P3.13 A NOVEL PARAMETERIZATION OF TURBULENT TRANSPORT IN THE STRATOCUMULUS−TOPPED BOUNDARY−LAYER

Alexandre Araújo Costa*, Gérson Paiva Almeida
Universidade Estadual do Ceará, Fortaleza, Brazil

Haroldo Fraga de Campos Velho
Instituto Nacional de Pesquisas Espaciais, São José dos Campos, Brazil

José Carlos Parente de Oliveira
Universidade Federal do Ceará, Fortaleza, Brazil

1. INTRODUCTION

In the past decades, meteorologists have given a great emphasis to the study of marine stratocumulus clouds formed in subtropical latitudes during summer. Those studies were primarily motivated because 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% areal coverage and lasting for a long residence time (almost half a year over Great Britain, as pointed out by Nicholls, 1984).

Due to those features, stratocumulus clouds can affect enormously the global radiative balance. In general, this is a problem still not well equated in general circulation models used in weather forecast and climate prediction.

In order to better understand the role played by such clouds, as well as their structure, many experiments were carried out recently (e.g., the Atlantic Stratocumulus Transition Experiment − ASTEX, Albrecht et al. 1995, and the 2nd Aerosol Characterization Experiment − ACE2, Raes 2000). Some aspects of this complex system have been investigated: turbulent transport, radiative cooling, entrainment, large−scale subsidence. In particular such experiments provided data to investigate turbulent structures and microphysical variability.

Some authors have reported the occurrence of a "decoupling", i.e., a discontinuity in the turbulent transport fields, between the cloud layer and the near−surface layer (e.g., Turton and Nicholls, 1987). More recently, the influence of precipitation formation in the life cycle of stratocumulus clouds was recognized. So far, however, the relationship between decoupling and the precipitation in stratocumulus−topped boundary−layers is not completely understood. The general idea is that decoupling can lead to the dissipation of stratocumuli, once the water vapor supply diminishes and no longer compensates for the entrainment of dry air from the top. Some authors argue that decoupling can be actually caused by the evaporation of drizzle at the sub−cloud layer (Wang and Wang, 1994; Stevens et al , 1998).

In this paper, a new turbulence parameterization for stratocumulus−topped boundary−layers is proposed and implemented in a single−column model. In conjunction with a modified microphysics parameterization, which takes into account subgrid−scale microphysical variability, the new turbulence scheme is used to simulate drizzle−induced decoupling in stratocumulus.

2. TURBULENCE PARAMETERIZATION

Many turbulence parameterizations used in atmospheric models are based on the simple assumption that the turbulent flux of a certain variable is proportional to its vertical gradient, i.e.,

$$\langle w'A' \rangle = K_A \frac{\partial A}{\partial z} \quad , \qquad (1)$$

where K is the so−called eddy diffusivity (or viscosity, for momentum transport).

A variety of formulas was proposed for K−type turbulence parameterizations. Smagorinsky (1963) suggested that the eddy diffusivity is proportional to the deformation tensor. Other schemes involve the calculation of the turbulent kinetic energy (e−l schemes) or its dissipation rate (ϵ −l schemes), as in Langland and Liou (1996). Alternatively, Degrazia and Moraes (1998) have demonstrated that, starting from Taylor's frozen turbulence hypothesis, it is possible to calculate K as

$$K = \frac{\sqrt{\pi}}{16} \sigma_w \lambda \qquad (2)$$

where σ_w is the vertical velocity variance and λ is the peak wavelength in the vertical velocity spectrum.

In this paper, vertical velocity spectra were derived from experimental data collected during ACE2−CLOUDYCOLUMN (Pawloska and Brenguier, 2000). Data were fitted to an analytic formula, as proposed by Lambert and Durand (1999) and implemented by Druilhet and Durand (1999) for a clear convective boundary−layer. Figure 1 shows values of λ as a function of the altitude (h), normalized by the boundary−layer height (z_i). The observations were fitted according to the law:

* *Corresponding author address*: Dr. Alexandre Costa. Universidade Estadual do Ceará, Departamento de Física e Química. Av. Paranjana, 1700. Campus do Itaperi. Fortaleza−CE, 60740−000. Brazil. E−mail: acosta@uece.br

$$\lambda = Ah, \qquad h < 0.1z_i$$

$$\lambda = Bz_i[1-\exp(-C\frac{h}{z_i})-D\exp(E\frac{h}{z_i})], \qquad 0.1z_i < h < 0.6z_i,$$

$$\lambda = Fz_i\exp(-G\frac{h}{z_i}), \qquad h > 0.6z_i \qquad (3)$$

where the empirical coefficients are: A = 3.7, B = 1.46, C = 3.15, D = 0.003, E = 7.07, F = 4.7 and G = 2.7.

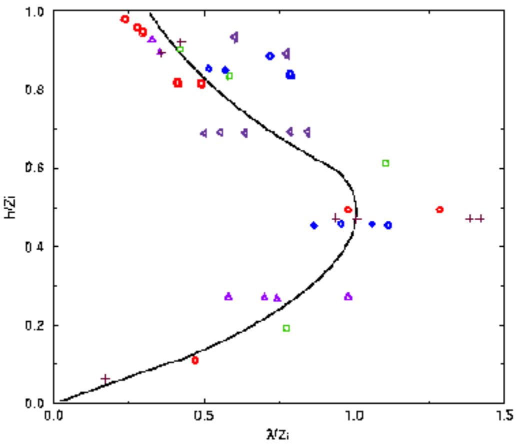

Figure 1 − Wavelength corresponding to the maximum vertical velocity variance: experimental data (discrete points) and proposed fitting (black line).

3. AUTOCONVERSION PARAMETERIZATION

In addition to the turbulence scheme, based on the vertical velocity spectrum, an autoconversion scheme was also proposed, in which the small−scale variability of cloud water content is taken into account.

It is well known that autoconversion formulas such as Kessler's (1969) and Berry−Reinhardt's (1974) underestimate drizzle formation in numerical models, especially if the horizontal grid spacing is large. Usually, a single value is used to represent the cloud water content (or mixing ratio) inside a grid−box, whereas, in reality, each grid−box has its own cloud water probability distribution function (PDF). For instance, Larson et al. (2001) showed the importance of the use of proper PDFs for liquid water content in order to reduce biases in Kessler's autoconversion calculations.

In this paper, ACE2 data were used to achieve a PDF for cloud water content (q_c) in stratocumulus clouds. First, data collected during horizontal flight legs were normalized by the mean q_c ($q_{c,mean}$). The PDF was then calculated with respect to fractions of $q_{c,mean}$ and fitted by a polinomial. 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−CLOUDYCOLUMN flights, as well as the polinomial fitting used in the present parameterization.

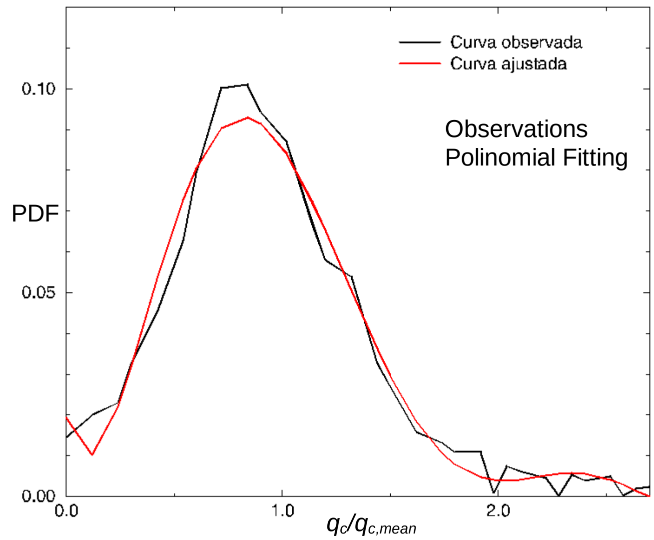

Figure 2 − Probability−distribution function for a non−dimensional cloud water content (normalized by its mean value)

4. SINGLE−COLUMN MODEL

The single−column model (SCM) used to test the turbulence and autoconversion schemes described in previous sections was proposed by Golaz (1997). The model comprises prognostic equations for the horizontal wind, the ice−liquid potential temperature, the total water mixing ratio and the turbulent kinetic energy. In addition to the parameterizations described earlier, the SCM uses a radiation transfer scheme developed by Harrington (1997) and the microphysical parameterization by Walko et al. (1995).

5. NUMERICAL EXPERIMENTS

5.1 *Case studies*

The SCM with the new parameterizations was used to simulate two ACE2−CLOUDYCOLUMN cases. The first case, 26 June 1997, was characterized by typically marine CCN, with droplet concentrations of the order of 55 cm^{-3}, on average, drizzle was significant and a decoupled boundary−layer was observed. In the second case, 8 July 1997, larger droplet concentrations occurred (196 cm^{-3}, on average), and the near−surface mixed layer and the cloudy layer were coupled. A detailed description of those case studies is presented by Almeida et al. (2002, this conference, hereafter ACO2002).

5.2 *Initial conditions*

In all cases, the model was initialized using observed vertical profiles of horizontal wind, potential temperature and water vapor mixing ratio, as shown in Figures 3 and 4.

For the 26 June case, near−northeasterly winds prevailed inside the boundary−layer, changing to westerlies, then to northwesterlies above the cloud top inversion (panel 3a). A sharp potential temperature change was present at the 1500 m level, with a 293.5 K found below the cloud layer (panel 3b). A water vapor mixing ratio of 10 g/kg occurred in most of the boundary−layer, followed by a significant drying above the stratocumulus top (panel 3c).

For the 08 July case, wind, potential temperature and water vapor mixing ratio profiles are shown in panels 4a, b, and c, respectively. The inversion is located approximately at the 1000 m height.

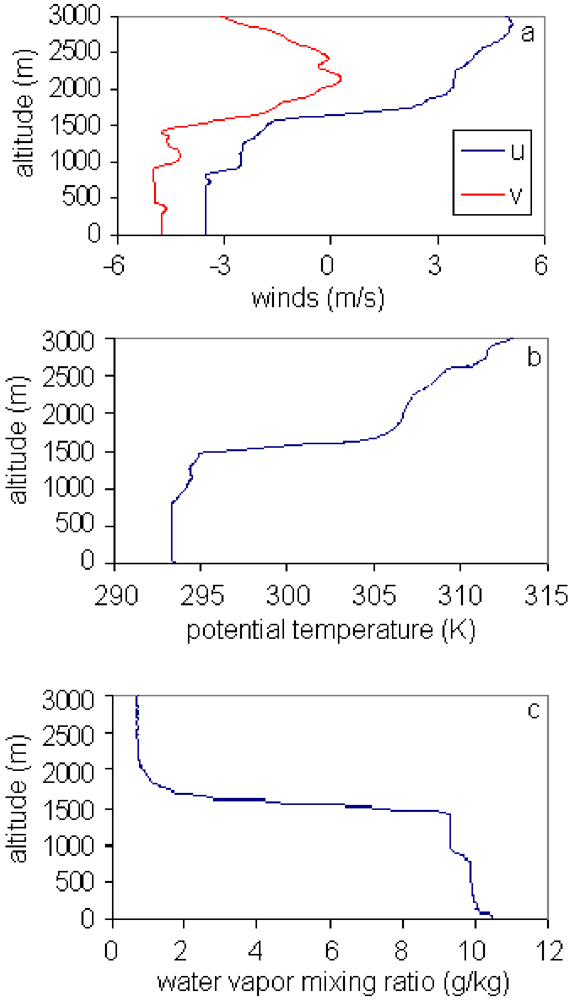

Figure 3 − Vertical profiles of the horizontal winds, potential temperature, water vapor mixing ratio, 26 June 1997, approximately at local noon.

5.3 *Model setup*

A high resolution grid was used, in order to represent features such as shallow cloud layers and sharp discontinuities in thermodynamic and humidity fields, as the ones found at the capping inversion at the top of the boundary−layer containing stratocumulus clouds. A total of 150 vertical levels were used, along with a 20 m grid−spacing. A 10 s time−step was adopted.

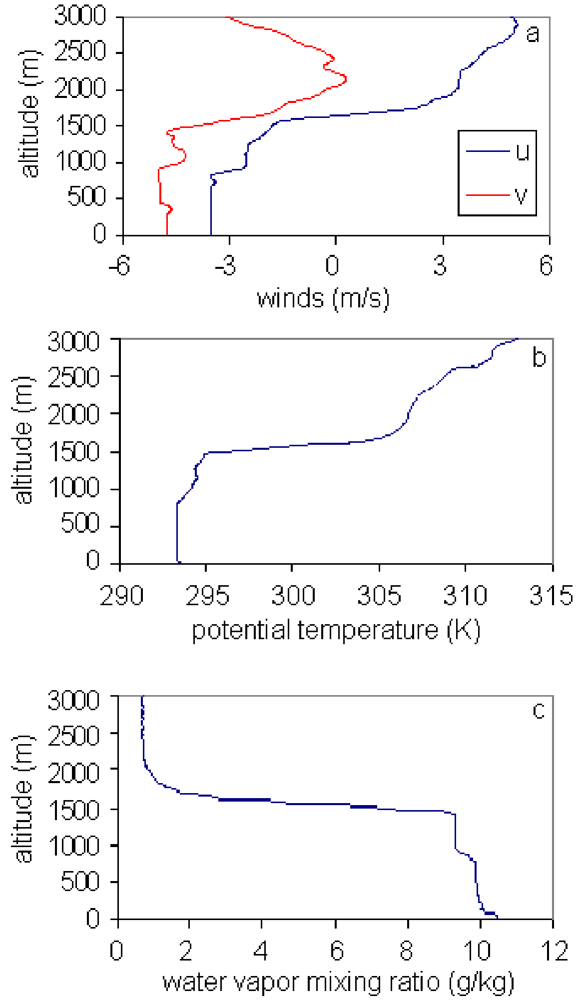

Figure 4 − Same as Figure 3, except for 08 July.

Both short−wave and long−wave effects were turned on in the radiative transfer calculations. In the microphysics parameterization, a specified concentration scheme was used for cloud water, according to the observations, as described in section 5.1.

6. RESULTS

6.1 *08 July 1997*

Figure 5 depicts the time evolution of the vertical profile of the cloud water content, using the SCM with the new parameterizations. The maximum cloud water content (about 0.12 g/m^3) was found close to the cloud top. Cloud base and cloud top heights in the simulation were located approximately at the 800 m and 950 m levels, respectively. The simulated cloud fraction was always close to 1.0 between those heights (figure not shown), indicating the presence of a solid stratocumulus deck, as shown by ACO2002.

Figure 6 shows the average cloud water content for the last three hours of simulation, exhibiting a peak of approximately 0,09 g/m³ about the 910 m level. The simulated mean cloud water content compares well with its observed counterpart (averages along two horizontal legs, indicated by blue diamonds in Figure 6).

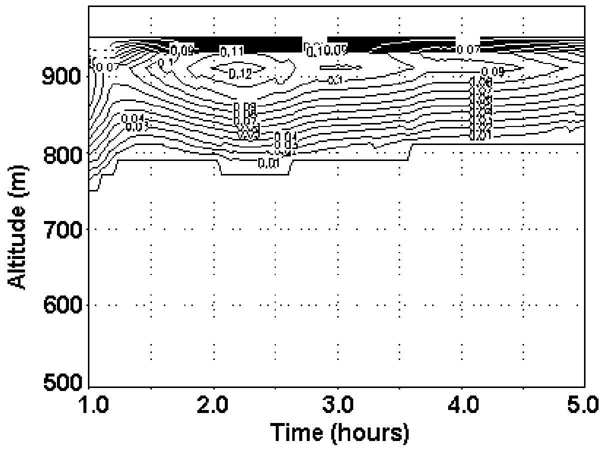

Figure 5 − Time evolution of the vertical distribution of cloud water content (in g/m³), 08 July 1997 case.

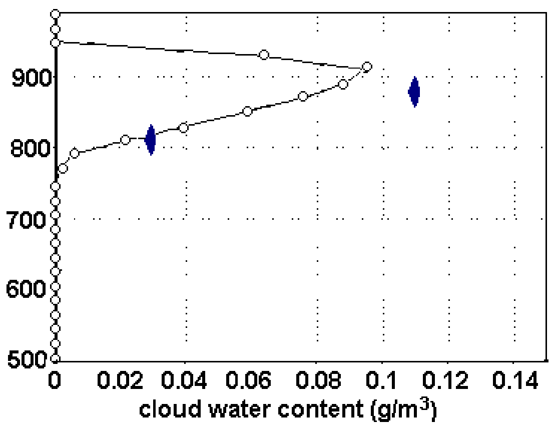

Figure 6 − 3−hour average of the simulated cloud water content (line with white circles in g/m³). Diamonds indicate averages of airborne observations at two horizontal levels, 08 July 1997 case.

Figures 7 and 8 show the simulated vertical velocity variance and the buoyancy flux. Diamonds represent estimated values from observations (averages over horizontal flight legs). Squares in Figure 7 correspond to filtered values. Again, the modeled fields agreed well with the observations. The buoyancy flux profile also exhibit a signature akin to the one produced by large−eddy simulations of stratocumulus−topped boundary−layers (e.g.,).

6.2 *26 June 1997*

In opposition to the previous case, the stratocumulus−topped boundary−layer on 26 June 1997 was characterized

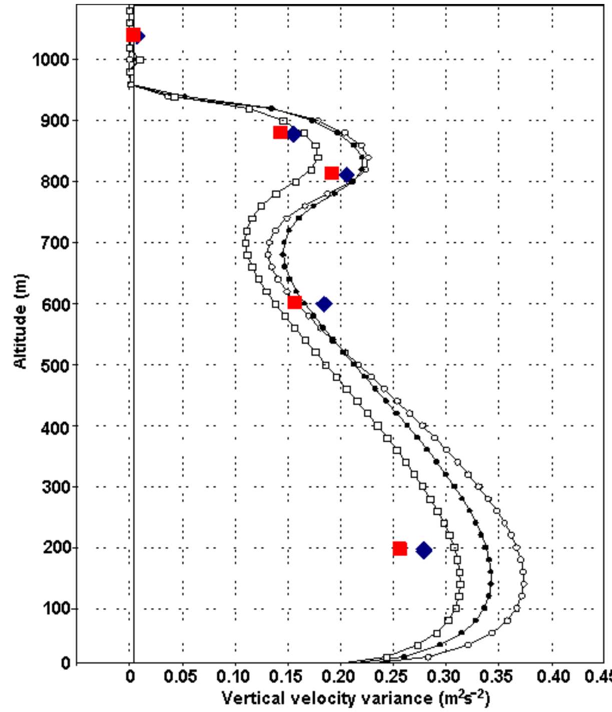

Figure 7 − Vertical profile of the simulated vertical velocity variance, after 2 hours (white circles), 3 hours (black circles) and 4 hours (white squares). Blue diamonds and red squares indicate observations (raw and filtered data, respectively). 08 July 1997 case.

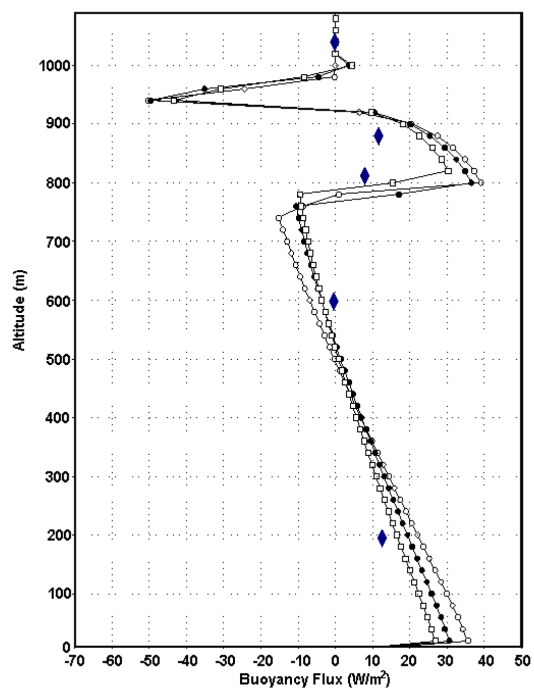

Figure 8 − Vertical profile of the simulated buoyancy flux, after 2 hours (white circles), 3 hours (black circles) and 4 hours (white squares). Blue diamonds indicate observations. 08 July 1997 case.

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 (ACO2002).

Figure 9 shows the time evolution of the simulated vertical distribution of cloud water content. Due to the small droplet number concentration and the high autoconversion rates, the simulated cloud water content rarely exceeded 0.1 g/m^3. Precipitation developed intermittently. Eventually, cumulus clouds formed under the stratocumulus layer.

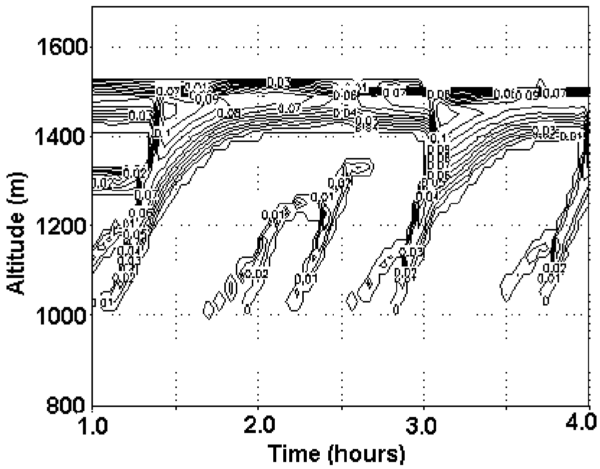

Figure 9 − Same as Figure 5, except for 26 June 1997 case.

As in the previous case, the simulated fields agreed well with the observations. In particular, the effect of drizzle evaporation, stabilizing the subcloud layer and decoupling the stratocumulus from the surface layer was well represented. This effect is shown in Figure 10, which depicts the vertical profile of the vertical velocity variance for the 26 June 1997 case.

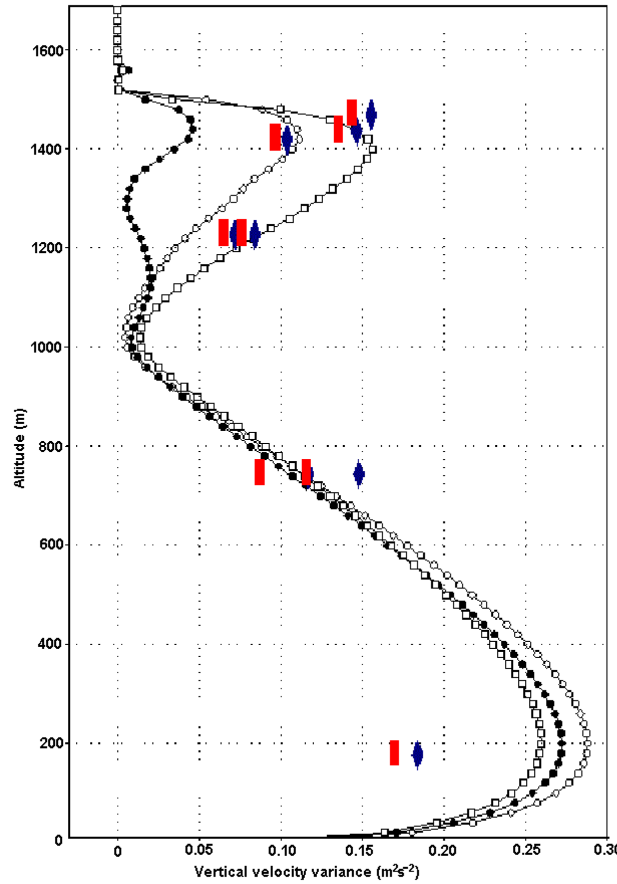

Figure 10 − Vertical profile of the simulated vertical velocity variance, after 2 hours (white circles), 3 hours (black circles) and 4 hours (white squares). Blue diamonds and red squares indicate observations (raw and filtered data, respectively). 26 June 1997 case.

7. SUMMARY AND FUTURE WORK

A parameterization based on the spectrum of vertical velocity variance was proposed to represent the turbulent transport in stratocumulus−topped boundary−layers. Along with an autoconversion scheme based on a probability distribution of cloud water content in stratocumulus clouds, the novel turbulence scheme was implemented in a single−column model.

SCM results agreed well with ACE2 CLOUDYCOLUMN observations, both in a case of solid stratocumulus clouds with high droplet number concentrations, coupled to the surface (08 July 1997) and in a case of broken stratocumuli, formed in a maritime air mass with little droplet concentration leading to significant drizzle production, showing decoupling (26 June 1997).

The SCM, with a proper representation of radiative transfer, cloud microphysics and turbulent transport can, therefore, be used to investigate the role of different physical processes in the evolution of stratocumulus−topped boundary layers.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Dr. Jean−Louis Brenguier, from Météo−France, for the access to ACE2 CLOUDYCOLUMN data. Dr. Jean−Christophe Golaz and Dr. William Cotton kindly allowed the authors to use and modify their single−column model. During this research, Gérson Paiva Almeida and Alexandre Araújo Costa received support from CAPES and CNPq, respectively.

REFERENCES

Albrecht, B. A., C. S. Bretherton, D. Johnson, W. H. Schubert, A. S. Frisch, 1995: The Atlantic stratocumulus transition experiment. *Bull. Amer. Meteorol. Soc.,* **76**, 889−904.

Almeida, G. P., A. A. Costa, and J. C. P. de Oliveira, 2002: Looking for evidences of drizzle−induced decoupling in the stratocumulus−topped boundary−layer. Proceedings of the 11th AMS Conference on Cloud Physics. 2−7 June, Ogden, UT.

Degrazia, G.A. and O.L.L. Moraes, 1992: A model for eddy diffusivity in a stable boundary−layer, *Boundary−Layer Meteor.*, **58**, 205−214.

Golaz, J.−C., 1997: Development of a single−column model for simulating precipitating stratocumulus clouds. M.S. Thesis. Atmospheric Science Paper No. 638, Colorado State University, Department of Atmospheric Science, Fort Collins, CO 80523, 90pp.

Harrington, J. Y., 1997: The effects of radiative and microphysical processes on simulated warm and transition−season Arctic stratus. Ph.D. dissertation. Atmospheric Science Paper No. 637, Colorado State University, Department of Atmospheric Science, Fort Collins, CO 80523, 270pp.

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulation. Meteor. Monograph, No. 10. Amer. Meteorol. Soc., 84 pp.

Langland, R. H., and C. S. Liou, 1996: Implementation of an E−epsilon parameterization of vertical subgrid−scale mixing in a regional model. *Mon. Wea. Rev.*, **124**, 905−918.

Larson, V. E., R. Wood, P. R. Field, J.−C. Golaz, T. H. Vonder Haar, W. R. Cotton, 2001: Small−scale and mesoscale variability of scalars in cloudy boundary layers: One−dimensional probability distribution functions. *J. Atmos. Sci*., **58**, 1978 − 1994.

Nicholls, S., 1984: The dynamics of stratocumulus: aircraft observations and comparisons with a mixed layer model. *Quart. J. Roy. Meteorol. Soc*., **110**, 783−820.

Raes, F., T. Bates, F. McGovern, and M. van Liedekerke, 2000: The second aerosol characterization experiment (ACE−2): General context, and main results. *Tellus*, 2000.

Smagorinsky, J., 1963: General circulation experiments with the primitive equations. Part I: The basic experiment. *Mon. Wea. Rev.*, **91**, 99−164.

Stevens, B., W.R. Cotton, G. Feingold, C.H. Moeng, 1998 : Large−eddy simulations of strongly precipitating, shallow, stratocumulus−topped boundary layers. *J. Atmos. Sci*., **55**, 3616 − 3638.

Turton, J. D. and S. Nicholls, 1987: A study of the diurnal variation of stratocumulus using a multiple mixed layer model. *Quart. J. Roy. Met. Soc*., **113**, 969−1009.

Walko, R. L, W. R. Cotton, J. L. Harrington, M. P. Meyers, 1995: New RAMS cloud micro−physics parameterization. Part I: The single−moment scheme. *Atmos. Res.,* **38**, 29−62.

Wang, S., and Q. Wang, 1994: Roles of drizzle in a one−dimensional third−order turbulence closure model of the nocturnal stratus−topped marine boundary layer. *J. Atmos. Sci*., **51**, 1559 − 1576.