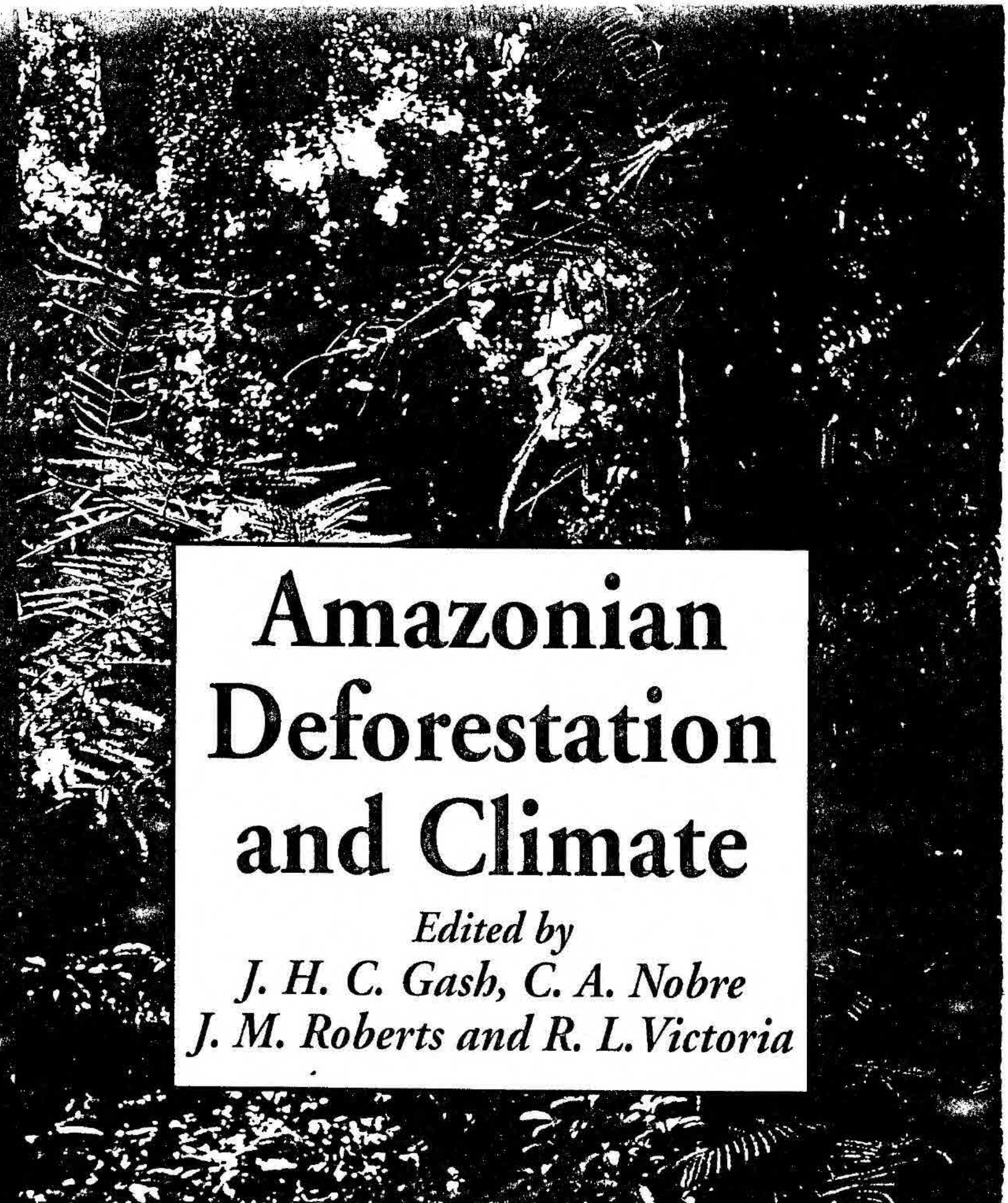
Gash
Nobre
Roberts
Victoria
(Editors)

Amazonian Deforestation and Climate

WILEY



Amazonian Deforestation and Climate

Edited by
J. H. C. Gash, C. A. Nobre
J. M. Roberts and R. L. Victoria

WILEY

25 Modelling convective boundary layer growth in Rondônia

G. FISCH[1], A.D. CULF[2] and C.A. NOBRE[3]
[1] *Centro Técnico Aeroespacial, São José dos Campos, Brazil*
[2] *Institute of Hydrology, Wallingford, UK.*
[3] *Instituto Nacional de Pesquisas Espaciais, Brazil*

INTRODUCTION

The dynamics of the convective boundary layer (CBL) play an important role in the land-surface atmosphere interaction by controlling the transfer of the turbulent fluxes from the surface to the free atmosphere. The depth of the CBL gradually increases during the day, not only due to direct heating from the surface, but also because the surface fluxes (thermal and mechanical) provide the energy necessary for air parcels to rise, overshoot the top of the inversion and return (due to their negative buoyancy in the air above the mixed layer) entraining warm and dry air from aloft into the layer. The CBL does not merely grow passively in response to this turbulence but has mechanisms of interaction in the opposite direction: the entrainment flux brings drier air into the layer, changing the saturation deficit and hence modifying the partition of energy in terms of sensible and latent heat fluxes at the surface.

As an active link between the surface and the free atmosphere, the CBL has to be well understood and accurately represented in General Circulation Models (GCMs) if they are to provide realistic simulations of the climate. It is also an essential component of pollutant dispersion models (Raynor and Watson, 1991). The parameterization of the CBL in GCMs has been reviewed by Garratt (1993) who summarized the most important components of a CBL scheme in such models as: the depth of the CBL for vertical distribution of momentum and energy; the values of the turbulent fluxes and other turbulent properties, and the role of clouds.

Deardoff (1972) has discussed two contrasting methods of representing the CBL in GCMs: the multi-layer schemes where the lowest levels of the GCM vertical grid are used to describe the CBL, and the bulk layer approach which considers the entire CBL as a single layer. Although schemes of the first type are more realistic, as the parameters are represented explicity, they can consume a great deal of computer time. In contrast, bulk layer representations are simple and permit one to obtain a prognostic equation for the height of the CBL. However, they have the disadvantage of being difficult to implement in GCMs as they require the model to have a variable vertical grid spacing to be able to represent the temporal variability of the CBL height.

The objective of the present work is to examine the ability of a slab model to

Amazonian deforestation and climate. Edited by J.H.C. Gash, C.A. Nobre, J.M. Roberts and R.L. Victoria.

simulate the evolution and the structure of the CBL, based on the theory developed by Tennekes (1973), using data collected over pasture and forest sites in the Amazon region of Brazil.

SITE AND INSTRUMENTATION

The dataset used in this paper was collected during the Rondônia Boundary Layer Experiment - II (RBLE II) which took place at the ABRACOS forest and pasture sites in Rondônia, Brazil in July and August 1993 and is described fully by Nobre *et al.* (1996). These two sites, Reserva Jaru and Fazenda Nossa Senhora, and the permanent ABRACOS instrumentation installed there, are described by Gash *et al.* (1996). At the forest site, the micrometeorological data and turbulent fluxes have been measured at the top of an aluminium tower 52 m high. The mean height of the canopy is 30 m, although some emergent trees reach up to 42 m. The pasture site, covered predominantly by *Brachiaria brizantha*, was deforested about 15 years ago and is typical ranchland for this part of Amazonia. During RBLE II, measurements were made by radiosondes, a tethered balloon system and surface micro-meteorological intrumentation. At the forest site the CBL measurements were made at the IBAMA field station, about 2 km from the ABRACOS tower. At the pasture site, all the CBL and surface measurements instrumentation was set up together, inside a circle of radius less than 500 m.

The radiosounding data were collected using radiosondes (Vaisala-Finland), during daytime hours at 08.00, 11.00, 14.00 and 17.00 h local time. The tethered balloon system (A.I.R. Inc., Colorado, USA) consists of a tethersonde measuring pressure, dry and wet bulb temperatures, windspeed and wind direction, attached to a 7.0 m^3 balloon, which can be operated at heights of up to 1000 m. The tethered

Table 1 Energy ($w'\theta_v'$) and momentum (proportional to u_*) surface fluxes observed at the forest and pasture sites and used as inputs for the CBL model

	Forest		Pasture	
Local time h	$w'\theta_v'$ m K s^{-1}	u_* m s^{-1}	$w'\theta_v'$ m K s^{-1}	u_* m s^{-1}
08.00	-0.04	0.04	0.009	0.06
09.00	0.016	0.16	0.06	0.14
10.00	0.059	0.25	0.136	0.26
11.00	0.08	0.26	0.182	0.31
12.00	0.092	0.3	0.19	0.3
13.00	0.133	0.38	0.21	0.3
14.00	0.135	0.43	0.194	0.28
15.00	0.098	0.41	0.14	0.28
16.00	0.075	0.38	0.094	0.27
17.00	0.021	0.29	0.029	0.23

balloon was operated during the night and in the early morning with the profile of temperature measured at 08.00 h being used as an initial value for the model simulations. Hourly values of surface fluxes were obtained from an eddy-correlation instrument (Hydra) described in detail by Shuttleworth *et al.* (1988). The average surface fluxes (momentum and energy) obtained from this instrument are used to prescribe the input of energy to the CBL model and are presented in Table 1. The data obtained over the forest were collected between 3 and 10 July 1993 and at the pasture site from 10 to 25 July 1993. However, during the forest data collection period, a cold front or "friagem" moved across the area, modifying the atmosphere structure. Surface fluxes measured during this event (7 to 8 July) have not been included in the calculation of average surface fluxes.

THE MODEL

The model of the CBL used here can be visualised as a single layer box. The box grows in height due the input of energy from the bottom (the surface fluxes) and from the top (the entrainment flux which includes contributions from both thermally and mechanically generated turbulence). Inside the box, the air is well mixed with a uniform profile of virtual temperature θ_v. This type of model has been studied under different atmospheric conditions and types of surface by several researchers (e.g. Tennekes, 1973; Driedonks, 1982; McNaughton and Spriggs, 1986; Batchavarova and Gryning, 1990; Culf, 1992). Following Tennekes (1973), Tennekes and Driedonks (1981) and Driedonks (1982), it is assumed that all transfer of energy occurs vertically (i.e. the model is one-dimensional) and that large-scale subsidence can be neglected. The conservation of energy of a homogeneous layer can then be written as:

$$\frac{d}{dt}(\theta_v) = \frac{1}{h}\left[\overline{(w'\theta_v')_o} - \overline{(w'\theta_v')_b}\right] \quad (1)$$

where θ_v is the average virtual potential temperature of the mixed layer, $w'\theta'_v$ represents virtual heat flux at the surface (subscript o) and at the inversion height (subscript b). h is the height of the mixed layer (see Figure 1).

Applying energy conservation at the step in θ_v at the top of the mixed layer gives:

$$\frac{d}{dt}(\Delta\theta_v) = S_o\left(\frac{dh}{dt}\right) - \frac{d\theta_v}{dt} \quad (2)$$

where $\Delta\theta_v$ is the size of the step in virtual potential temperature at the top of the mixed layer and S_o is the vertical gradient of θ_v above the CBL which is taken to be invariant with time. The entrainment flux is related to $\Delta\theta_v$ and the rate of boundary layer growth as (Lilly, 1968):

$$-\left(\overline{w'\theta_v'}\right)_b = \Delta\theta_v \frac{dh}{dt} \quad (3)$$

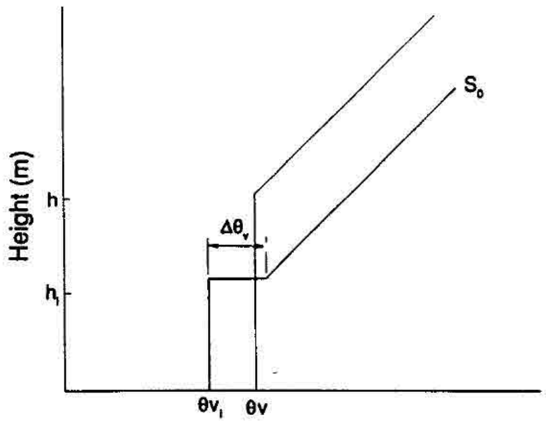


Figure 1 The vertical distribution of virtual potential temperature in and above a convective boundary layer (CBL).

Equations 1, 2 and 3 are the kernel of the CBL growth model, but it is not a closed system as it has four unknowns (θ_v, $\Delta\theta_v$, h, and $w'\theta'_v$). To close the system, Tennekes (1973) suggested that, based on the conservation of turbulence kinetic energy, the entrainment flux can be parameterized in terms of the other variables as:

$$-\left(\overline{w'\theta'_v}\right)_b = C_F\left(\overline{w'\theta'_v}\right)_o + A\,\frac{u_*^3\theta_v}{gh} \tag{4}$$

where C_F and A are empirical constants. The first term on the right-hand side is the contribution from thermally generated turbulence and the second term is the contribution from mechanically generated turbulence. We define the ratio of these two terms as G, a parameter which describes the relative importance of the two contributions to the entrainment flux. Substituting Equation 4 into Equation 3 yields, after some rearrangement:

$$\frac{dh}{dt} = 0.2\frac{\left(\overline{w'\theta'_v}\right)_o}{\Delta\theta_v} + 5\frac{u_*^3\theta_v}{gh\Delta\theta_v} \tag{5}$$

where C_F and A have been replaced with the usual values of 0.2 and 5 respectively (Driedonks, 1982; Driedonks and Tennekes, 1984) The system of Equations 1, 2 and 5 can now be solved numerically. Using a forward scheme for numerical integration the equations can be rewritten in finite difference form as:

$$\frac{h^{n+1}-h^n}{\Delta t} = 0.2\,\frac{\left(\overline{w'\theta'_v}\right)_o^{n+\frac{1}{2}}}{\Delta\theta_v^n} + \frac{5(u_*^3)^{n+\frac{1}{2}}\,\theta_v^n}{gh^n\Delta\theta_v^n} \tag{6}$$

$$\frac{\theta_v^{n+1} - \theta_v^n}{\Delta t} = \frac{1}{h^n}\left[1.2\overline{(w'\theta_v')}^{\,n+\frac{1}{2}} + \frac{5u_*^{3^{\,n+\frac{1}{2}}}\theta_v^n}{gh^n}\right] \tag{7}$$

$$\frac{\Delta\theta_v^{n+1} - \Delta\theta_v^n}{\Delta t} = S_o\left[\frac{h^{n+1} - h^n}{\Delta t}\right] - \frac{(\theta_v^{n+1} - \theta_v^n)}{\Delta t} \tag{8}$$

where the subscripts n and n+1 represent the variable at two sucessive time steps (a time interval of 60 s was used in the current model) and the subscript n+½ denotes the average value of a variable during the time interval. The average values were interpolated from the observed data given in Table 1. This forward scheme is potentially numerically unstable, but with a time step of 60 s instabilities do not appear. Tests with other explicit numerical schemes, such as Adam-Bashfort, Leap-Frog and Runge-Kutta (Mesinger and Arakawa, 1982), have given similar results that are not presented here.

RESULTS

The growth of the CBL over the forest and pasture sites has been simulated using Equations 6, 7 and 8, the boundary conditions given in Table 1, and the appropriate initial values given in Table 2. For each simulation, it is necessary to provide initial values for h, θ_v, $\Delta\theta_v$ and S_0 measured at the time of the nocturnal boundary layer breakdown, or in the early morning soon afterwards. The first three of these values were obtained from a tethered balloon profile measured at 08.00 h whilst S_0 was obtained from the simultaneous radiosonde ascent. The main results obtained from the simulations are given in Table 3. In Figure 2 the values of the height of the CBL and the virtual potential temperature are shown along with the observed values, extracted from Fisch (1995) and Nobre *et al.* (1996), for comparison. In all the analyses throughout this paper average values have been calculated and compared with average observational aspects. This approach (composite time evolution) has

Table 2 Initial conditions for boundary layer height, thermal gradient (S_0), virtual potential temperature (θ_v) and the discontinuity in virtual potential temperature at the top of the mixed layer ($\Delta\theta_v$) for the forest and the pasture sites.

	Height (m)	S_0 (K km^{-1})	θ_v (K)	$\Delta\theta_v$ (K)
Forest	200	1.8	298.8	5.8
Pasture	110	3.6	298.6	5.3

Table 3 Results of the numerical simulation of the growth of the CBL over the forest and the pasture sites

	Forest					Pasture				
Local time h	height m	$\Delta\theta_v$ K	θ_v K	G	w_* ms^{-1}	height m	$\Delta\theta_v$ K	θ_v K	G	w_* ms^{-1}
08.00	200	5.80	298.8			110	5.3	298.6	0.17	0.32
09.00	201	5.66	298.9	0.99	0.47	117	3.95	300.0	0.30	0.61
10.00	211	4.77	299.8	0.96	0.74	175	0.77	303.4	0.57	0.92
11.00	234	3.26	301.4	0.72	0.85	645	0.38	305.4	0.20	1.56
12.00	281	1.69	303.1	0.81	0.94	975	0.55	306.5	0.11	1.81
13.00	461	0.40	304.7	0.70	1.25	1232	0.68	307.3	0.08	2.02
14.00	949	0.33	305.6	0.48	1.60	1445	0.79	307.9	0.06	2.07
15.00	1270	0.42	306.1	0.43	1.59	1600	0.87	308.4	0.08	1.93
16.00	1464	0.48	306.4	0.39	1.52	1702	0.92	308.7	0.10	1.72
17.00	1562	0.51	306.5	0.58	1.02	1754	0.96	308.9	0.19	1.17

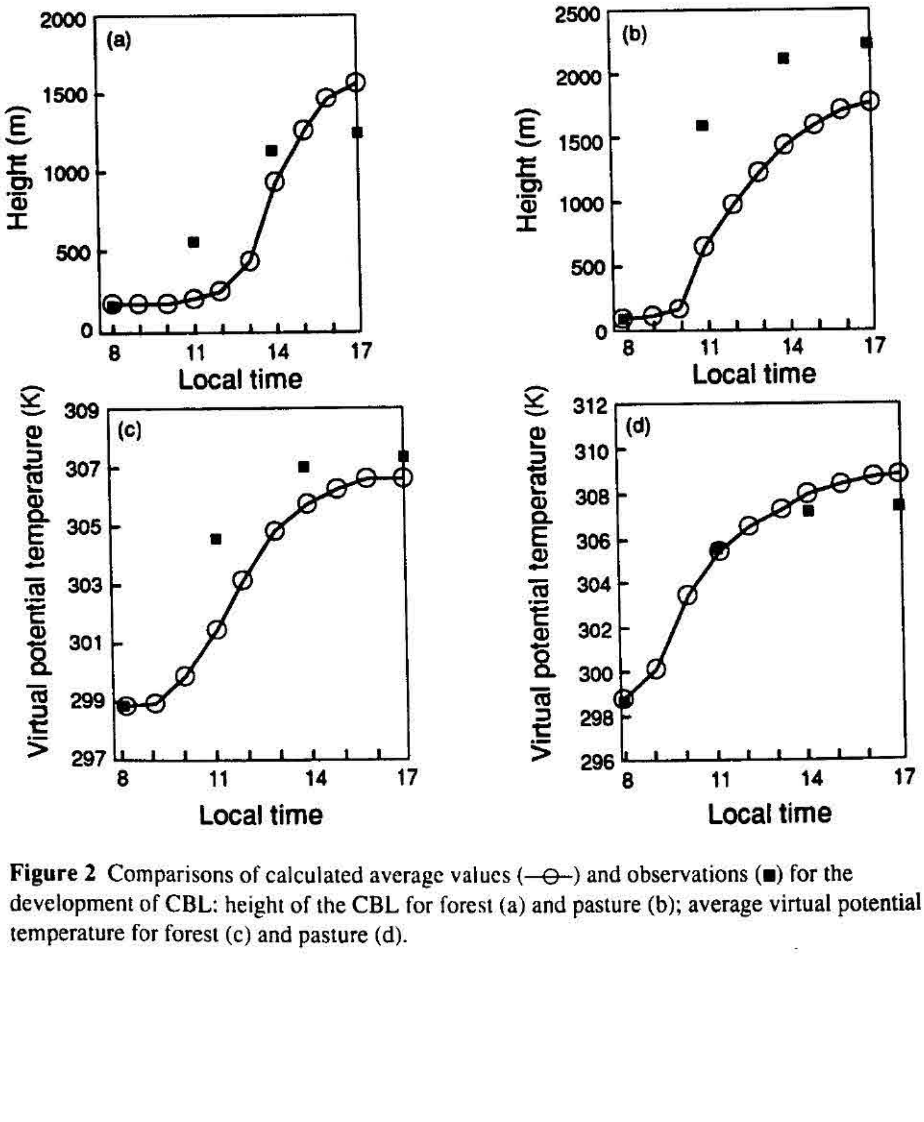


Figure 2 Comparisons of calculated average values (—o—) and observations (■) for the development of CBL: height of the CBL for forest (a) and pasture (b); average virtual potential temperature for forest (c) and pasture (d).

been chosen, instead of predicting values for individual days, to remove some of the observational noise and day-to-day variability from the results.

For the forest site, the model predicts that the CBL grows higher than observed: at 17.00 h the final height was computed as 1562 m against an observed value of 1250 m. The calculated value of θ_v was 0.7 K less than the observed value. The lower value of temperature computed by the model can be explained by the long time period used by the model to decrease the value $\Delta\theta_v$. Only after 13.00 h is the value of $\Delta\theta_v$ small enough to allow the entrainment flux to become significant. Because of this slow initial increase, the calculated value of θ_v is less than the observed value throughout the integration period. The results obtained from the simulation over the pasture site show a similar feature: the model is unable to reproduce the rapid development of the CBL during the early and mid morning. The height at 11.00 h was computed to be 645 m, compared with an observed value of 1590 m, resulting in a lower height at 17.00 h (1754 m compared with an observation of 2220 m). The value of θ_v calculated by the model is 1.5 K higher than observed, but at midday the model reproduces the observed temperature reasonably well.

The performanace of the model was investigated qualitatively by using an even simpler representation of the CBL. If the mechanical contribution to entrainment can be neglected, the height of the CBL can be considered to be dependent on square root of time (Driedonks, 1982) and can be computed as (Garratt, 1992):

$$h(t) = \left[2(1 + 2C_F) \int_{t8}^{t17} \frac{\overline{w'\theta'_v}}{S_o} \, dt \right]^{\frac{1}{2}} \tag{9}$$

Using typical data for forest and pasture (from Tables 1 and 2), Equation 9 gives a value of 1200 m for forest and 1150 m for pasture. For the forest site, this estimate of final CBL height is reasonable, as we have observed values of around 1250 m. However, for the pasture, the difference between the value from Equation 9 and the observations is very large (around 1200 m), indicating that an additional source of energy is missing from the model.

Further investigation into the cause of the poor representation of the CBL during the morning was carried out by performing a second numerical simulation of CBL growth for both the forest and the pasture sites. For these simulations, however, the time integration was started later in the day (11.00 h) when free convection is dominant. The results of this second pair of model runs are shown in Table 4 and Figure 3. For the forest site there is no improvement on the results of the first simulation, but for the pasture site, which previously had the worst results, the predictions of height and average virtual potential temperature of the CBL are improved. These results further identify the mid-morning before 11.00 h as the period poorly represented by the model for simulations of the CBL over the pasture site.

Table 4 Results of the numerical simulations of the growth of the CBL over the forest and pasture sites starting at 11.00 h when free convection is dominant

	Forest		Pasture	
Local Time	Height (m)	θ_v (K)	Height (m)	θ_v (K)
11.00	580	304.5	1590	305.6
12.00	771	305.1	1750	306.1
13.00	1026	305.7	1893	306.6
14.00	1281	306.2	2023	307.0
15.00	1471	306.6	2123	307.4
16.00	1596	306.8	2190	307.6
17.00	1663	307.0	2225	307.7

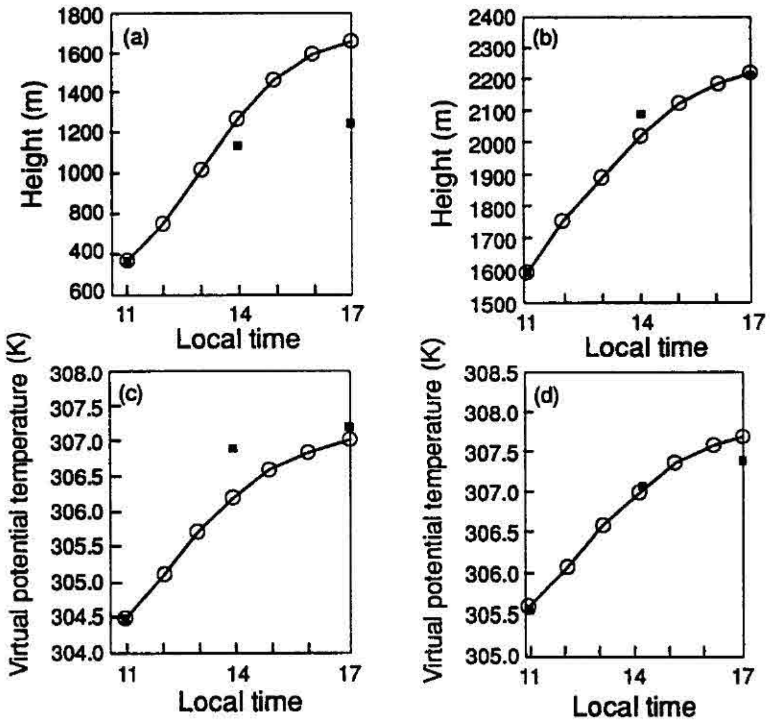


Figure 3 Comparisons of calculated average values (—⊖—) and observations (■) for the development of CBL after 11.00 h when free convection is predominant: height of the CBL for forest (a) and pasture (b); average virtual potential temperature for forest (c) and pasture (d).

DISCUSSION

In both the forest and the pasture cases, the model is unable to reproduce the observed rapid development of the CBL during the mid-morning period. The calculated values of the parameter G, defined above as the ratio of the thermal and mechanical contributions to the entrainment flux, and listed in Table 3, can help to explain this aspect of the model's performance. Table 3 shows that G is of the order of unity for both the forest and pasture simulations in the early morning when the mechanical contribution to the entrainment flux would be expected to be dominant. For example Culf (1992) showed that the contribution to the entrainment flux from mechanical turbulence can be ten times greater than the thermal contribution during the mid-morning period in the semi-arid Sahel. Despite these low values of G, the values of the vertical velocity scale, or mixing velocity, $w_* = g\, h\, w'\theta_v'/\theta_v$, which represents the thermally induced turbulence, are of the same order of magnitude as the values observed by Martin *et al.* (1988) in Manaus, with typical values of about 1.0 m s^{-1}. Since the values of w_* appear to be reasonable, the low values of G may be evidence of a significant underestimation of mechanically generated turbulence in the model.

The large deforested area around Ji-Paraná has strips of forest 2-4 km wide embedded in it (Skole and Tucker, 1993). These are typical of the type of surface features which may induce mesoscale thermal circulations (Segal and Arrit, 1992). The forest is typically wetter and colder than the pasture (see results from Nobre *et al.*, 1996) and it is possible that secondary thermal circulations develop in the morning leading to advection of energy and a more rapid breakdown of the nocturnal boundary layer than would otherwise be observed.

Another possible explanation for the apparent underestimation of the mechanically generated turbulence is that, on the area average scale relevant to CBL development, the nature of the landscape surrounding the pasture site may mean that the value of u_* is actually much larger than the values measured by micrometeorological instruments mounted at the surface and used for forcing data in these simulations. The use of an increased area average value of u_* in the model simulations would increase the mechanical contribution to the entrainment flux and increase the rate of CBL growth.

A third hypothesis is that strong wind shear develops over the pasture areas at night due to the decoupling of the nocturnal boundary layer flow from the free atmosphere above. Such a decoupling of the surface from the flow aloft has been shown to occur over a small pasture area near Manaus (Bastable *et al.*, 1993). The wind shear developed would tend to lower the Richardson number above the nocturnal boundary layer, increase the turbulence there and hasten the morning breakdown.

CONCLUSION

The model used to study the growth of CBL was able to reproduce some of the characteristics of the observed CBL, although there were discrepancies in the virtual potential temperature profiles and the CBL height. The simulation of the development of the CBL for the forest site is reasonable, with the final height only about 200 m higher than observed. For the pasture scenarios, the results of the numerical exercise showed poor agreement with the observations, especially in the mid-morning. The results of a second simulation, starting when the free convection is predominant, were better, indicating that the problem with the model simulation was occurring between sunrise and mid-morning. It is likely that the juxtaposition of patches of forest and pasture in the area of the experiment means that several processes can take place which all have the effect of increasing the turbulence in the early morning, leading to a more rapid breakdown of the nocturnal boundary layer than would be observed over a uniform surface.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to all Brazilian and British participants of ABRACOS/RBLE II involved in the data collection at Ji-Paraná. RBLE II was partially funded by Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Conselho Nacional Científico e Tecnológico (CNPq). G.Fisch received a grant from the Coordenadoria de Aperfeiçoamento de Pessoal do Nível Superior (CAPES) to carry out analyses at the Institute of Hydrology (UK) during 1993. Special thanks go to J.H.C. Gash, A. Beljaars, J.M. Roberts and I.R. Wright for their encouragement to produce this work. The authors would also like to thank the anonymous referees for their useful comments and suggestions.

REFERENCES

Bastable, H.G., Shuttleworth, W.J., Dallarosa, R.L.G., Fisch, G. and Nobre, C.A. 1993. Observations of climate, albedo and surface radiation over cleared and undisturbed Amazonian Forest. *Int. J. Climatol.* **13**, 783-796.

Batchvarova, E. and Gryning, S.E. 1990. Applied model for the growth of the daytime mixed layer. *Bound.-Layer Met.* **56**, 261-274.

Culf, A.D. 1992. An application of simple models to Sahelian convective boundary layer growth. *Bound.-Layer Met.* **58**, 1-18.

Deardoff, J.W. 1972. Parameterization of the planetary boundary layer for use in general circulation models. *Mon. Weath. Rev.* **100**, 93 -106.

Driedonks, A.C.M. 1982. A model and observations of the growth of the atmospheric boundary layer. *Bound.-Layer Met.* **23**, 283-306.

Driedonks, A.C.M., and Tennekes, H. 1984. Entrainment effects in the well mixed atmospheric boundary layer. *Bound.-Layer Met.* **30**, 75-105.

Gash, J.H.C., Nobre, C.A., Roberts, J.M. and Victoria, R.L. 1996. An overview of ABRACOS. This volume.

Garratt, J.R. 1992. *The atmospheric boundary layer*. Cambridge Press University, London. 316p.

Garratt, J.R. 1993. Sensivitiy of climate simulations to land-surface and atmospheric boundary layer treatments - a review. *J. Climate* **6**, 419-449.

Fisch, G., 1995. Camada limite Amazonica: aspectos observacionais e de modelagem. PhD thesis, INPE, São José dos Campos, Brazil.

Lilly, D.K. 1968. Models of cloud topped mixed layers under a strong inversion. *Q. J. Roy. Met. Soc.* **94**, 292-309.

Martin, C.M., Fitzjarrald, D.R., Garstang, M., Oliveira, A.P. de, Greco, S. and Browell, E. 1988. Structure and growth of the mixing layer over the Amazonian rain forest.*J.Geophys. Res.* **93**, 1361-1375.

Mesinger, F. and Arakawa, A. 1982. Numerical methods used in atmospheric models. GARP Publications Series. **17**, 65pp.

McNaughton, K.G. and Spriggs, T.W. 1986. A mixed-layer model for regional evaporation. *Bound.-Layer Met.* **34**, 243-262.

Nobre, C.A., Fisch, G., Rocha, H.R. da, Lyra, R.F.F., Rocha, E.P., Costa, A.C.L.da and Ubarana, V.N. 1996. Observational aspects of atmospheric boundary layer in Rondonia. This volume.

Rayner, K.N. and Watson, I.D. 1991. Operational prediction of daytime mixed layer heights for dispersion modelling. *Atmos. Environ.* **25A**, 1427-1436.

Segal, M. and Arrit, R.W. 1992. Non-classical mesoscale circulations caused by surface sensible heat flux gradients. *Bull. Am. Met. Soc.* **73**, 1593-1604.

Shuttleworth, W.J., Gash, J.H.C., Lloyd, C.R., McNeil, D.D., Moore, C.J. and Wallace, J.S. 1988. An integrated micrometeorological system for evaporation measurements. *Agric. For. Met.* **43**, 295-317.

Skole, D. and Tucker, C. 1993. Tropical deforestation and habitat fragmentation in Amazonia: satellite data from 1978 to 1988. *Science* **260**, 1905-1910.

Tennekes, H. 1973. A model for the dynamics of the inversion above a convective boundary layer. *J. Atmos. Sci.* **30**, 558-567.

Tennekes, H. and Driedonks, A.C.M. 1981. Basic entraiment equations for the atmospheric boundary layer. *Bound.-Layer Met.* **20**, 515-531.

RESUMO

Um modelo uni-dimensional simples foi utilizado para estudar o crescimento da camada limite convectiva (CLC) desenvolvidas sobre superfícies de floresta e pastagem na região Amazônica do Brasil, durante o Experimento da Camada Limite de Rondônia. Este modelo foi baseado na teoria desenvolvida por Tennekes (1973) e é capaz de reproduzir algumas das características observadas da CLC, embora diferenças do valor final da temperatura potencial e virtual e altura da camada limite tenham sido observadas. Estas diferenças são maiores para a simulação realizada para a pastagem. Os resultados de uma nova simulação, na qual o modelo é integrado a partir do instante em que a convecção livre torna-se dominante, mostrou melhores resultados. Baseado nestas análises, sugere-se que possa existir uma fonte de turbulência extra no início da manhã na área de pastagem e que o modelo uni-dimensional não contabiliza. Esta turbulência é gerada pela existência de circulação térmica secundária, devida à justaposição de áreas de floresta e pastagem e é muito importante na erosão da camada limite noturna.