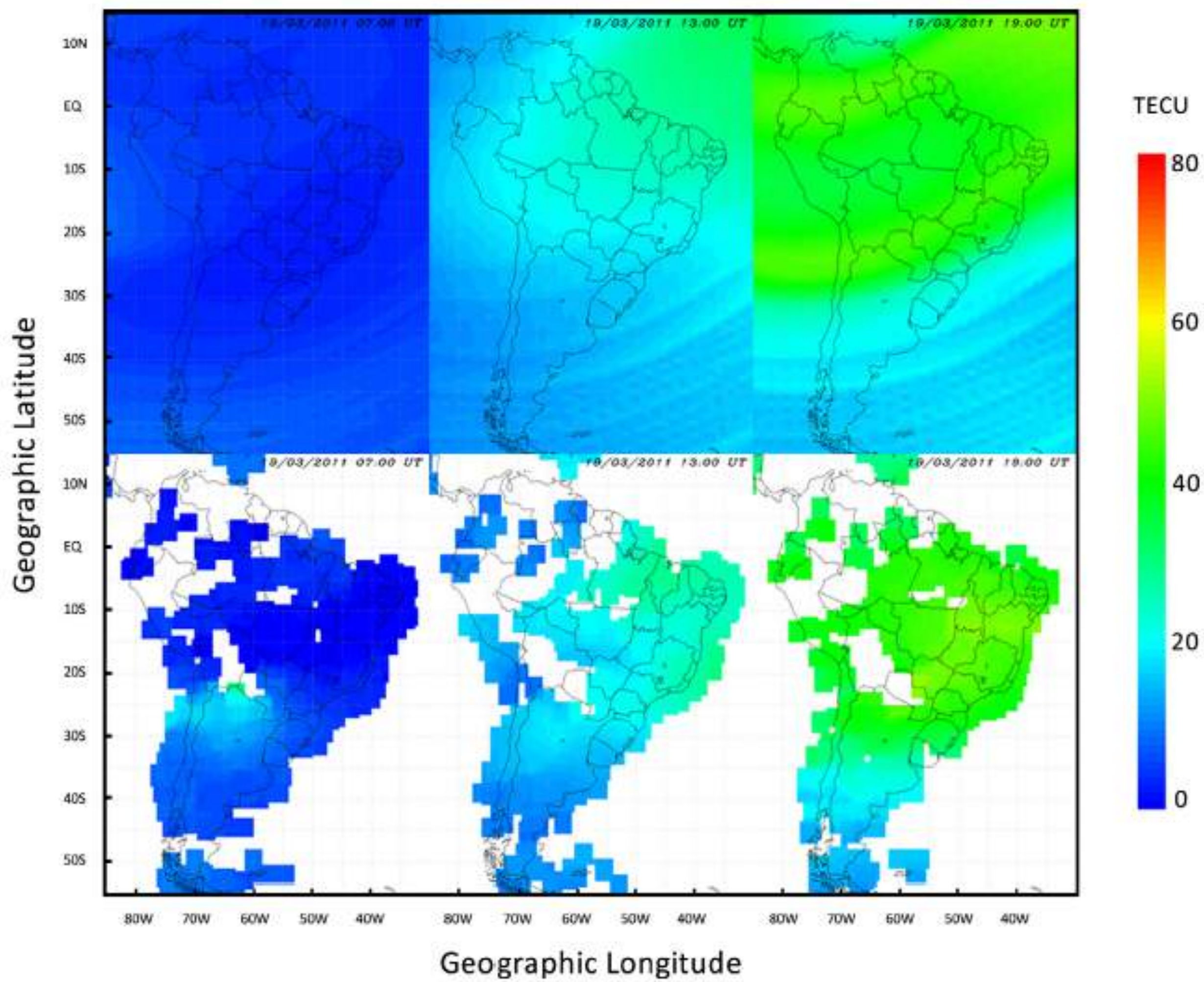
www.elsevier.com/locate/asr

First results of operational ionospheric dynamics prediction for the Brazilian Space Weather program

Adriano Petry [a,*], Jonas Rodrigues de Souza [b,1], Haroldo Fraga de Campos Velho [c,2], André Grahl Pereira [d,3], Graham John Bailey [e]

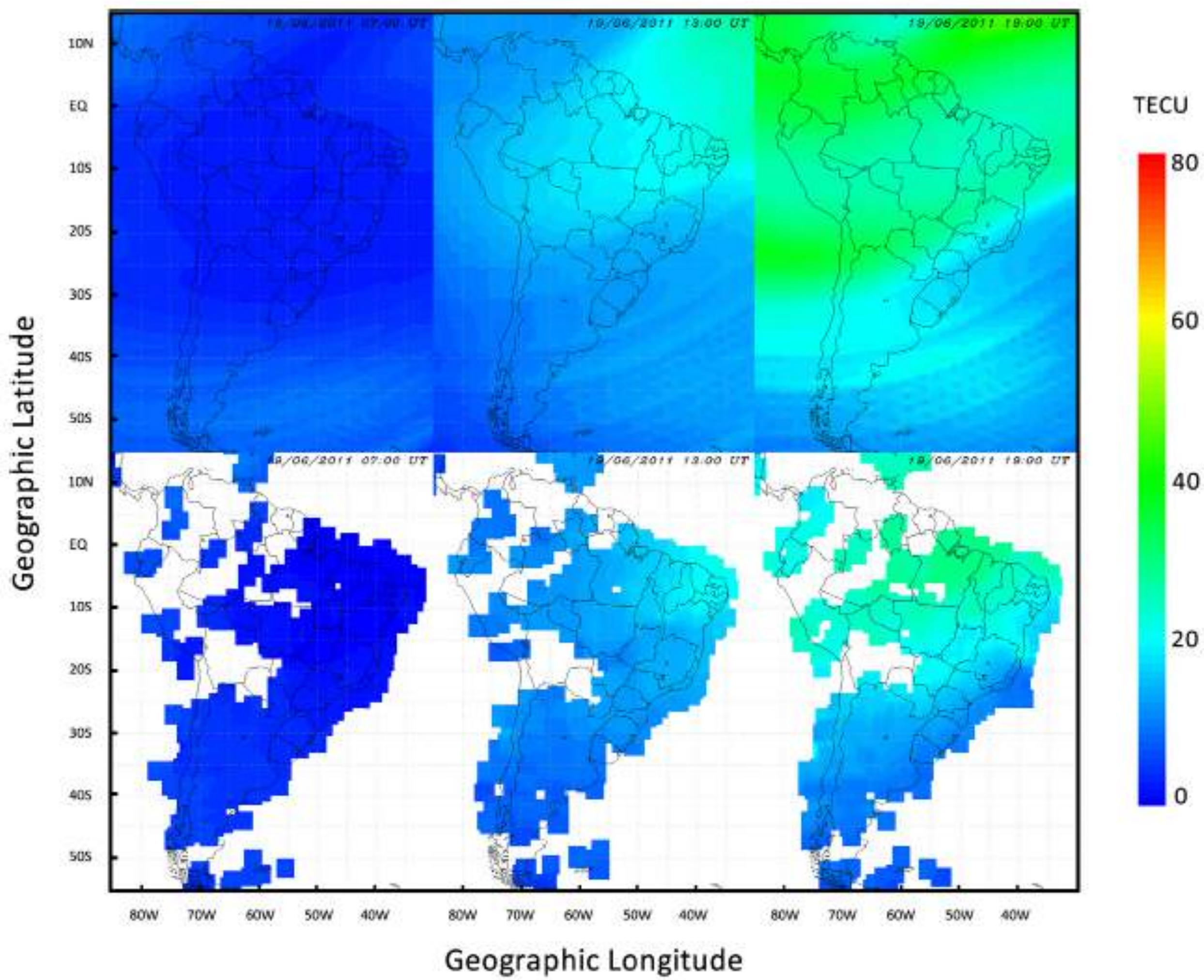
SUPIM: Space weather prediction

- 7, 13, 19 UT: March 19th, 2011



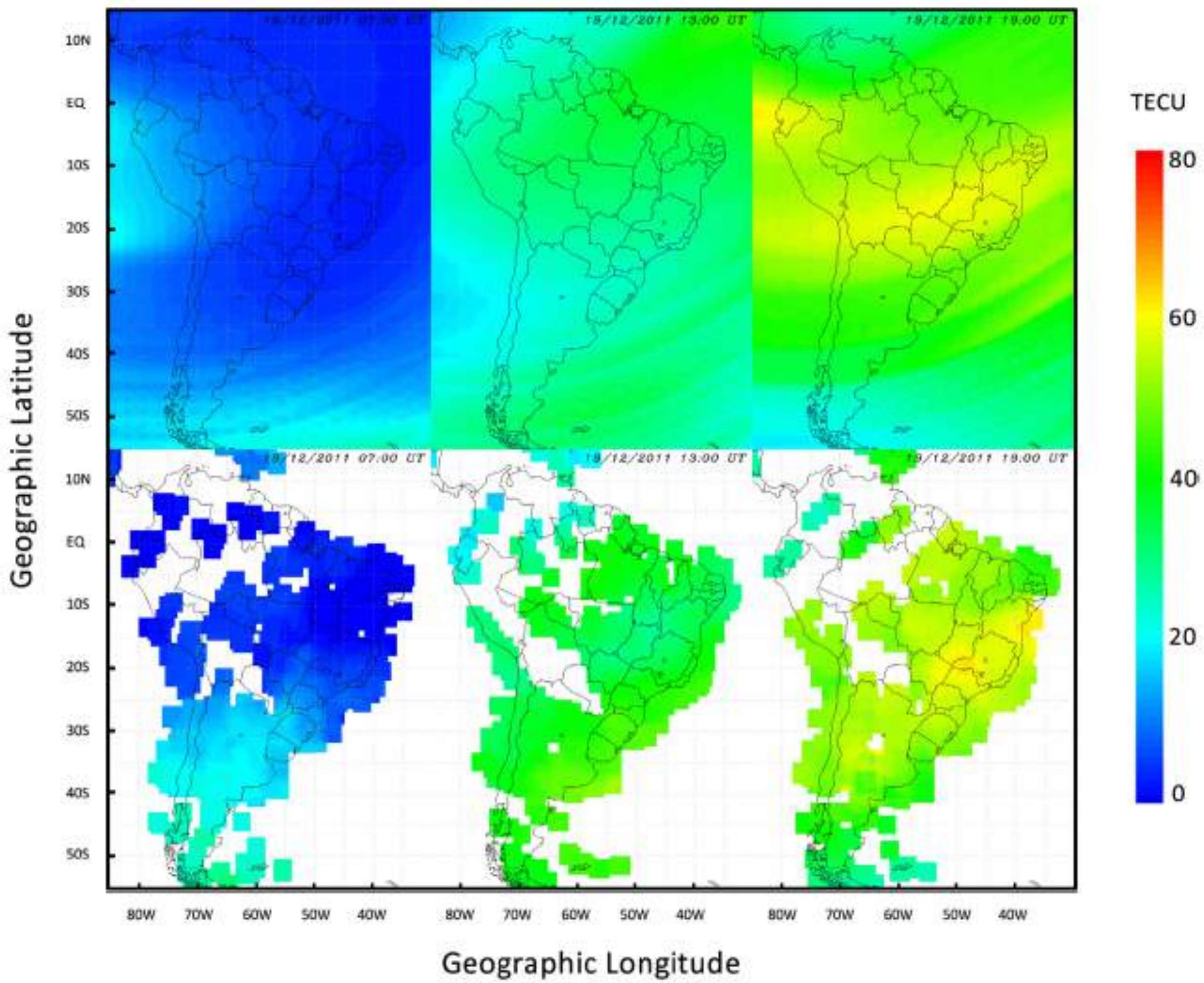
SUPIM: Space weather prediction

- 7, 13, 19 UT: June 19th, 2011



SUPIM: Space weather prediction

- 7, 13, 19 UT: December 19th, 2011



Atmospheric turbulence modeling

- Planetary boundary layer representation
  - Application to the atmospheric numerical models
  - Application to the turbulence inside the clouds
  - Transition boundary layers parameterization
  - Intermittency parameterization
  - Cosmological evolution: turbulent dynamics?

NOTAS EM MATEMÁTICA APLICADA

Esta série tem como objetivo a publicação de textos expositivos que tanto podem resultar de pesquisas quanto de cursos, seminários ou eventos científicos patrocinados pela SBMAC.

Em especial, os textos dos minicursos, tradicionalmente ministrados no Congresso Nacional de Matemática Aplicada e Computacional, serão publicados nesta série.

Sociedade Brasileira de Matemática Aplicada e Computacional SBMAC

FAPESP

CAPES

CNPq

Volume 48

MODELAGEM MATEMÁTICA EM TURBULÊNCIA ATMOSFÉRICA

Campos Velho

SBMAC

Volume 48

ISSN 2175-3385

MODELAGEM MATEMÁTICA EM TURBULÊNCIA ATMOSFÉRICA

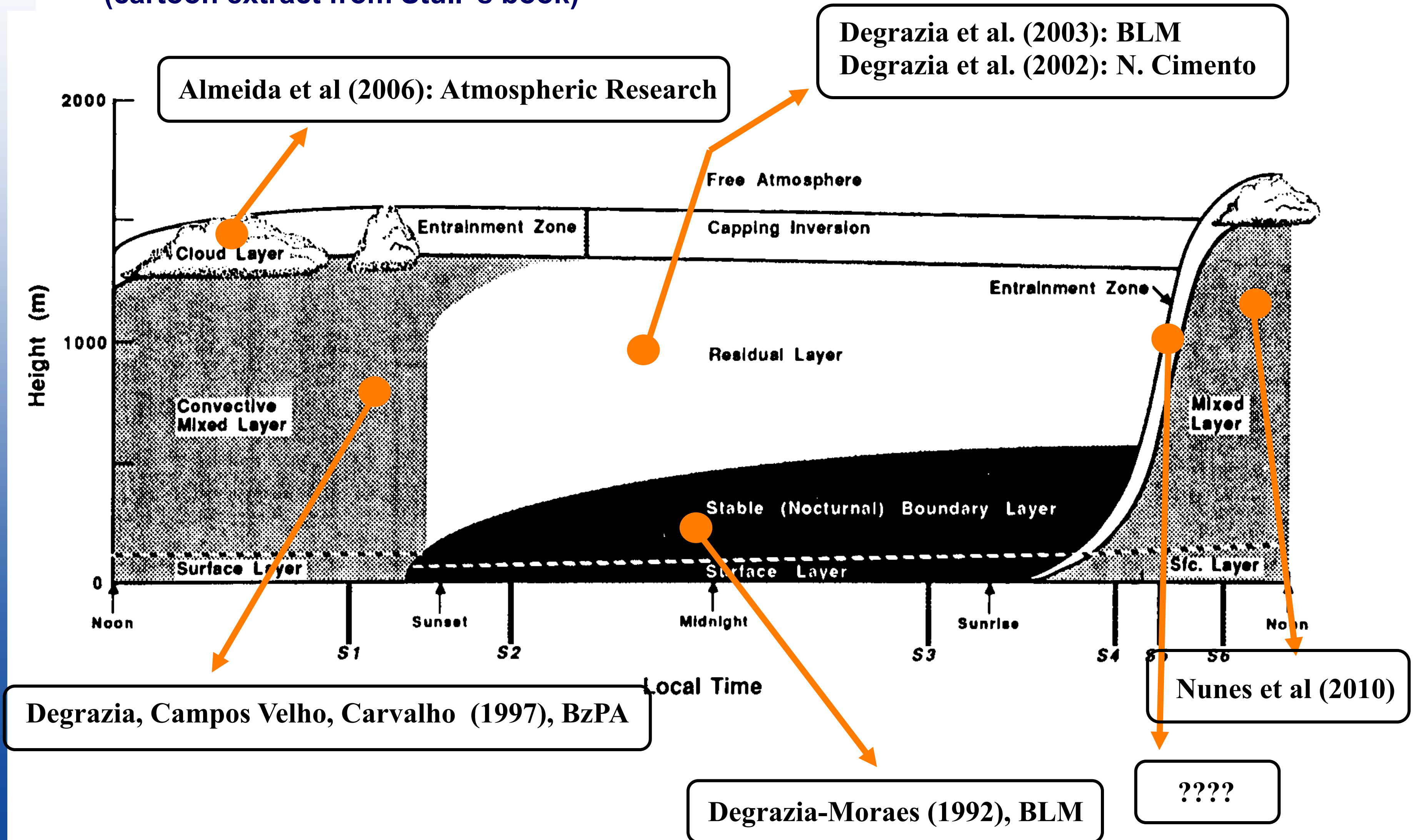
NOTAS EM MATEMÁTICA APLICADA

Uma publicação da Sociedade Brasileira de Matemática Aplicada e Computacional SBMAC

Haroldo Fraga de Campos Velho

Sketch of physical processes on the atmospheric boundary layer

(cartoon extract from Stull’s book)



Application of G. I. Taylor theory on PBL

PERGAMON

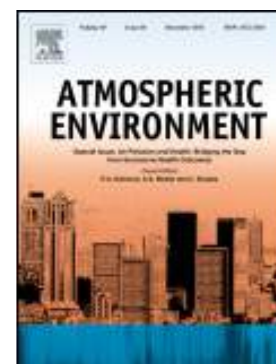
Atmospheric Environment 34 (2000) 3575–3583

ATMOSPHERIC ENVIRONMENT

www.elsevier.com/locate/atmosenv

Turbulence parameterisation for PBL dispersion models in all stability conditions

G.A. Degrazia[a,*], D. Anfossi[b], J.C. Carvalho[c], C. Mangia[d], T. Tirabassi[e], H.F. Campos Velho[f]



STABLE BOUNDARY LAYER (SBL)

$$\frac{K_{zz}}{u_* h} = \frac{0.32(1 - z/h)^{\alpha_1/2}(z/h)}{1 + 3.7(z/\Lambda)}$$

$$\frac{\Lambda}{L_{MO}} = \left(1 - \frac{z}{h}\right)^{3\alpha_1/2+\alpha_2} .$$

CONVECTIVE BOUNDARY LAYER (CBL)

$$\frac{K_{zz}}{w_* h} = 0.15\,\Psi^{1/3}\left[1 - \exp\left(-4\,\frac{z}{h}\right) - 0.0003\exp\left(8\,\frac{z}{h}\right)\right]$$

Implementation of New Turbulence Parameterization in the B-RAMS

Joice Parmezani Staben Barbosa[1] Haroldo Fraga de Campos Velho[1]
Saulo Ribeiro de Freitas[2]

[1]Associated Laboratory for Computing and Applied Mathematics - LAC/INPE

[2]Center for Weather Forecasting and Climate Studies - CPTEC/INPE

V Brazilian Micrometeorology Workshop
12 to 14 December - UFSM

Brazilian Regional Atmospheric Model System – BRAMS

An atmospheric model able for simulating several types of the atmospheric flows, from large scale circulations up to microscale.

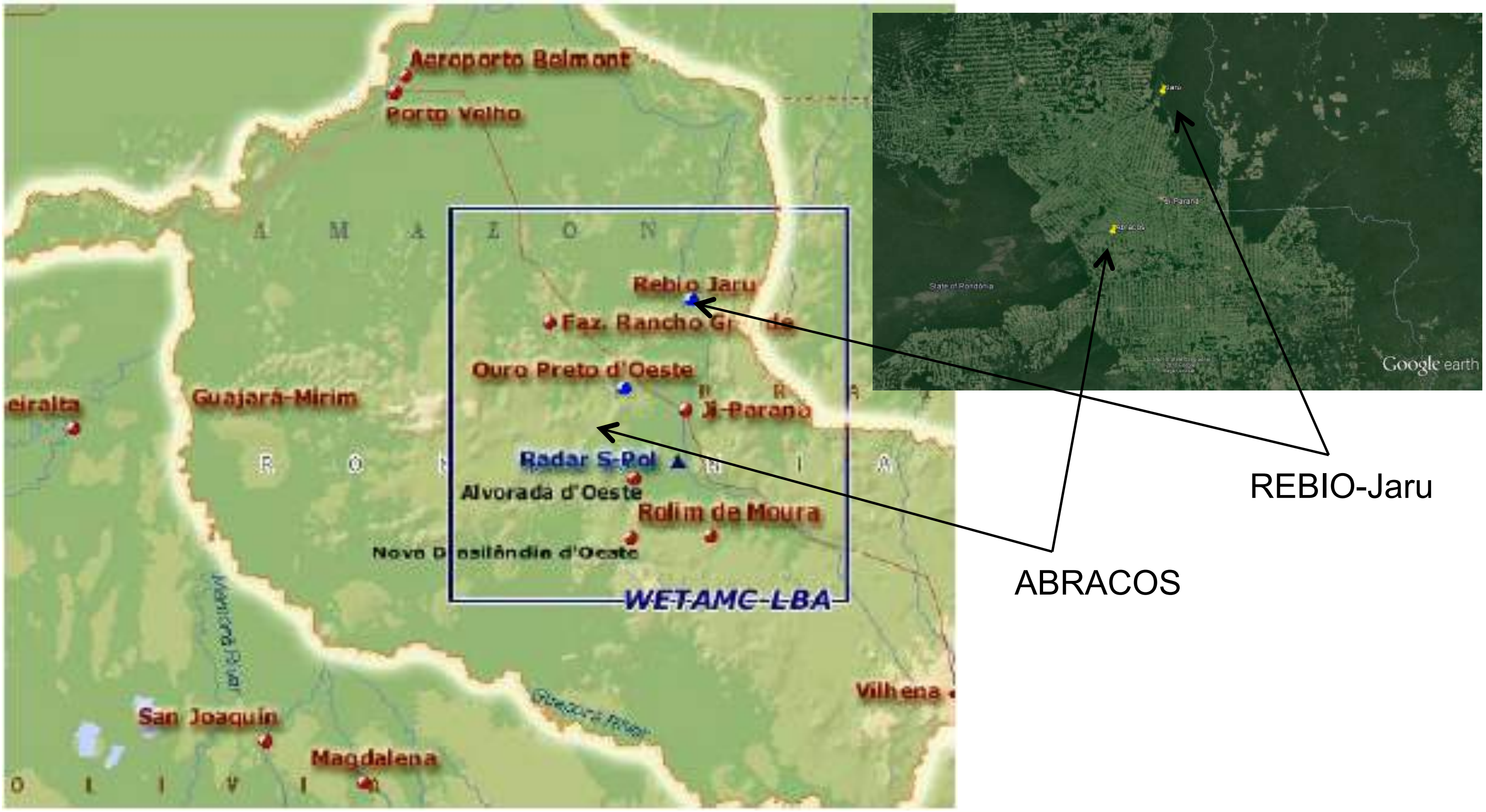
Starting its development at 70's:

Mesoscale model (Pielke,1974)
Model of clouds (Trípoli e Cotton, 1982)

RAMS first version (1986) ⇒ Department of Atmospheric Sciences
Colorado State University

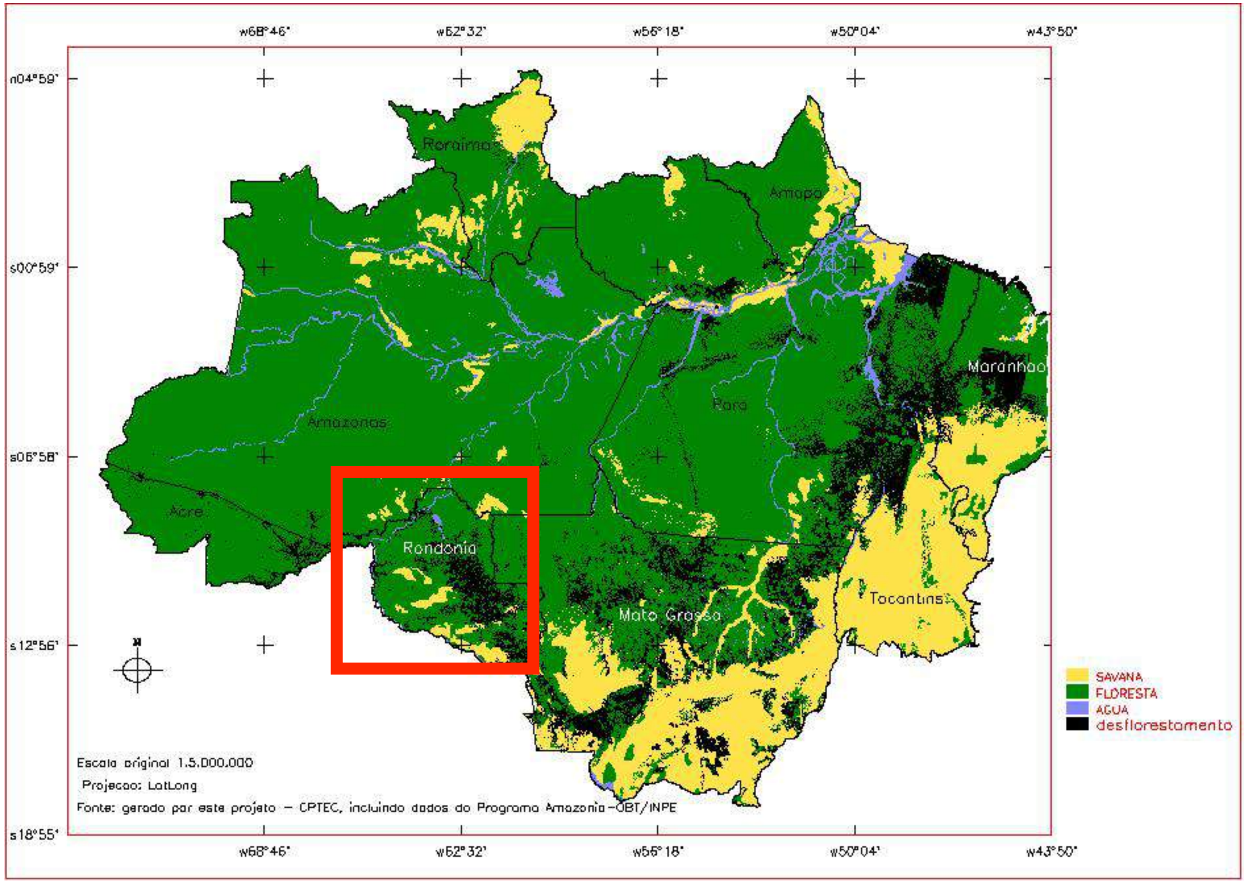
DATA

- Radiosonde ⇒ it was obtained exprerimentally by the WETAMC/LBA project during the period from Jan. up to Feb. 1999.



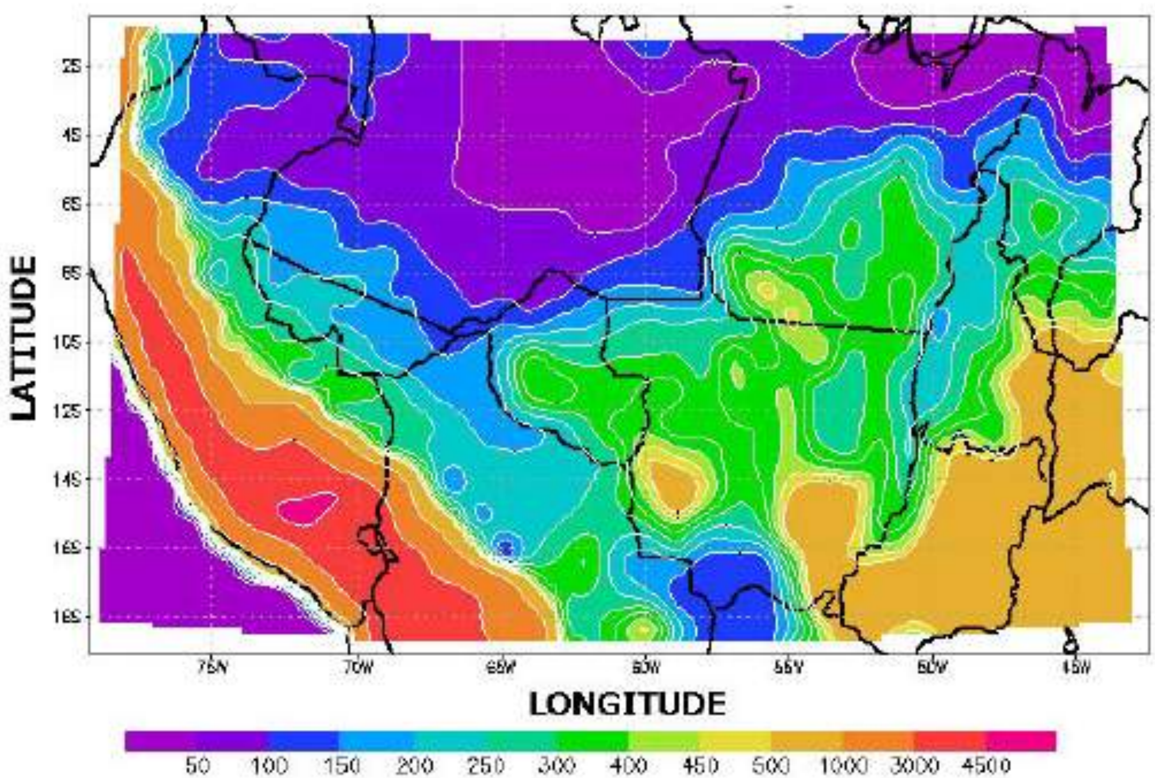
DATA

- Global Analysis ⇒ provided by European Global Model - **ECMWF**.
- Vegetable Coverage ⇒ data from the Proveg/INPE.



DATA

- The adopted period $\Rightarrow$ from Feb 10_{th} $(00UTC)$ up to Feb 12_{th} $(00\ UTC)$ with 48 hs of analysis.



Metodology

Model of initialization $\Rightarrow$ radiosonde data and from the ECMWF data.

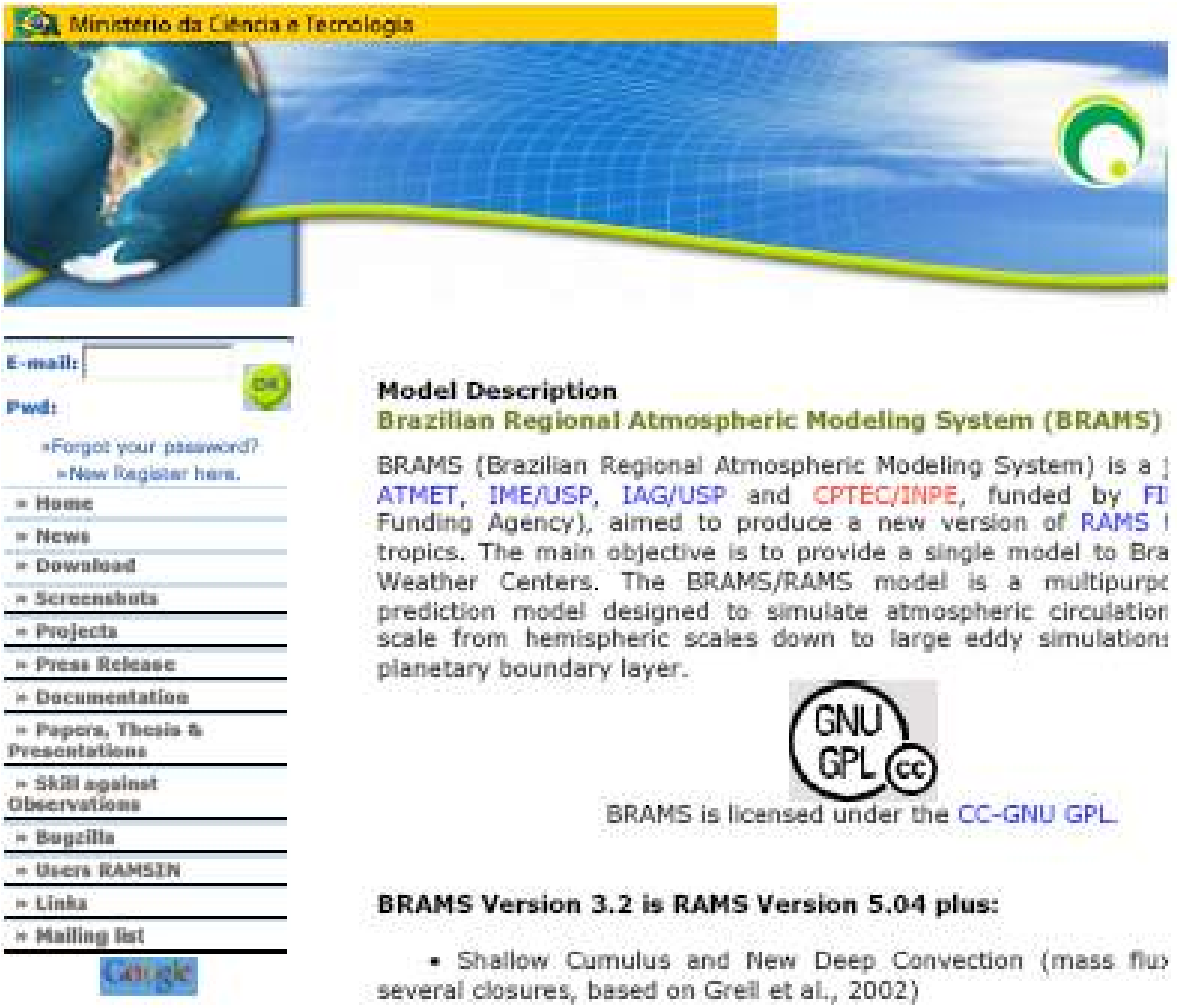
1$^{\text{st}}$ step: perform a simulation that uses two parameterizations of B-RAMS $\Rightarrow$ Mellor - Yamada (1982) and Smagorinsky (1963).

2$^{\text{nd}}$ step: implement the new parameterization of the statistical diffusion Taylor's theory of the turbulence (Degrazia, et al. 2000) in the B-RAMS model, dealing with all atmospheric stability condition.

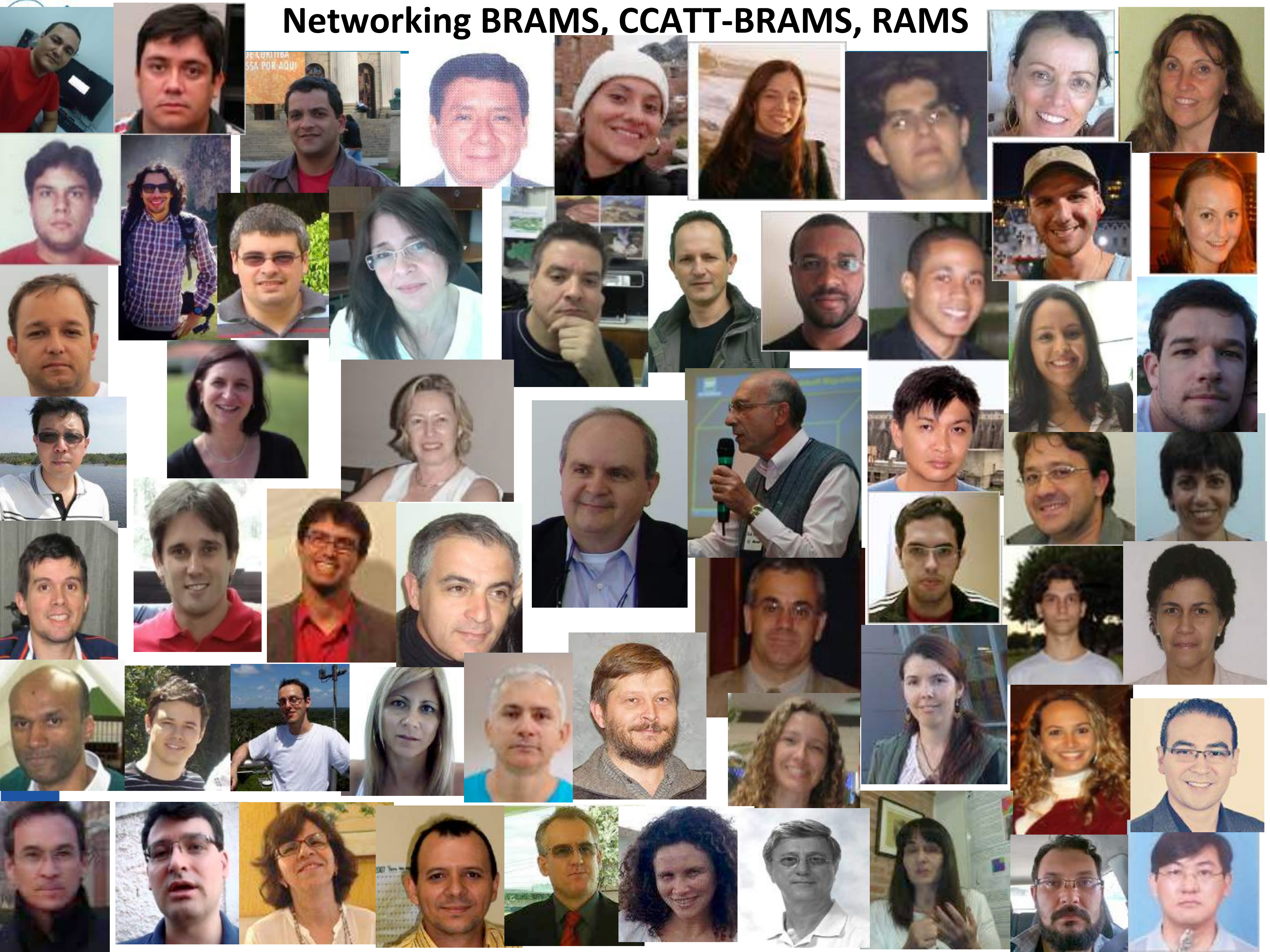
3$^{\text{rd}}$ step: compare the obtained simulations with of radiosonde (at each 3 hs) $\Rightarrow$ WET/AMC Campaign of LBA project in the adopted period $\Rightarrow$ Preliminary Results.

B-RAMS is a free software

http://brams.cptec.inpe.br



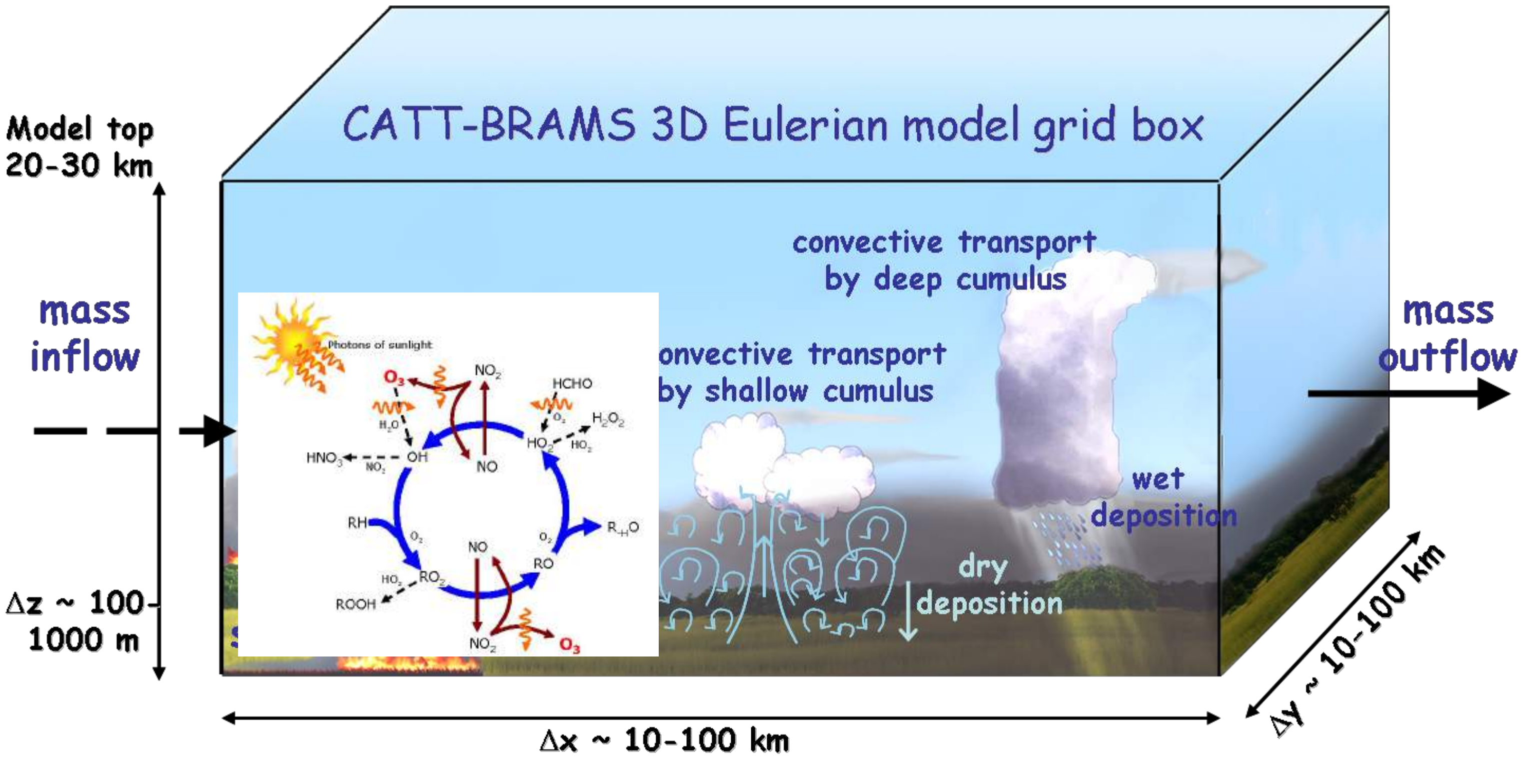
Networking BRAMS, CCATT-BRAMS, RAMS



BRAMS: represented processes

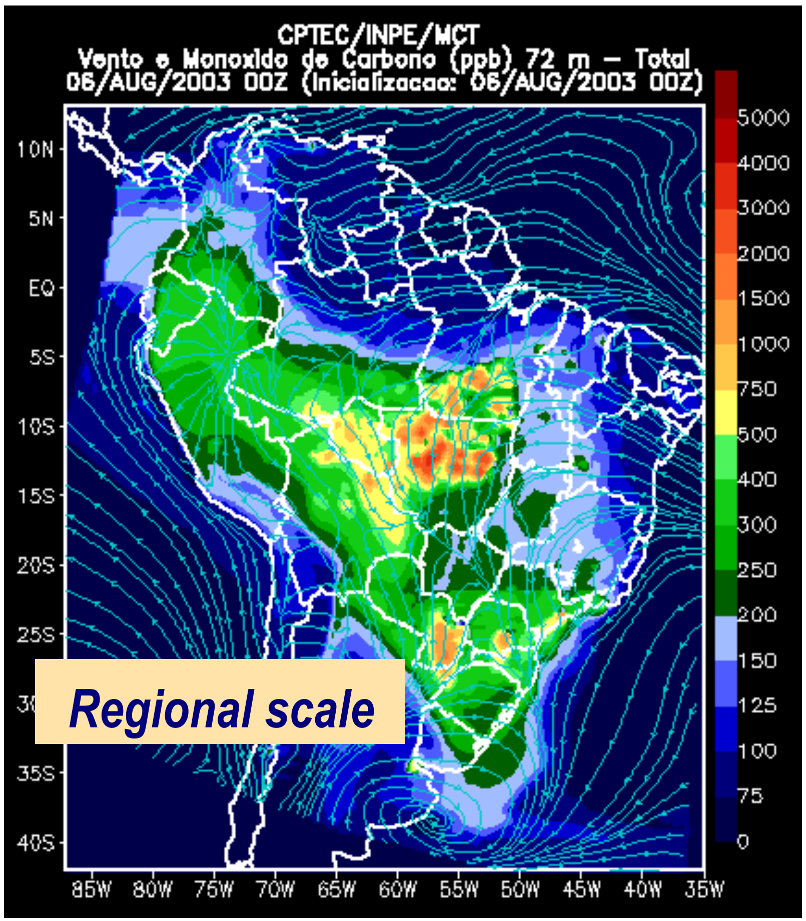
BRAMS: Atmospheric simulation model

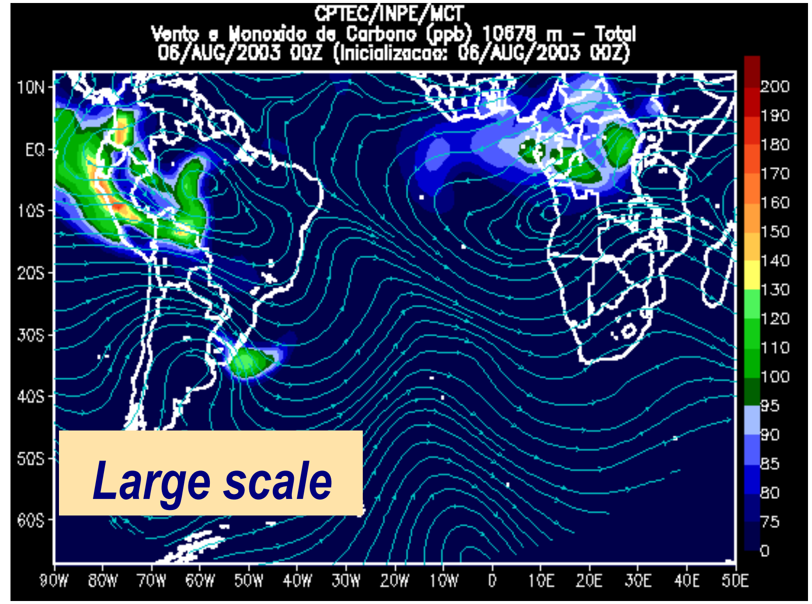
Chemical process

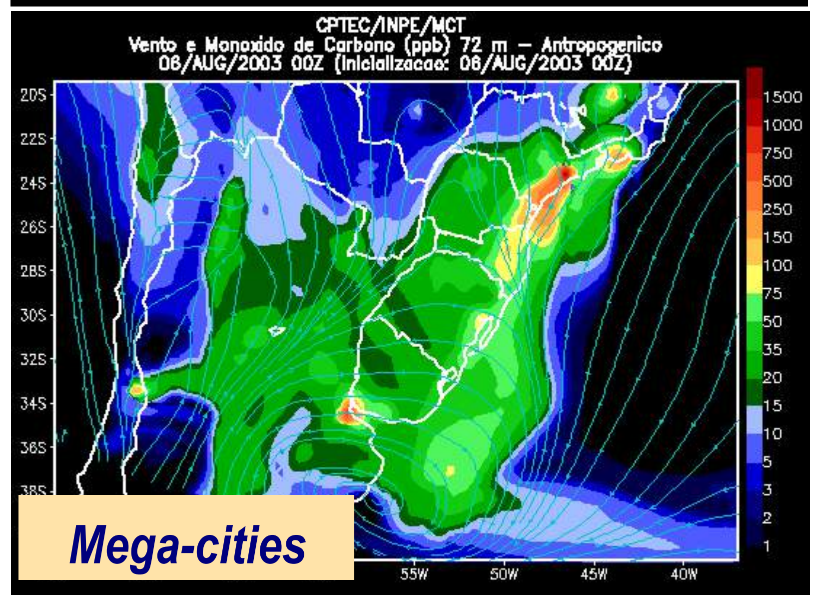


BRAMS environmental prediction

Pollutant emission by forest fires and urban-industries







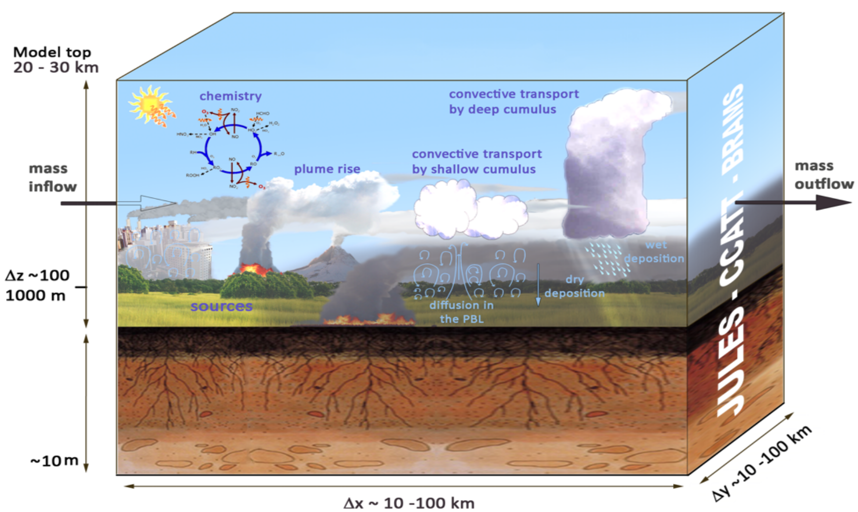
BRAMS – research in progress …

Adv. Geosci., 35, 123–136, 2013
www.adv-geosci.net/35/123/2013/
doi:10.5194/adgeo-35-123-2013

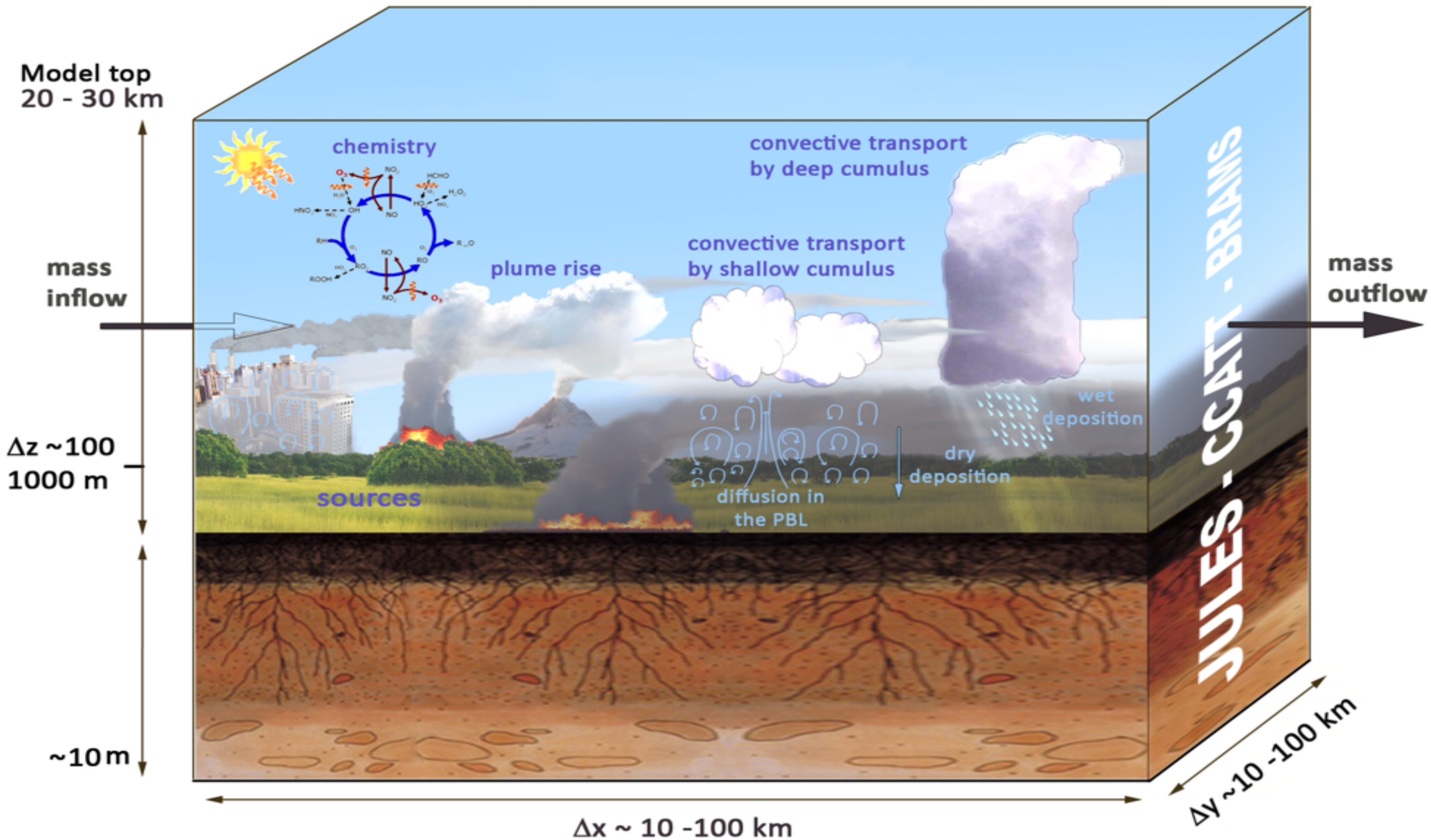
Advances in Geosciences
Open Access

Using the Firefly optimization method to weight an ensemble of rainfall forecasts from the Brazilian developments on the Regional Atmospheric Modeling System (BRAMS)

A. F. dos Santos[1], S. R. Freitas[1], J. G. Z. de Mattos[1], H. F. de Campos Velho[2], M. A. Gan[1], E. F. P. da Luz[2], and G. A. Grell[3]



BRAMS 5.2 (new version)
Air quality and weather prediction



BRAMS – New version 5.2

Geosci. Model Dev. Discuss., doi:10.5194/gmd-2016-130, 2016
Manuscript under review for journal Geosci. Model Dev.
Published: 7 June 2016

Geoscientific Model Development Discussions
Open Access

The Brazilian developments on the Regional Atmospheric Modeling System (BRAMS 5.2): an integrated environmental model tuned for tropical areas

Saulo R. Freitas[1,a], Jairo Panetta[2], Karla M. Longo[1,a], Luiz F. Rodrigues[1], Demerval S. Moreira[3,4], Nilton E. Rosário[5], Pedro L. Silva Dias[6], Maria A. F. Silva Dias[6], Enio P. Souza[7], Edmilson D. Freitas[6], Marcos Longo[8], Ariane Frassoni[1], Alvaro L. Fazenda[9], Cláudio M. Santos e Silva[10], Cláudio A. B. Pavani[1], Denis Eiras[1], Daniela A. França[1], Daniel Massaru[1], Fernanda B. Silva[1], Fernando Cavalcante[1], Gabriel Pereira[11], Gláuber Camponogara[5], Gonzalo A. Ferrada[1], Haroldo F. Campos Velho[12], Isilda Menezes[13,14], Julliana L. Freire[1], Marcelo F. Alonso[15], Madeleine S. Gácita[1], Maurício Zarzur[12], Rafael M. Fonseca[1], Rafael S. Lima[1], Ricardo A. Siqueira[1], Rodrigo Braz[1], Simone Tomita[1], Valter Oliveira[1], Leila D. Martins[16]

Turbulence closure problem

Mathematical equations

$$\rho \frac{d\bar{v}_i}{dt} = -\frac{\partial \bar{p}}{\partial x_i} - 2\varepsilon_{ikj}\Omega_k \bar{v}_j + \rho g \delta_{3i} + \sum_j \frac{\partial}{\partial x_j}\left[\bar{\sigma}_{ij} - \rho \overline{v_i' v_j'}\right]$$

$$\frac{\partial e}{\partial t} = -u\frac{\partial e}{\partial x} - v\frac{\partial e}{\partial y} - w\frac{\partial e}{\partial z} + \frac{\partial}{\partial x}\left(K_e \frac{\partial e}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_e \frac{\partial e}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_e \frac{\partial e}{\partial z}\right) + P_s + P_b + \epsilon, \quad (3.29)$$

First order closure:

$$\left[K_m \frac{\partial \bar{\alpha}}{\partial x_j} - \overline{v_j'\alpha'}\right] \approx -\overline{v_j'\alpha'} = K_{ij}\frac{\partial \bar{\alpha}}{\partial x_j}$$

Taylor

Smagorinsky

Smagorinsky (1963) – (Hill, 1974)

$$K_{mv} = (cs_z \Delta z)^2 \left[|D_v| + H(N) \right] f(R_i)$$

cs_z tunning parameter

Δz vertical grid space

$|D_h|$ norm of the horizontal deformation tensor

$$|D_h| = \sqrt{2\left(\frac{\partial \bar{u}}{\partial x}\right)^2 + 2\left(\frac{\partial \bar{v}}{\partial y}\right)^2 + \left(\frac{\partial \bar{v}}{\partial x} + \frac{\partial \bar{u}}{\partial y}\right)^2}$$

$$H(N) = \sqrt{\max\left[0, -N^2\right]}, \qquad f(Ri) = \sqrt{\max\left[0, 1 - \frac{K_{hv}}{K_{mv}} Ri\right]}$$

Turbulence closure problem

First order closure

$$\rho \frac{d\overline{v}_i}{dt} = -\frac{\partial \overline{p}}{\partial x_i} - 2\varepsilon_{ikj}\Omega_k \overline{v}_j + \rho g \delta_{3i} + \sum_j \frac{\partial}{\partial x_j}\left[-\rho\ \overline{v_i' v_j'}\right]$$

$$\overline{u'w'} = -K_m \frac{\partial \overline{u}}{\partial z},$$

$$\overline{w'\theta_l'} = -K_h \frac{\partial \overline{\theta_l}}{\partial z},$$

$$\overline{v'w'} = -K_m \frac{\partial \overline{v}}{\partial z},$$

$$\overline{w'q_t'} = -K_q \frac{\partial \overline{q_t}}{\partial z}.$$

$$\overline{w'w'} = -K_m \frac{\partial \overline{w}}{\partial z},$$

Turbulence closure problem

Second order closure

$$\left[K_m \frac{\partial \bar{\alpha}}{\partial x_j} - \overline{v_j'\alpha'}\right] \approx -\overline{v_j'\alpha'} = \mathrm{PDE_t}\{\overline{v_j'\alpha'}\}$$

$$\frac{\partial \overline{(u'u')}}{\partial t} = -2\left(\frac{\partial \bar{u}}{\partial z}\right)\overline{u'w'} - \frac{2}{3}\frac{E}{\tau_{DM}} - \left(\overline{u'u'} - \frac{E}{3}\right)\frac{1}{\tau_{IM}} + \frac{\partial}{\partial z}\left(K_1 \frac{\partial \overline{u'u'}}{\partial z}\right), \quad (3.50)$$

$$\frac{\partial \overline{(v'v')}}{\partial t} = -2\left(\frac{\partial \bar{v}}{\partial z}\right)\overline{v'w'} - \frac{2}{3}\frac{E}{\tau_{DM}} - \left(\overline{v'v'} - \frac{E}{3}\right)\frac{1}{\tau_{IM}} + \frac{\partial}{\partial z}\left(K_1 \frac{\partial \overline{v'v'}}{\partial z}\right), \quad (3.51)$$

$$\frac{\partial \overline{(w'w')}}{\partial t} = 2\left(\frac{g}{\theta_0}\right)\overline{\theta'w'} - \frac{2}{3}\frac{E}{\tau_{DM}} - \left(\overline{w'w'} - \frac{E}{3}\right)\frac{1}{\tau_{IM}} + \frac{\partial}{\partial z}\left(K_1 \frac{\partial \overline{w'w'}}{\partial z}\right), \quad (3.52)$$

Turbulence closure problem

Second order closure

$$\frac{\partial(\overline{u'w'})}{\partial t} = \left(\frac{\partial \overline{u}}{\partial z}\right)\overline{w'w'} + \left(\frac{g}{\theta_0}\right)\overline{\theta' u'} - \frac{\overline{u'w'}}{\tau_{IM}} + \frac{\partial}{\partial z}\left(K_1 \frac{\partial \overline{u'w'}}{\partial z}\right), \qquad (3.53)$$

$$\frac{\partial(\overline{v'w'})}{\partial t} = \left(\frac{\partial \overline{v}}{\partial z}\right)\overline{w'w'} + \left(\frac{g}{\theta_0}\right)\overline{\theta' v'} - \frac{\overline{v'w'}}{\tau_{IM}} + \frac{\partial}{\partial z}\left(K_1 \frac{\partial \overline{v'w'}}{\partial z}\right), \qquad (3.54)$$

$$\frac{\partial(\overline{\theta' u'})}{\partial t} = \left(\frac{\partial \overline{u}}{\partial z}\right)\overline{\theta' w'} - \left(\frac{\partial \overline{\theta}}{\partial z}\right)\overline{u'w'} - \frac{\overline{\theta' u'}}{\tau_{IT}} + \frac{\partial}{\partial z}\left(K_2 \frac{\partial \overline{\theta' u'}}{\partial z}\right), \qquad (3.55)$$

$$K_1 = 0.12 L E^{1/2} \quad e \quad K_2 = 0.20 L E^{1/2}.$$

Turbulence closure problem

Second order closure

$$\frac{\partial\overline{(\theta' v')}}{\partial t} = \left(\frac{\partial \overline{v}}{\partial z}\right)\overline{\theta' w'} - \left(\frac{\partial \overline{\theta}}{\partial z}\right)\overline{v' w'} - \frac{\overline{\theta' v'}}{\tau_{IT}} + \frac{\partial}{\partial z}\left(K_2 \frac{\partial \overline{\theta' v'}}{\partial z}\right), \quad (3.56)$$

$$\frac{\partial\overline{(\theta' w')}}{\partial t} = \left(\frac{\partial \overline{\theta}}{\partial z}\right)\overline{w' w'} + \left(\frac{g}{\theta_0}\right)\overline{\theta' \theta'} - \frac{\overline{\theta' w'}}{\tau_{IT}} + \frac{\partial}{\partial z}\left(K_2 \frac{\partial \overline{\theta' w'}}{\partial z}\right), \quad (3.57)$$

$$\frac{\partial\overline{(\theta' \theta')}}{\partial t} = -2\left(\frac{\partial \overline{\theta}}{\partial z}\right)\overline{\theta' w'} - \frac{\overline{\theta' \theta'}}{\tau_{DT}} + \frac{\partial}{\partial z}\left(K_2 \frac{\partial \overline{\theta' \theta'}}{\partial z}\right), \quad (3.58)$$

$$K_1 = 0.12 L E^{1/2} \quad e \quad K_2 = 0.20 L E^{1/2}.$$

Turbulence closure problem

Second order closure

$$\frac{\partial\overline{(q'u')}}{\partial t} = -\left(\frac{\partial\overline{q}}{\partial z}\right)\overline{u'w'} - \left(\frac{\partial\overline{u}}{\partial z}\right)\overline{q'w'} - \frac{\overline{q'u'}}{\tau_{IT}} + \frac{\partial}{\partial z}\left(K_2\frac{\partial\overline{q'u'}}{\partial z}\right), \qquad (3.59)$$

$$\frac{\partial\overline{(q'v')}}{\partial t} = -\left(\frac{\partial\overline{q}}{\partial z}\right)\overline{v'w'} - \left(\frac{\partial\overline{v}}{\partial z}\right)\overline{q'w'} - \frac{\overline{q'v'}}{\tau_{IT}} + \frac{\partial}{\partial z}\left(K_2\frac{\partial\overline{q'v'}}{\partial z}\right), \qquad (3.60)$$

$$\frac{\partial\overline{(q'w')}}{\partial t} = \left(\frac{\partial\overline{q}}{\partial z}\right)\overline{w'w'} + \left(\frac{g}{\theta_0}\right)\overline{\theta'q'} - \frac{\overline{q'w'}}{\tau_{IT}} + \frac{\partial}{\partial z}\left(K_2\frac{\partial\overline{q'w'}}{\partial z}\right), \qquad (3.61)$$

$$\frac{\partial\overline{(q'q')}}{\partial t} = -2\left(\frac{\partial\overline{q}}{\partial z}\right)\overline{q'w'} - \frac{\overline{q'q'}}{\tau_{DT}} + \frac{\partial}{\partial z}\left(K_2\frac{\partial\overline{q'q'}}{\partial z}\right), \qquad (3.62)$$

$$\frac{\partial\overline{(\theta'q')}}{\partial t} = \left(\frac{\partial\overline{q}}{\partial z}\right)\overline{\theta'w'} - \left(\frac{\partial\overline{\theta}}{\partial z}\right)\overline{q'w'} - \frac{\overline{q'w'}}{\tau_{DT}} + \frac{\partial}{\partial z}\left(K_2\frac{\partial\overline{\theta'q'}}{\partial z}\right), \qquad (3.63)$$

Mellor-Yamada (1982)

$$K_m = S_m l\sqrt{2e}$$

$$K_h = S_h l\sqrt{2e}$$

$$K_e = S_e l\sqrt{2e}$$

Taylor

S_m e ***S_h*** are turbulent diffusivities
S_e = 0.20, and ***l*** is mixing length

$$l = \frac{\kappa(z+z_0)}{1+\kappa(z+z_0)/l_\infty} \qquad l_\infty = 0{,}1\frac{\int_0^{ll} z\sqrt{e}dz}{\int_0^{ll}\sqrt{e}dz}$$

κ Is the Von Karman constant, ***z_0*** is rugosity

Vertical eddy diffusivity from the Taylor's approach

- **Neutral Boundary Layer (NBL)**

$$K_z^n = \frac{0.4\,(1 - z/h)^{0.85}\,(u_*)\,z}{\left[1 + 15 f_c z/\,(u_*)\right]^{4/3}}. \quad (1)$$

Z : vertical coordenate;
f_c : Coriolis parameter ($f_c = 1^{-4}$);
u_* : friction velocity (computed from the B-RAMS);
h : boundary layer heigh for NBL and SBL (Zilitinkevich, 1972):

$$h = B_v u_*^{3/2}, \quad (2)$$

B_v : 2.4 X $10^3 (m^{-1/2} s^{2/3})$.

Vertical eddy diffusivity from the Taylor's approach

- **Stable Boundary Layer (SBL)**

$$K_z^e = \frac{0.4\,(1 - z/h)^{3/4}\,(u_*)\,z}{1 + 3.7z/\Lambda}. \tag{3}$$

Λ : local Monin-Obukhov's length:

$$\frac{\Lambda(z)}{L} = \left(1 - \frac{z}{h}\right)^{5/4} \tag{4}$$

and

$$L = -\frac{u_*^3}{\kappa(g/\Theta_0)(\overline{w'\theta'})|_{z=0}}. \tag{5}$$

Vertical Eddy Diffusivity

- **Convective Boundary Layer (CBL)**

$$K_z^c = 0.16 w_* z_i \left(0.01 \frac{z_i}{-L}\right)^{1/2} \left[1 - exp\left(-\frac{4z}{z_i}\right) - 0.0003 exp\left(\frac{8z}{z_i}\right)\right]^{4/3}. \quad (6)$$

w_* : is the velocity scale for the CBL, given by:

$$w_* = \left[(g/\theta_v)\left(\overline{w'\theta_v'}\right) h\right]^{1/3}. \quad (7)$$

h : boundary layer heigh for CBL (critical the Richardson number):

$$Ri_g = \frac{(g/\theta_{v_s})(\theta_{v_h} - \theta_{v_s})(h - z_s)}{(u_h - u_s)^2 + (v_h - v_s)^2}. \quad (8)$$

g : gravity acceleration;
u e v : zonal and meridional wind components, respectively;
θ_v : virtual potential temperature.

ABRACOS: Temperature of Air

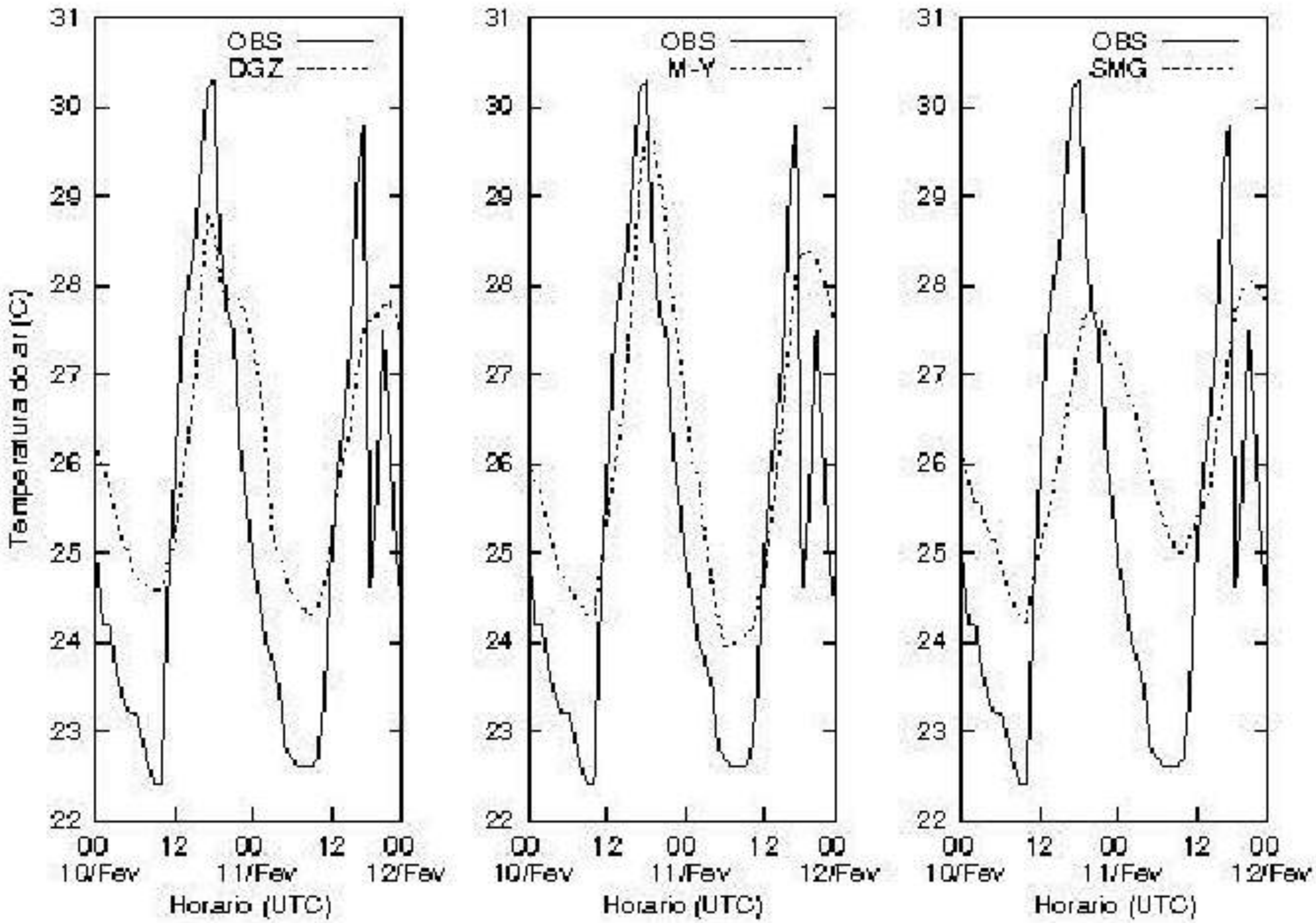


Figure 5: Turbulence Parameterization - **DGZ:** Degrazia et al. (2000), **M-Y:** Mellor and Yamada (1982), **SMG:** Smagorinsky (1963) and **OBS:** observacional data for the ABRACOS site.

ABRACOS: Relative Humidity

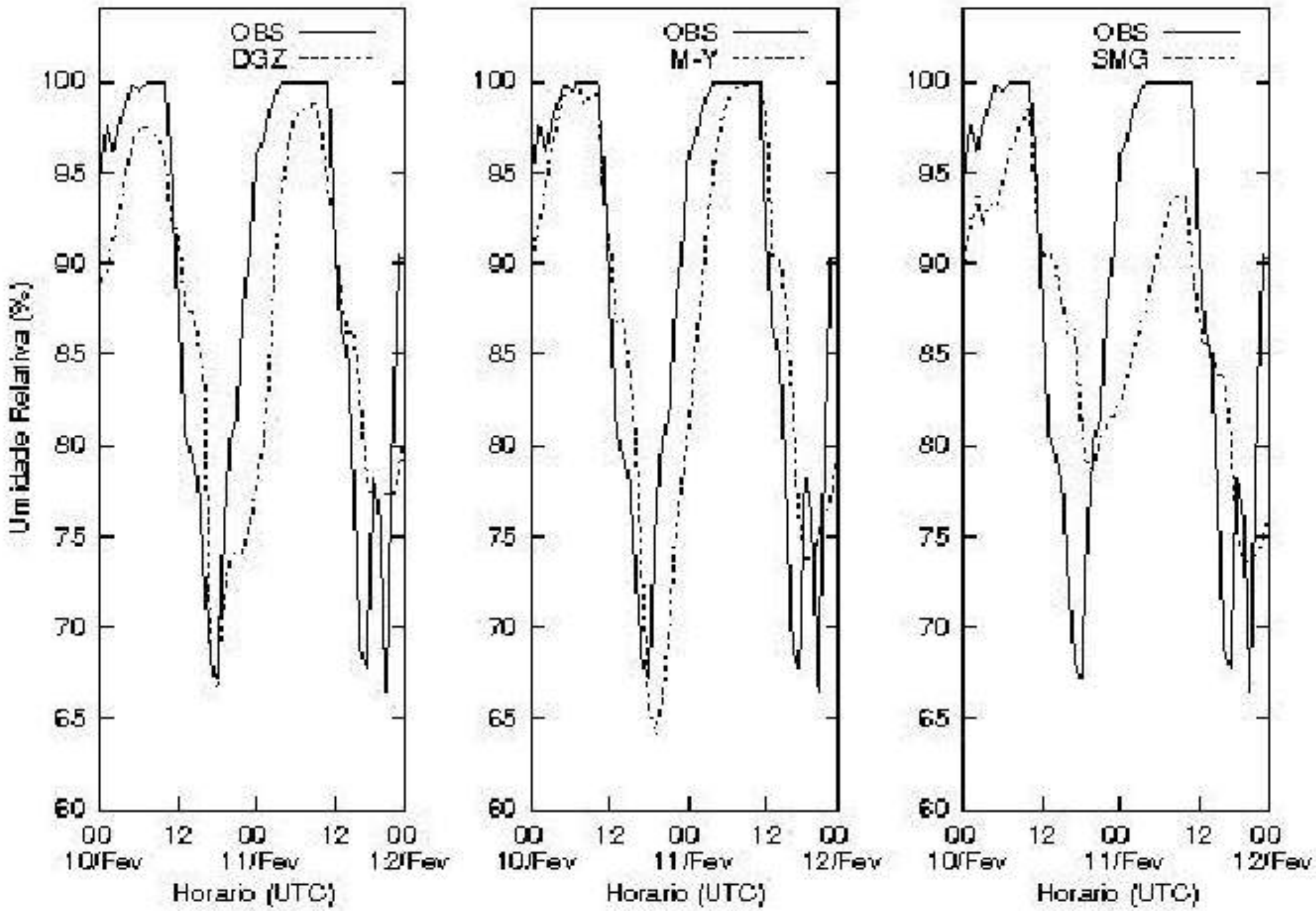


Figure 6: Turbulence Parameterization - **DGZ:** Degrazia et al. (2000), **M-Y:** Mellor and Yamada (1982), **SMG:** Smagorinsky (1963) and **OBS:** observacional data for the ABRACOS site.

ABRACOS: Flux of Latent Heat

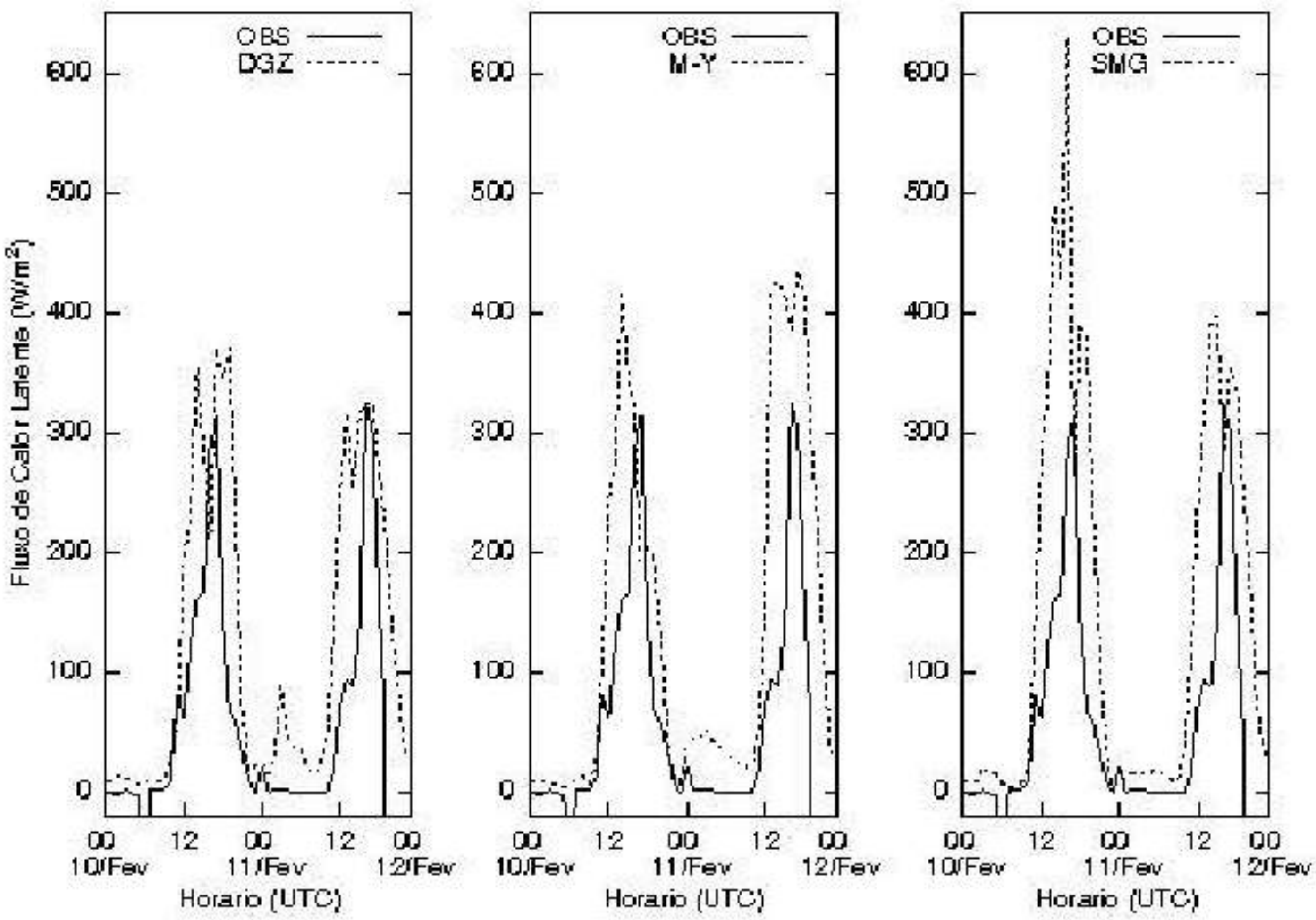


Figure 7: Turbulence Parameterization - **DGZ:** Degrazia et al. (2000), **M-Y:** Mellor and Yamada (1982), **SMG:** Smagorinsky (1963) and **OBS:** observacional data for the ABRACOS site.

ABRACOS: Flux of Sensible Heat

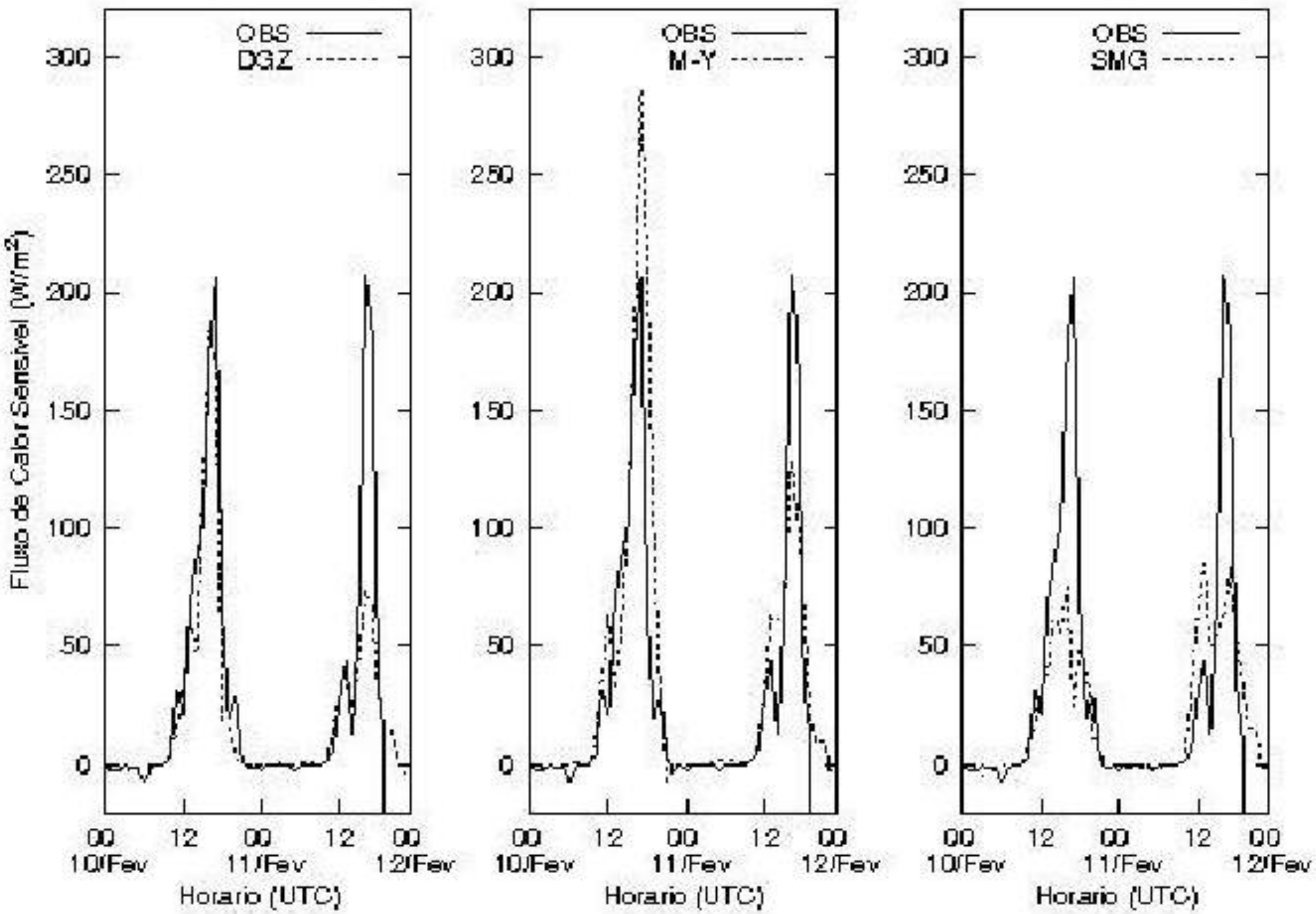


Figure 8: Turbulence Parameterization - **DGZ:** Degrazia et al. (2000), **M-Y:** Mellor and Yamada (1982), **SMG:** Smagorinsky (1963) and **OBS:** observacional data for the ABRACOS site.

ABRACOS: Potencial Temperature Profile

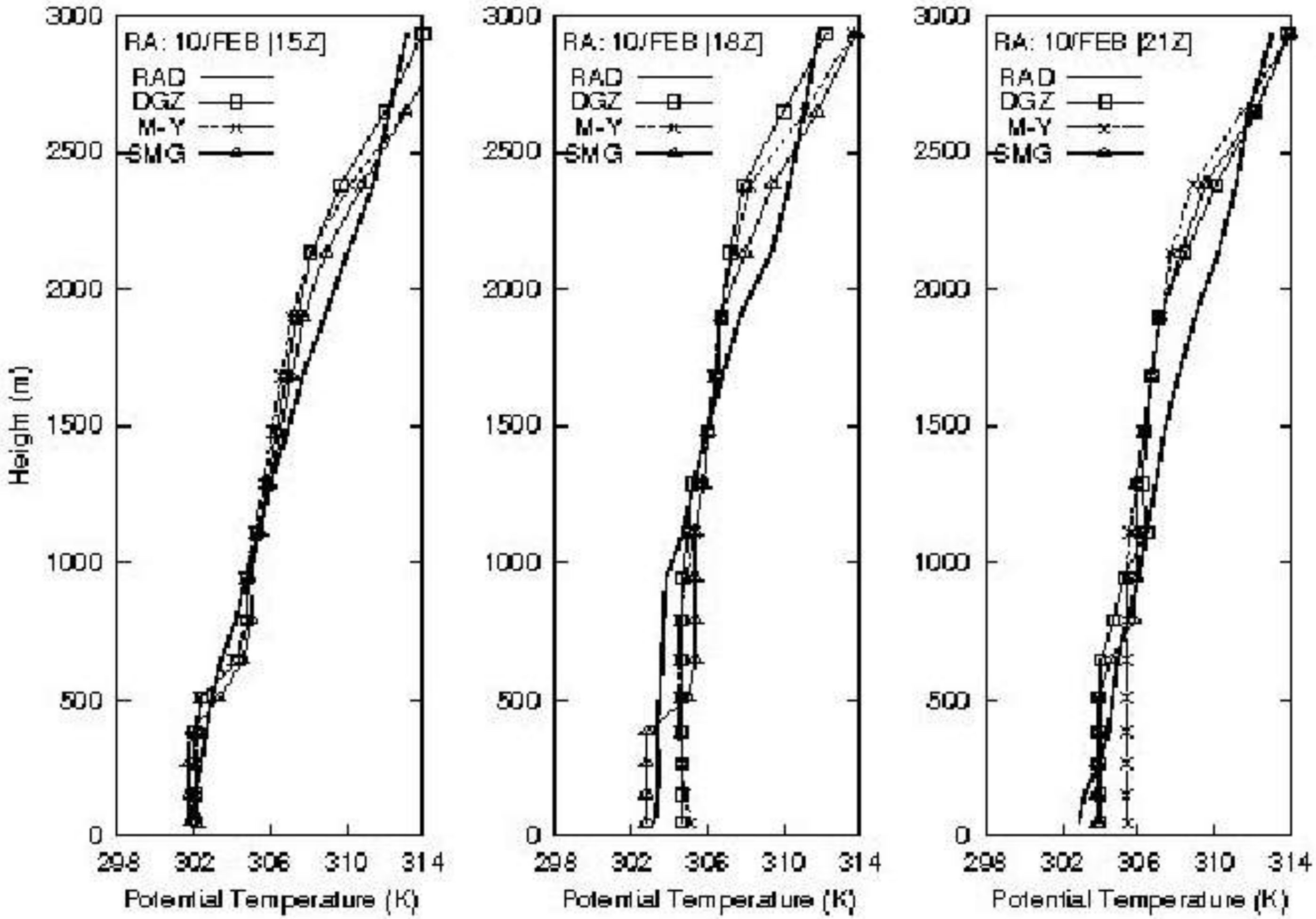


Figure 9: Turbulence Parameterization - **DGZ:** Degrazia et al. (2000), **M-Y:** Mellor and Yamada (1982), **SMG:** Smagorinsky (1963) and **RAD:** Radiosonde for the ABRACOS site (10/Fev/99 - 15Z/18Z/21Z).

Rebio Jaru: Potencial Temperature Profile

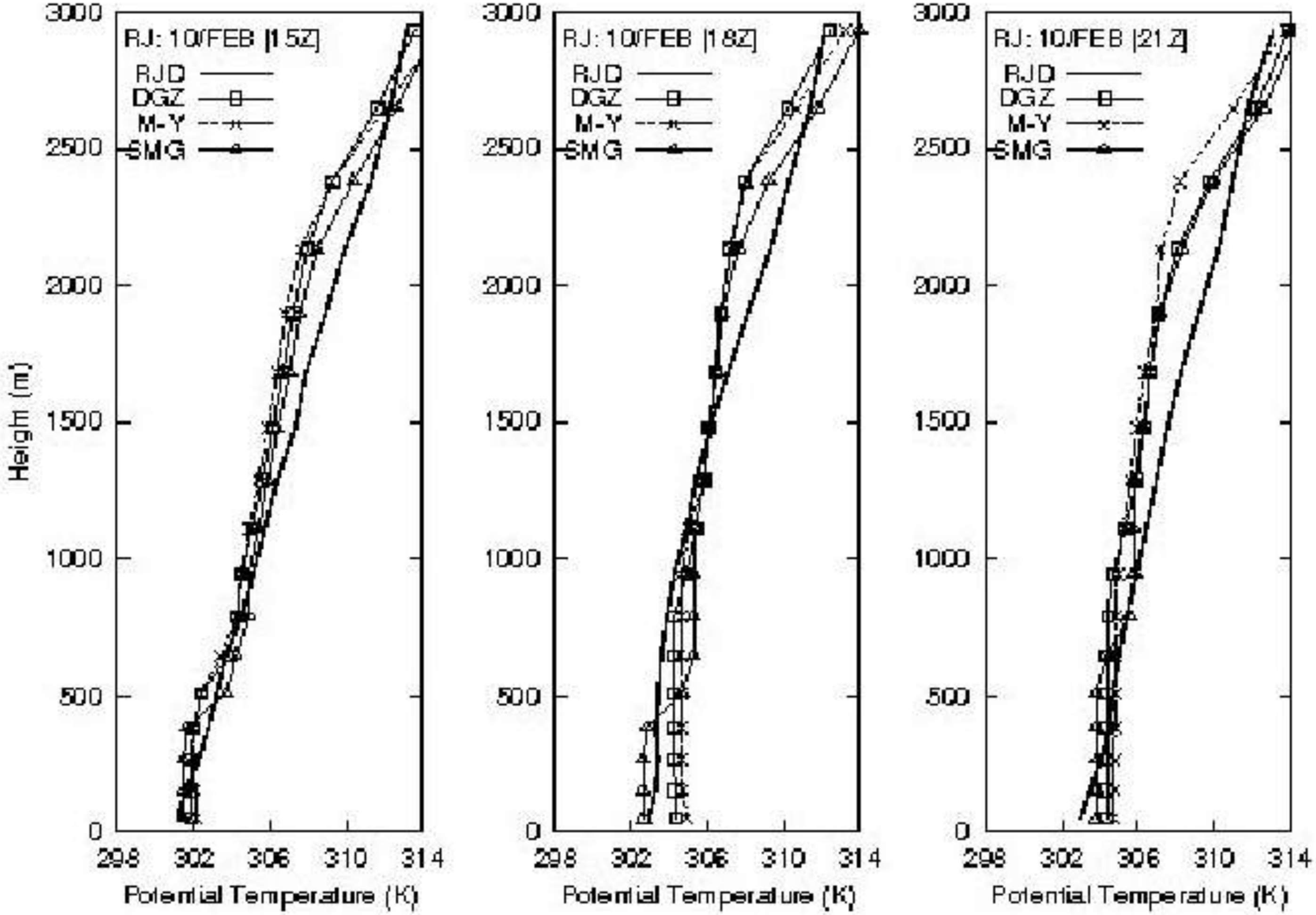


Figure 9: Turbulence Parameterization - **DGZ:** Degrazia et al. (2000), **M-Y:** Mellor and Yamada (1982), **SMG:** Smagorinsky (1963) and **RAD:** Radiosonde for the Rebio Jaru site (10/Fev/99 - 15Z/18Z/21Z).

ABRACOS: Potencial Temperature (Feb/10 - 1999)

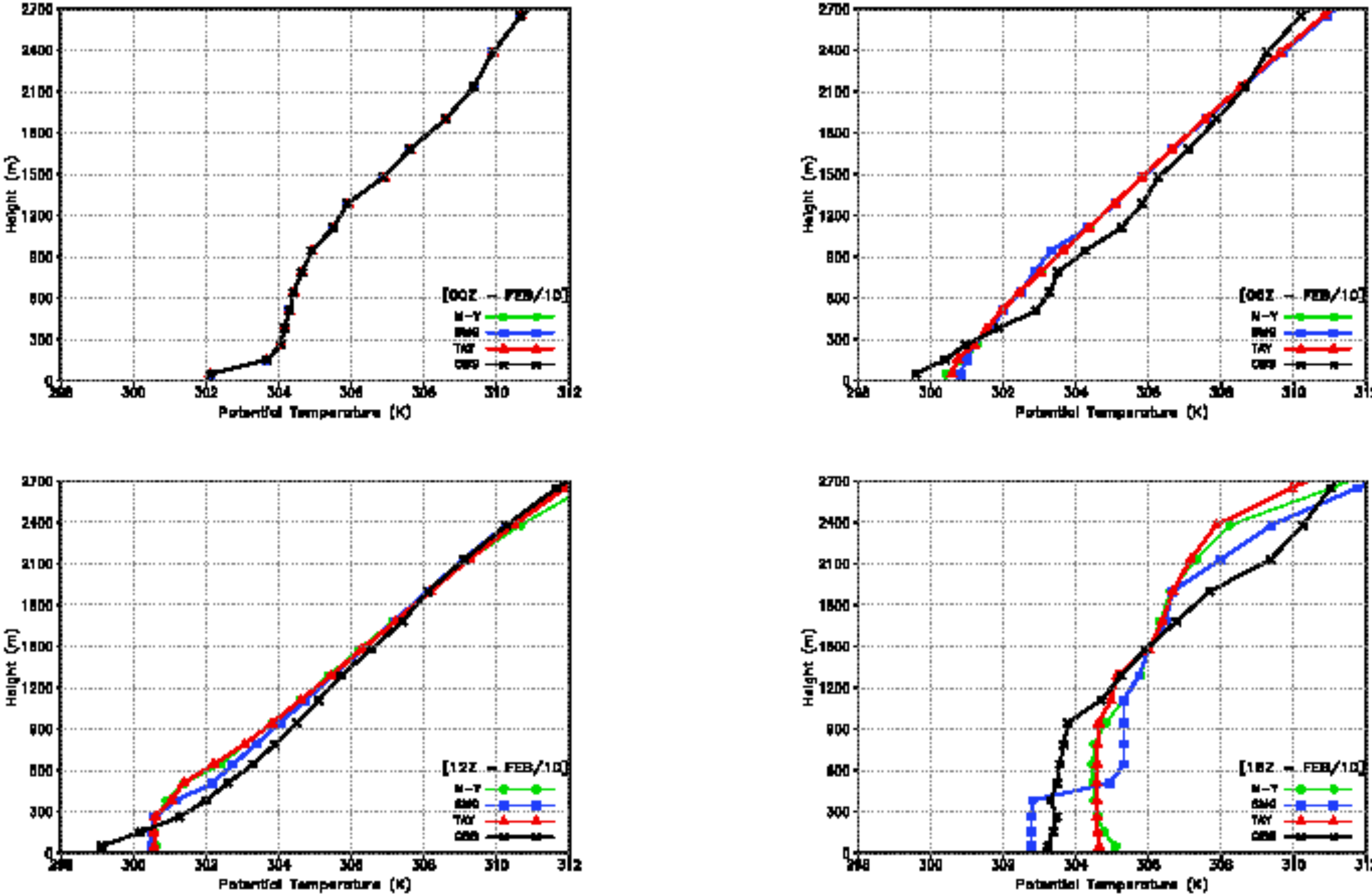


Figure 5: Potencial temperature profile for the ABRACOS site (00Z / 06Z / 12Z and 18Z - Feb/10).

ABRACOS: Potencial Temperature (Feb/11 - 1999)

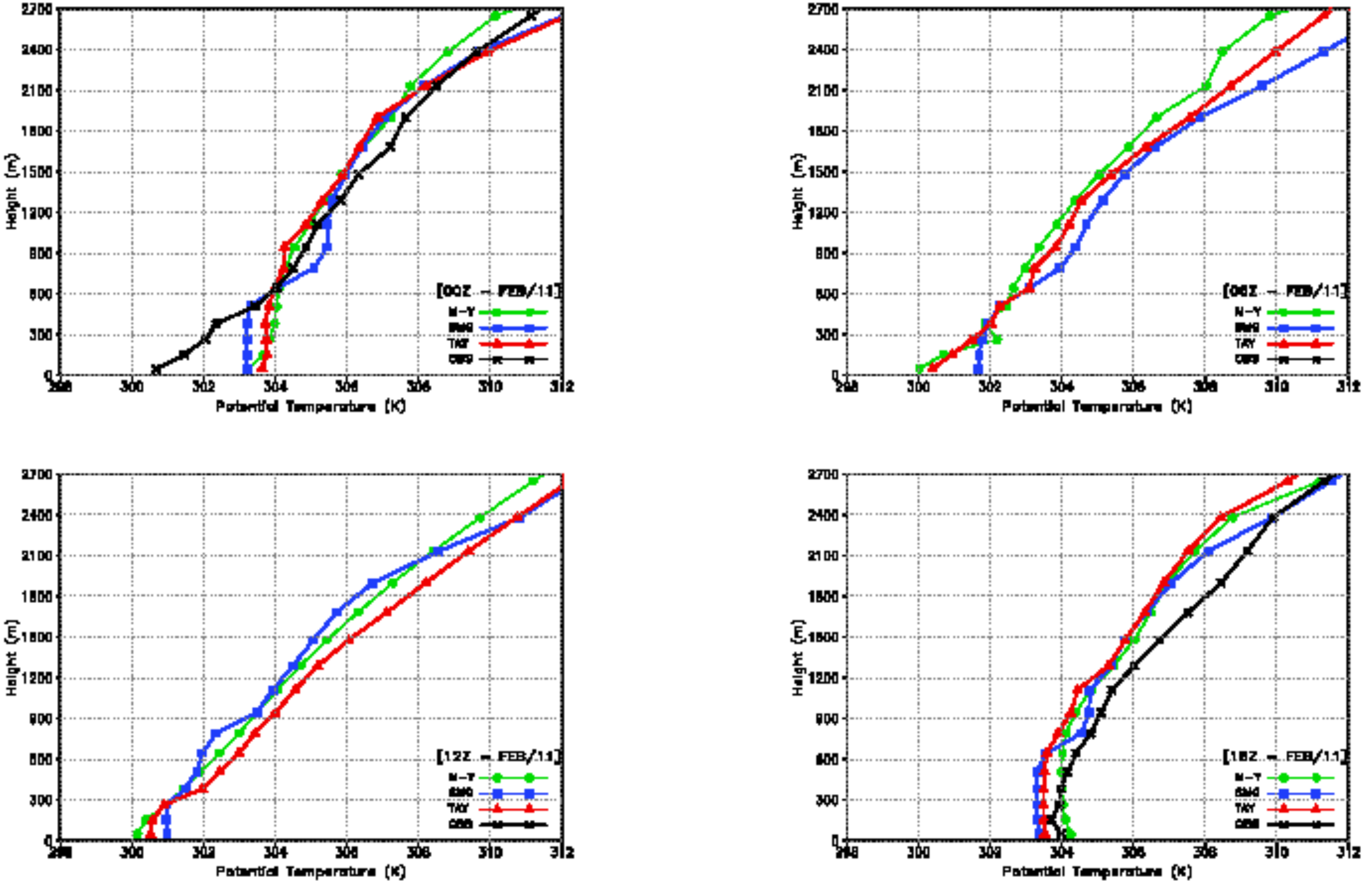


Figure 6: Potencial temperature profile for the ABRACOS site (00Z / 06Z / 12Z and 18Z - Feb/11).

ABRACOS: Potential Temperature (Feb/12 - 1999)

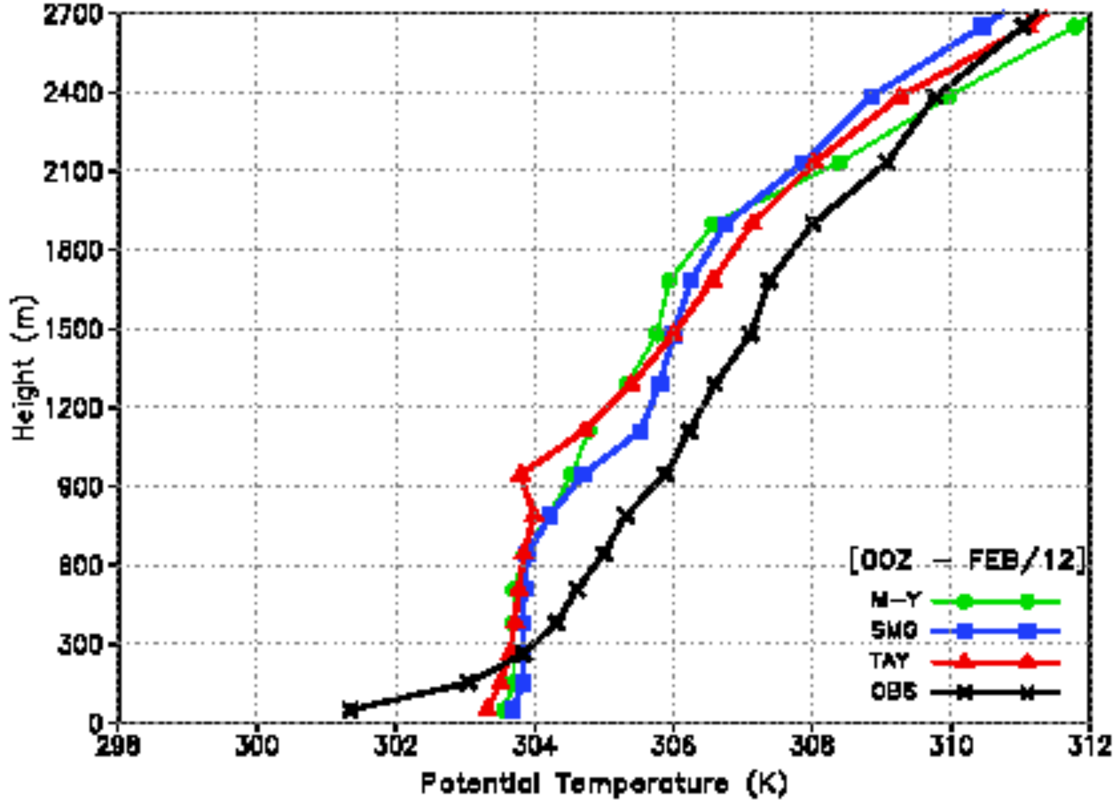


Figure 7: Potencial temperature profile for the ABRACOS site (00Z - Feb/12).

REBIO JARU: Potencial Temperature (Feb/10 - 1999)

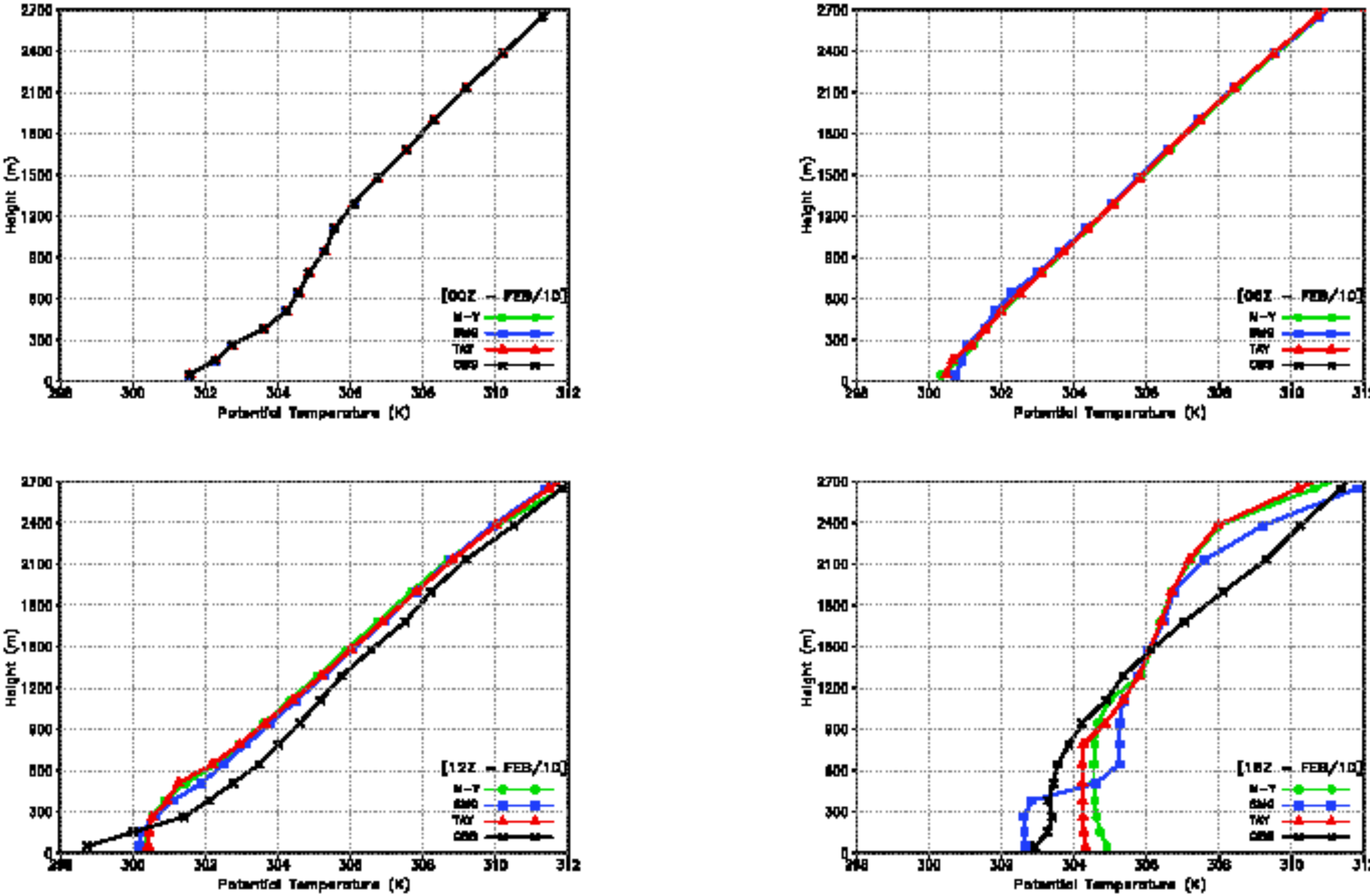


Figure 8: Potencial temperature profile for the REBIO JARU site (00Z / 06Z / 12Z and 18Z - Feb/10).

REBIO JARU: Potencial Temperature (Feb/11 - 1999)

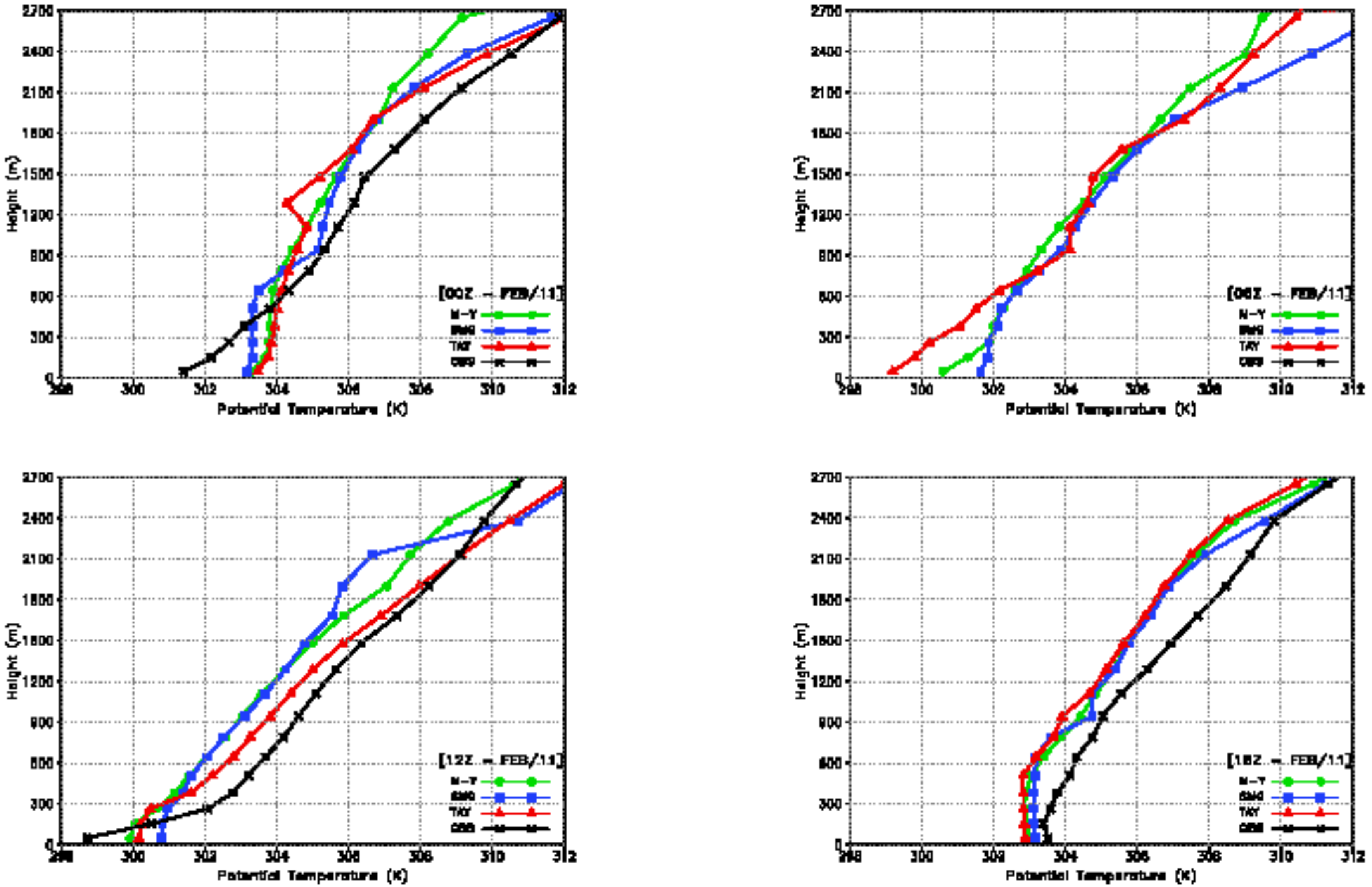


Figure 9: Potencial temperature profile for the REBIO JARU site (00Z / 06Z / 12Z and 18Z - Feb/11).

REBIO JARU: Potencial Temperature (Feb/12 - 1999)

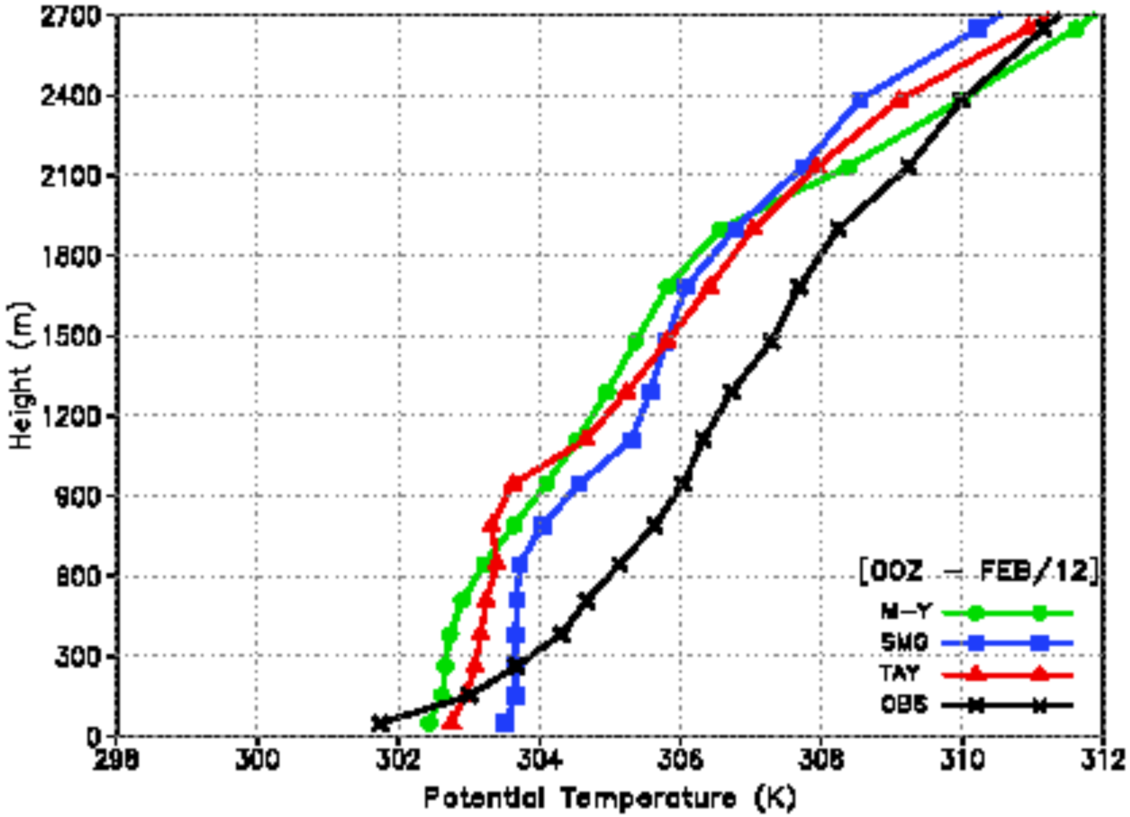
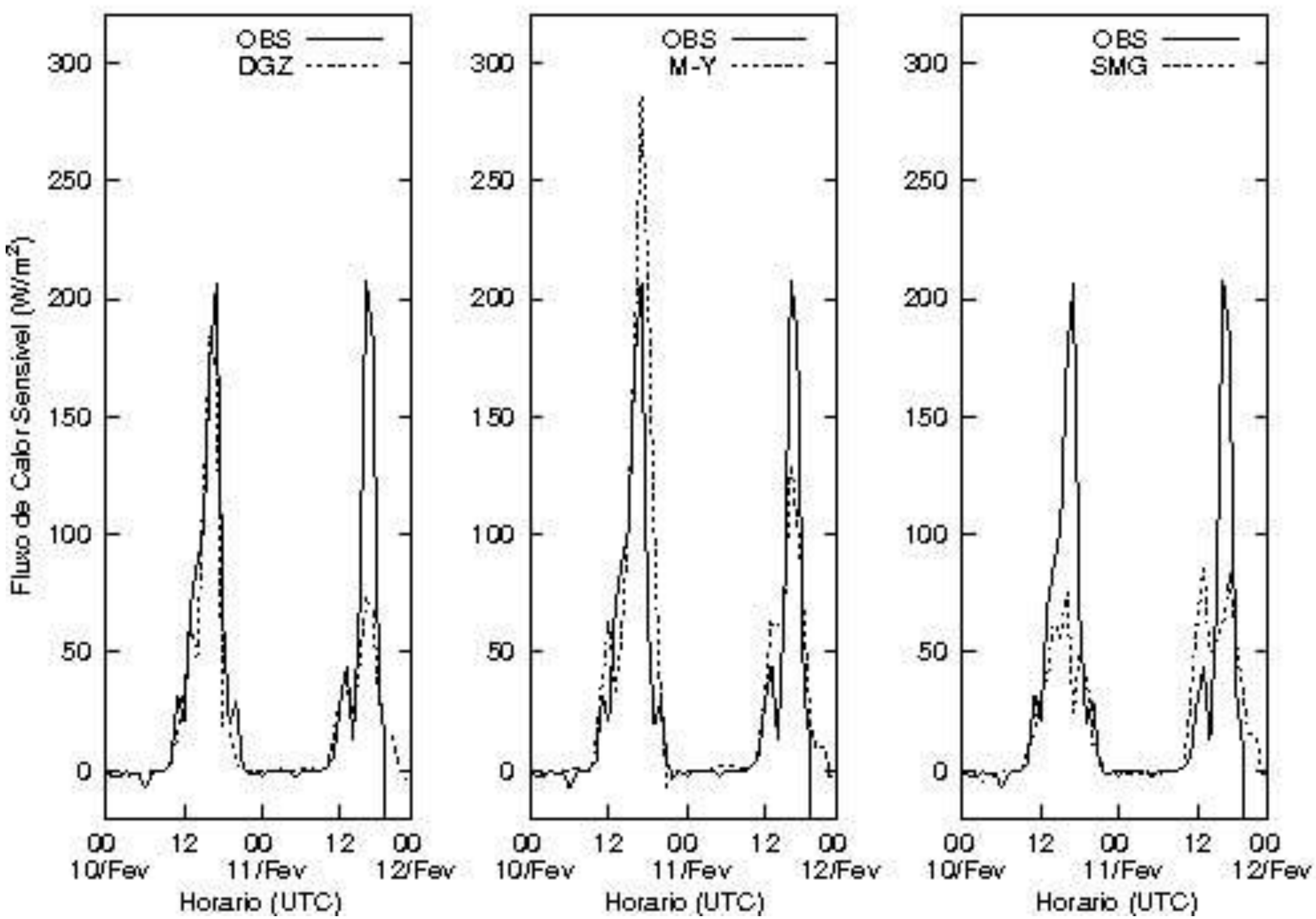


Figure 10: Potencial temperature profile for the REBIO JARU site (00Z - Feb/12).

Sensible heat



Counter gradient parameterization

First order closure and counter-gradient:

$$\overline{w'\varphi'} \approx -K_{zz}\frac{\partial\overline{\varphi}}{\partial z} \quad \Rightarrow \quad \overline{w'\varphi'} \approx -K_{zz}\left(\frac{\partial\overline{\varphi}}{\partial z} - \gamma_z\right)$$

Cuijpers e Holtslag (1998):

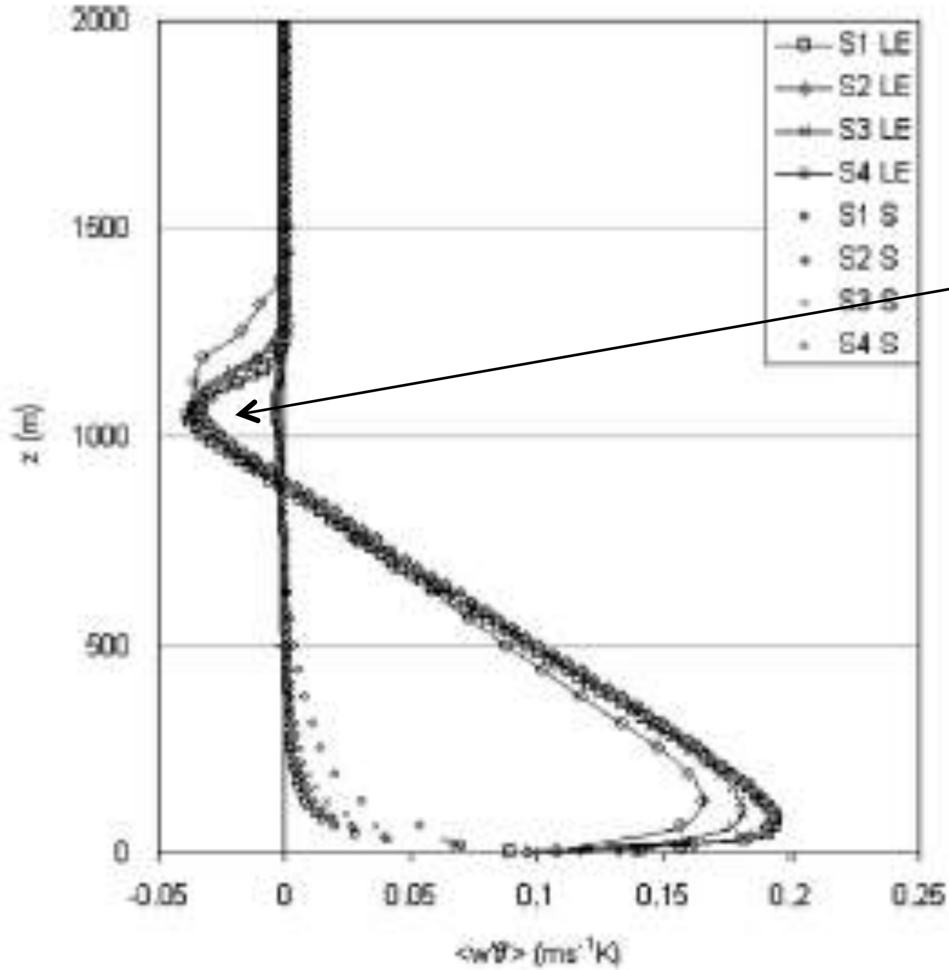
$$\gamma_\varphi = \beta_g \ell_w \frac{w_*^2}{\sigma_z}\frac{\varphi_*}{h}$$

$$\varphi_* = \frac{1}{w_* h}\int_0^h \overline{w'\varphi'}dz$$

From Taylor's theory:

β_φ	Empirical constant
ℓ_w	Mixing length
w_*^2	Velocity sclae
σ_*^2	Wind speed standard deviation
h	PBL height

Why do we need a counter gradient term?



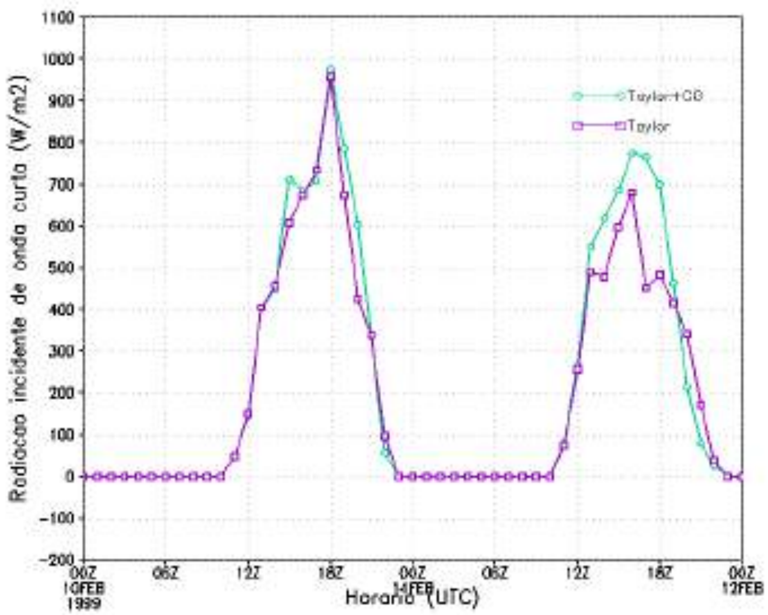
Heat flux × height:

1. On the top of PBL: counter gradient appears
2. Only second order closure can present this.
3. The idea: add a term for representing the counter gradient for the first order closure.

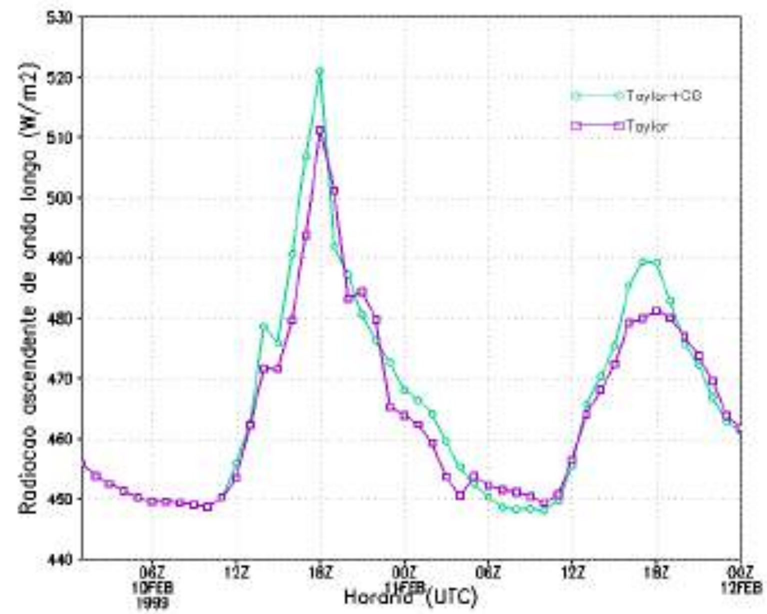
Counter gradient in BRAMS

Taylor vs. Taylor-CG

(Farm, Abracos) Radiation: (a) short wave, (b) long wave



(a)

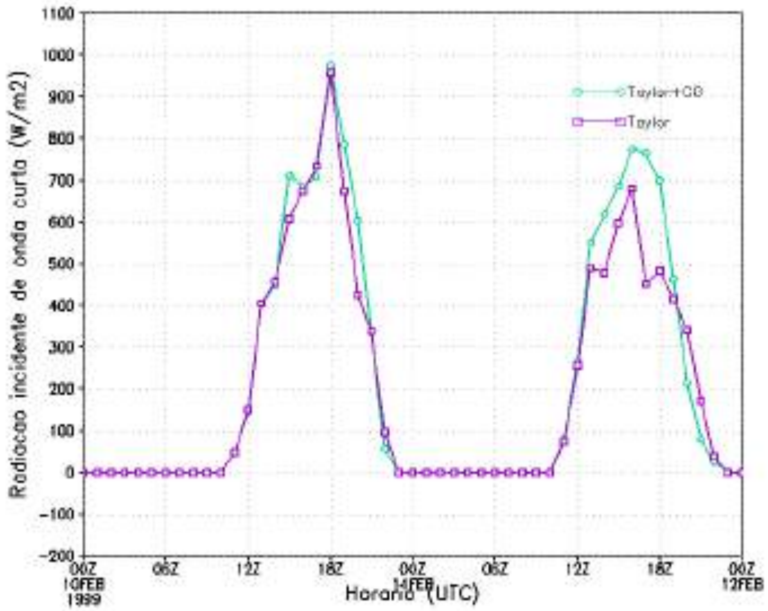


(b)

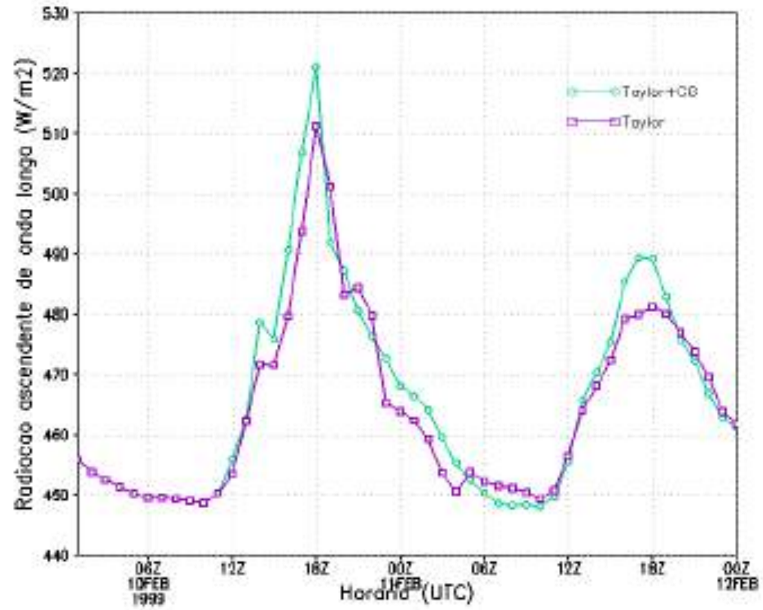
Counter gradient in BRAMS

Taylor vs. Taylor-CG

(Farm, Abracos) Radiation: (a) short wave, (b) long wave



(a)

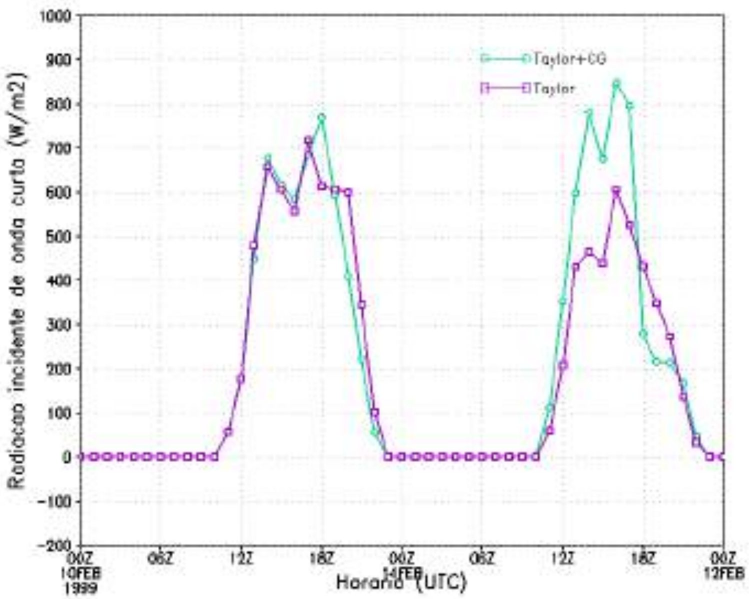


(b)

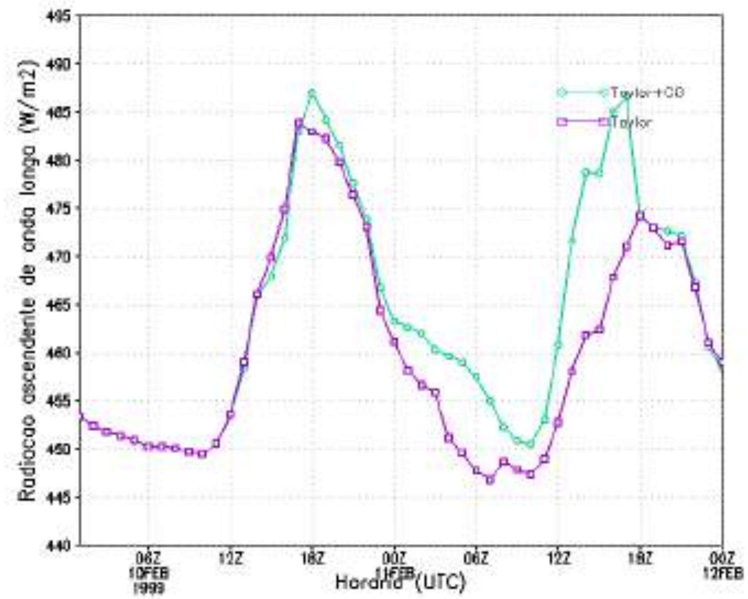
Counter gradient in BRAMS

Taylor vs. Taylor-CG

(ReBio-Jaru) Radiation: (a) short wave, (b) long wave



(a)

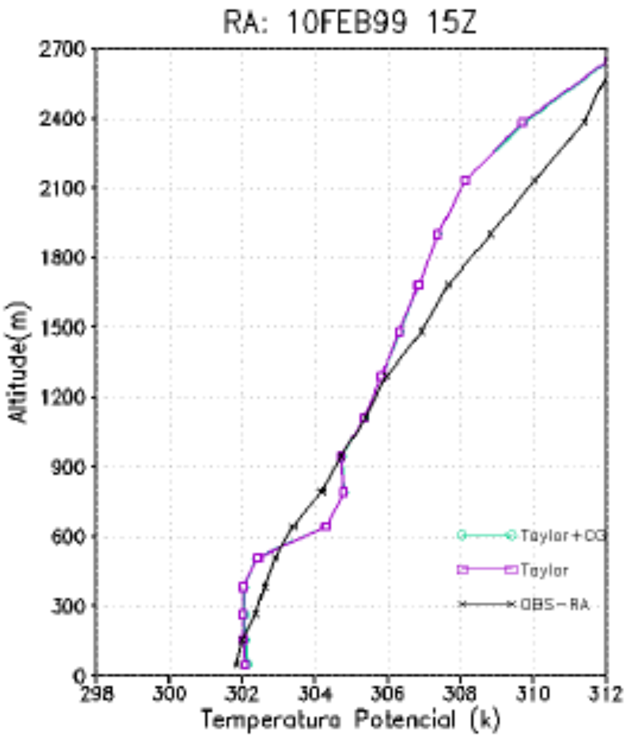


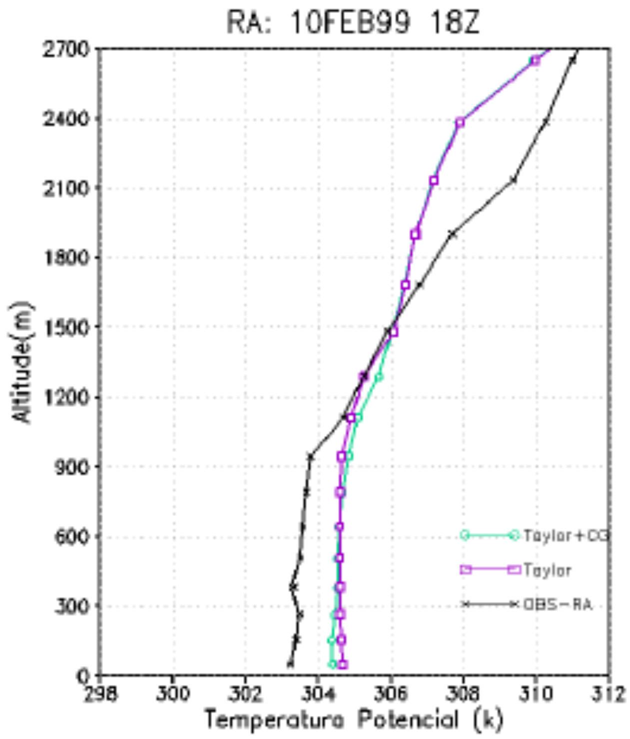
(b)

Counter gradient in BRAMS

Taylor vs. Taylor-CG

(Farm, Abracos) Potential temperature

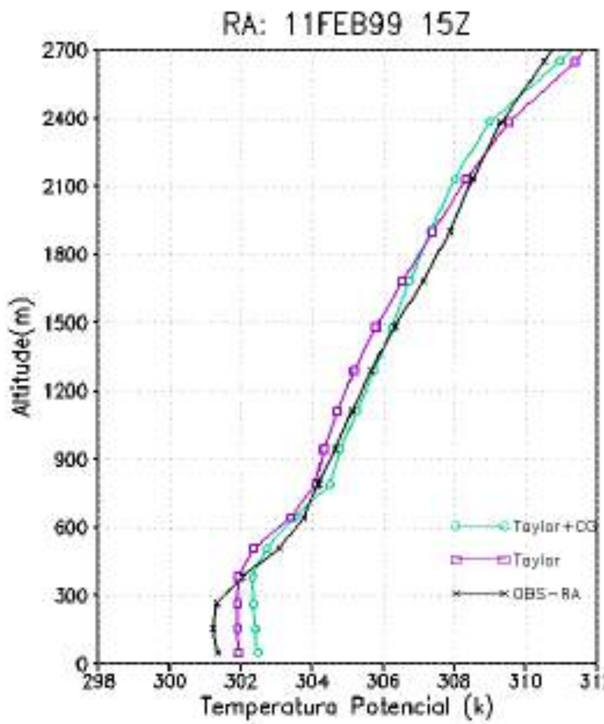


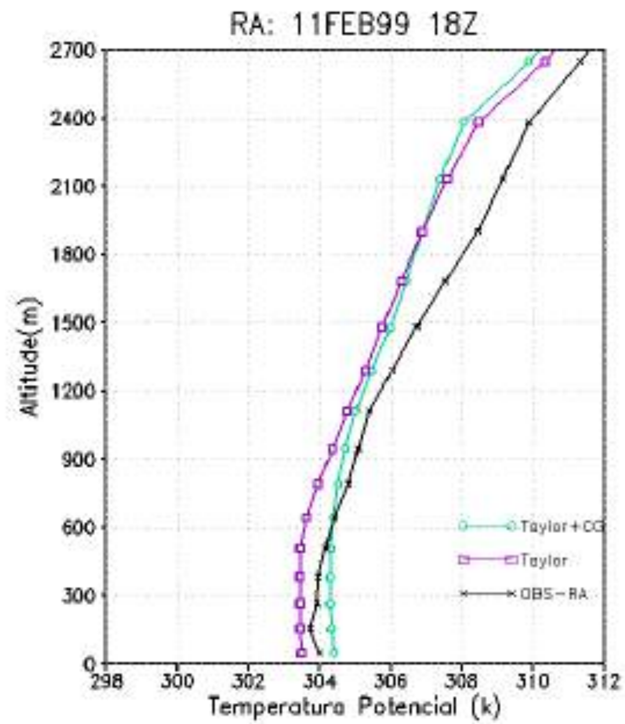


Counter gradient in BRAMS

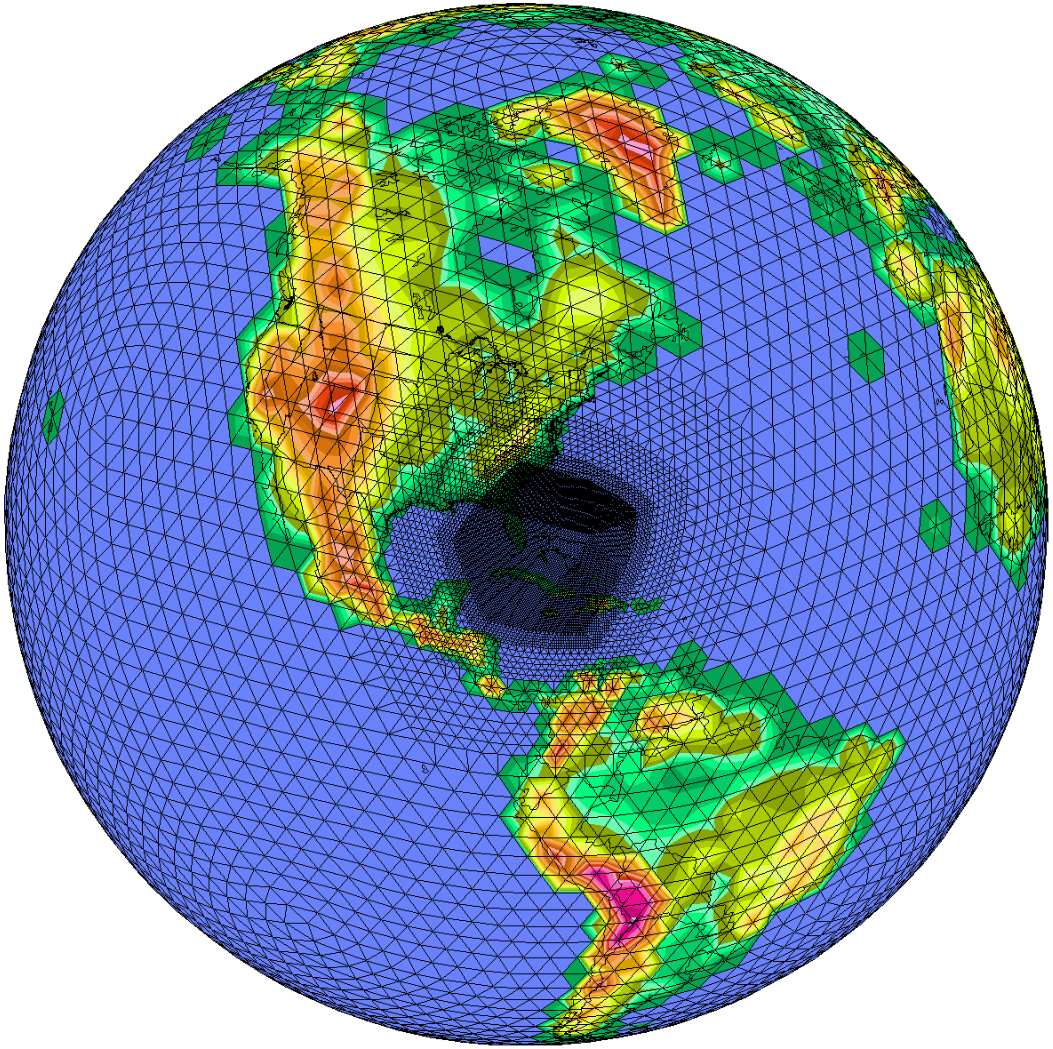
Taylor vs. Taylor-CG

(ReBio-Jaru) Potential temperature



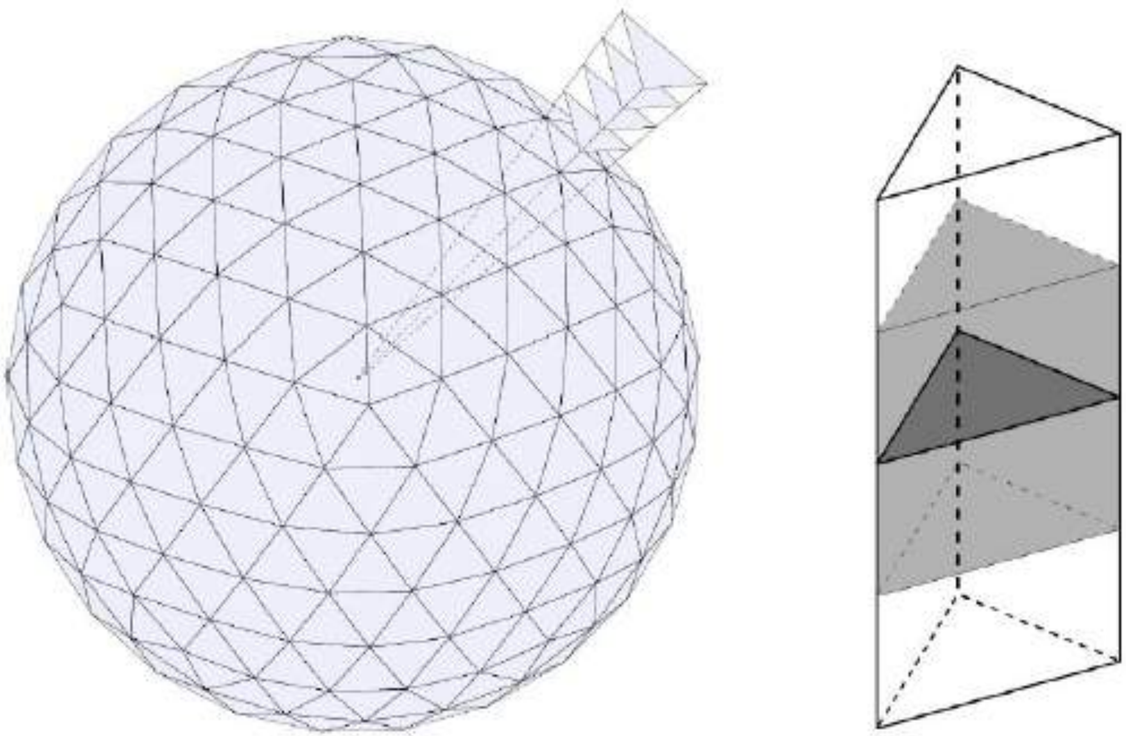


PBL parameterization for new numerical schemes



Future developments

Apply the same parameterization for the OLAM (Ocean-Land-Atmosphere Model): a global model employing finite volume scheme with non-structured mesh.



ITALIAN PHYSICAL SOCIETY
SOCIETÀ ITALIANA DI FISICA

A Model Based on Heisenberg's Theory for the Eddy Diffusivity in Decaying Turbulence Applied to the Residual Layer

G. Degrazia[1], A. Goulart[2], D. Anfossi[3], H. F Campos Velho[4], P. Lukaszczyk[5]

Il Nuovo Cimento C, Vol. 26, Issue 01, p. 39-51 (2003).

Modeling for residual boundary layer (RL)

The decay of energy-containing eddies in the CBL is the physical mechanism that can maintain the dispersion process in the RL.

Homogeneous isotropic turbulence, when buoyant and shear production terms are not important, satisfies the following energy transfer relation:

$$\frac{\partial E(k,t)}{\partial t} = W(k,t) - 2\nu k^2 E(k,t)$$

k: the wavenumber;
E(*k*,*t*): 3D energy density spectrum function (EDS);
W(*k*,*t*): the energy-transfer-spectrum function (contribution due to the inertial transfer of energy among different wavenumbers)
viscous dissipation: second term on the r.h.s..

Considering frequency instead of wavenumber, the energy spectra is written as

$$\frac{\partial S(n,t)}{\partial t} = T(n,t) - \frac{8\pi^2 n^2 \nu}{U^2} S(n,t)$$

where: *n = kU/2*π ; and *U*: mean wind speed;
T(*k*,*t*) = W(*k*,*t*)2π /*U* ; S(*k*,*t*) = E(*k*,*t*)2π /*U* .

Using the Heisenberg's assumption, where the mechanism of inertial transfer of energy from large to small eddies is given in terms of an additional eddy viscosity, called kinematic turbulence viscosity (KTV):

$$T(n,t) = -\frac{8\pi^2 n^2}{U^2} \nu_T S(n,t)$$

ν_T: kinematic turbulence viscosity caused by the eddies with frequency ranging from *n* to infinity.

The following assumption is taken into account:

$$n_e << n_I << n_d$$

where: n_e: characteristic frequency in the energy-containing subrange;
n_I: characteristic frequency in the inertial subrange;
n_d: characteristic frequency in the dissipation subrange;
are considered statistically independent.

ν_T can be calculated directly from Taylor's statistical diffusion theory for large travel times $\tau \rightarrow \infty$ (Hanna, 1981; Weil, 1989) as:

$$\nu_T = \frac{\beta}{6}\frac{\sigma_I^2}{n_I}$$

where: σ_I^2 is the turbulent velocity variance in the inertial subrange.

Therefore, the evolution equation for the spectra can be presented:

$$S(n,t) = S_0(n)\exp\left[-8\pi^2 \nu_T (n/U)^2 t\right]$$

being $S_0(n) = S(n, t=0)$.

As the energy-containing spectral range is characterized by n_e, a similar equation of that expressed for ν_T can be written for eddy diffusivity:

$$K(z,t) = \frac{\beta}{6}\frac{\sigma_e^2(z,t)}{n_e}$$

where

$$\frac{1}{2}\sigma_e^2(z,t) = \int_{n_e}^{\infty} S_0(n)\exp\left[-8\pi^2 \nu_T (n/U)^2 t\right]dn$$

Comparison ν_T: Taylor's theory x Heisemberg's model

3D spectra in the inertial subrange:

$$S(n) = \frac{\alpha}{(2\pi)^{2/3}} \left(\frac{U \Psi_\varepsilon}{h} \right)^{2/3} n^{-5/3} w_*^2$$

where $\Psi_\varepsilon = \varepsilon h / w_*^3$; $\alpha \approx 1.52$. **By setting:**

$$\beta \approx 0.55 U / \sigma_I \; ; \quad \text{and} \quad \sigma_I^2 = \int_{n_I}^{\infty} S(n) dn$$

an expression for KTV can be derived:

$$\nu_T = 0.1 \left(\frac{\Psi_\varepsilon}{h} \right)^{1/3} \left(\frac{U}{n_I} \right)^{4/3} w_*$$

Dimensional analysis yields:

$$\nu_T = \int_{k'=k_I}^{\infty} C_H \sqrt{\frac{S(k')}{k'^3}}\, dk'$$

where $C_H \sim 0.47$ is the Heisenberg's spectral transfer constant. In the inertial subrange:

$$S(k) = \alpha \varepsilon^{2/3} k^{-5/3}$$

an expression for KTV can be obtained:

$$\nu_T = 0.44 \varepsilon^{1/3} k^{-4/3}$$

or using $k = 2n\pi / U$ **:**

$$\nu_T = 0.04 \left(\frac{\Psi_\varepsilon}{h} \right)^{1/3} \left(\frac{U}{n_I} \right)^{4/3} w_* \qquad \left\lfloor (\nu_T)_T / (\nu_T)_H \approx 2.5 \right\rfloor$$

Derivation of a One-Dimensional KTV and K_z in the RL:

Vertical spectrum in the inertial subrange (Kaimal et al., 1976):

$$S(n) = 0.36\left(\frac{\kappa U \Psi_\varepsilon}{h}\right)^{2/3} n^{-5/3} w_*^2$$

where $\kappa = 0.4\,(\text{von Karman constant})$; $\Psi_\varepsilon \approx 0.65.$ **By setting:**

$$\beta \approx 0.55 U / \sigma_w \,; \quad \text{and} \quad \sigma_I^2 = \int_{n_I}^{\infty} S(n)\,dn$$

an expression for KTV can be derived:

$$\nu_T = 0.067\left(\frac{\kappa \Psi_\varepsilon}{h}\right)^{1/3}\left(\frac{U}{n_I}\right)^{4/3} w_*$$

For CBL the vertical spectrum is given by (Degrazia et al., 1997):

$$S_{w,0}(n) = \frac{0.38 \frac{z}{U} \left(\frac{z \Psi_{\varepsilon}}{h} \right)^{2/3} w_*^2}{(f_m)_w^{5/3} \left[1 + \frac{1.5 n z}{U (f_m)_w} \right]^{5/3}}$$

where $(f_m)_w$ is convective spectral peak. Since the spectral peak for the vertical component can be approximated:

$$(f_m)_w = \frac{z}{(\lambda_m)_w} = \frac{z}{a_w h q_w}; \quad n_e = \frac{U}{a_w h q_w}$$

the vertical spectrum becomes:

$$S_{w,0}(n) = \frac{0.38 \frac{h}{U} (a_w q_w)^{2/3} \Psi_{\varepsilon}^{2/3} w_*^2}{\left[1 + \frac{1.5 n h a_w q_w}{U} \right]^{5/3}}$$

For vertical wind component $a_w \approx 1.8$, and

$$q_w = 1 - \exp(4\,z/h) - 3\times10^{-4}\exp(8\,z/h)$$

where $\lambda_w \approx 0.1h \Rightarrow n_I \approx 10$; and $n_e = U(1.8q_w h)^{-1}$**.Using the relation**

$$15 < n_I / n_e < 20$$

the condition $n_I << n_e$ is verified that the inertial subrange is statistically Independent of the subrange energy-containing eddies. Hence, KTV:

$$\nu_T = 1.98\times10^{-3}\,hw_*$$

Considering typical values for CBL:

$$w_* = 2\,\mathrm{ms}^{-1} \text{ and } h = 1500\,\mathrm{m} \Rightarrow \nu_T = 6\,\mathrm{m}^2\mathrm{s}^{-1}.$$

Integrating the time-dependent spectrum equation:

$$\sigma_w^2(z,t) = 0.76 q_w^{5/3} w_*^2 \int_{(1.8q_w)^{-1}}^{\infty} \frac{\exp\left[-0.16 f_k^2 \left(w_* t/h\right)\right]}{\left(1 + 2.7 q_w f_k\right)^{5/3}} df_k$$

where $f_k = nh/U$. Fig. 1 shows the vertical velocity variance averaged across the boundary layer and normalized by w_*^2 as a function of tw_*/h.

The expression for the decaying vertical eddy diffusivity results

$$\frac{K_{zz}(z,t)}{w_* h} = 0.15 q_w^{11/6} \left[\int_{(1.8q_w)^{-1}}^{\infty} \frac{\exp\left[-0.16 f_k^2 \left(w_* t/h\right)\right]}{\left(1 + 2.7 q_w f_k\right)^{5/3}} df_k \right]^{1/2}$$

Figure 2 shows the temporal evolution for $K_{zz}(z,t)$.

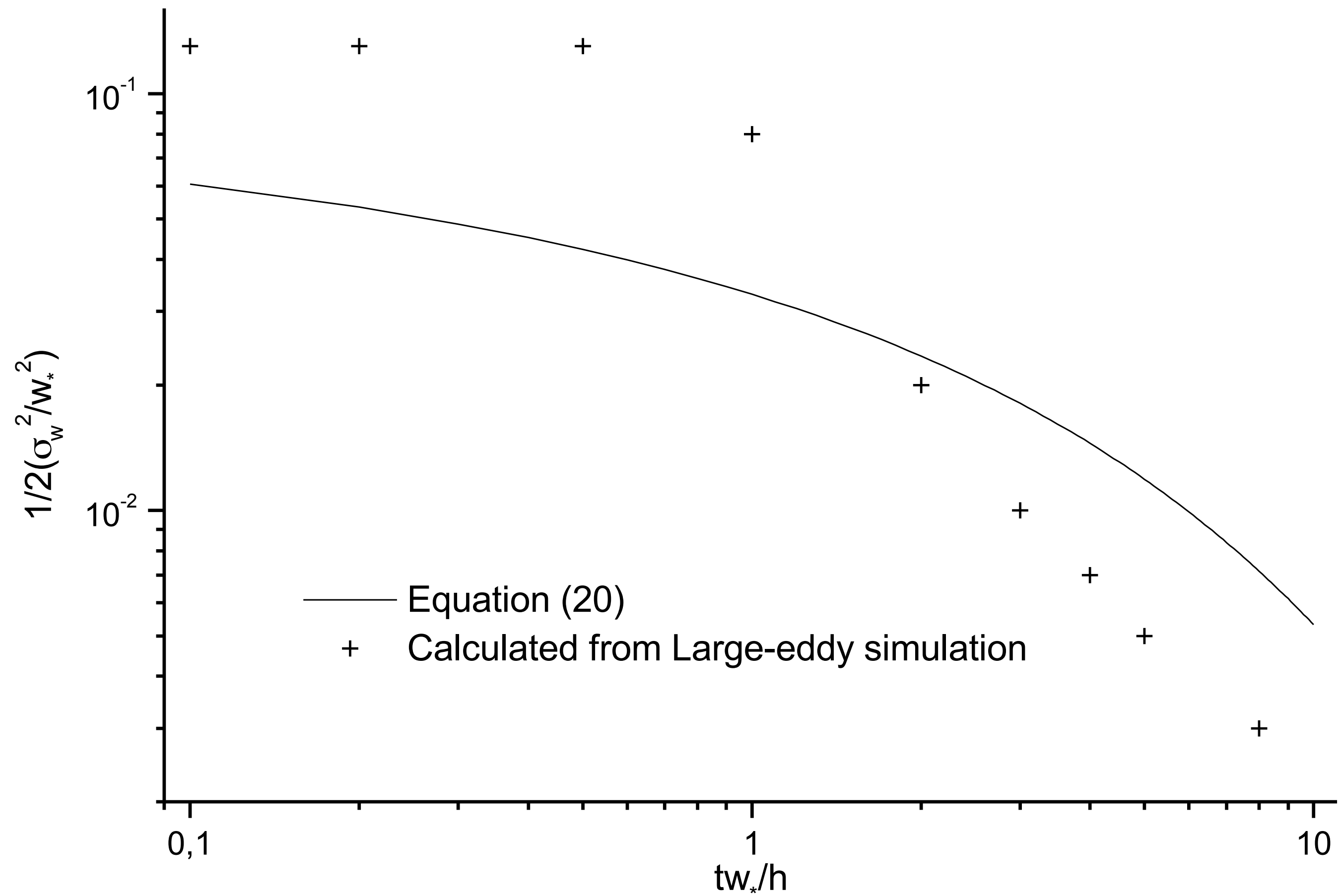


Figure 1: Temporal of the evolution vertical velocity variance.

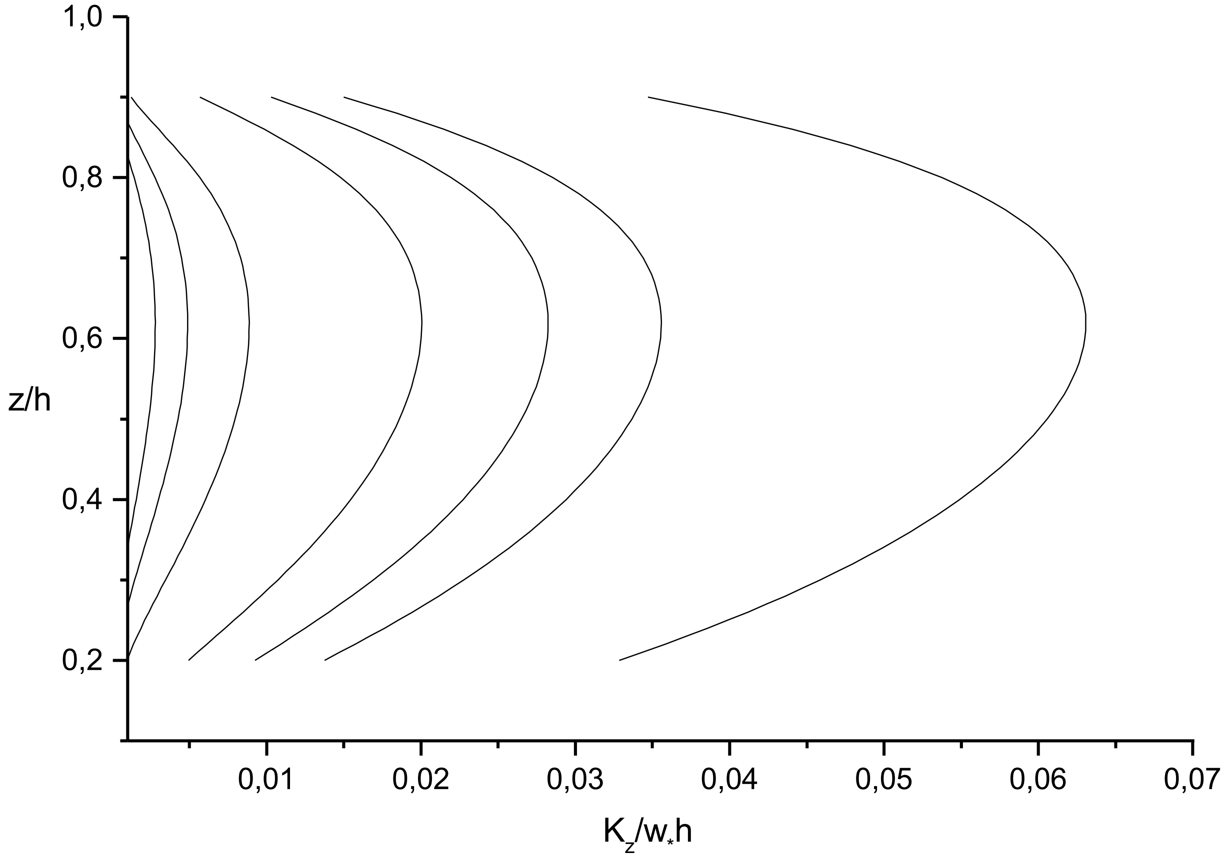


Figure 2: Temporal evolution of the vertical profiles of normalized RL eddy diffusivity.

Algebraic approximation for K_{zz}(z,t) in the RL:

Based on the Nieuwstadt-Brost (1986) study, integral form to the vertical eddy diffusivity can be approximated by a simple algebraic formula

$$\frac{K_{zz}(z,t)}{w_* h} = 0.16 q_w \left[C_1 + C_2 \sqrt[m]{\frac{w_* t}{h}} \right]$$

for $0 \le w_* t/h \le 24:$

$$C_1 = \left(\frac{\sigma_w}{w_*}\right)_0 = 0.48 q_w^{1/3}\ ; \quad C_2 = \frac{\left(\frac{\sigma_w}{w_*}\right)_{24} - \left(\frac{\sigma_w}{w_*}\right)_0}{\sqrt[m]{24}}\ ; \quad m = 4$$

for $24 \le w_* t/h \le 48:$

$$C_1 = \left(\frac{\sigma_w}{w_*}\right)_{24} - C_2 \sqrt[m]{24}\ ; \quad C_2 = \frac{\left(\frac{\sigma_w}{w_*}\right)_{48} - \left(\frac{\sigma_w}{w_*}\right)_{24}}{\sqrt[m]{48} - \sqrt[m]{24}}\ ; \quad m = 10$$

Algebraic approximation for $K_{zz}(z,t)$ in the RL:

Based on the Nieuwstadt-Brost (1986) study, integral form to the vertical eddy diffusivity can be approximated by a simple algebraic formula

$$\frac{K_{zz}(z,t)}{w_* h} = 0.16 q_w \left[C_1 + C_2 \sqrt[m]{\frac{w_* t}{h}} \right]$$

for $0 \le w_* t / h \le 24:$

$$C_1 = \left(\frac{\sigma_w}{w_*} \right)_0 = 0.48 q_w^{1/3} \; ; \quad C_2 = \frac{\left(\frac{\sigma_w}{w_*} \right)_{24} - \left(\frac{\sigma_w}{w_*} \right)_0}{\sqrt[m]{24}} \; ; \quad m = 4$$

for $24 \le w_* t / h \le 48:$

$$C_1 = \left(\frac{\sigma_w}{w_*} \right)_{24} - C_2 \sqrt[m]{24} \; ; \quad C_2 = \frac{\left(\frac{\sigma_w}{w_*} \right)_{48} - \left(\frac{\sigma_w}{w_*} \right)_{24}}{\sqrt[m]{48} - \sqrt[m]{24}} \; ; \quad m = 10$$

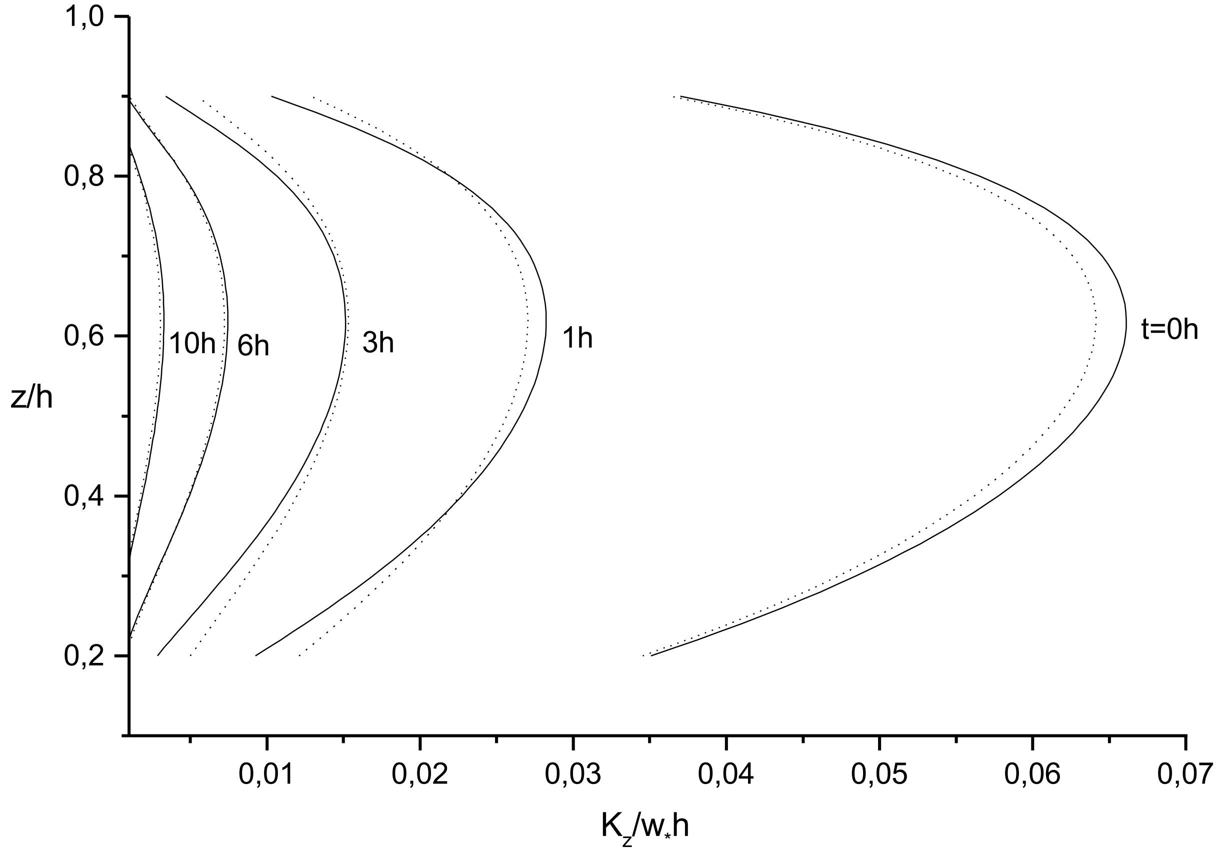


Figure 3: Vertical eddy diffusivity calculated from eqs.(21), (integral, solid line) and (23) (algebraic, dot line). The profiles are evaluated at five different times: *t* = 0, 1, 3, 6, and 10 hours.

Boundary-Layer Meteorol (2010) 134:23–39
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ARTICLE

Morning Boundary-Layer Turbulent Kinetic Energy by Theoretical Models

A. B. Nunes · H. F. Campos Velho · P. Satyamurty ·
G. Degrazia · A. Goulart · U. Rizza

A model for CBL growth:

From the spectral evolution equation

$$\frac{\partial E(k,t)}{\partial t} = W(k,t) + M(k,t) + H(k,t) - 2\nu k^2 E(k,t)$$

E(k,t): 3D energy density spectrum function (EDS);
W(k,t): the energy-transfer-spectrum function (contribution due to the inertial transfer of energy among different wavenumbers)
M(k,t): mechanical production term (≈ 0);
H(k,t): thermal production term;
viscous dissipation: second term on the r.h.s..

As before: $$W(k,t) = 2\nu_T k^2 E(k,t)$$

however, $$H(k,t) = \begin{cases} H(k) & \text{for } t \geq 0 \\ 0 & \text{for } t < 0 \end{cases}$$

Therefore the spectral evolution equation becomes

$$\frac{\partial E(k,t)}{\partial t} = -2k^2\left(\nu_T + \nu\right)E(k,t) + H(k)$$

Using the Laplace transform, where $\hat{E}(k,s) = \int_0^\infty E(n,t)\, e^{-st} dt$

following operational equation is obtained

$$\left[s + 2k^2\left(\nu_T + \nu\right)\right]\hat{E}(k,s) = E_0(k) + \frac{H(k)}{s}$$

with analytical inverse Laplace transform:

$$E(k,t) = E_0(k)e^{-k^2(\nu_T+\nu)t} + \frac{H(k)}{2k^2(\nu_T+\nu)}\left[1 - e^{-k^2(\nu_T+\nu)t}\right]$$

for t → ∞ the asimptotic expression for the spectrum is

$$E(k) = \frac{H(k)}{2k^2(\nu_T+\nu)}\,.$$

The spectral model from Kristensen et al. (1989):

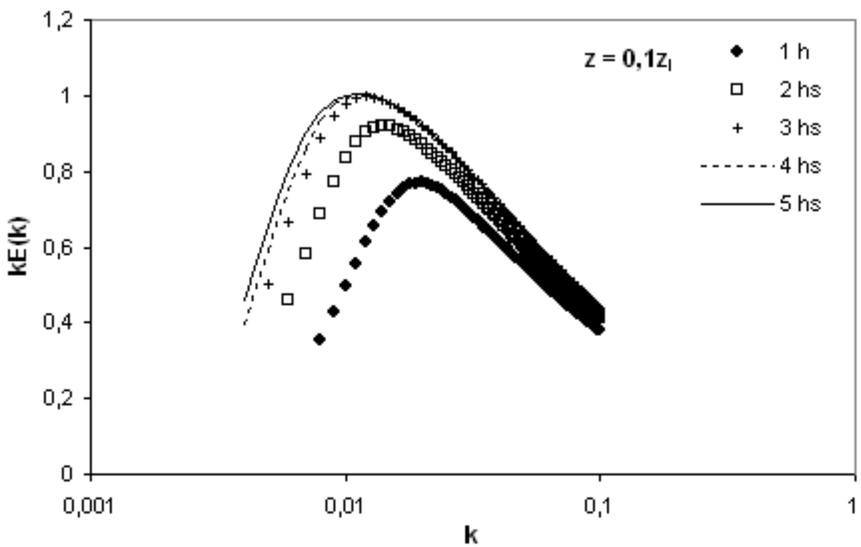
$$E(k) = k^3 \frac{d}{dk}\frac{1}{k}\frac{dF_L}{dk} + 2k^4 \int_0^{1/k^2} s^2 g'''(s)ds - \frac{14}{9}k^{4/3}\int_0^{1/k^2} s^{2/3} g'''(s)ds$$

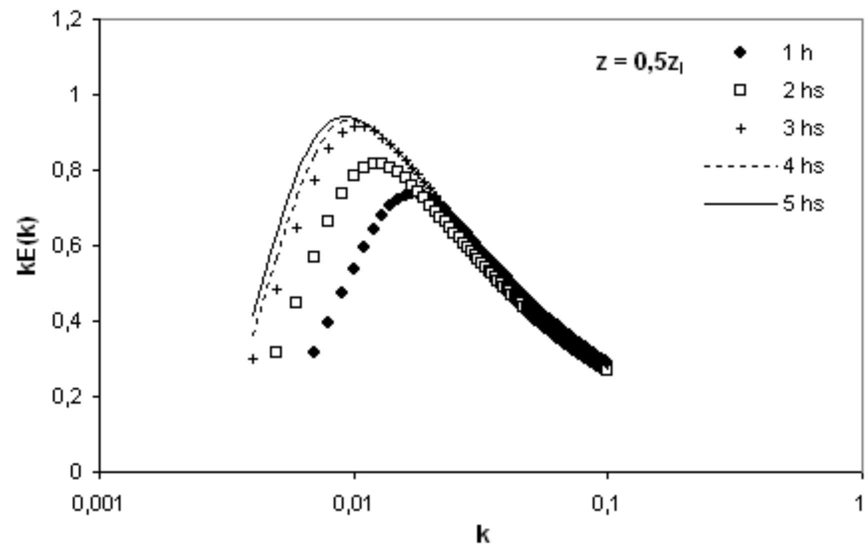
$$F_L = \frac{\ell_L \sigma_L^2}{\pi} \frac{1}{\left\{1 + \left(\frac{\ell_L k}{a(\mu_L)}\right)^{2\mu_L}\right\}^{\frac{5}{6\mu_L}}} \qquad s = k^{-2}$$

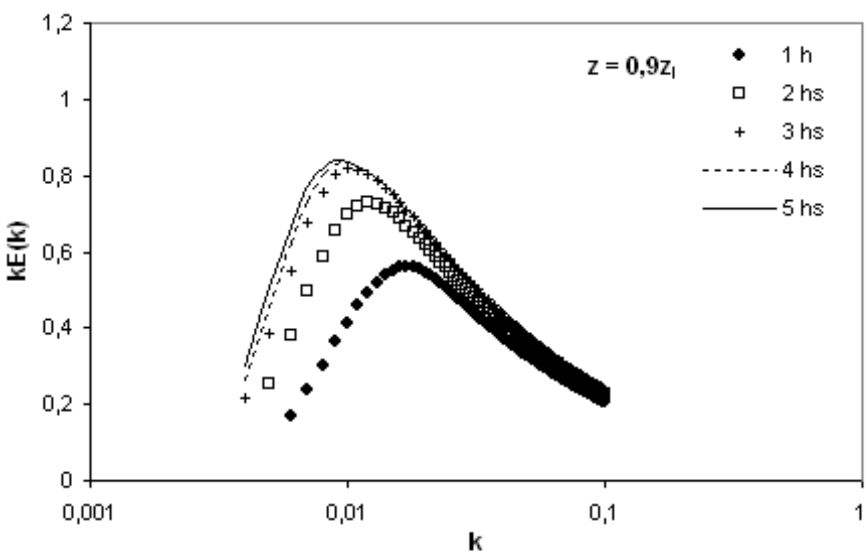
$$g'''(s) = 2 f_0'''\left(\sigma_L^2, \ell_L, \mu_L; s\right) - f_0'''\left(\sigma_T^2, \ell_T, \mu_T; s\right) - f_0'''\left(\sigma_V^2, \ell_V, \mu_V; s\right)$$

$$f_0'''\left(\sigma_i, \ell_i, \mu_i; s\right) = \left(\frac{1}{96\pi}\right)\frac{\sigma_i^2 a^2(\mu_i)}{\ell_i}\left(\frac{a^2(\mu_i)}{\ell_i^2}s\right)^{-1/6} \times \sum_{n=1}^{4} \frac{c_n(\mu_i)}{\left[1 + \left(\frac{a^2(\mu_i)}{\ell_i^2}s\right)^{\mu_i}\right]^{\frac{5}{6\mu_i}+n}}$$

Results for the analytical model:







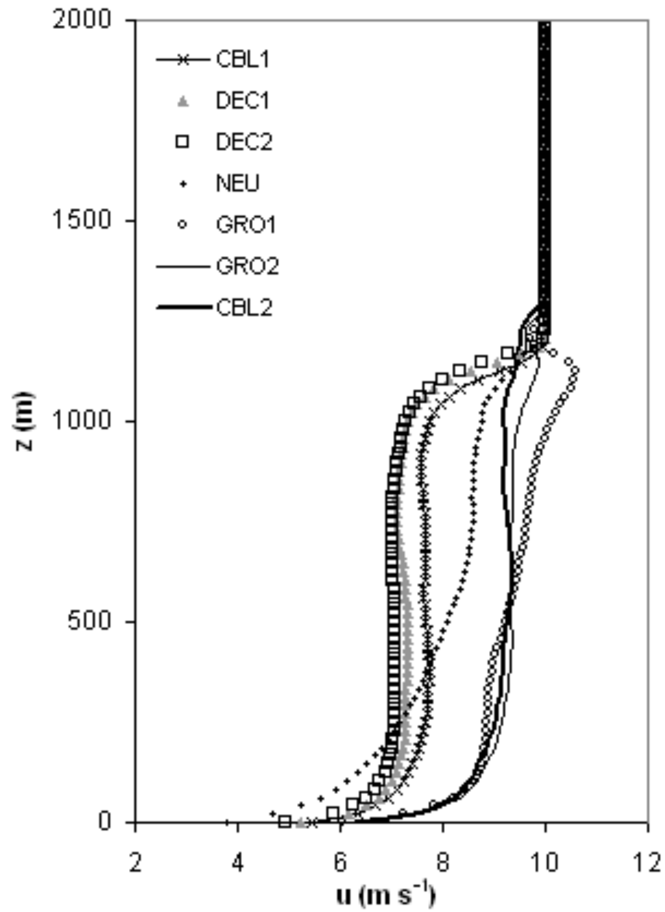
$$E(k,t) = E_0(k)e^{-k^2(\nu_T+\nu)t} + \frac{H(k)}{2k^2(\nu_T+\nu)}\left[1-e^{-k^2(\nu_T+\nu)t}\right]$$

LES for simulating the CBL growing

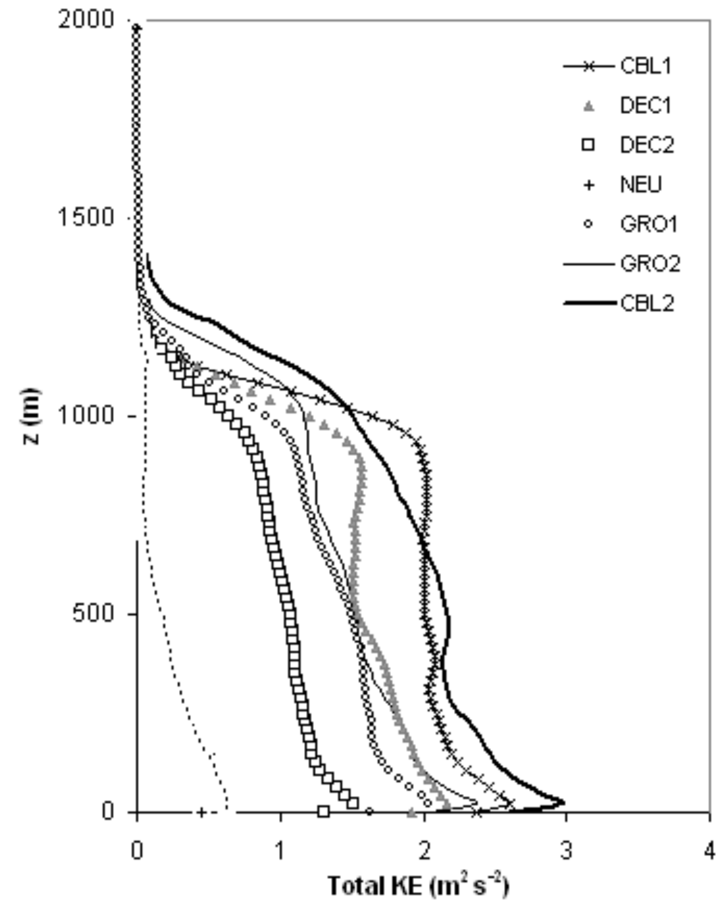
Acronym	*Turbulence type*	H_s (Kms^{-1})	*Time of the profile (after QSS)* (h)	*Period of the stage (after QSS)* (h)
CBL1	Fully developed CBL	0.24	0.45	0 to 1.09
DEC1	Starting the decay	0.16	1.73	1.09 to 1.73
DEC2	Decaying	0.08	2.37	1.73 to 2.37
NEU	Neutral stage	0.00	3.65	2.37 to 4.94
GRO1	Starting the growth	0.08	5.58	4.94 to 5.58
GRO2	Growing	0.16	6.28	5.58 to 6.28
CBL2	Fully developed CBL	0.24	6.91	6.28 to 8.14

LES for simulating the CBL growing

(a) u-component of the wind

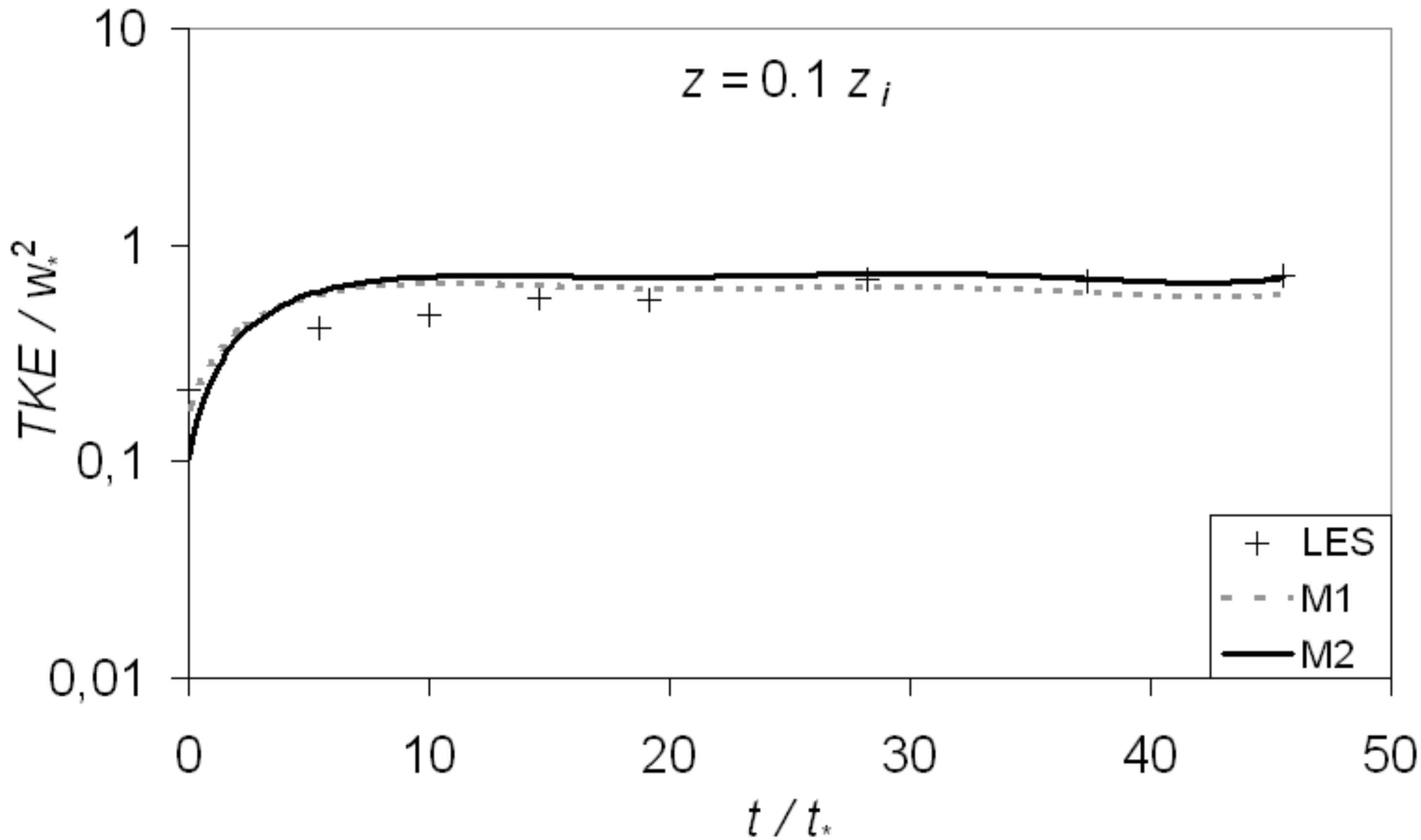


(b) Total kinetic energy



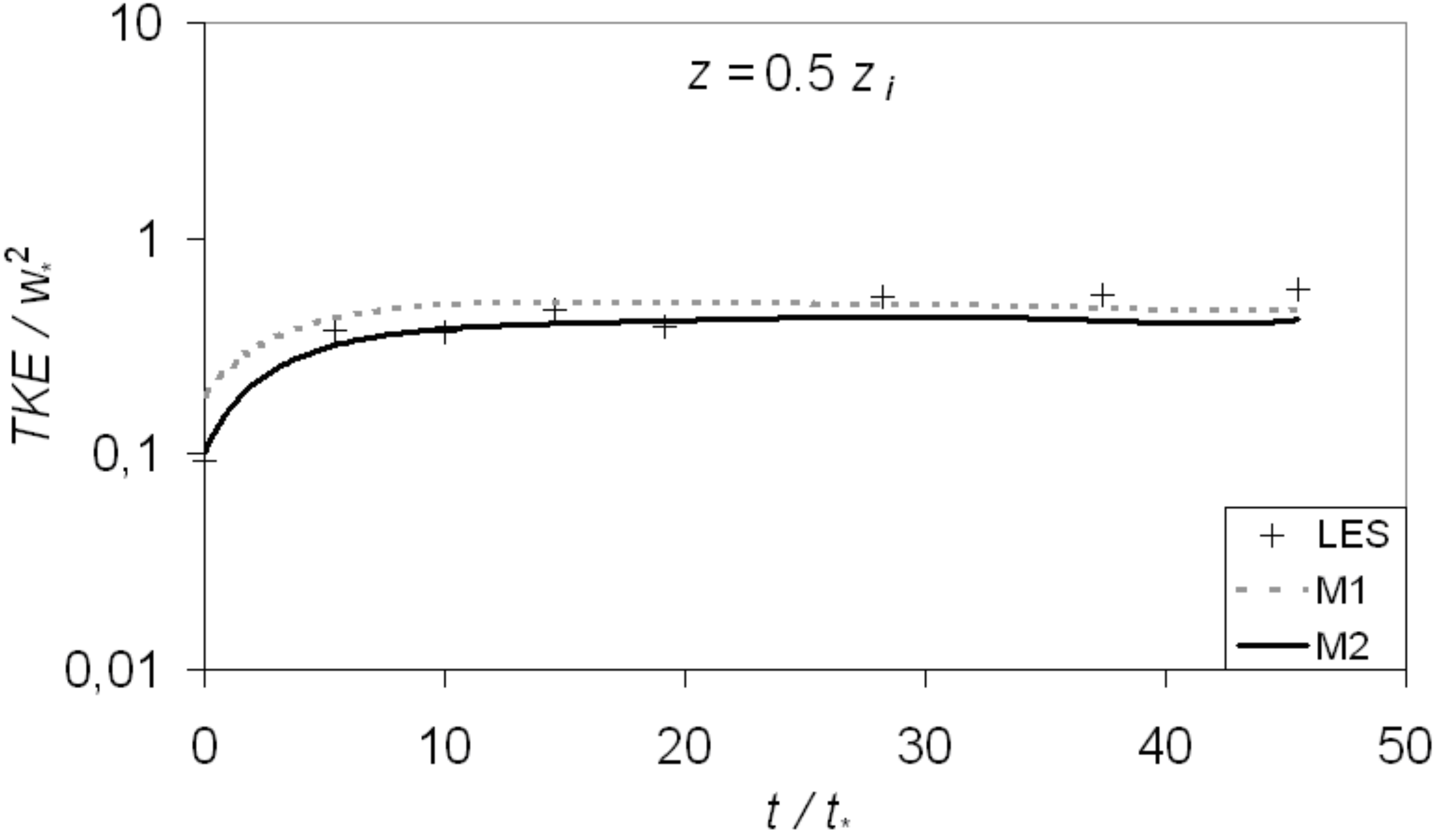
LES versus analytical CBL growing:

Time evolution of the TKE



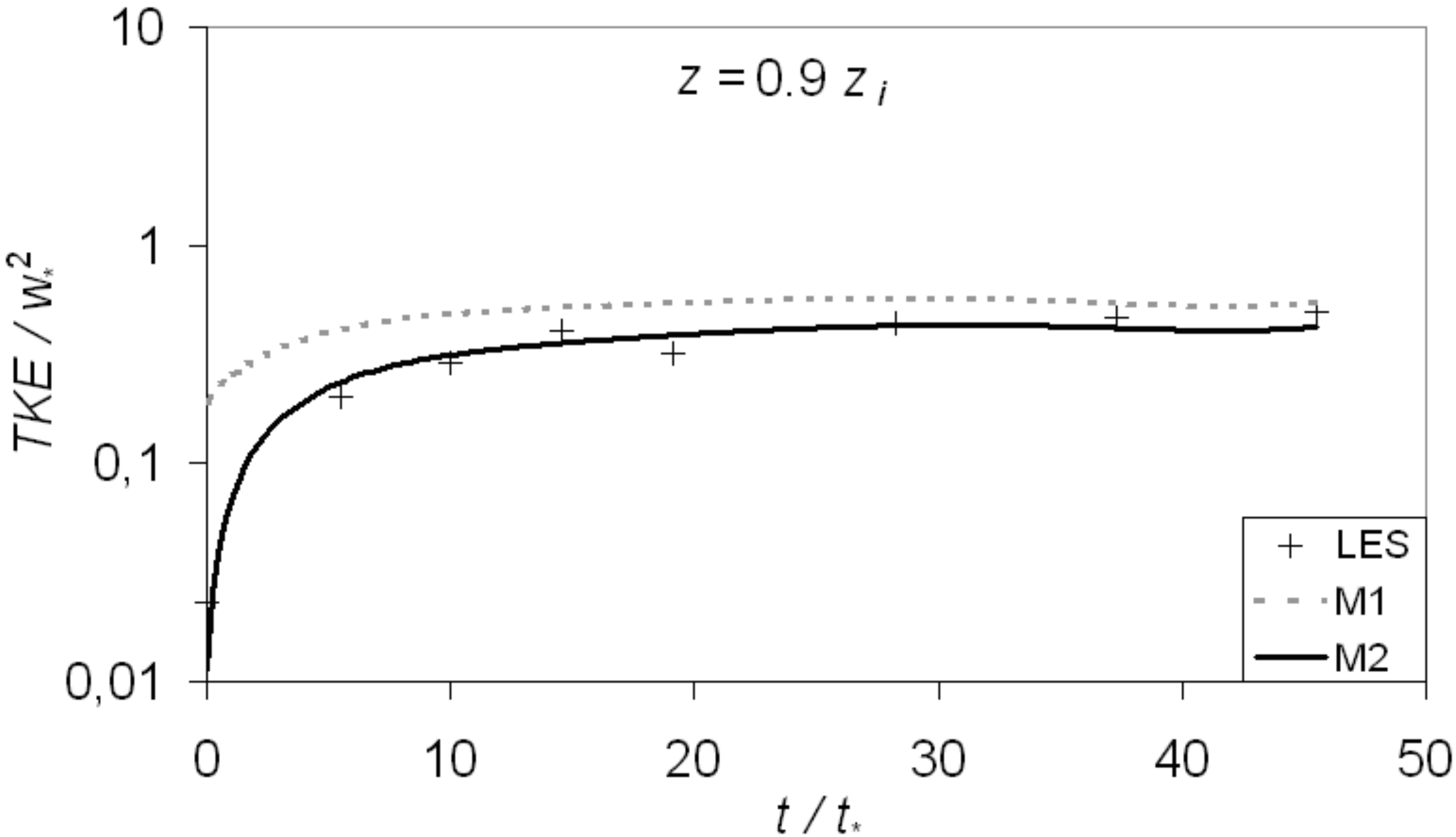
LES versus analytical CBL growing:

Time evolution of the TKE



LES versus analytical CBL growing:

Time evolution of the TKE



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Modeling stratocumulus-topped boundary-layer structure with statistical diffusion theory

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Turbulence model for cloud dynamics

Taylor' s theory can also be applied for turbulence parameterization in the cloud dynamics problems. The method is illustrated for the turbulent transport in the stratocummulus-topped boundary-layer.

Meteorologists have given a great emphasis to the study of marine stratocumulus clouds formed in subtropical latitudes during summer. First of all, stratocumulus formation is a very common phenomenon. This type of clouds is often present in great extensions (usually 10^6 km^2), showing an almost 100% area coverage and lasting for a long residence time (about a half part of the year in the UK).

From the Taylor's theory, the vertical eddy diffusivity is given by (BzPA, 97):

$$K_{zz} = \sigma_w l_w = \frac{\sqrt{\pi}}{16} \sigma_w \lambda_w$$

where parameter λ_w is the peak wavelength in the vertical velocity spectrum. The value of σ_w and a fitting curve for λ_w are obtained from ACE-2 experiment.

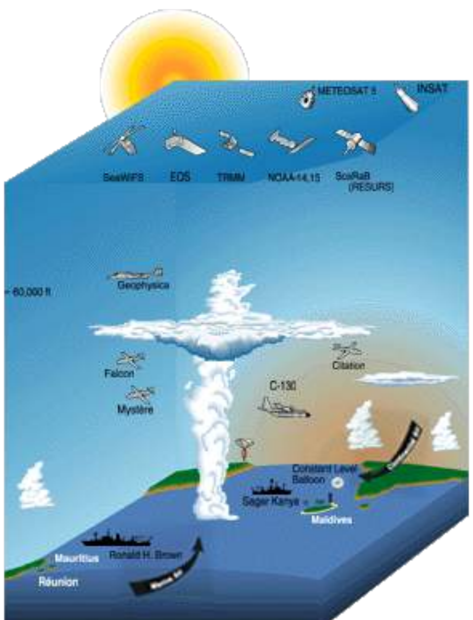
An expression for λ_w – h is the boundary layer height:

$$\lambda_w = \begin{cases} a_1 z & z < 0.1h \\ a_2 h\left[1 - \exp[b_1(z/h)] - a_3 \exp[b_2(z/h)]\right] & 0.1h < z < 0.6h \\ a_4 h \exp\left[-b_3(z/h)\right] & z > 0.6h \end{cases}$$

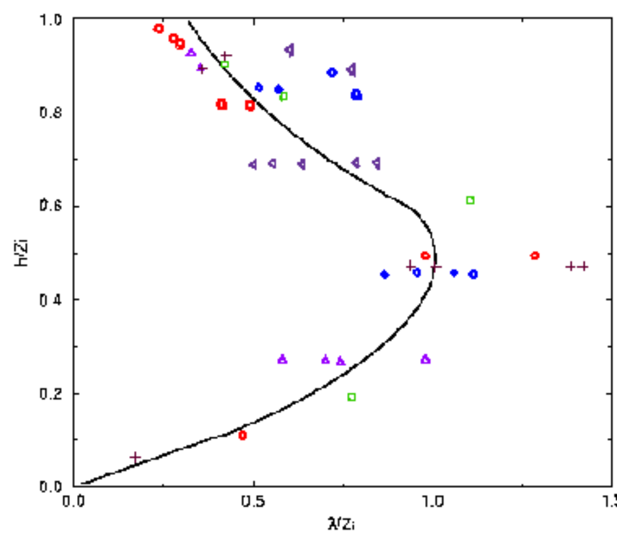
with the numerical values for the constants:

$a_1 = 3.7$ $\quad a_2 = 1.46$ $\quad a_3 = 0.003$ $\quad a_4 = 4.7$

$b_1 = 3.15$ $\quad b_2 = 7.07$ $\quad b_3 = 2.7$



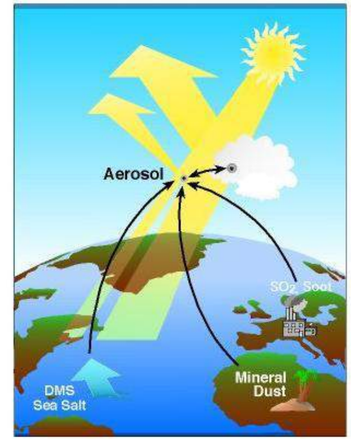
Fitting curve for λ_w

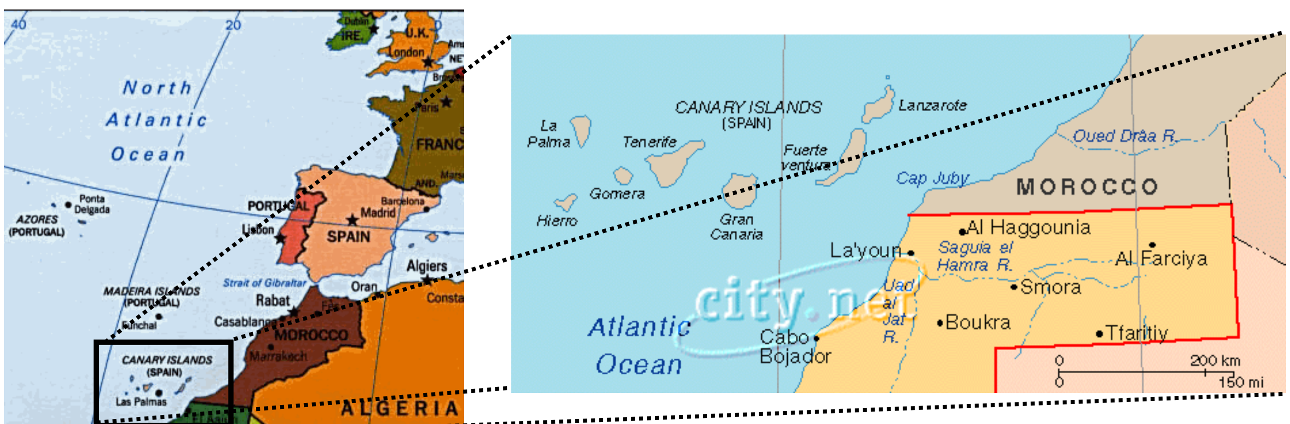


Aerosol Characterization Experiment (ACE):

Investigation for understanding some aspects of cloud system:

- turbulent transport,
- radiative cooling,
- entrainment,
- large-scale subsidence.





Geographic position of the ACE-2 experiment

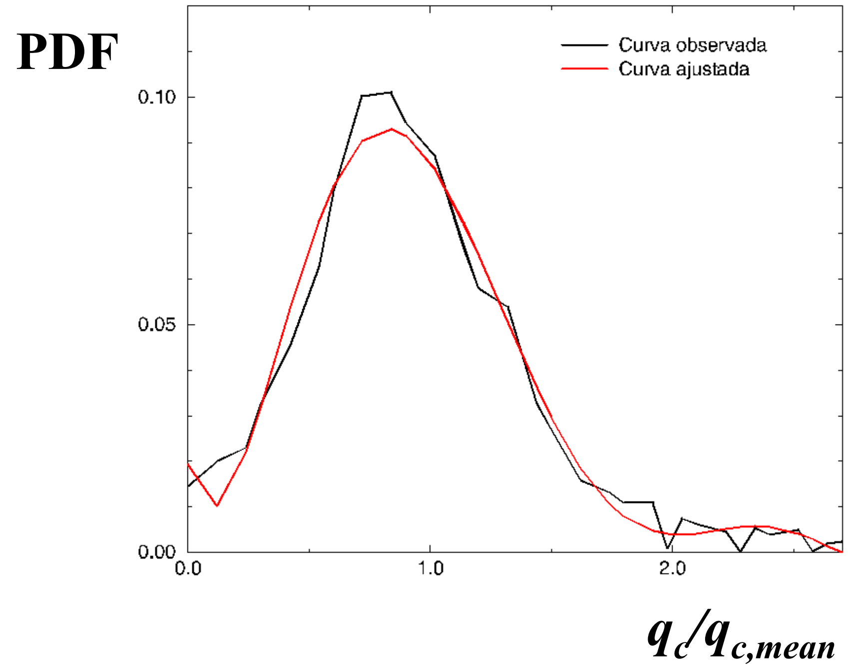
Autoconvertion parameterization

An autoconversion scheme was also proposed, in which the small-scale variability of cloud water content is taken into account.

ACE2 data were used to achieve a PDF for cloud water content (q_c). First, data collected during horizontal flight legs were normalized by the mean q_c ($q_{c,mean}$). The PDF was computed with respect to fractions of $q_{c,mean}$ and fitted by a polynomial. In the parameterization, autoconversion is calculated for ten cloud water content categories, according to Berry-Reinhardt's formula.

Figure 2 depicts the average cloud water content PDF for the several ACE2-cloudcolumn flights, as well as the polinomial fitting used in the present parameterization.

$$(\mathrm{PDF})_{q_c} = \sum_{k=0}^{6} a_k \left(q_c / q_{c,\mathrm{mean}}\right)^k$$



Single-column model

The single-column model (SCM) used to test the turbulence and autoconversion schemes comprises prognostic equations for the horizontal wind, the ice-liquid potential temperature, the total water mixing ratio, and the turbulent kinetic energy (Golaz 1997). The SCM uses a radiation transfer scheme developed by Harrington (1997) and the microphysical parameterization used in RAMS (Walko et al., 1995):

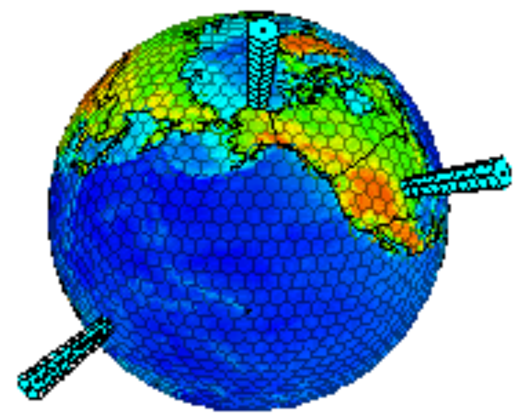
$$\frac{\partial \bar{u}}{\partial t} = -\bar{w}\frac{\partial \bar{u}}{\partial z} + f(\bar{v} - v_g) - \frac{\partial \overline{w'u'}}{\partial z}$$

$$\frac{\partial \bar{v}}{\partial t} = -\bar{w}\frac{\partial \bar{v}}{\partial z} + f(\bar{u} - u_g) - \frac{\partial \overline{w'v'}}{\partial z}$$

$$\frac{\partial \bar{\theta}_{il}}{\partial t} = -\bar{w}\frac{\partial \bar{\theta}_{il}}{\partial z} - \frac{\partial \overline{w'\theta'_{il}}}{\partial z} + \left.\frac{\partial \bar{\theta}_{il}}{\partial t}\right|_{\mathrm{rad}} + \left.\frac{\partial \bar{\theta}_{il}}{\partial t}\right|_{\mathrm{sedim}}$$

$$\frac{\partial \bar{r}_i}{\partial t} = -\bar{w}\frac{\partial \bar{r}_i}{\partial z} - \frac{\partial \overline{w'r_i'}}{\partial z} + \left.\frac{\partial \bar{\theta}_{il}}{\partial t}\right|_{\mathrm{sedim}}$$

$$\frac{\partial e}{\partial t} = -\bar{w}\frac{\partial e}{\partial z} - \overline{w'u'}\frac{\partial \bar{u}}{\partial z} - \overline{w'v'}\frac{\partial \bar{v}}{\partial z} + \frac{g}{\bar{\theta}_v}\overline{w'\theta_v'} - \frac{\partial}{\partial z}\left(\overline{w'e} + \frac{\partial \overline{w'p'}}{\bar{\rho}}\right) - c_s\frac{e^{3/2}}{l_s}$$



SCM representation

Parameterization of turbulent fluxes:

$$\overline{w'u'} = -\left(K_{zz}\right)_m \frac{\partial \bar{u}}{\partial z} \qquad \overline{w'v'} = -\left(K_{zz}\right)_m \frac{\partial \bar{v}}{\partial z} \qquad \overline{w'e} + \frac{\overline{w'p'}}{\bar{\rho}} = -\left(K_{zz}\right)_m \frac{\partial e}{\partial z}$$

$$\overline{w'\theta_{il}'} = -\left(K_{zz}\right)_h \frac{\partial \bar{\theta}_{il}}{\partial z} \qquad \overline{w'r_i'} = -\left(K_{zz}\right)_h \frac{\partial \bar{r}_i}{\partial z}$$

$$K_h = \alpha K_m \quad \text{where}: \quad \alpha = \begin{cases} 1.318 \dfrac{0.2231 - R_i}{0.2341 - R_i} & \text{if } R_i < 0.16 \\ 1.12 & \text{if } R_i \geq 0.16 \end{cases}$$

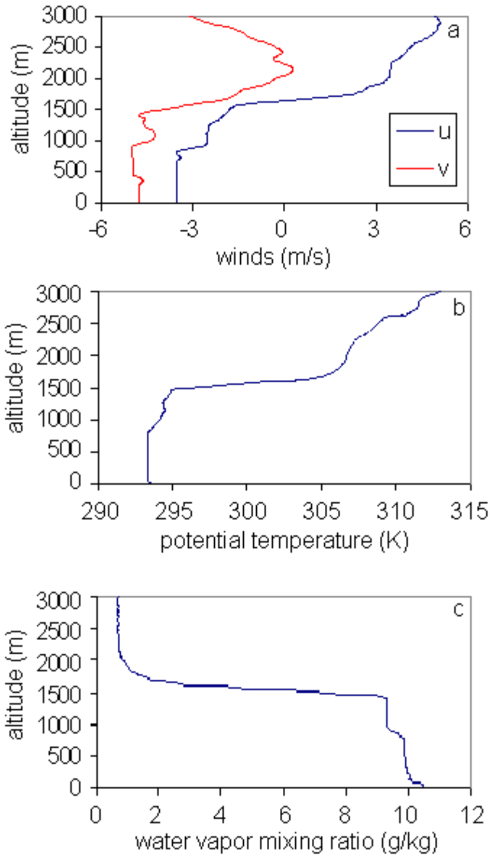
Autoconversion ratio:

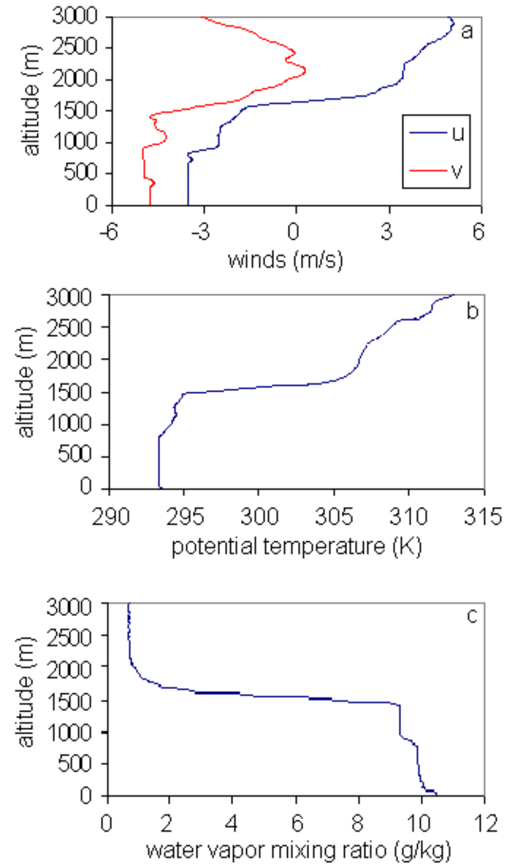
$$\frac{\partial q_{\mathrm{rain}}}{\partial t} = \frac{\rho_w \xi}{\rho_a \tau} \quad \text{with}: \quad \xi = 2.7 \times 10^{-2} q_c \left[(10^{20}/16) D_{\mathrm{mean}}^4 (1+v)^{-0.5} - 0.75 \right]$$

$$\tau = \frac{3.7}{\rho_a q_c} \left[0.5 \times 10^6 D_{\mathrm{mean}}^4 (1+v)^{-0.5} - 0.75 \right]^{-1}$$

<u>Initial conditions</u>: Vertical profiles of the horizontal winds, potential temperature, water vapor mixing ratio, 26 June 1997, approximately at local noon.

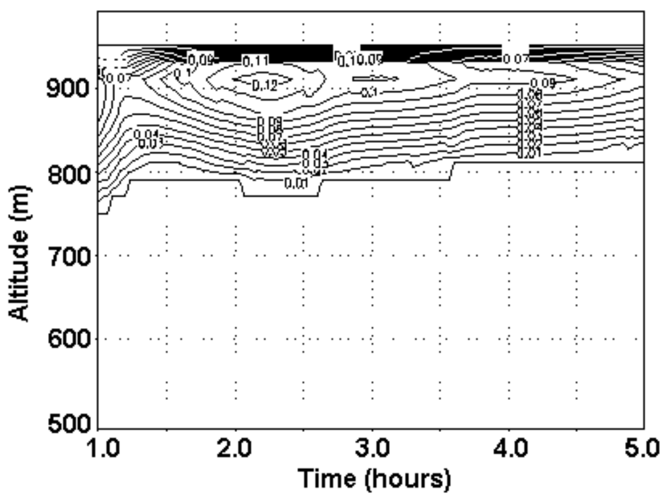
Discretization parameters: $N_z = 150$, $\Delta z = 20$ m, $\Delta t = 10$ s.



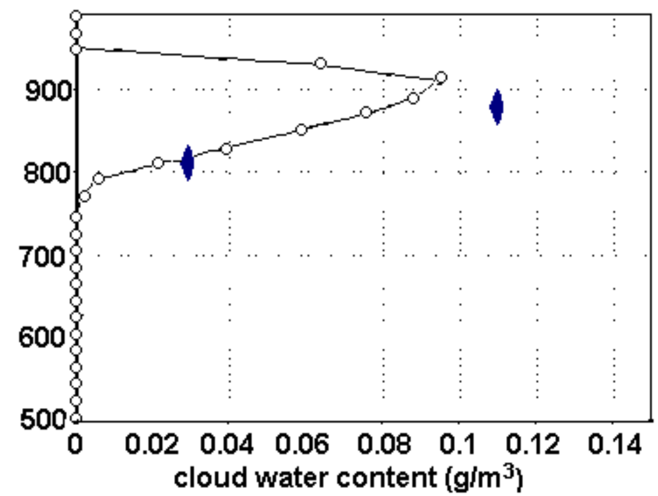


Numerical results

The new parameterizations were used to simulate two ACE2-cloudcolumn cases. 08 July 1997: larger droplet concentrations occurred (196 cm^{-3}, on average), and the near-surface mixed layer and the cloudy layer were coupled.



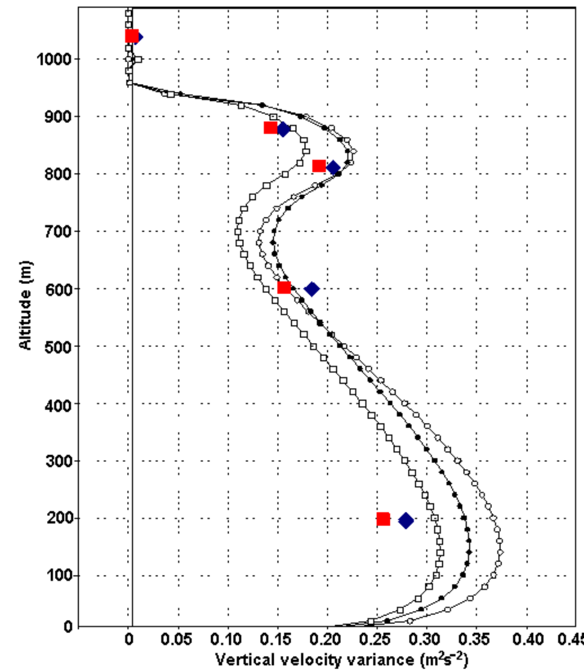
Time evolution of the vertical distribution of cloud water content.

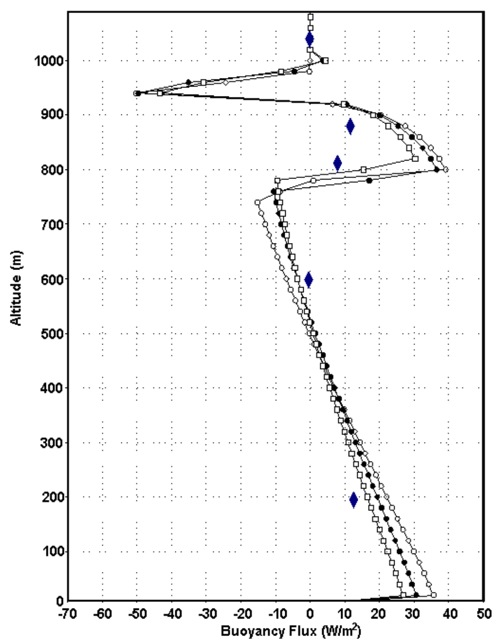


3-hour average of the simulated cloud water content (line with white circles in g/m^3). Diamonds indicate averages of airborne observations at two horizontal levels.

08 July 1997:

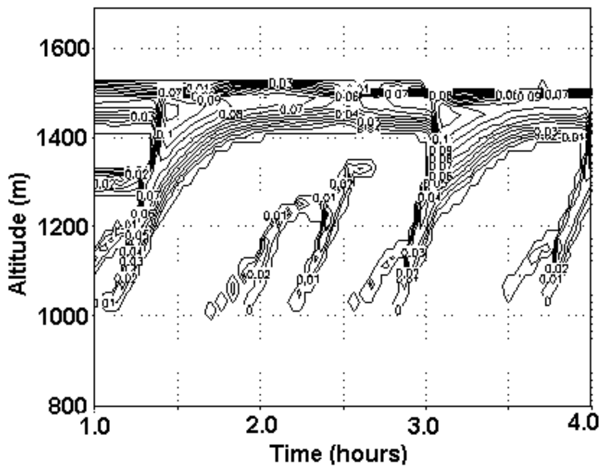
Vertical profile of the simulated vertical velocity variance, after 2 hours (white circles), 3 hours (black circles) and 4 hours (white squares). Blue diamonds and red squares indicate observations (raw and filtered data, respectively)



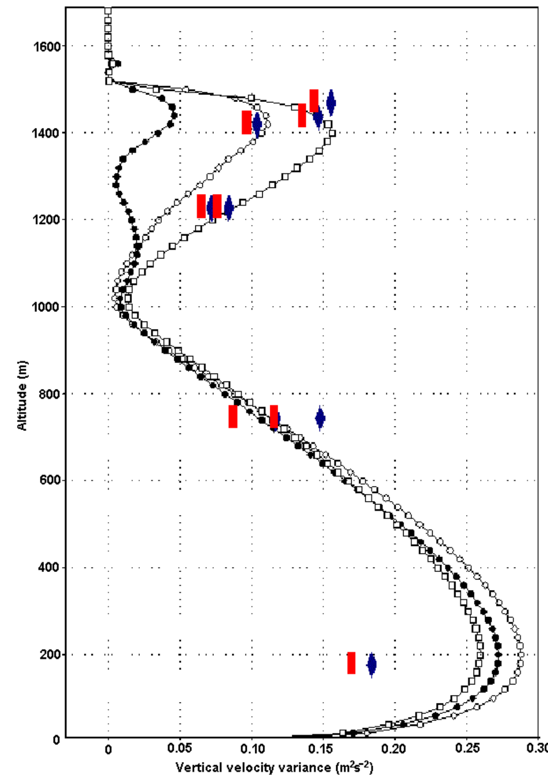


Vertical profile of the simulated buoyancy flux, after 2 hours (white circles), 3 hours (black circles) and 4 hours (white squares). Blue diamonds indicate observations.

<u>26 June 1997</u>: droplet concentrations of the order of 55 cm^{-3}, on average, drizzle was significant and a decoupled boundary-layer was observed.



Time evolution of the vertical distribution of cloud water content. This case was characterized by a deeper cloud-top height, significant drizzle formation, decoupling between the cloudy-layer and the near-surface layer and breaking of the stratocumulus deck.



σ_w^2 after 2 hours (white circles), 3 hours (black circles) and 4 hours (white squares). Blue diamonds and red squares indicate observations (raw and filtered data).

Turbulent boundary layer modeling

Questions?

Comments?

Suggestions?

Thank you!