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ROLE OF NOCTURNAL TURBULENCE AND ADVECTION IN THE FORMATION OF SHALLOW CUMULUS

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1. MOTIVATION

This extended abstract is a short summary of the complete research presented at de Arellano (2007). The formation and further development of shallow cumulus over land is driven by the daily variations in surface turbulent fluxes. Their evolution is also dependent on the thermodynamic characteristics and on the atmospheric stability within and above the atmospheric boundary layer (ABL). To date, studies have focused on the role of the land-atmosphere interaction in controlling shallow cumulus formation (Ek and Holtslag, 2004; van Heerwaarden and de Arellano, 2008) and in discussing their main dynamic characteristics and their controlling processes (Zhu and Albrecht, 2002; Brown et al., 2002).

In comparison with the formation of fair-weather cumuli above maritime conditions, above land, shallow cumulus are highly dependent on the diurnal cycle of the atmospheric boundary layer, external forcings and the horizontal variability of surface properties. Therefore, and as a result of their non-steady development, their representation in large-scale models is more problematic than above the sea (Neggers et al., 2004), (Lenderink et al., 2005), (Berg and Stull, 2006).

However, an important condition, the initial morning characteristics of the thermodynamic vertical structure, has received little attention, particularly with regard to how the structure of the nocturnal boundary layer (NBL) and the layer above it evolve to establish the optimal stability conditions for triggering shallow cumulus formation during the day. As mentioned by (Zhu and Albrecht, 2002), weaker stratification and smaller inversion potential temperature jump favour cloud formation. Both are largely dependent on the initial thermodynamic state at dawn. In this paper, we present observational evidence of these feedbacks mechanisms during the transition from nocturnal to diurnal boundary layer conditions.

In order to assess the role of nocturnal boundary layer on shallow cumulus over land, two consecutive nights were studied by means of detailed surface and upper air observations. These measurements were taken on the Southern Great Plains of the Atmospheric Radiation Measurement (SGP-ARM) site in Oklahoma and Kansas, USA. The high spatial distribution, more than four radiosounding launching stations within a radius of 200 km around the central facility, and the high temporal frequency, with a radiosonde was launched every three hours, made the ARM site particularly suitable for the purpose of this study. Moreover, the ARM site has been previously used to study cloudy boundary layers over land (Zhu and Albrecht, 2002).

The nights under study were the 19-20 June 1997 and the 20-21 June 1997. Although both nights presented very similar characteristics in synoptic and mesoscale terms, differences above the nocturnal boundary layer and the intense turbulent mixing in the NBL led to the development of two diurnal boundary layer with very different turbulent characteristics. Hence, on the 20th June 1997, a cloudless boundary layer was formed with a large entrainment rate driven partly by shear at the surface and at the inversion zone (Pino et al., 2003) while on the 21st June, shallow cumuli were observed with a coverage of 20%-30% above the ARM site (Zhu and Albrecht, 2002; Brown et al., 2002).

The primary goals of this study were: (i) to analyze the observational evidence of the role of advection and turbulent mixing during the night in establishing the conditions required to form daily shallow cumuli and (ii) to examine, by means of sensitivity analysis, the dependence of cloud development to modifications of the initial morning values of the atmospheric stability and the properties within the entrainment region.

2. RESEARCH FINDINGS IN BRIEF

2.1 *Temporal evolution*

The temporal sequence (23,02,05,08 LT) of the vertical profile of potential temperature at site C during the two consecutive nights is shown in figure 1. In order to distinguish between the evolution of the profiles within and above the nocturnal boundary layer (NBL), the boundary layer height h estimated as the height of the mean wind maximum (LLJ) is also shown. The similar evolution of the longwave radiative cooling and intense ver-

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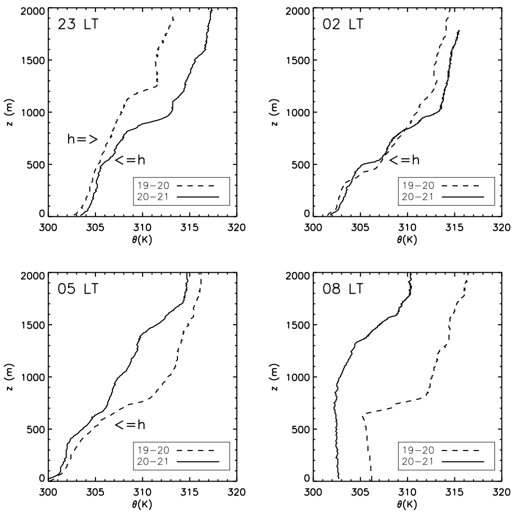

FIG. 1: *Temporal evolution of the potential tempertaure vertical profiles at site C during the nights of 19-20 and 20-21 June. The boundary layer height h is also indicated. At 02 and 05 LT the boundary layer height was the same on both nights (500 m).*

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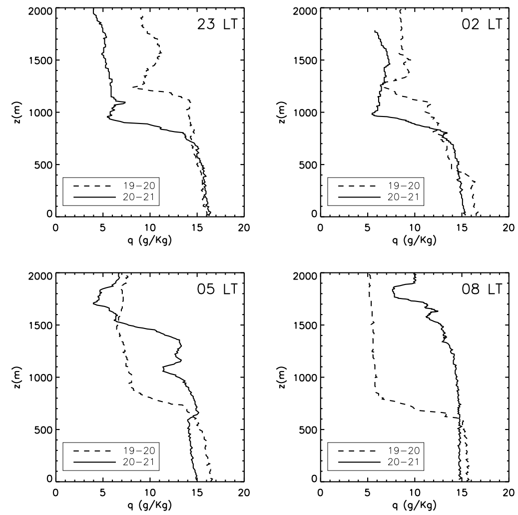

FIG. 2: *Same as figure 1, but showing specific humidity.*

tical mixing within the NBL yields to a very similar development of the stable stratification during both nocturnal boundary layers. Above the NBL, the θ-profile at 23 LT during the first night is slightly colder. However, at 02 LT, both profiles are almost identical characterized by the same boundary layer height and slightly higher stability values for the second night.

On the 21st June, during the time interval between 02 and 05 LT, the air mass above the NBL cooled strongly down. For instance, if we take 1000 m as a reference height, we observed that during the night 19-20 June, the θ values remain almost constant ($\approx$ 312 K) whereas during the second night they have decreased by 4 K. Closely associated with this cooling is an increase in the instability of the upper layer.

The temporal evolution of the specific moisture profiles is similar (figure 2). The drier layer above the BL during the night of 20-21 June compared within the first night is modified by a large increase in moisture content. During the period 02-05 LT, this increase is from 5 $g(Kg)^{-1}$ to 15 $g(Kg)^{-1}$ at 1000 m. At 05 LT of 21st June, and except for the maximum and minimum values of the specific humidity at 650 m and 1000 m respectively, we observed higher water vapour contents up to 1300 m, well above the NBL. It is also worth pointing out that the strong mechanical turbulent mixing with the NBL leads to a well mixed-layer on both nights, *i.e.* the difference between the surface values and the top NBL is less than 1 $g(Kg)^{-1}$ due to the almost constant on time positive value of the moisture flux. To complete the previous analysis of figure 2, the specific moisture vertical profile at 08 LT (21 June) once again demonstrate the establishment of optimal conditions for the formation of shallow cumulus: a well-mixed profile upto 1500 m with high water vapour content ($\approx$ 15 g/Kg).

2.2 *Dependance of cloud formation on initial morning conditions*

As shown by the previous analysed observations above, thermodynamic modifications of the layer above the NBL result in wide variations in the potential temperature and the moisture content vertical distribution. The morning transition conditions are therefore influenced by these variations, particularly by the formation of the initial potential temperature ($\Delta\theta_{vo}$) and moisture (Δq_o) interface jump during the early stages of the development of the convective boundary layer. These nocturnal variations have a strong influence on the further evolution of the boundary layer growth and are thus responsible for setting up the optimal conditions for the formation of boundary layer clouds once diurnal convection begins. Here, a sensitivity analysis was carried out to study the dependence of boundary layer height and the lifting condensation level on the initial values of the potential temperature and moisture jump at the interface and the potential temperature lapse rate.

A mixed layer model (Lilly, 1968; Tennekes, 1973) was used to calculate the boundary layer evolution and to estimate wether water vapour saturates (*i.e.* *LCL* below h (clouds potentially can be formed) or above h (absence of clouds). See de Arellano (2007) for more details on the model formulation. The mixed layer model reproduces the evolution of the slab convective boundary layer variables (sub-cloud layer) observed during the 21st June and it includes the explicit calculation of the time evolution of the LCL by using a parcel method couple to the evolution of the thermodynamic variables solved by the mixed-layer model. We take a similar approach as Zhu and Albrecht (2002) who employed the mixed layer model as a conceptual tool that is able to reproduce accurately the bulk characteristics of the convective boundary layer.

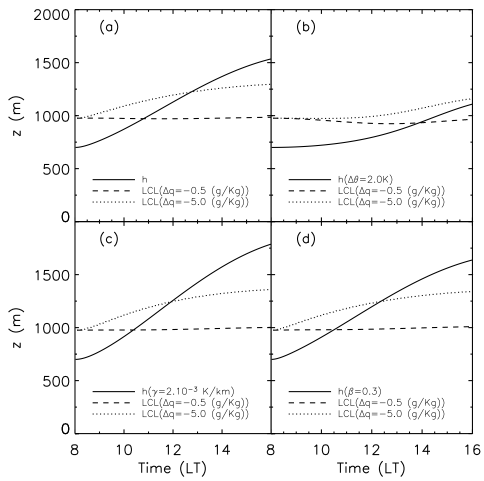

FIG. 3: *Time evolution of the boundary layer height h (continuous line) and lifting condensation level LCL for the following initial values of the moisture jump: -0.5 g/Kg (dashed line) and -5.0 (g/Kg) (dotted line). (a) Prescribing initial values similar to the early morning conditions at 08 LT 21st June (see Table 2); (b) similar to Table 2 but initial $\Delta\theta = 2\ K$; (c) similar to Table 2 but $\gamma_\theta = 2.10^{-3}\ K/m$ and (d) similar to Table 2 but $\beta = 0.3$.*

Our mixed layer model initial conditions are similar to the ones prescribed by Brown *al.* (2002) in order to to reproduce similar convective boundary layer conditions to those observed on 21st June 1997 at site C (Zhu and Albrecht 2002, Brown *al.* 2002). de Arellano (2007) summarizes the initial conditions prescribed in the mixed-layer model. The sensitivity tests focus on the inital values of $\Delta\theta_{vo}$, Δq_o, γ_θ and the ratio of the entrainment heat flux to the surface heat flux ($\beta_{\theta v}$). As previously analyzed, the first three variables were largely influenced by the arrival of the colder and moister air mass above the NBL bewteen 02 and 05 LT. Figure 3 presents the time evolution of the boundary layer height and the lifting condensation level calculated for two different cases: $\Delta q_o = -0.5\ (g/Kg)$ (closer to the sunrise conditions of 21st June) and $\Delta q_o = -5.0\ (g/Kg)$ (closer to the sunrise conditions of 20th June). Figure 3a shows the model results closer to the initial observations (for $\Delta q_o = -0.5\ (g/Kg)$) and the other figures show the results of the sensitivity tests. Notice, however, that in all the cases, we found that the absolute decrease of the moisture jump at the inversion (from -5.0 to -0.5) leads always to a moistly boundary layer (lower LCL) due to the less entrainment of dry into the boundary layer.

In Figure 3a, we show the evolution of h and LCL using the initial conditions closer to the situation oberved during the 21st June (see Table 2). The model results using an initial $\Delta q_o = -0.5\ (g/Kg)$ reaches the condition $h = LCL$ at around 11 LT. At approximately this time, clouds were observed over the central facility C and the ceilometer reported a cloud-base height (similar to LCL) at around 1000 m between 10 and 11 LT (see figure 5 at Brown *et al* (2002)). A decrease in the initial jump of the specific humidity ($\Delta q_o = -5.\ (g/Kg)$) would lead to a dealy in one hour of the necessary condition $h = LCL$ due to the enhancement of the entrainment of dry air and the subsequent raise of LCL.

Figure 3b shows the same situation but now increasing the initial jump of the virtual potential temperature at the interface to 2.0 K. This test is illustrative for the previous day situation (20th June) characterized by large inversion jumps for $\Delta\theta_o$ and Δq_o at the entrainment zone. A shallow boundary layer with a slow growth rate is the main feature of this sensitivity test leading to a late onset of the condition $h = LCL$ (for case $\Delta q_o = -0.5\ (g/Kg)$) or a cloudless boundary layer because of $LCL > h$ (initial $\Delta q_o = -5.\ (g/Kg)$).

The increase of atmospheric instability above the boundary layer is studied by reducing the temperature lapse rate to the value 2.10^{-3} K/m (see Figure 3c). In consequence, the boundary layer deepens faster and the condition $h = LCL$ is attained earlier than in the case presented at figure 3a. It is also important to notice that this rapid growth leads an increase on the entrainment of dry air yielding to higher LCL (see case $\Delta q_o = -5.\ (g/Kg)$). This decrease of the temperature lapse rate was also used by Brown *et al* (2002) to reproduce by means of LES shallow cumulus with an enhanced vertical development.

Finally, we show at figure 3d a sensitivity test to the ratio of the entrainment heat flux to the surface heat flux. As studied by Pino *et al* (2003) during the previous day, larger values of this ratio are expected due to the enhancement of the entrainment flux by the presence of shear at the surface and at the entrainment zone. The model results show that in spite of the increase of warm and dry air brought into the boundary layer by the entrainmnet process, the condition $h = LCL$ is reached slightly before than in the observed case (for case $\Delta q_o = -0.5\ (g/Kg)$) due to the more rapid growth of the boundary layer.

In spite of the conceptuality of the study, the analysis indicate the subtlety in setting up optimal conditions to the formation of shallow cumulus over land. Briefly, a decrease on the morning initial potential jump and temperature lapse rate leads to a higher rate of the boundary layer growth increasing the possibility of cloud formation. In turn, this higher rate is normally associated with larger entrainment events of warmer and drier air into the boundary layer which can delay reaching the condition $h = LCL$. A small jump of moisture at the entrainment region could compensate for this drying effect of the boundary layer and facilitate cloud formation.

3. CONCLUSIONS

We investigated the role of the nocturnal boundary layer and its layer aloft in setting up appropriate conditions for the formation of shallow cumuli. Surface and upper-air observations of two consecutive nights were studied and compared in order to determine the processes involved in producing two different diurnal boundary layers (one clear and the other cloudy) under similar driving diurnal surface conditions. Both nights displayed very similar turbulent structures and evolution, characterized by an intense turbulent mixing (friction velocity between 0.5 and 0.6 m/s) driven by the wind shear generated by the low level jet. However, during the second night, the air mass above the NBL was modified by a low-level advection event becoming colder (a decrease of approximately 4 K) and with a higher specific humidity content (an approximate increase 10 g/Kg). As a result, the conditions at the interface between the NBL and the layer aloft were greatly modified during the second night. We can summarize these key observed conditions in the generation of favourable conditions for cloud formation during the day as follows: (1) reduction in the potential temperature and moisture jump at the interface near sunrise, (2) increase in the instability above the boundary layer during morning transition and (3) possibility of rapid formation of well-mixed profiles of potential temperature and specific humidity due to high levels of turbulence at nigh and in the morning transition.

By means of a mixed layer model, we demonstrate the sensitivity of the evolution of a diurnal boundary layer to changes in the initial values of the inversion potential temperature and moisture jump (condition 1) and to the temperature lapse rate (condition 2). The analysis aimed to determine the conditions under which the boundary layer height becomes higher than the lifting condensation level. Higher boundary layer values are found when the potential temperature jump and the temperature lapse rate in the free troposphere are reduced. However, this enhancement is closely associated with a warmer and drier boundary layer which leads to higher lifting condensation levels. The drying effect can be compensated for if the moisture levels in the free troposphere are fairly similar to those of the boundary layer (relatively small jump in moisture content at the entrainment region).

To conclude, at a similar order of magnitude and range of variability of the surface turbulent conditions during the night, these three mentioned factors will lead to vertical profiles of the potential temperature and the specific humidity that are optimal for triggering shallow cumulus development over land. This study thus indicates the importance of accurately modelling vertical thermodynamic variables at night in order to be able to reproduce cloud formation and their thermodynamical characteristics during diurnal conditions. The high spatial density and high frequency of the vertical profiles measurements of U, θ and q and of the measurements of the surface condition around the ARM site make this observational data set very appropriate for the study of how boundary layer processes interact with large scale horizontal advection in mesoscale models.

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