# Lecture 17. Dynamics of shallow cumulus boundary layers

## *General description*

The dynamics of cumulus-topped boundary layers is an interplay between surface buoyancy and moisture input, latent heating and evaporation around the cumulus clouds, radiative cooling, and precipitation. The general features of such boundary layers are fairly universal and well understood, but many of the important details, including how to quantitatively predict the cloud cover and optical properties, remain poorly understood and important parameterization problems. Oceanic shallow cumulus boundary layers are important because of their enormous areal extent and climatic importance. Over land, shallow cumulus boundary layers are often precursors to deep convection, and can play an important role in its timing and location. In addition, even the small fractional cloud cover of shallow cumuli can have important feedbacks on the evolution of land surface temperature. Shallow cumulus clouds also vertically mix momentum.

## *Dynamics of a shallow cumulus BL*

We discussed the typical observed structure of a shallow Cu BL in Lecture 14, and identified four sublayers - a subcloud mixed layer extending up to the cumulus cloud bases, a thin transition layer, usually identifiable on individual soundings but blurred out in the horizontal mean, a conditionally unstable layer and an inversion layer. It has been many years since a state-of-the-art shallow cumulus field experiment has been performed, and LES simulate this type of BL fairly well. Hence we first present LES simulations of a shallow cumulus ensemble based on a composite sounding, SST, and winds from a three-day period of nearly steady-state trade-cumulus convection on 22-24 June 1969 over the tropical west Atlantic Ocean during the BOMEX experiment. During this period, there were strong easterly trade winds and persistent mean subsidence. Then we discuss the dynamical balances that maintain this structure. The most comprehensive textbook description of shallow cumulus convection is Ch. 8 of Cotton and Anthes; there is also some useful, mainly theoretical, discussion at the end of Ch. 13 of Emanuel's *Atmospheric Convection,* (Oxford University Press, 1994) pp. 443-457.

### LES ensemble structure

Figure 1 shows the mean initial sounding of temperature and winds, and model-simulated sounding after six simulated hours, showing that the models can maintain the observed steady-state if the combined advective and radiative forcings and the observed surface fluxes are specified.

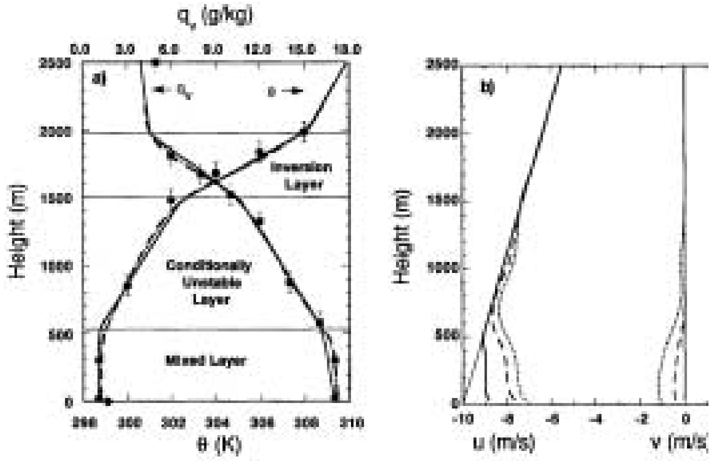
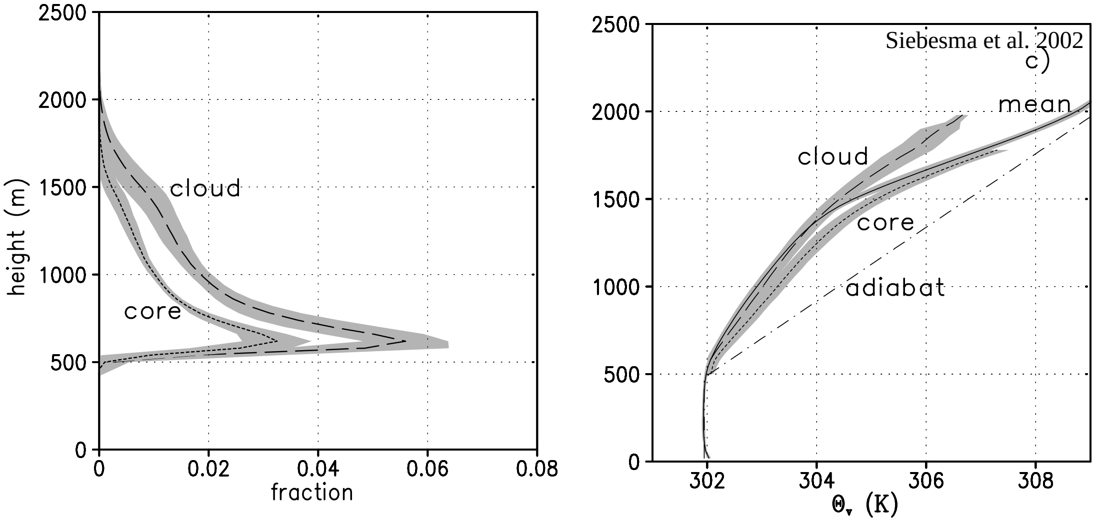


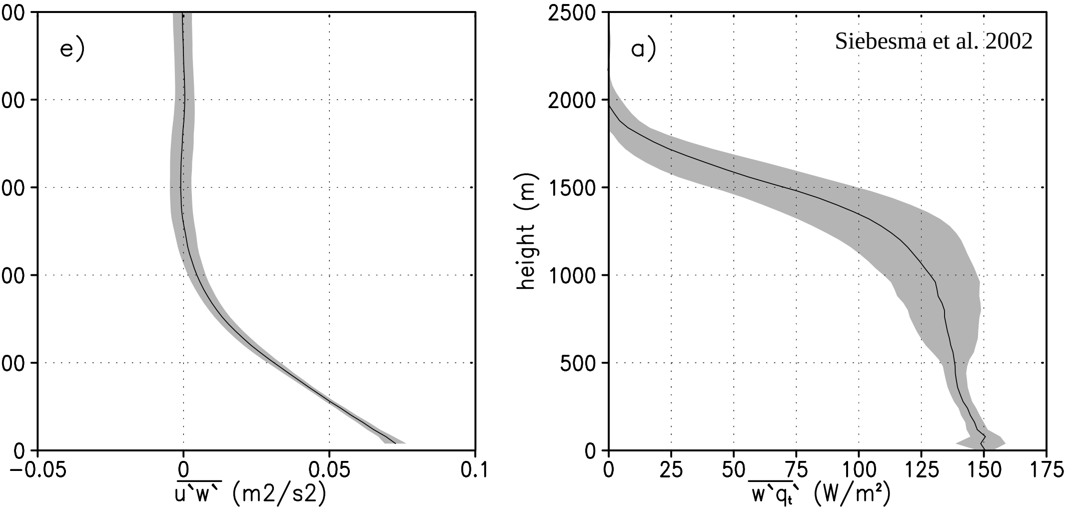
FIG. 1. Horizontally averaged vertical profiles of θ and $q_v$ (a) and the u and v components of the velocity (b) at time t = 0 h (full = 3 h (dotted lines), and t = 7 h (dashed lines). The circles and squares are the observed values. The thin line in (b) is the ge geostrophic wind profile.

This period was chosen for a model intercomparison (Siebesma et al. 2002, *J. Atmos. Sci.*, in press), so eight LES models were run on the same case. Figure 2 shows the mean cloud fraction vs. height. The line is the mean, the grey shows intermodel variability (which is pretty small in this case). As is typical in shallow cumulus ensembles, cloud fraction is small at all levels, and decreases with height. Due to vertical shearing of the clouds, the fraction of grid columns with cloud is about 15%, which is larger that the cloud fraction at any height. 'Cores' indicate positively buoyant cloud; even within the conditionally unstable layer about 50% of the cloud is negatively buoyant as a result of mixing with the environment and consequent evaporative cooling of the mixed air. This is also clear in the $\theta_v$ profiles of clouds and cores shown in Fig. 2b. These show that even though the stratification is much more unstable than a moist adiabat, on average the clouds are only marginally buoyant. Of course, this is an average over all clouds during all phases of their lifecycle, and small amounts of nearly undilute air can be found at all levels, helping to form the most buoyant and penetrative cumulus updraft that set the upper limit of the inversion. .



Siebesma et al. 2002

Fig. 2. LES shallow Cu profiles of (a) cloud fraction and (b) $\theta_v$



Siebesma et al. 2002

Fig. 3. LES-derived momentum and total water flux profiles.

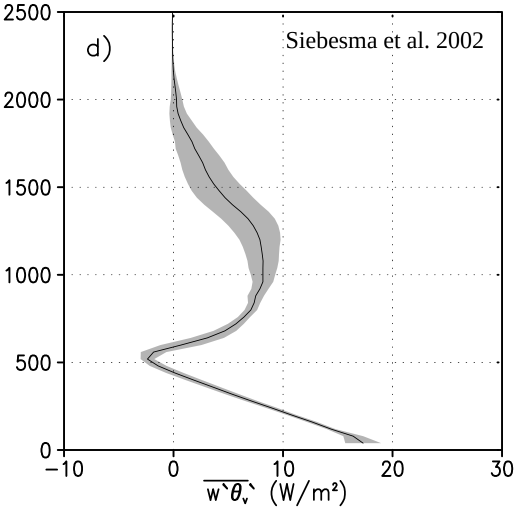


Fig. 4. LES-derived buoyancy flux profile.

The transport properties of the clouds are seen in Fig. 3, which show the LES-derived momentum, and moisture flux profiles. The momentum fluxes are largest in the subcloud layer, but are significant in the cumulus layer as well. Most of the moisture evaporated at the surface is fluxed by cumulus clouds into the inversion, where it moistens the above-inversion air being entrained into the BL. Figure 4 shows the buoyancy flux profile. Beneath the clouds it looks nearly identical to a dry convective BL, with an entrainment zone at cloud base. The buoyancy flux is positive in the conditionally unstable layer. More surprising, it remains positive even in the inversion layer, where the cumuli are overshooting their levels of neutral buoyancy. This is due to sub-cloud scale eddies..

<u>Subcloud layer</u>

Figure 5 shows an idealization of air parcel circuits in a shallow Cu boundary layer. We start with the subcloud layer. Typically there is fairly uniform dry convection within this layer with eddy velocities of less than 1 m s$^{-1}$, driven by surface buoyancy fluxes associated with air that is slightly colder than the ocean surface. Within the subcloud layer, the circuit of $\theta_v$ shows slight ra-

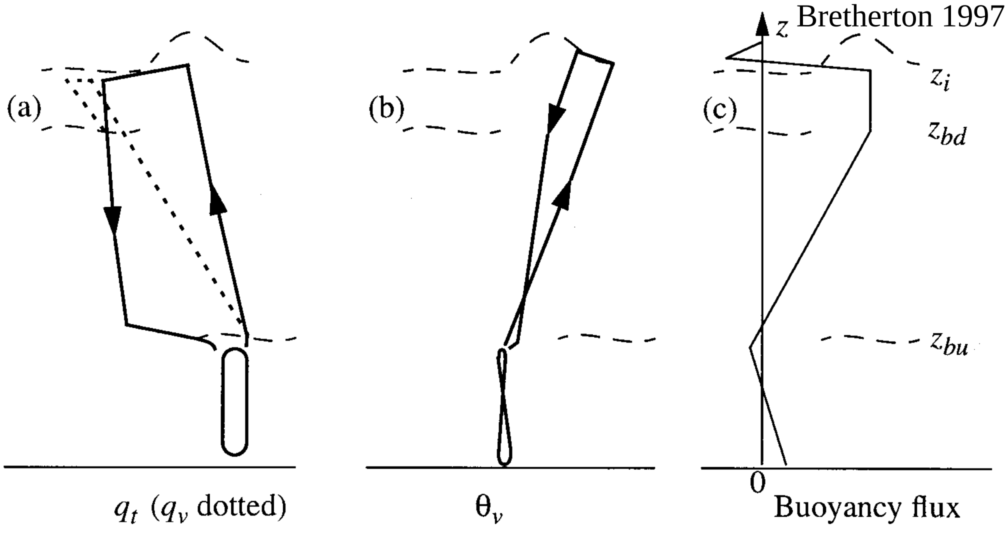


Figure 5.. Parcel paths in a shallow Cu BL capped by thin Sc.

diative cooling both as air ascends in the updraft and descents in the downdraft. The air experiences moistening and slight warming by surface fluxes and drying and slight warming by entrainment of warmer air at the top of the subcloud layer.

## Transition layer

The top of this dry convection zone is marked by the weak stable transition layer (marked by a $\theta_v$ increase of a few tenths of a K), which is near the cumulus cloud base. Most of the convective updrafts in the subcloud layer do not have sufficient inertia and buoyancy to penetrate through the transition layer; this is indicated by separating the branch of the circulation that goes up into cumulus clouds from the subcloud layer circuit. In fact, it is useful to think of the transition layer as a 'valve' which regulates the number of cumuli so as to keep the top of the subcloud mixed layer close to the cumulus cloud base. This valve is subject to very rapid feedback. Were the transition layer initially above the mean LCL of subcloud air , many updrafts would form clouds on top, and the resulting latent heating would allow these updrafts to penetrate the transition layer to form cumuli. In order for lots of mass to ascend in these cumuli, a comparably large amount of mass would have to descend around the clouds ('compensating subsidence'), bringing down higher $\theta_v$ air from the upper part of the cumulus layer. This would lower and strengthen the transition layer inversion. On the other hand, were the transition layer initially well below the mean LCL of subcloud air, then no updrafts could become saturated before they become negatively buoyant. The subcloud layer would then deepen rapidly due to entrainment (a typical subcloud layer entrainment rate is about 1-2 cm $s^{-1}$) until the tops of updrafts start developing into Cu clouds. In equilibrium, the transition layer regulates the mass flux from the subcloud layer vented into Cu to roughly balance entrainment such that the top of the subcloud layer remains close to its LCL.

## Conditionally unstable layer

Inside active cumuli, air rises vigorously through the conditionally unstable layer in turbulent updrafts of 1-5 m $s^{-1}$ . Outside the cumuli, air is slowly subsiding (indicated by downward arrows in the circuits of $q_t$ and $\theta_v$) at an average rate of around 1-2 cm $s^{-1}$ and is considerably drier than the cumulus updrafts. Mass balance implies that the cumulus updrafts comprise only about 1% of the total area at any height. Lateral entrainment of the drier ambient air by the updrafts decreases their mean $q_t$ as they rise. Many smaller cumuli may never reach the top of the cumulus layer. These cumuli detrain moist air into the lower and middle parts of the cumulus layer, moistening the subsiding air slightly as it descends. Penetrative entrainment by cumuli mixes in warm dry air from within the inversion layer, so that the air detrained from the clouds (from which the subsiding branch of the circulation is composed) is much drier than the updraft air before it begins to subside. The resulting evaporation of cloud water also makes the detrained air less buoyant than the cloudy updrafts. As the air subsides, it cools radiatively, creating a stratification of $\theta_v$.of around

$$d\theta_v/dz \approx \text{(radiative cooling rate)/(subsidence rate)} \approx (2\text{ K}/10^5\text{ s})/(1\text{-}2\text{ cm s}^{-1}) = 1\text{-}2\text{ K/km}$$

This is less than the moist adiabatic lapse rate, maintaining conditional instability within the cumulus layer.

When the subsiding air reaches the cumulus cloud base, it is entrained back into the much moister subcloud layer. The typical circulation time for air to rise a height of 1 km or so within a cumulus cloud, then sink back to the subcloud layer is

$$\tau_{Cu} = 1\text{ km}/(1\text{-}2\text{ cm s}^{-1}) = 0.5\text{-}1\times10^5\text{s} \approx 0.5\text{-}1\text{ day}$$

This is much longer than the 20 minute circulation time of a typical stratocumulus-capped mixed layer.

## Capping Inversion

In a Cu-topped BL the capping inversion is be a stably stratified layer up to 500 m thick, over which $\theta_v$ increases by 1-5 K. Air subsiding into this inversion is subject to penetrative mixing with the most vigorous Cu updrafts. A spectrum of mixtures is created, all of which are cooler than the ambient inversion air due mainly to evaporative cooling. The most dilute of these mixtures remain within the inversion layer, causing a systematic cooling and moistening of air lower in the inversion layer, while the more strongly cooled mixtures detrain below the capping inversion.

## *Role of radiative forcing*

Over land, the dominant thermodynamic forcing for shallow cumulus convection is surface buoyancy fluxes, augmented by latent heating within the cumulus clouds. Over the oceans, longwave radiative cooling within the boundary layer is often dominant. Shallow cumulus clouds have a typical fractional sky cover of 10-30% and a cloud fraction which is largest near the cloud base. Longwave cooling is due both to clear air and cloud sides and tops at various heights within the BL, and is distributed fairly uniformly throughout the BL, typically with cooling rates of 2 K day$^{-1}$ or so in the subtropics, if there is no overlying stratiform cloud. Over the midlatitude and colloer subtropical oceans, where the capping inversion is stronger, shallow cumuli are commonly overlain by a thin, possibly patchy stratocumulus layer. In this case, there is a strong radiative flux divergence (cooling) at the stratocumulus cloud top and little flux divergence lower in the BL. In both cases, shortwave absorption in the clouds and clear air reduces the cooling somewhat during the day, so convection tends to be a little more vigorous at night.

For a 500 m deep boundary layer, the net diurnally averaged radiative flux divergence would typically be around 40-50 W m$^{-2}$, and 10 W m$^{-2}$ if there is no cloud, so cloud greatly increases the overall BL cooling. For a 2 km deep BL typical of subtropical trade wind cumulus regimes, the typical flux divergence would be 40-50 W m$^{-2}$ with or without cloud on top. For the deeper BL, cloud alters mainly the *distribution* of cooling within the BL, not the total amount. By comparison, surface virtual heat (buoyancy) flux tends to be only about 10 W m$^{-2}$ over the subtropical oceans, while (though latent heat fluxes are 100-200 W m$^{-2}$).

## *Shallow Cu layers topped by Sc*

Large regions of the ocean are covered by CTBLs intermediate between the Sc-topped mixed layer and the shallow Cu BLs. These BLs have a layer of Cu rising into patchy Sc. This structure is favored when the Cu layer is less than 1 km deep. In this case, the Cu updrafts tend to be less vigorous, limiting penetrative entrainment and there is less depth for them to be diluted by lateral entrainment, so the air detrained by Cu beneath the trade inversion is moist and still contains liquid water. Thus, the Sc are formed due to detrainment of liquid water from the Cu. Hence, this type of BL is sometimes called *cumulus-coupled.* The main modifications to the circulation compared to a pure shallow Cu BL are due to the radiative effects of the Sc. First, the strong radiative cooling atop the Sc helps induce turbulence within and below the Sc layer and adds a component of entrainment into the BL by the Sc. Second, there is little radiative cooling below the Sc to cool subsiding air. Hence, the stratification in the Cu layer tends to be very weak. This permits the radiatively driven turbulence induced by the Sc to extend well below the cloud layer. In fact, it is common to see a nearly well-mixed thermodynamic profile from the inversion down nearly all the way to the transition layer, with a jump of 1-3 g kg$^{-1}$ in mixing ratio across the transition layer.

This structure cannot persist if the BL is deeper, because it is highly conditionally unstable. Hence, if the BL is deep, the Cu updrafts would become very vigorous, forcing extensive penetrative entrainment of dry air from above the inversion, and evaporating the Sc layer. Wyant et al. (1997, JAS) demonstrate this feedback in a numerical model simulation. A conceptual model of the entire transition from subtropical stratus to cumulus capped CTBLs is presented in Figure 6.

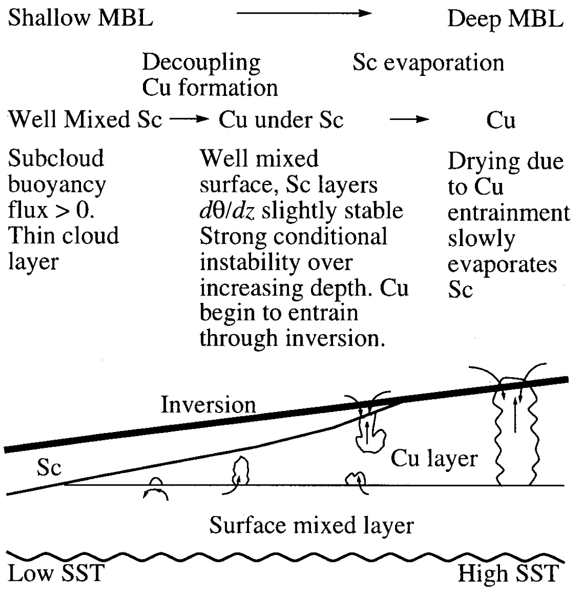


Fig. 6. A conceptual model of the subtropical stratocumulus to trade Cu transition

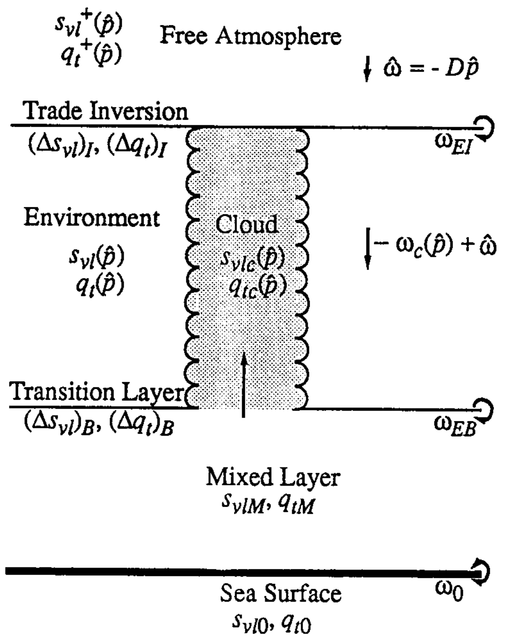


Fig. 7. Parameterized view of shallow Cu BL.

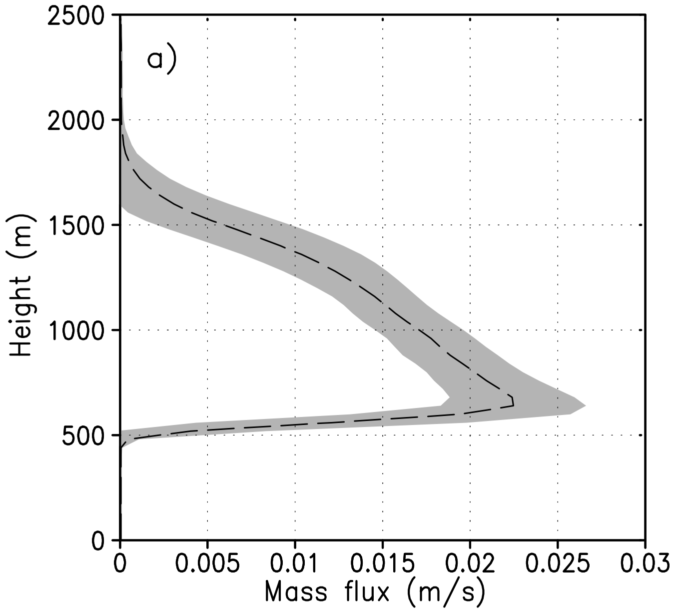


Fig. 8. LES shallow Cu core mass flux profile

### *Mass-flux parameterization of shallow Cu*

A common approach for parameterizing shallow cumulus boundary layers is to treat the cloud ensemble as one aggregate homogeneously mixed plume that laterally entrains and detrains at each height (Fig. 7). Some parameterizations use ensembles of plumes to better represent the spectrum of observed cloud sizes; others consider a spectrum of mixtures that can be created by mixing updraft air with environmental air, and incorporate only sufficiently buoyant mixtures into the plume while detraining the rest (‘buoyancy sorting’). A single entraining/detraining plume seems to capture the fluxes transported by a shallow convective layer fairly well. By looking at profiles of cumulus updraft mass flux (Fig. 8) and the dilution of an average cloud with height (fig. 2b) one can diagnose the required entrainment and detrainment rates from LES (Siebesma and Cuijpers, *J. Atmos. Sci.*, 1995 ).

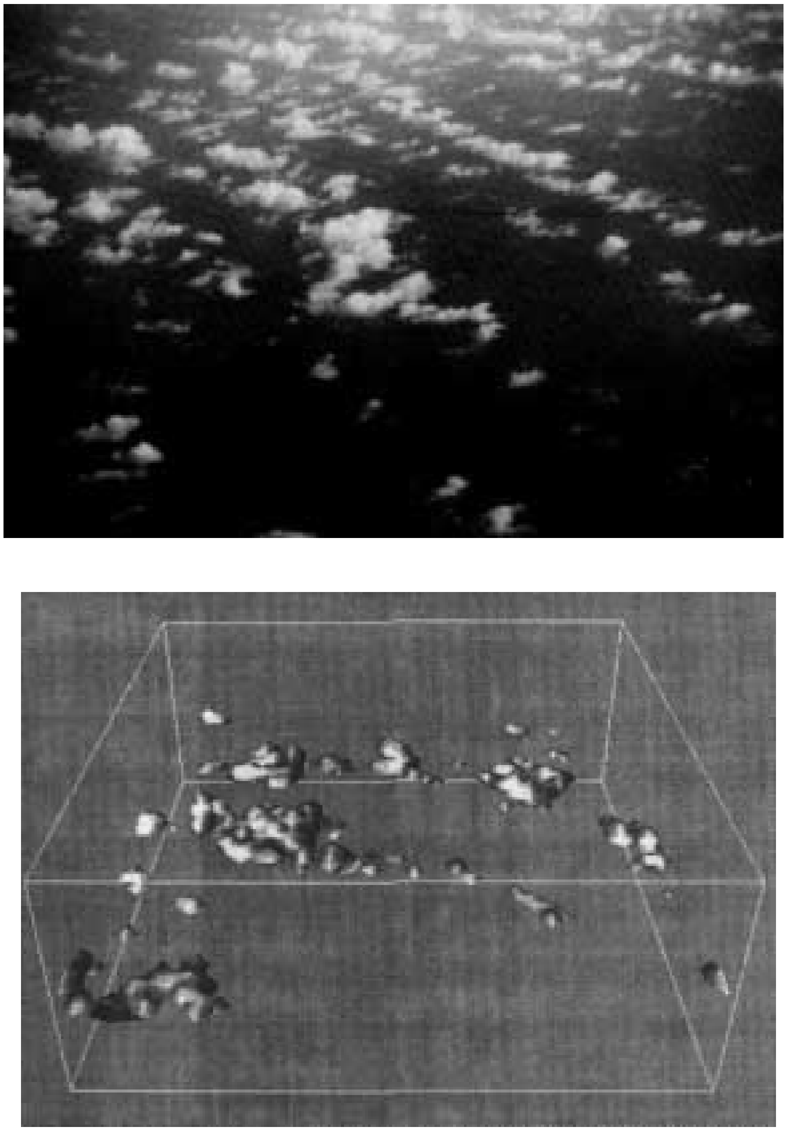


Fig. 9. Aerial view of BOMEX trade Cu and LES simulation of BOMEX cloud field.