Turbulence representation with counter-gradient term to the BRAMS

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Abstract

In the Brazilian Regional Atmospheric Modeling System (BRAMS), several schemes of turbulence parameterization are available, one of them is based on Taylor's statistical theory on turblence. Here, an extra term is included in the Taylor's parametrization. This term is called counter-gradient for the Convective Boundary Layer (CBL). Observational data is obtained from the Wet season Atmospheric Mesoscale Campaign (WETAMC), an activity of the LBA project. The analysis from the European Center for Medium Range Weather Forecast (ECMWF) is used as initial and boundary conditions for the numerical simulations. The new parameterization show satisfactory results when comparing with observational datasets from ABRACOS and Rebiu Jaru stations.

Keywords: Planetary Boundary Layer (PBL), Atmospheric turbulence, Counter-gradient term, Brazilian Regional Atmospheric Modeling System (BRAMS), Taylor's theory..

1. Introduction

The Brazilian developments on Regional Atmospheric Model (BRAMS) [9, 11] is a joint project of several Brazilian institutes. For now, the code is supported and developed by the Center for Weather Prediction and Climate Studies (CPTEC) of the National Institute for Space Research (INPE). BRAMS is based on the Regional Atmospheric Modeling System (RAMS) [13], with several new functionalities and parameterizations. RAMS is a numerical model designed to simulate atmospheric circulations at many scales. It has a set of state-of-art physical parameterizations appropriate to simulate processes, such as surface-air exchanges, turbulence, convection, radiation and cloud microphysics.

There are 6 different parameterizations to represent turbulent fluxes. The more recent turbulent parameterization is a first order closure scheme based on the Taylor's statistical theory on turbulence [1]. The higher order closure methods need to include more partial differential equations to be solved, enhacing the model complexity and computational effort. On the other hand, first order approach is unable to represent the counter-gradient flow observed for the convective boundary layer formation. The latter behaviour is simulated to the second order, or higher, closure schemes.

This paper presents a counter-gradient representation associated to a Taylor's parameterization [8]. The scheme follows the approach suggested by Campos Velho et al. [2]. Experimental Data from the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) experiment[1] is used for comparison, showing good agreement between experiments and observation.

2. BRAMS: Limited Area Atmospheric Model

BRAMS is employed to be the system for numerical wethear prediction over the South America with 5 km of horizontal resolution, executed on a massively parallel machine Cray XE6 by using 9600 processing cores[2] for the diary operational task. There is a version of the model designed to be the operational environmental predition system (this version is used to be called as CCATT-BRAMS) of the CPTEC-INPE. The BRAMS model is under continous development [10].

The model is codified by using the finite difference numerical scheme on type-C Arakawa grid for solving the fully compressible non-hydrostatic equations, and is equipped with a multiple grid nesting scheme, allowing the model equations to be solved simultaneously on any number of two-way interacting computational meshes of increasing spatial resolution. In the type-C grid, the variables temperature (T), pressure (p), and density (ρ) are defined in the center of a computational cell, and the wind components (u, v, w) are described in center of the cell edge.

BRAMS features include an ensemble version of a deep and shallow cumulus scheme based on the mass flux approach [15] – the original RAMS cumulus scheme was not based on mass flux approach. The surface model is the LEAF (Land Ecosystem Atmosphere Feedback model) [19], representing the surface-atmosphere interaction.

[1]See: `https://daac.ornl.gov/LBA/lba.shtml`

[2]The CPTEC-INPE supercomputer Cray XE6 is a machine with 1280 processing nodes and 30,720 cores (2 processors per node and 12-cores for each processor).

3. Turbulence Parameterization

BRAMS has several models for representing turbulent fluxes. The most used schemes are parameterizations derived by Smagorinsky [16] and Mellor-Yamada [12], approaches of first and 2.5 orders – respectively. The most recent turbulent model implemented for the BRAMS has used the Taylor's theory [1]. For the latter approach, a counter-gradient was added, and the results are shown in the paper.

According with Taylor's statistical theory on turbulence [17, 18] the eddy diffusivity can be represented as product between an average velocity and a characteristic length: $K_{\alpha\alpha} \sim \langle v_i(t)\rangle\langle x(t)\rangle$, where the index i indicates the wind components (u, v, w), space directions are associated the α index ($\alpha = x, y, z$), and the operator $\langle\cdot\rangle$ denotes time average. Another way to express eddy diffusivity is the time rate of average distance among particles:

$$K_{\alpha\alpha} = \frac{d}{dt}\left[\langle x^2(t)\rangle\right] = 2\langle v_i^2(t)\rangle \int_0^t \int_0^\tau \rho_{L_i}(\tau)\, dt' d\tau \ , \tag{1}$$

where $v_i(t)$ is the i-th Lagrangian wind component of a *fluid particle*, and $x(t)$ is its displacement on the direction-i. The self-correlation function is denoted by ρ_{L_i}, normalized by the Lagrangian velocity:

$$\rho_{L_i}(\tau) = \frac{\langle v_i(t+\tau)v_i(t)\rangle}{\langle v_i^2(t)\rangle} \ . \tag{2}$$

The Gifford-Hay and Pasquill's assumption is applied to change the Langrangian quantities into Eulerian ones:

$$\rho_i(\tau) = \rho_{L_i}(\beta_i\tau) \ , \qquad \beta_i = \frac{\sigma_i}{U}\frac{\sqrt{\pi}}{4} \ , \qquad \sigma_i \equiv \sqrt{\langle v_i^2(t)\rangle} \ , \tag{3}$$

with U the wind intensity.

Applying the Fourier transform to Eq. (1), and noting that $\rho_i(\tau)$ is an even function, the Eulerian eddy diffusity can be expressed by [6, 7, 4]

$$K_{\alpha\alpha} = \frac{\sigma_i^2\beta_i}{2\pi}\int_0^\infty \left[\frac{F_i^E(n)\sin(2\pi n t/\beta_i)}{n}\right] dn \tag{4}$$

where $F_i^E(n) \equiv S_i^E(n)/\sigma_i^2$, being $S_i^E(n)$ the turbulent kinetic energy on direction i, and n is a frequency. For large diffusion time ($t \to \infty$), an asymptotic expression for the $K_{\alpha\alpha}$ can be derived [6, 7, 4] as

$$K_{\alpha\alpha} = \frac{\sigma_i^2\beta_i F_i^E(0)}{4} \ . \tag{5}$$

An explicit formulation for eddy diffusivities $K_{\alpha\alpha}$ can be obtained by using empirical relations and Obukhov's similarity theory. A key issue is to derive an analytical formulation to the spectrum. Degrazia et al. [8] have derived a spectral formula for all atmspheric stability conditions:

$$\begin{aligned} nS_i^E(n) &= \frac{1.06 c_i f\, \psi_\epsilon^{2/3}\, (z/h)^{2/3}\, w_*^2}{[(f_m^*)_i^c]^{5/3}\, (1 + 1.5\, [f/(f_m^*)_i^c])^{5/3}} \\ &\quad + \frac{1.5 c_i f (\Phi_\epsilon)^{2/3} u_*^2}{[(f_m^*)_i^{n+es}]^{5/3} \left(1 + 1.5\, [f^{5/3}/(f_m^*)_i^{n+es}]\right)^{5/3}} \end{aligned} \tag{6}$$

where c_i are empirical constants, z is the level over the surface, h is the planetary boundary layer height, w^* is the velocity scale for the convective condition, u^* is the friction velocity, $f = nU/z$ is the frequency in Hertz, U is the wind velocity, ψ_ϵ and Φ_ϵ are nondimensional dissipation functions for convective and stable/neutral conditions, $(f_m^*)_i^c$ and $(f_m^*)_i^{n+es}$ are the maximum frequencies for a convective and stable/neutral conditions – respectively. The wind variances can be calculated by integrating the spectra over all frequencies: $\sigma_i^2 = \int_0^\infty S_i^E(n)\, dn$.

3.1 Counter-gradient model

For the first order closure, the turbulent fluxes can be represented by a gradient of the average quantity:

$$\overline{u'_\alpha \chi'} = -K_{\alpha\alpha,\chi} \left[\frac{\partial \langle \chi \rangle}{\partial x_\alpha} - \gamma_\chi \right] \tag{7}$$

being γ_χ the counter-gradient associated to the scalar quantity χ.

The counter-gradient term is only applied under convective condition, i.e. it is not used for neutral and stable boundary layers. The γ_χ is employed for heat and mass transport, but it is not used to the momentum due to the pressure effect. The stabilityfo the planetary boundary layer can be identified by the Obukhov's length L:

$$\begin{cases} 0 < L \leq 500 : \text{Stable} \\ |L| > 500 : \text{Neutral} \\ -500 \leq L < 0 : \text{Convective} \end{cases}$$

where the Obukhov's length is given by

$$L = \frac{-u_*^3}{\kappa\, (g/\theta_{v0}) \left(\overline{w'\theta'_v}\right)}. \tag{8}$$

here κ is the von Kármán's constant, g is the gravity acceleration, θ_v virtual potential temperature. The friction velocity u_* is calculted as:

$$u_* = \left[\left(\overline{u'w'} \right)^2_{z=0} + \left(\overline{v'w'} \right)^2_{z=0} \right]^{1/4} . \tag{9}$$

Cuijpers and Holtslag [5] described the counter-gradient term by the following formula:

$$\gamma_\chi = \beta_g \ell_w \frac{w_*^2}{\sigma_w} \frac{\chi_*}{h} , \qquad \text{with:} \quad \chi_* = \frac{1}{h w_*} \int_0^h \overline{w'\chi'} \, dz . \tag{10}$$

where β_g is an experimetal constant. Clearly, this counter-gradient modeling depends on the wind variance parameterization (σ_w^2), the mixing length (ℓ), and the average of χ (χ^*).

The expressions for wind variance (σ_i^2) and mixing lenght ($\ell_i = K_{\alpha\alpha}/\sigma_i$) are calculate from the Taylor's theory [4]:

$$\sigma_i^2 = \frac{0.98 c_i}{(f_m)_i^{2/3}} \left(\frac{\psi_\epsilon}{q_i} \right)^{2/3} \left(\frac{z}{h} \right)^{2/3} w_* \tag{11}$$

$$\ell_w = 0.2h \left[1 - \exp\left(-4\frac{z}{h} \right) - 0.003 \exp\left(8\frac{z}{h} \right) \right] \tag{12}$$

where $c_i = 0.3$ for u and 0.4 for (v, w), $f_m = 0.33$ is the freqency for the spectral peak, $q = (f_m)_i \, (f_m)_{n,i}^{-1}$ is a stability function. The dissipation function was derived by Campos Velho et al. [3]:

$$\psi_\epsilon = 3 \left(1 - \frac{z}{h} \right) \left(\frac{z}{h} \right) \left[1 - \exp\left(4\frac{z}{h} \right) - 0.0003 \exp\left(8\frac{z}{h} \right) \right]^{-1} . \tag{13}$$

By using different parameterizations in Eq. (10) imply different values to the constant β_g. Therefore, there is a necessity to calibrate the constant according to the employed parameterization. Cuijpers and Holtslag [5] have used $\beta_g = 1.5$, and Roberti and co-authors [14] employed $\beta_g = 0.07$. For our present study, the value $\beta_g = 0.02$ has presented the better results [20].

4 Simulation on the Amazon Region

The counter-gradient parameterization presented in the Section 3 was codified in the BRAMS version 3.2. We are dealing the same version as used by Barbosa [1], just to promote a better comparison. BRAMS was executed employing different turbulence parameterizations. A comparison of all simulation results was done against the observations obatined during the LBA experiment.

The simulation region was the North part of the Brazil. Figure 1 shows the region for the BRAMS simulation (left), where the zoom of the red box, on the right, indicates the two LBA stations – the yellow points: Biological reserve Rebio Jaru, and Farm "Nossa senhora Aparecida" (Farm NSA), both in the Rondonia state (Brazil).

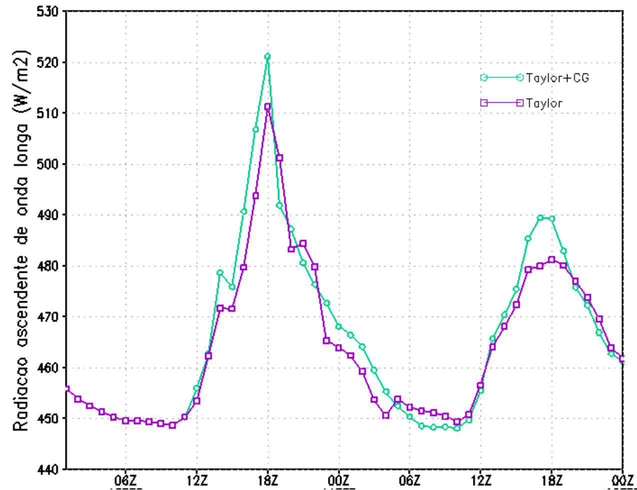
Figure 1 - Satellite images, where the yellow points indicate the location for the Rebio Jaru and Abracos LBA's stations in the South America.

Rebio Jaru): located at 100 km North to the Ji-Paraná city. This area is part of the rain forest. There is a tower 60 m high, intalled at the end of the year 1998 placed at $10\,°04'42"S$ and $61\,°56'01"W$, 145 m over the sea level.

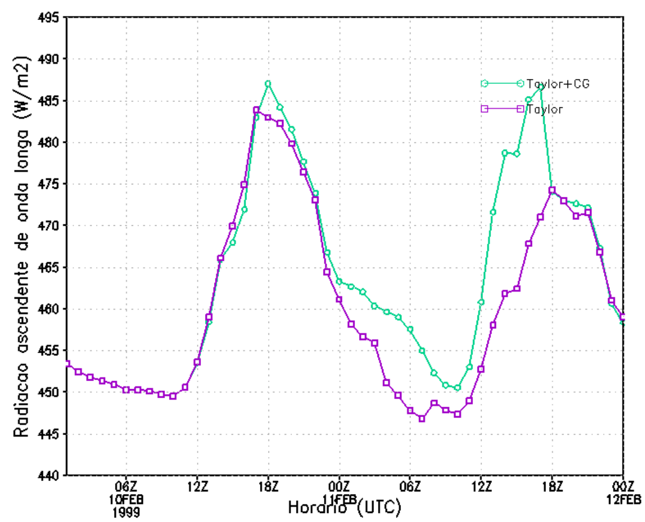
Farm Nossa senhora Aparecida – site for the ABRACOS (Anglo Brazilian Amazonian Climate Observation Study): located at 50 km west direction from the Ji-Paraná city. The site characterizes a deforestation area, and from 1991 has a pasture covering the surface. The farm has a tower placed at $10\,°45"S$ and $62\,°22"W$, 293 m over the sea level.

BRAMS was initiated with data from ECMWF re-analysis. The meteorological variables in the latter data set are: temperature, moisture, geopotential, zonal and meridional winds, with space resolution of 2.5×2.5 degrees. The LBA data are also jointed to the re-analysis for providing initial and boundary conditions. The simulation covers the period without rainfall. The first day for the simulation started at 00UTC February 10th up to 12th, 1999, performing 48 hours of simulation.

BRAMS was configured with 194 and 100 mesh points for Longitude and Latitud, respectively. The horizontal resolution is 20 km over a steriograph polar grid, with center at Latitud 10S and Longitud 61W. For vertical direction, 40 mesh points were defined, with finer resolution close to the surface. Time discretization $\Delta t = 30$ seconds.



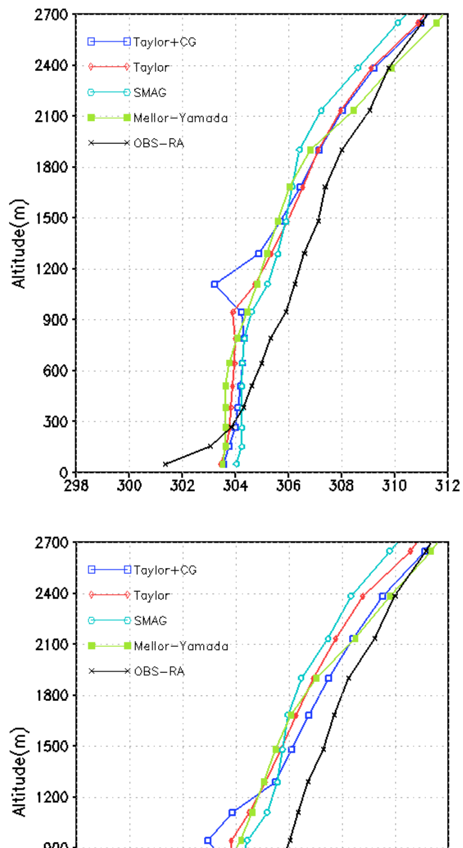
(a)



(b)

Figure 2 - Long wave radiation for Taylor's theory (Taylor), and Taylor + Counter-Gradient (Taylor+CG): (a) ABRACOS, (b) Rebio Jaru.

Figure 2 shows the long wave radiation comparing the Taylor approach alone and the same simulation with counter-gradient term, considering two days of simulation for both experimental sites. Figure 3 displays the vertical profiles for the potential temperature for different parameterizations for turbulence at the end of the simulation. The comparison with the observation shows similar results for all turbulent schemes.



(a)

(b)

Figure 3 - Vertical potential temperature profiles for Taylor's theory (Taylor), Taylor + Counter-Gradient (Taylor+CG), Smagorinsky (SMAG), Mellor-Yamada, radiosonde data (OBS), day 12/Feb/1999 at 00UTC: (a) ABRACOS, (b) Rebio Jaru.

5. Final Remarks

The paper describes a formulation for the counter-gradient term, and associated it to the Taylor's statistical theory on turbulence. According with Figure 3, the simulation results were similar for all parameterizations used. However, the Smagorinsky and Mellor-Yamada approaches has a higher computational effort than Taylor's schemes. For now, the Taylor's parameterization can also simulate a counter-grandient flow. All parameterization worked in this paper are codified to the BRAMS version 5.2 [10] too.

Considering the radiation for long and short waves the counter-gradient approach had a little better representation [20]. But, more simulations are needed in order to have a definitive conclusion.

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