Formation and Development of Nocturnal Boundary Layer Clouds over the Southern Great Plains

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Introduction

Boundary layer clouds are important for modulating the earth's radiation budget, affecting local weather and interacting with trace gases to complicate air pollution problems. Previous studies show that some physical processes are critical to the development, maintenance, and dissipation of these clouds. These processes include synoptic subsidence, longwave radiative cooling at cloud top, the entrainment process, and surface fluxes. In this paper, we are concerned primarily with the evolution of nocturnal boundary layer (NBL) clouds. One question that has not been adequately answered is what are the major mechanisms for forming nocturnal clouds? Or in other words, where do these clouds come from? One possibility is that this type of cloud forms during the daytime due to turbulent mixing, and then persists through the night (Rogers et al. 1995). But we do find many cases at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site where stratus clouds form in the middle of night (Figure 2 shows an example that will be discussed later). Obviously, it is possible that these clouds are advected from elsewhere, but in Figure 2 the observed cloud bases and the lifting condensation level (LCL) from surface meteorological data are coupled very well. Thus it is reasonable to ask if it is possible that these clouds are produced by the boundary layer process themselves. Unlike the daytime convective boundary layer, in the evening there is no solar radiative heating at the underlying surface to produce positive buoyancy. Furthermore, surface longwave radiative cooling results in negative buoyancy that suppresses turbulent mixing. In this sense, it would be difficult to form NBL clouds by the same mechanisms that operate in the daytime. However, turbulence within the boundary layer can also be generated and maintained by wind shear that dominates under neutral and stable boundary layer conditions. If the turbulence induced by shear production is strong enough, under some circumstances, the moisture in the lower level can be efficiently transported upward to form clouds. One objective of this paper is to determine the conditions that may form forced NBL clouds.

Conditions for NBL Cloud Formation

The fundamental condition for forming forced boundary layer clouds under well mixed conditions is that the LCL be lower than the boundary layer height. For nighttime conditions over land, wind shear is the only major factor that can produce turbulence before cloud formation. For steady homogeneous conditions, we can integrate the turbulent kinetic energy (TKE) budget equation for the whole boundary layer using simple mixed layer theory under assumptions that: 1) fluxes at the top of mixed layer are proportional to the entrainment rate and the difference across the mixed layer, and 2) just above the surface, the pressure perturbation term and the viscous dissipation term are proportional to the rate of mechanical production of turbulence. Thus, the integrated TKE equation can be simplified as:

$$\alpha U_*^3 = -\frac{gh}{2\overline{\Theta}}\overline{w'\theta_0'} + \Lambda\frac{\partial h}{\partial t}\frac{gh}{2\overline{\Theta}}\Delta\overline{\Theta} \tag{1}$$

where Λ is the Heaviside unit function, α is a proportionality factor, U_* is the frictional velocity, $\overline{\Theta}$ is the mean potential temperature, h is the boundary layer height, $\overline{w'\theta_0'}$ is the temperature flux at the surface, and $\Delta\overline{\Theta}$ is the difference across the boundary layer. During the evening if the buoyant damping due to the negative surface heat flux is sufficiently large, then this term alone can balance the wind-stirring term. When this happens, the nocturnal mixed layer will not develop. In this case, Eq. (1) gives us a critical level:

$$h_{critical} = -\frac{2\overline{\Theta}\alpha U_*^3}{g\overline{w'\theta_0'}} = 2\alpha\kappa L_{ob} \tag{2}$$

where L_{ob} is Monin-Obukhov length scale, and κ is the Von-Karman constant.

Therefore, to deepen the mixed layer in the evening, the following condition has to be satisfied.

$$\alpha U_*^3 + \frac{gh}{2\overline{\Theta}}\overline{w'\Theta'} > 0 \tag{3}$$

Under normal conditions, Eq. (3) is difficult to satisfy after sunset. Therefore, the nocturnal mixed layer seldom forms and develops, or the depth is very shallow. However, if Eq. (3) is satisfied, then it is possible to develop a mixed layer. If the condition:

$$Z_{lcl} < h_{critical} \tag{4}$$

is also satisfied, then, NBL clouds could form and develop, otherwise it is impossible to form the NBL clouds. The ratio between the LCL and the critical level gives a very important non-dimensional parameter

$$\frac{Z_{lcl}}{2\alpha\kappa L_{ob}} \tag{5}$$

Basically, this ratio combines the different influences of the physical processes that control the formation of NBL clouds.

The preceding analysis involves a very important proportionality factor α, which has to be established empirically. In this study, we design a numerical experiment to determine α for the nocturnal boundary layer using the Regional Atmospheric Modeling System (RAMS) model with on a high-order turbulent closure scheme.

Values of α verse L_{ob} from this simulation are shown in Figure 1. A least-square fit of these values to the function

$$\alpha = \frac{m}{\sigma L_{ob}} \exp\left(- \frac{(\ln L_{ob} - \mu)^2}{2\sigma^2} \right) \tag{6}$$

gives m = 12238.52; μ = 9.302; and σ = 2.301.

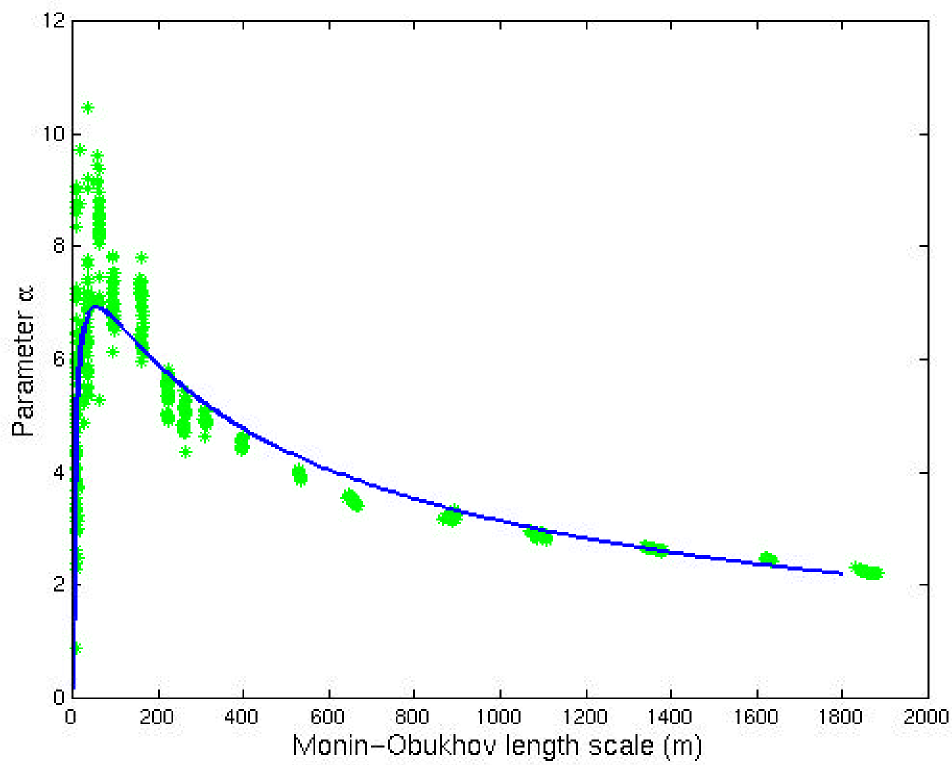

Figure 1. Simulated proportionality factor α vs. Monin-Obukhov length scale and the fitting curve.

Case Study Results

The data that we used here were collected at the ARM site in the SGP. In this study, the NBL cloud case for November 6, 1997, was studied based on the analysis and derivation presented in the section on “Conditions for NBL Cloud Formation.” The surface weather map and satellite image show that there were no strong synoptic scale influences on the research area. Figure 2 shows the cloud base observed by ceilometer. We see that the cloud began forming from 4:30 Universal Time Coordinates (UTC) (23:30 LST).

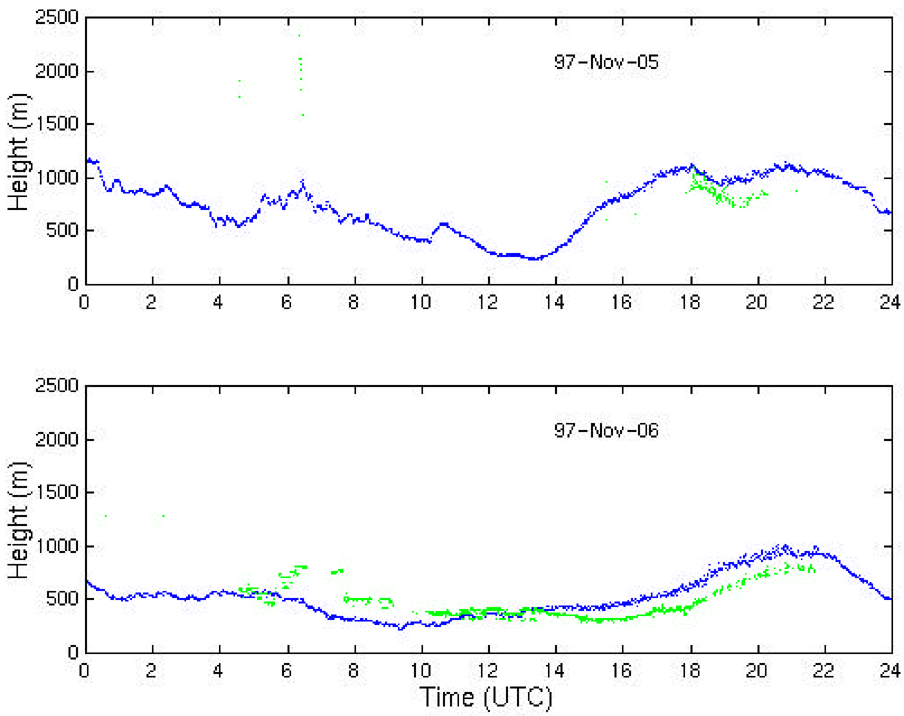

Figure 2. The observed boundary layer cloud base height on November 5 and 6, 1997. (Local time = UTC – 5 h). Blue: calculated LCL; Green: cloud base height observed by ceilometer.

The mean vertical profiles of potential temperature and specific humidity (not show here) show that beneath the cloud top there exists a well-developed mixed layer that is not observed in the previous evening (November 5) or the day after (November 7). Observations show that there is no major difference between the surface heat fluxes in the two evenings on November 5 and 6 at the central facility.

According to our analysis, the relative importance of thermodynamic and dynamic processes can be evaluated by the ratio between the LCL and the critical level. To confirm this result, which we obtained in the section on “Conditions for NBL Cloud Formation,” we calculated the LCL and the critical level on November 5 and 6 (Figure 3). We see that on November 5, when there is no cloud, that the LCLs are

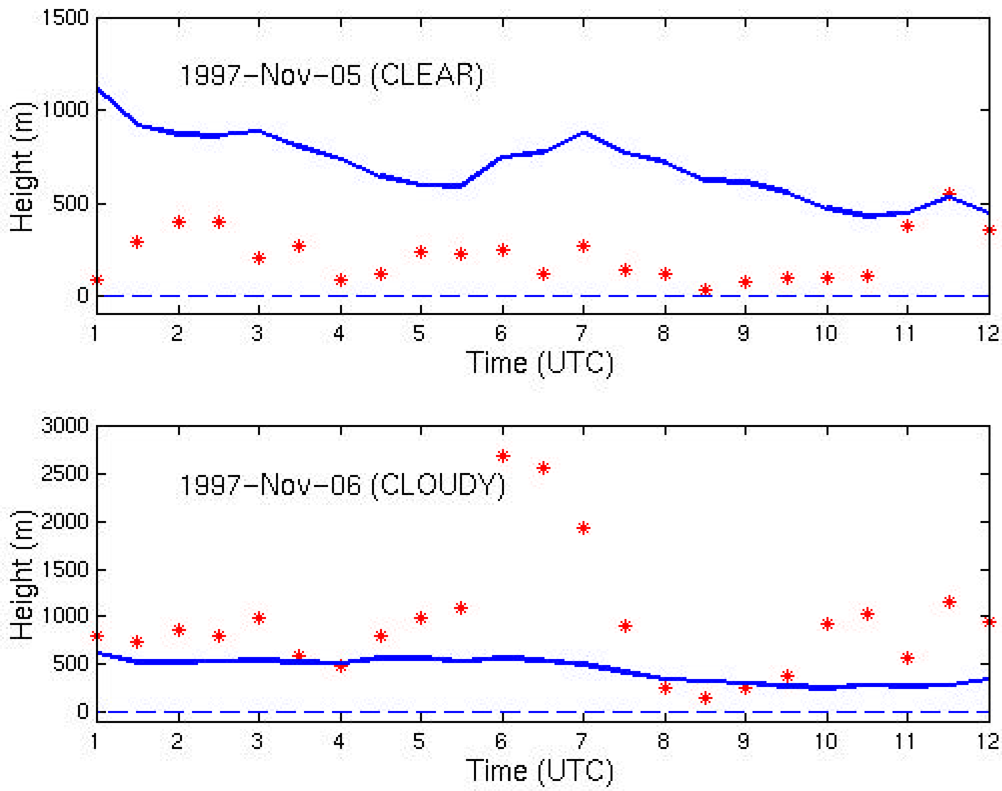

Figure 3. The calculated LCL (line) and the critical level (star) on November 5 and 6, 1997, at the ARM SGP central facility.

higher than the critical levels. But on November 6, when the NBL clouds did form and develop, the LCL is lower than the critical level, consistent with our previous discussion. To further determine if the relation between the LCL and the critical level is a good indicator of NBL cloud formation and to consider the effects of surface flux heterogeneity, we calculated LCLs and the critical levels at all the observational facilities in the research area. Figure 4 shows the results averaged over the whole night. On November 5, there are no clouds observed, and the critical levels are lower than the LCLs. We also note that on November 6, along the southwest boundary of the research area, the calculated critical levels are lower than the LCLs. This indicates that there should be no clouds in this region. Satellite images and the longwave radiation observations at these facilities (not shown here) show that clear-sky conditions prevailed at this time. The results indicate that our cloud prediction parameter is sensitive to whether the clouds form or not and exposes the basic physics for NBL cloud formation.

Conclusions and Discussion

Based on the general observation that there is a well-mixed layer beneath the cloud top, we assume the basic condition for the NBL cloud formation is that the LCL is lower than the mixed layer depth. The analysis of the deepening rate of the mixed layer results in an important parameter, the ratio of the LCL

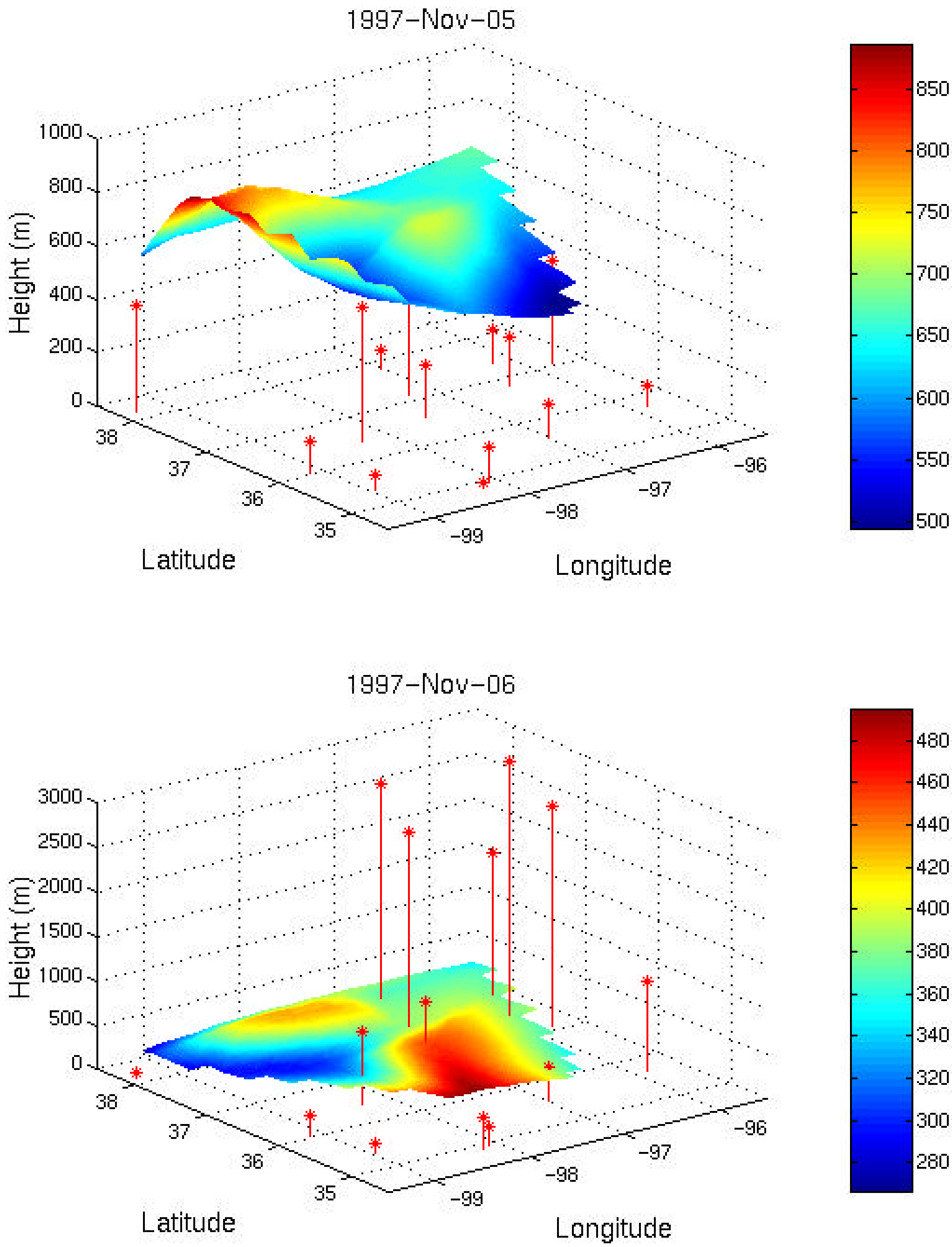

Figure 4. The calculated LCL (surface) and the critical level (star-bar) over the whole ARM SGP research area.

and the critical level. This ratio fundamentally controls the formation of NBL clouds. If the LCL is larger than the critical level, then it is impossible to form clouds through boundary layer mixing, while if the LCL is smaller than the critical level, clouds may form.

The data collected from the ARM SGP site are used in this study to examine the results of our theoretical analysis. The cases that we studied did show that the wind shear can be an important factor in the formation nocturnal stratus.

Reference

Rogers, D. P., X. Yang, and P. M. Norris, 1995: Diurnal evolution of the cloud-topped marine boundary layer. Part I: Nocturnal stratocumulus development. *J. Atmos. Sci.*, **52**, 2953-2966.