Numerical simulation of the planetary boundary layer at Candiota using a second order closure model

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Abstract

In this work an one-dimensional second order closure model is used to simulate the time and the vertical evolution of the Planetary Boundary Layer over the region of Candiota for winter conditions. The model includes a mixing length scale proposed by Mellor and Yamada (1986) for convective conditions and by Degrazia et al. (1996) for stable conditions. It was coupled to an active surface by the budget equations of heat and moisture according to the "forced-restore" method (Soares, et al. 1996). The results indicate that surface and vertical structure follow the observed diurnal pattern in Candiota.

1 Introduction

The Planetary Boundary Layer (PBL) is the portion of the atmosphere where the turbulent fluxes plays major role. The vertical extent of the PBL is proportional to the intensity of the turbulence, varying from few hundred meters (stable conditions) to few kilometers (unstable conditions). Most of the time, it can be identified by the top of the inversion layer at the surface (stable conditions) and above the mixed layer (unstable conditions).

The time and space evolution of the pollutants release at the surface depend primarily upon the evolution of the PBL. In order to describe the concentration of a pollutant in the air it is necessary to have a good description of the PBL.

The second order closure model (SOCM) has been used to simulate the evolution of PBL in middle latitude some degree of success (Yamada and Mellor, 1975, André et al., 1978). This type of model is a better representation of the properties of atmospheric turbulence than first order closure models, and does not require too much computer time.

The SOCM consists into a description of the flow in terms of mean momentum, energy and moisture budget equations supplemented with variance and covariance equations and appropriate modeling of all third order moments (Mellor and Yamada, 1982).

The objective of the work is to simulate numerically the vertical evolution of the PBL over the area located in Candiota (31º28'S, 53º40’W), country side of Rio Grande do Sul, Brazil. Observations used here were obtained during the Candiota field project (Moraes, et al, 1994).

The SOCM used here is one dimensional, and it has been applied to investigate the time evolution of the PBL at low latitudes (Oliveira and Fitzjarrald, 1994, Oliveira et al, 1995, Vasconcelos, 1995).

2 Model description

In the model is used the following set of equations for the mean momentum and energy in a horizontally homogeneous atmosphere and in the absence of vertical motion:

$$\frac{\partial \bar{u}}{\partial t} = -\frac{1}{\rho_o}\frac{\partial \bar{p}}{\partial x} + f\bar{v} - \frac{\partial\,\overline{(u'w')}}{\partial z} \quad (1)$$

$$\frac{\partial \bar{v}}{\partial t} = -\frac{1}{\rho_o}\frac{\partial \bar{p}}{\partial y} - f\bar{u} - \frac{\partial\,\overline{(v'w')}}{\partial z} \quad (2)$$

$$\frac{\partial \bar{\theta}}{\partial t} = -\frac{\partial\,\overline{(\theta'w')}}{\partial z} \quad (3)$$

$$\frac{\partial \bar{q}}{\partial t} = -\frac{\partial\,\overline{(q'w')}}{\partial z} \quad (4)$$

where $\bar{u}$ and $\bar{v}$ are respectively the zonal and meridional components of the mean wind, $\bar{p}$ is the mean atmospheric pressure, ρ_o is the air density, f is the Coriolis parameter, $\overline{(u'w')}$ and $\overline{(u'w')}$ are respectively covariance of the zonal and meridional components and the vertical component the wind, $\bar{\theta}$ is the mean potential temperature and $\overline{(\theta'w')}$ is the covariance of the potential temperature and vertical component of the wind. $\bar{q}$ is the mean specific humidity and $\overline{(q'w')}$ is the covariance of the specific humidity and vertical component of the wind.

The variance and covariance equations correspond to a level four model in Mellor and Yamada's (1982) classification are given bellow

$$\frac{\partial\,\overline{(u'u')}}{\partial t}=\frac{\partial}{\partial z}\left(K_M\,\frac{\partial\,\overline{(u'u')}}{\partial z}\right)-2\,\overline{(u'w')}\,\frac{\partial\,\bar{u}}{\partial z}-\left(\frac{3\,\overline{(u'u')}-e}{3\,\tau_{IM}}\right)-\frac{2}{3}\frac{e}{\tau_{DM}} \quad (5)$$

$$\frac{\partial\,\overline{(v'v')}}{\partial t}=\frac{\partial}{\partial z}\left(K_M\,\frac{\partial\,\overline{(v'v')}}{\partial z}\right)-2\,\overline{(v'w')}\,\frac{\partial\,\bar{v}}{\partial z}-\left(\frac{3\,\overline{(v'v')}-e}{3\,\tau_{IM}}\right)-\frac{2}{3}\frac{e}{\tau_{DM}} \quad (6)$$

$$\frac{\partial\,\overline{(w'w')}}{\partial t}=\frac{\partial}{\partial z}\left(K_M\,\frac{\partial\,\overline{(w'w')}}{\partial z}\right)-2\,\overline{(\theta'w')}\,\frac{g}{\theta_o}-\left(\frac{3\,\overline{(w'w')}-e}{3\,\tau_{IM}}\right)-\frac{2}{3}\frac{e}{\tau_{DM}} \quad (7)$$

$$\frac{\partial\,\overline{(u'w')}}{\partial t}=\frac{\partial}{\partial z}\left(K_M\,\frac{\partial\,\overline{(u'w')}}{\partial z}\right)-\left(\overline{(w'w')}-c_1\,e\right)\frac{\partial\,\bar{u}}{\partial z}+\overline{(\theta'u')}\,\frac{g}{\theta_o}-\frac{\overline{(u'w')}}{\tau_{IM}} \quad (8)$$

$$\frac{\partial\,\overline{(v'w')}}{\partial t}=\frac{\partial}{\partial z}\left(K_M\,\frac{\partial\,\overline{(v'w')}}{\partial z}\right)-\left(\overline{(w'w')}-c_1\,e\right)\frac{\partial\,\bar{v}}{\partial z}+\overline{(\theta'v')}\,\frac{g}{\theta_o}-\frac{\overline{(v'w')}}{\tau_{IM}} \quad (9)$$

$$\frac{\partial\,\overline{(\theta'u')}}{\partial t}=\frac{\partial}{\partial z}\left(K_T\,\frac{\partial\,\overline{(\theta'u')}}{\partial z}\right)-\overline{(\theta'w')}\,\frac{\partial\,\bar{u}}{\partial z}-\overline{(u'w')}\,\frac{\partial\,\bar{\theta}}{\partial z}-\frac{\overline{(\theta'u')}}{\tau_{IT}} \quad (10)$$

$$\frac{\partial\,\overline{(\theta'v')}}{\partial t}=\frac{\partial}{\partial z}\left(K_T\,\frac{\partial\,\overline{(\theta'v')}}{\partial z}\right)-\overline{(\theta'w')}\,\frac{\partial\,\bar{v}}{\partial z}-\overline{(v'w')}\,\frac{\partial\,\bar{\theta}}{\partial z}-\frac{\overline{(\theta'v')}}{\tau_{IT}} \quad (11)$$

$$\frac{\partial\,\overline{(\theta'w')}}{\partial t}=\frac{\partial}{\partial z}\left(K_T\,\frac{\partial\,\overline{(\theta'w')}}{\partial z}\right)-\overline{(w'w')}\,\frac{\partial\,\bar{\theta}}{\partial z}+\overline{(\theta'\theta')}\,\frac{g}{\theta_o}-\frac{\overline{(\theta'w')}}{\tau_{IT}} \quad (12)$$

$$\frac{\partial\,\overline{(\theta'\theta')}}{\partial t}=\frac{\partial}{\partial z}\left(K_T\,\frac{\partial\,\overline{(\theta'\theta')}}{\partial z}\right)-2\,\overline{(\theta'w')}\,\frac{\partial\,\bar{\theta}}{\partial z}-\frac{\overline{(\theta'\theta')}}{\tau_{DT}} \quad (13)$$

$$\frac{\partial\,\overline{(q'u')}}{\partial t}=\frac{\partial}{\partial z}\left(K_E\,\frac{\partial\,\overline{(q'u')}}{\partial z}\right)-\overline{(q'w')}\,\frac{\partial\,\bar{u}}{\partial z}-\overline{(u'w')}\,\frac{\partial\,\bar{q}}{\partial z}-\frac{\overline{(q'u')}}{\tau_{IT}} \quad (14)$$

$$\frac{\partial\,\overline{(q'v')}}{\partial t}=\frac{\partial}{\partial z}\left(K_T\,\frac{\partial\,\overline{(q'v')}}{\partial z}\right)-\overline{(q'w')}\,\frac{\partial\,\bar{v}}{\partial z}-\overline{(v'w')}\,\frac{\partial\,\bar{q}}{\partial z}-\frac{\overline{(q'v')}}{\tau_{IT}} \quad (15)$$

$$\frac{\partial\,\overline{(q'w')}}{\partial t}=\frac{\partial}{\partial z}\left(K_T\,\frac{\partial\,\overline{(q'w')}}{\partial z}\right)-\overline{(w'w')}\,\frac{\partial\,\bar{q}}{\partial z}+\overline{(\theta'q')}\,\frac{g}{\theta_o}-\frac{\overline{(q'w')}}{\tau_{IT}} \quad (16)$$

$$\frac{\partial\,\overline{(q'q')}}{\partial t}=\frac{\partial}{\partial z}\left(K_T\,\frac{\partial\,\overline{(q'q')}}{\partial z}\right)-2\,\overline{(q'w')}\,\frac{\partial\,\bar{q}}{\partial z}-\frac{\overline{(q'q')}}{\tau_{DT}} \quad (17)$$

$$\frac{\partial\,\overline{(\theta'q')}}{\partial t}=\frac{\partial}{\partial z}\left(K_T\,\frac{\partial\,\overline{(\theta'q')}}{\partial z}\right)-\overline{(q'w')}\,\frac{\partial\,\bar{\theta}}{\partial z}-\overline{(\theta'w')}\,\frac{\partial\,\bar{q}}{\partial z}-\frac{\overline{(\theta'q')}}{\tau_{DT}} \quad (18)$$

where e is twice the turbulent kinetic energy $\left(\overline{(u'u')}+\overline{(v'v')}+\overline{(w'w')}\right)$, τ_{DM} and τ_{DT} are the characteristic time scales for molecular dissipation of variance of momentum and temperature, τ_{IM} and τ_{IT} are the characteristic time scales for tendency toward isotropy of variance and covariance of momentum and temperature, K_M and K_T are the coefficients of turbulent diffusion of variance and covariance of momentum and temperature, and $c_1\ (=0.08)$ is a numerical constant. It was assumed that moisture behaves like temperature in the PBL in order to derived (13)-(17).

The characteristic time scales in the eqs. (5-18) are expressed by $\{\tau_{DM}, \tau_{DT}, \tau_{IM}, \tau_{IT}\} = \{16.6, 10.1, 0.92, 0.74\}\, l/\sqrt{e}$ and diffusion coefficients by $\{K_M,\ K_T\} = \{0.12,\ 0.20\}\ l\sqrt{e}$, where l is the mixing length scale.

It was used two mixing length scales. One for convective conditions, proposed by Mellor and Yamada (1982) and given by $1/l = 1/\kappa z + 1/l_0$, where $\kappa\ (=0.40)$ is the von Karman constant, z is the vertical coordinate and l_o is the characteristic length scale of the PBL, determined by the following relation $l_o = 0.10\int_0^h z\, e\, dz \Big/ \int_0^h e\, dz$, where h is the height of the PBL. Another one, for stable conditions, proposed by Degrazia et al. (1996), and given by $1/l = 1/0.22\, z + 16.8/\Lambda$, where $\Lambda = L(1 - z/h)^{3/4}$, is the local Obukhov length and L is the Obuhov length. The PBL height is evaluated in the model by the level where the Reynold stress is equal to 5% of its surface value.

3 Boundary and initial conditions

For the mean quantities the upper boundary condition is assumed to be the value of the free atmosphere. In the lower boundary, the mean quantities are determined from surface heat budget force-restore method. In this method the soil is divided in two layer, one shallow where the time evolution of the temperature and moisture content is forced by the diurnal cycle, and another more deep where ruled by the seasonal cycle . This method includes the effect of vegetation on the heat budget. It was assumed that the surface is plain and cover by a short vegetation (height = 0.23 m). The foliage surface factor assumed for this kind of surface is 0.25. The other surface and soil parameters can be found in Soares et al (1996).

The boundary conditions for the variance and covariance fields are evaluated according to Mellor and Yamada (1974). In the upper boundary these fields are set equal zero, and in the lower boundary they are expressed in terms of u_*, θ_* and q_*.

For initial conditions it is assumed that the PBL has reached a final stage of the nocturnal evolution with a 250 m. All variances and covariance vary linearly in the vertical direction from a specific value at the surface to nearly zero at 250 m.

For the mean state, this initial condition for potential temperature and specific humidity correspond to the interpolated in grid point the sounding measured at 06:53 LT., on July 23, 1994, (Fig. 1a and 1b). The mean wind speed was assumed constant equal to 5 m/s and the wind direction SW in the domain of the model (up to 2500 m). It was assumed also a presence of the synoptic scale horizontal pressure gradient corresponding to a geostrophic value of 10 m/s from the SW direction.

It was assumed a constant horizontal warm advection of 0.31 degrees per hour, associated with a synoptic situation prevailing during July 23 and 24, 1994, in Candiota.

(1a) **(1b)**

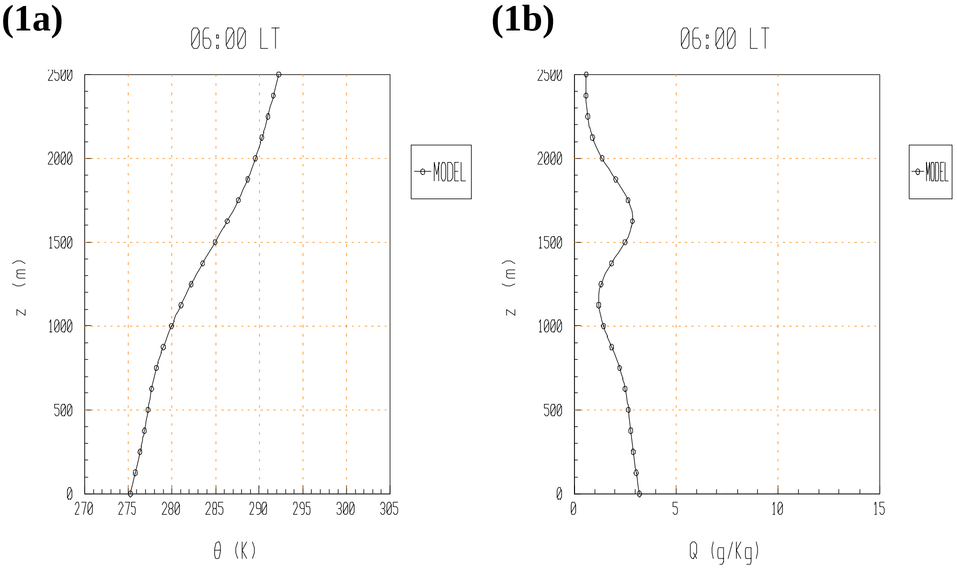


Figure (1): Initial conditions for **(a)** potential temperature **(b)** specific humidity.

4 Numerical scheme

Numerical solutions of the set of equations described in sections above are obtained by using a finite difference scheme: forward in time and centered in space for the mean equations (1)-(4); Implicit for the variance and covariance equations (5)-(18).

The equations (01)-(18) are discretized in 81 levels in a staggered grid of 31.25 meters size. All mean quantities are located in the odd levels and the variance and covariance were located in the even levels. Even though the numerical scheme applied to solve equations (01)-(17) is unconditionally stable for systems of partial differential equations with constant coefficients, in this case the actual numerical stability was only achieved for time steps of 5 seconds.

5 Results and conclusion

The model was used to simulate the PBL for 48 hours, starting at 06:00 LT. for the July 23, 1994 (Julian day 204). In the Figs. 2 and 3 are shown the time evolution air temperature and specific humidity. The numerical results are similar to the observed ones.

In the figure (4) - (7) are shown the components of the surface heat budget obtained from the model and observed. The comparison with observations indicated that the model is capable to generate the amplitude and the phase of turbulent sensible and latent heat fluxes which is similar to the observed ones (Figs. 4 and 5). On the other hand, the there is a lag for the soil heat flux and the net radiation obtained from the model and measured (Figs. 6 and 7).

Despite the uncertainty in the synoptic conditions and the geostrophic wind used in this simulation, the simulated friction velocity follows the pattern observed (Fig. 8).

The vertical evolution of the PBL simulated by the model is shown after 6 hours (convective period) and 18 hours (stable period) of simulation (Figs. 9 and 10). The potential temperature obtained from the model is comparable to the observed by tethered balloon on July 23, 1994 at 12:16 LT. (Fig. 9a). A discrepancy appears for the specific humidity (Fig. 9b). For stable conditions the model did not perform as well as for convective conditions..

Next step in this work is to evaluate the synoptic conditions and include radiational cooling.effects in the model.

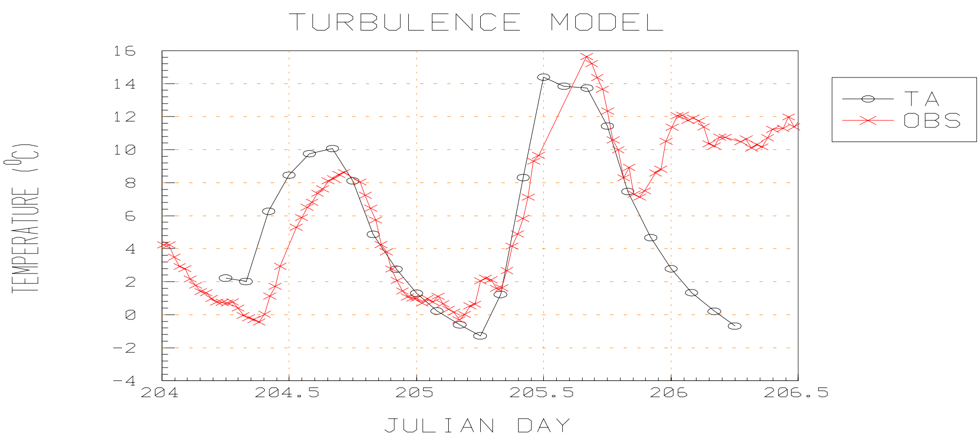


Figure (2): Time evolution of the air temperature simulated by the model (TA) and the observed during second campaign in Candiota

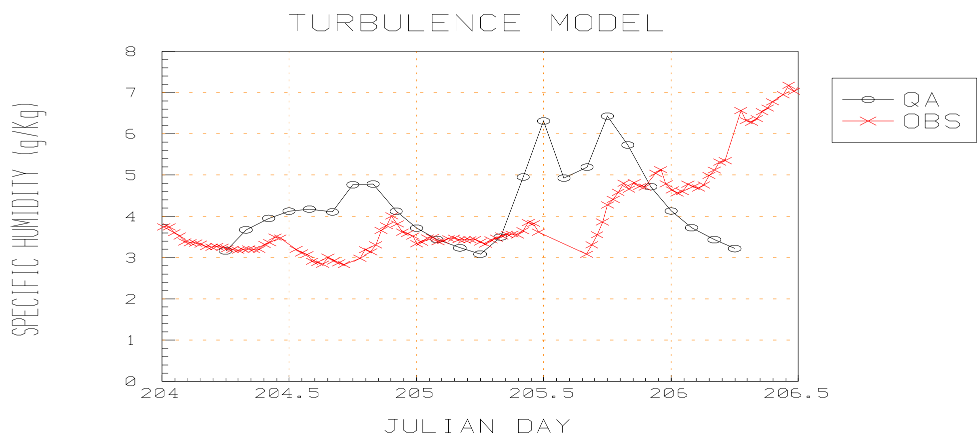


Figure (3): Time evolution of the air specific humidity simulated by the model (QA) and the observed (OBS) during second campaign in Candiota (July, 1994).

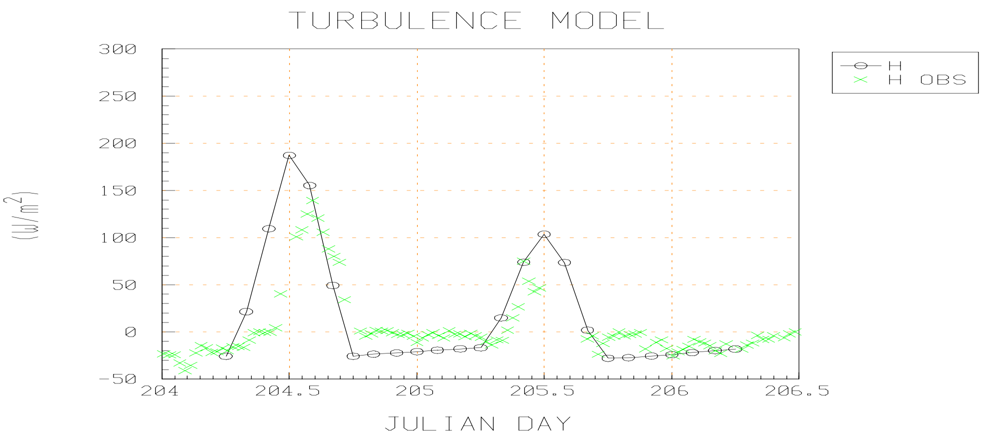


Figure (4): Time evolution of the sensible heat flux simulated by the model (H) and the observed (H OBS) during second campaign in Candiota (July, 1994).

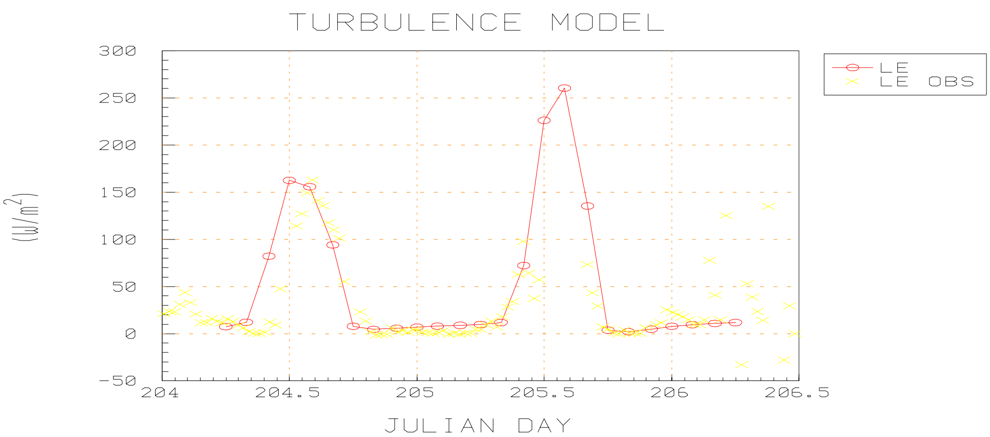


Figure (5): Time evolution of the latent heat flux simulated by the model (LE) and the observed (LE OBS) during second campaign in Candiota (July, 1994).

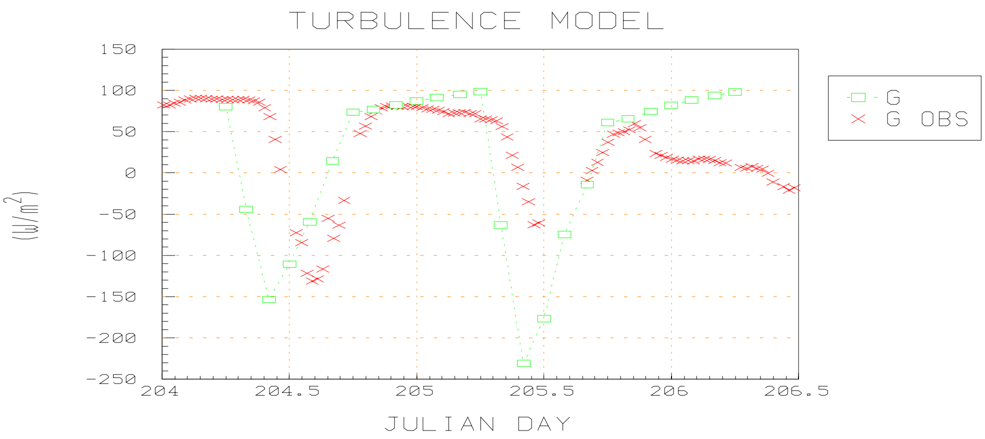


Figure (6): Time evolution of the soil heat flux simulated by the model (G) and the observed (G OBS) during second campaign in Candiota (July, 1994).

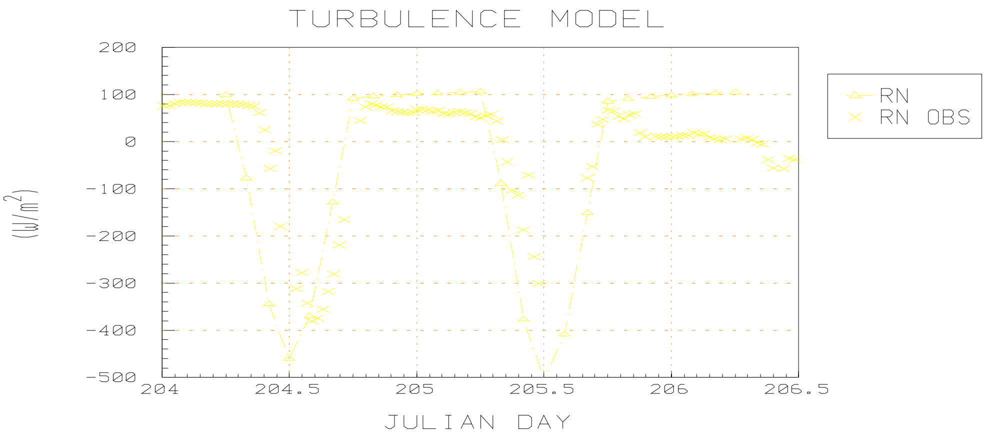


Figure (7): Time evolution of the net radiation simulated by the model (RN) and the observed (RN OBS) during second campaign in Candiota (July, 1994).

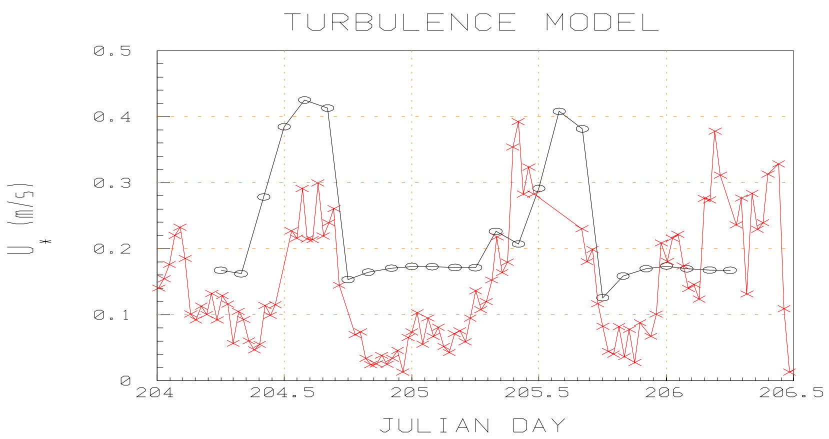
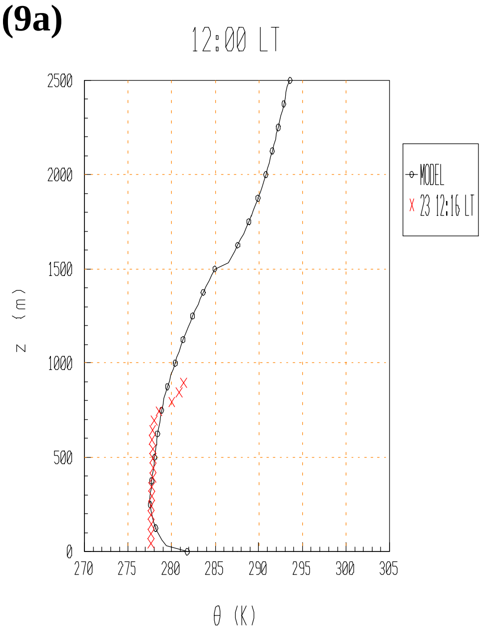


Figure (8): Time evolution of the net radiation simulated by the model (RN) and the observed (RN OBS) during second campaign in Candiota (July, 1994).

(9a)



(9b)

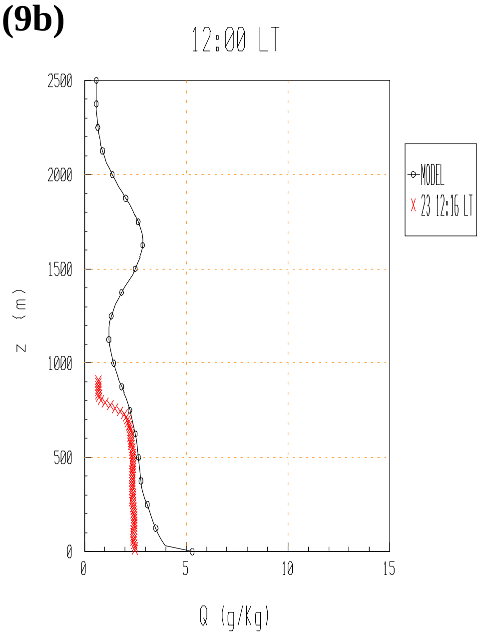


Figure (9): Vertical profile of **(a)** potential temperatura **(b)** specific humidity obtained by the model after 6 hours of simulation. The observations were obtained from tethered balloon sounding carried out on July 23, 1994, at 12:16 LT.

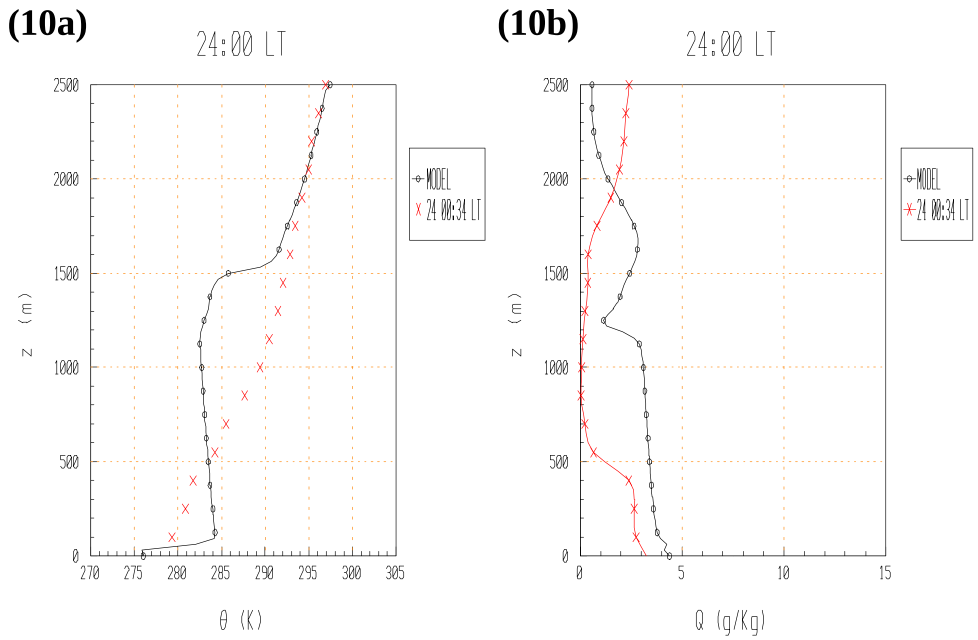


Figure (10): Vertical profile of **(a)** potential temperature **(b)** specific humidity obtained by the model after 6 hours of simulation. The observations were obtained from tethered balloon sounding carried out on July 23, 1994, at 12:16 LT.

Acknowledgments

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