Boundary-Layer Cumulus Over Land: Some Observations and Conceptual Models

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1. Cumulus research at Univ. Wisconsin

Starting in 1980, the Boundary Layer Research Team at the University of Wisconsin has been systematically studying the formation and evolution of non-precipitating boundary-layer cumulus clouds (BLCu) in regions of fair weather (anticyclones) over land (Stull, 1980). These investigations were guided by the following hypotheses regarding the evolution of clouds:

- The sun heats the surface, causing heat and moisture fluxes into the surface layer.
- Warm air from the surface layer rises as thermals.
- The altitude of the top of thermals is controlled by the mixed-layer (ML) depth, which generally increases during the day, but can be modulated by large-scale and mesoscale subsidence.
- Forced clouds form when thermals rise high enough to reach their lifting condensation levels (LCL).
- Active clouds form if the tops of the forced clouds reach the level of free convection (LFC).
- Passive clouds form in the free atmosphere from active clouds that stop extracting air from the boundary layer (BL).
- Passive clouds eventually evaporate and disappear in the free atmosphere.
- The total BLCu coverage is the sum of forced, active, and passive clouds. On some days only forced clouds might exist, while on other days all three might exist.
- BLCu have various feedback processes (e.g., shading of the ground, venting of air from the ML) that affect the equilibrium cloud cover.

These hypotheses may not be appropriate for other types of boundary-layer cumulus clouds, such as stratocumulus, fog, cumulus in regions of disturbed weather such as fronts and cyclones, strongly advective situations, and cumulus over oceans.

Our approach is to quantify the average statistical characteristics of the surface, thermals, boundary layer, and clouds over horizontal regions of roughly 20 km in diameter. Within such a region over land, there is typically quite a variation in land use, and associated variations in surface albedo and moisture. Most of our investigations have focused on regions where surface-induced mesoscale circulations (such as the inland sea-breeze) are not dominant. We have also not looked at detailed biophysics and micrometeorology of individual plants or trees. Our methodology is optimized to gain understanding of the "subgrid" processes such as could be incorporated into climate and weather forecast models (Stull 1977).

We have used data from field experiments that employed aircraft, lidar, sodar, radar, surface stations, rawinsondes, and other sensors. The BLX83 field program in Oklahoma USA (Stull 1983b & c; Stull and Eloranta 1984; Stull et al 1992) was designed by us specifically to study the interaction between fair-weather Cu and the boundary layer. The HAPEX experiment in southwest France (Stull 1986; André et al 1988), and ARM-CART data in Oklahoma are also being analyzed. Large-eddy simulation was also used (Hechtel and Stull 1985, Hechtel et al 1990).

What follows is a very brief descriptive summary of the findings of our research team, along with some recommendations. This summary is meant to organize and put into perspective the individual research results on BLCu that we have published over the years. Quantitative details, equations, theories, models, and experimental results can be found in the papers listed in the reference section. Our current research is elaborated in sections 7 - 9.

2. Feedbacks and impacts

Radiative: By shading the ground, clouds reduce the growth rate of the mixed layer. If larger-scale subsidence is present, then an equilibrium can be reached where the rise rate of the mixed layer equals the rise rate of the LCL (which is related to evaporation from the surface, entrainment of dry air from aloft, and heating from both top and bottom).

The approach to this equilibrium is as follows: cloud coverage below the equilibrium value allows sunlight to heat the surface, causing the ML to grow in spite of entrainment. As more of the ML rises above the LCL, more clouds form, thereby shading the ground more and reducing the rise rate of the ML. When the rise rate of the ML finally equals the rise rate of the LCL, then the cloud coverage stops increasing and an equilibrium is reached. All types of BLCu can cause this feedback.

Dynamic: Active clouds can also withdraw air from the ML (Stull, 1973b). Vertical mass fluxes out of the ML up through active BLCu are so large that just a small percentage coverage is enough to balance the entrainment (Stull, 1976a, c) into the ML between clouds. Thus, an equilibrium can quickly be reached.

Others feedbacks: Stull (1985) discusses other feedbacks, such as moistening of the cloud layer by evaporating passive BLCu.

Climatic impact: While BLCu are commonly ignored by the general population because they occur during generally nice weather with blue skies between clouds, BLCu can make a significant impact on the overall climate. Fields of these little cotton-balls of clouds can reflect a significant portion of incoming solar radiation. More importantly, the clouds frequently have a diurnal evolution that modulates incoming radiation during mid-day and afternoon, but disappear at night. Aqueous-phase chemical reactions can occur while boundary layer air is cycled through the clouds. The active clouds can also vent pollutants and greenhouse gases from the boundary layer into the free atmosphere.

To quantify potential cumulative impact of BLCu, Stull (1992d) defines a quantity called cover-hours (ch), which is the fractional cloud cover times the number of hours during which it occurs. For example, 3 hours of cumulus with 4/10 coverage contribute 1.2 ch to the total yearly cover-hours. Using case-study data reported by the US National Weather Service office in Madison, Wisconsin, low-level clouds of all types contributed a total of 1476.6 ch during 1990, which is a relatively large number compared to the total number of hours in a year (8760).

Cumulus, towering cumulus, non-precipitating cumulonimbus, and cumulus fractus together accounted for 15% of the total cover-hours, most of which occurred during the warm half of the year. Stratocumulus clouds of 0.7 coverage or less contributed 19% of the ch, with contributions all year but with a peak in the warm months. Stratocumulus of 0.8 coverage or greater contributed 48%, mostly in the cold half of the year. Stratus and fracto-stratus contributed the remaining 18% of the ch.

3. Sun and the surface

Input of energy from the sun is the ultimate limiting factor for BLCu formation. Incoming solar radiation occurs at a finite maximum rate, depending on location on earth, time of day, atmospheric transmissivity and the presence of upper layers of clouds. If the sun would turn off, as in an eclipse, then thermals would stop rising from the surface, new BLCu would not form, and existing BLCu would eventually disappear.

The two most important surface characteristics are albedo and moisture availability. The albedo determines how much of the incoming solar radiation can cause surface heating, and the moisture availability determines the partition of that heating into sensible and latent portions into the air. More sensible heat would cause warmer air, which could rise higher in thermals. More latent heat would cause moister air, which could have lower LCLs.

Hechtel et al (1990) used a large eddy simulation (LES) to demonstrate that for days when the mean wind is not calm, there is no discernible resonance or enhancement of thermal strengths over the mosaic of land-use patterns typical for Oklahoma. Thus, we concluded that we can successfully look at the statistical characteristics of the whole surface area, rather than being forced to examine individual farm fields.

They also noted that LES models can have significant numerical errors in humidity (namely, humidities that are too large) at the tops of thermals where clouds might form, caused by the inability of some advection schemes to handle the sharp humidity gradients across the tops of moist thermals overshooting into a dry free atmosphere. We **recommend** caution when interpreting LES simulations of BLCu.

The usual tricks needed to acquire robust turbulence statistics (Stull 1990) include flying fast (to allow quasi-stationarity) over an adequately-long flight track (to reduce sampling error) but within a limited area of similar land use (for quasi-homogeneity in the horizontal), and at different altitudes (assuming similarity relationships of statistics with height). Normally the aircraft speed is so slow that all of these tricks must be used together to yield robust statistics. However, when a heterogeneous field of time-varying clouds are present over land, it might be nearly impossible to get robust statistics such as surface heat fluxes and convective velocity scales (Otles, 1990, Stull and Jochum, 1993). We **recommend** that investigators don't blindly assume that airborne measurements of turbulence statistics are relevant, if made when BLCu are present.

During daytime heating, the convective boundary layer is sufficiently well mixed as to have a nearly adiabatic lapse. Nevertheless, the boundary layer is nonlocally unstable (Stull 1991a, b). In such a boundary layer, thermals cause fluxes of heat, moisture, momentum, and tracers from the ground into the mixed layer, even in the absence of wind. Traditional drag or bulk-transfer formulations fail for such calm-wind free convection situations, but convective transport theory can be used instead to parameterize the surface fluxes in terms of surface and ML variables (Stull 1992b, 1993).

4. Thermals and cloud-base height

Crum and Stull (1985, 1987; also Stull 1987, 1992a) observed that thermals contain a large undiluted core of air rising from the surface layer to the top of the mixed layer. Surrounding this core is a region of lateral entrainment called the intromission zone (Crum et al 1987), consisting of a mixture of air with surface layer and free-atmospheric properties. Because the free atmosphere is usually drier than the surface layer under fair-weather conditions, this means that the core of the thermal has the most moist air, and thus has the air with the lowest LCL. Namely, this undiluted surface-layer air in the core is that which could first form a cloud.

An outcome is that the theoretical LCL computed from surface-layer air should equal the actual cloud-base height. This was confirmed by Stull and Eloranta (1985), comparing lidar observations of cloud base height with average surface-layer LCL computed from measurements of pressure, temperature, and humidity at the standard measurement height of 2 m above the surface. Thus, we **recommend** that lateral entrainment models causing dilution of the core of thermals and corresponding alteration of LCLs and cloud-base heights are inappropriate.

Stull and Eloranta (1985) were disappointed to discover that "observed" cloud-base heights as reported by the US National Weather Service and US military weather services are usually significantly in error (i.e., little correlation between reported height and actual height) for situations of scattered BLCu with bases higher than about 1 km above ground. The reason is apparently lack of need by pilots to have such accurate data, which results in lack of motivation by the weather services to provide it. We therefore **recommend** that models of BLCu verify cloud-base height against LCL computed from observed surface layer temperature and dew point, rather that against reported cloud base height.

They also found significant mesoscale variability of LCL heights computed from stations spaced roughly 50 km apart. Thus, we must **recommend** that verification of modeled cloud-base height be done with local surface-layer measurements of the LCL, and not with measurements at the "nearest" weather station which might be 50 km away.

5. Mixed layer growth and the entrainment zone

The top of the mixed layer is quite contorted: being locally higher where thermals are overshooting into the free atmosphere, and being lower between thermals where air is being entrained down into the mixed layer (Stull 1973a). The average mixed layer depth over a 20 km area is often given the symbol z_i, while the range of local depths centered about z_i is called the entrainment zone (EZ). As z_i increases during the day (Stull 1976b), the location of the EZ rises with it.

Deardorff et al (1980) measured the cumulative distribution of ML air vs height in a laboratory tank simulation of the mixed layer. Wilde et al (1985) found that a double exponential function well describes the probability distribution of finding the local mixed layer top at some height, which when integrated into a cumulative distribution fits the Deardorff et al data quite well.

If all thermals were to have the same LCL height (which is not the case as is described in the next section), then the cloud coverage is directly related to the LCL and the cumulative probability (CP) distribution in the EZ, as sketched in Fig 1.

The thickness of the EZ vs. entrainment or convective scales was found by Nelson et al (1989) to have a hysteresis behavior over time. Thus, we **recommend** that diagnostic relationships for EZ thickness are not appropriate.

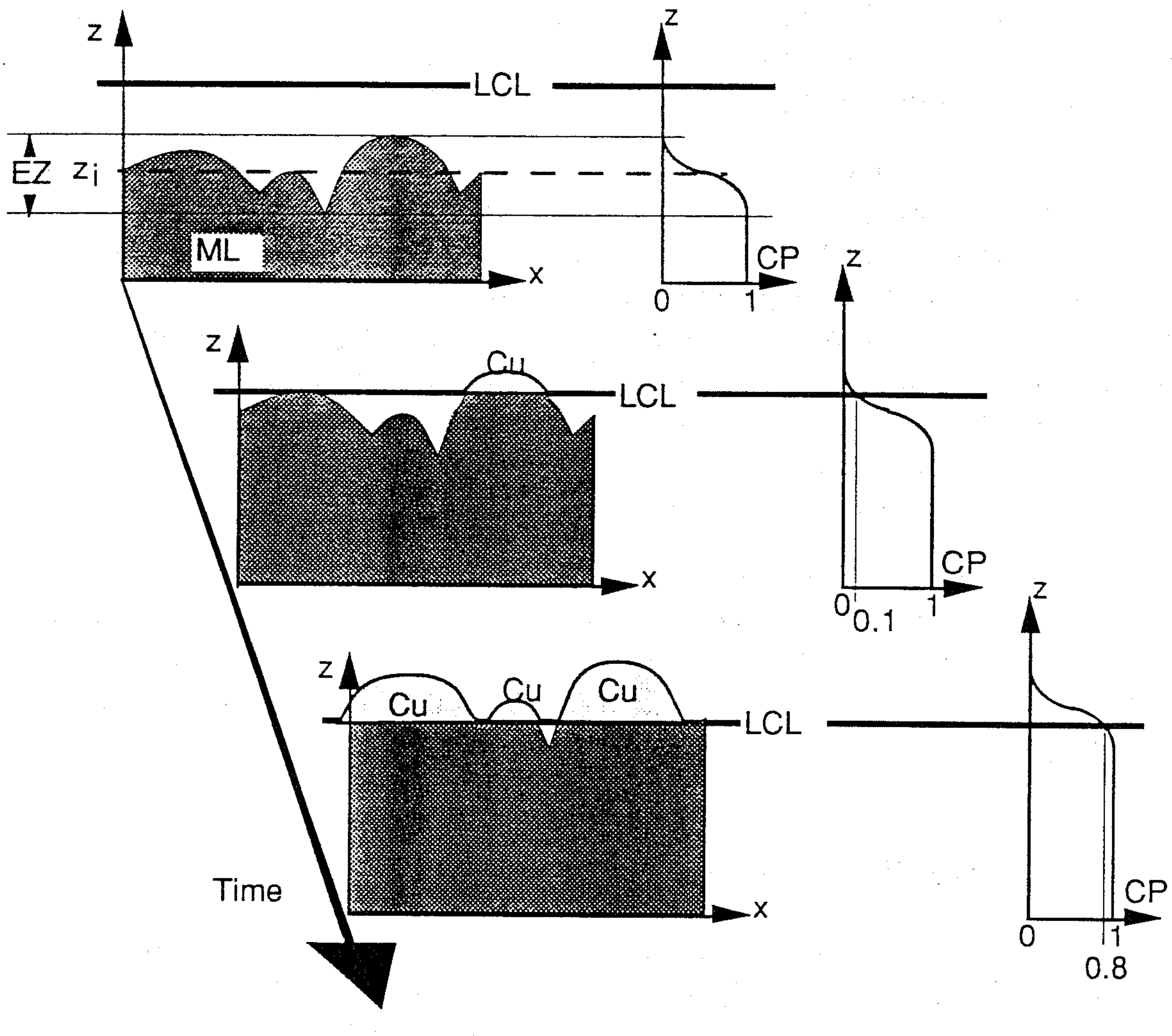


Fig. 1. Sketch of rise of the ML top with time. Those portions of the ML (shaded dark) that are above the LCL form clouds (shaded light). The cloud coverage fraction is found from the intersection of the LCL height with the cumulative probability (CP) distribution; namely, 10% coverage for the middle time, increasing to 80% later.

In late morning when the ML depth increases rapidly as it grows through the residual layer, it is possible that z_i is multi-valued (Stull and Eloranta 1991). Some of the thermals might be significantly warmer than others, by chance or by result of their formation over dark dry land areas. These could penetrate through the weak remains of the nocturnal inversion and rise through the residual layer until hitting the capping inversion at the base of the free atmosphere. Other weaker thermals might still be trapped at lower altitudes in the nocturnal inversion. The few strong thermals that rise first would be the ones most likely to form the first BLCu, assuming other conditions such as the LCL were favorable. Such formation of a few Cu could occur 30 to 60 min before the main increase in cloud coverage, when the nocturnal inversion is finally "burned off" and all the thermals rise to the free atmosphere to reform a single valued z_i .

Nelson et al (1989) suggested that one way to explain the multivalued ML top is to consider the probability distribution of surface layer temperatures within the 20 km diameter region. While the mean surface-layer temperature increases with time within the region, there will always be the spread or distribution of local temperatures about that mean. A natural filtering will occur whereby only the subset of air parcels that are warmer than average temperature will rise as thermals. By conceptually lifting each of these thermals until they hit the early-morning sounding, one can estimate the probability distribution (including multi-valued characteristics) in the EZ from the probability distribution of surface layer temperatures. Although it was a neat conceptual model, it didn't appear to work very well.

Over irregular topography, the ML top may or may not be level, depending on the balance between entrainment rate, hydrostatic settling, and other factors (Stull, 1992c). As a result, clouds might first form over those topographic regions possessing the highest ML top.

Subsidence magnitudes are frequently as large as entrainment rates in fair-weather anticyclonic conditions. This can reduce, stop, and even reverse the rise of the mixed layer and the resulting formation of clouds. Vachalek (1987) measured subsidence during the BLX83 experiment, and found a superposition of a wide range of temporal and spatial scales of subsidence (see Stull, 1988, for a published summary). We strongly **recommend** that field programs intending to study BLCu should make every effort to measure subsidence, and that modeling efforts should incorporate the observed subsidence for verification purposes rather than fudging the subsidence to give the best forecast.

6. LCL zone and cumulus onset

Over different land-use regions with different moisture availability, thermals acquire different humidities that result in different LCLs. Thus, instead of a single LCL over the whole region as idealized in Fig 1, there is a range of LCL heights, called the LCL zone by Wilde et al (1985). This distribution of LCL heights was also well fit by a double exponential probability distribution.

If one assumes that the EZ and LCL zone are independent (a bad assumption, as will be discussed in the next section), then one need only integrate (as a convolution) the overlap of these two zones to compute the cloud coverage of forced BLCu. Namely, when the whole EZ is below the whole LCL zone, then none of the thermals are reaching condensation and there are no clouds. At the opposite extreme when the EZ is completely above the LCL zone, cloud coverage is overcast. In between those extremes, the cloud coverage increases smoothly from zero to 100% as the mixed layer rises and more of the EZ overlaps the LCL zone. Wilde et al (1985) tested this model, and found it to work quite well for forced clouds.

7. Joint frequency distributions in the surface layer, and forced cloud coverage

Each rising thermal has a virtual temperature that determines its buoyancy and ultimate height of rise, and has a humidity that determines its LCL (Fig 2). Given a fixed input of solar energy absorbed at the surface, one would expect a positive correlation between LCL height and buoyancy over different surfaces. For example, over moist surfaces, more of the solar energy will be used for evaporation, leaving less to cause heating. Thus, the buoyancy will be relatively low, and the LCL height will also be low because of the higher humidity.

Nature is not quite so simple, because different land areas have different albedoes, resulting in a variation of the total energy available to be partitioned. Thus, if many thermals over a 20 km region are considered, instead of a perfect correlation along some line plotted in the z_{LCL} vs. θ_v plane, there is a broader scattering or "cluster" of data points (Stull et al 1993).

Instead of examining individual thermals, it is possible to form the cluster from data points measured by an aircraft flying level straight flight legs in the surface layer (sample rate = 20 Hz, which corresponds to data points taken at roughly 5 m intervals), and treat them as if they were independent air parcels. Fig 3 shows an example of such data from the HAPEX field program in France. These "air parcel" data points cluster into fairly well defined joint frequency distributions. The method of utilizing the statistics of many thermals, together with the

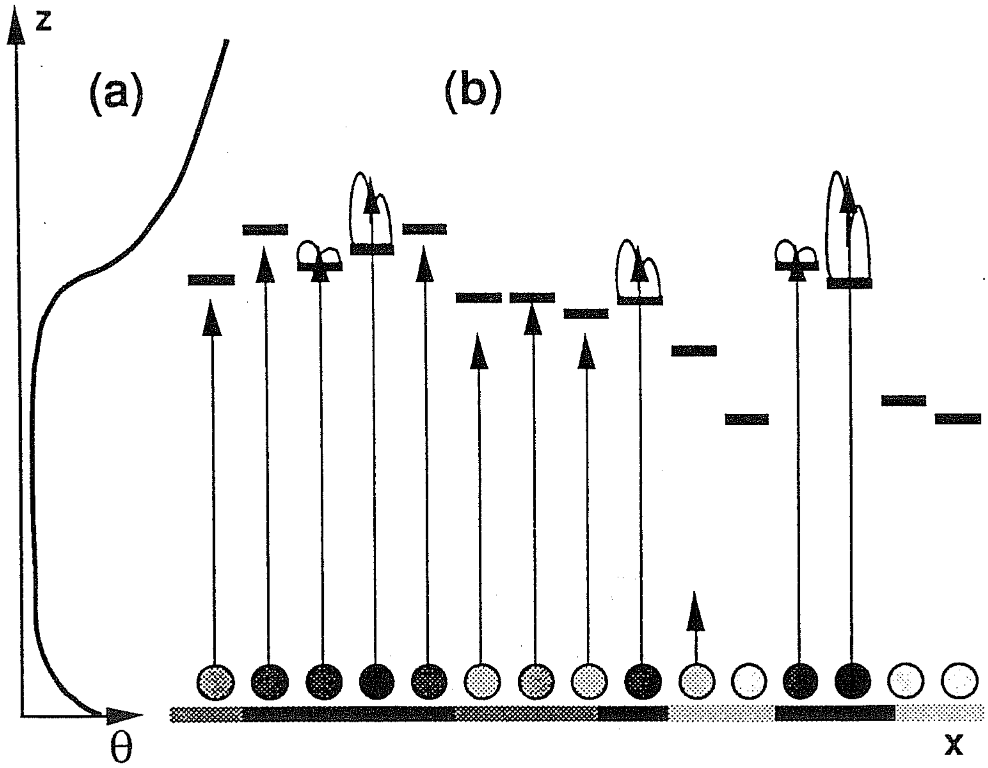


Fig 2. Heterogeneous land use, illustrated with the black and gray line segments at the bottom, cause turbulent temperature fluctuations in the surface-layer air, illustrated with air parcels of different shadings. These parcels rise to their level of neutral buoyancy, shown by the vertical arrows. Moisture also varies from parcel to parcel, causing corresponding fluctuations in the height of the lifting condensation level (LCL), shown by the black horizontal dashes. Those parcels that rise above their own LCL can create cumulus clouds.

phenomenological nature of thermal evolution, is called a stochastic/phenomenological approach (Stull 1986b).

By overlaying the mean sounding (measured by an ascent or descent aircraft flight) of z vs. θ_v on the same graph as described above, it is possible to diagnose cloud coverage. Referring to Fig 3, those "surface-layer air parcel" data points lying above and to the left of the sounding would be ones not likely to form clouds, because they will hit the inversion and stop rising before they reach their respective LCLs. Similarly, those "air parcel" points below and to the right of the sounding could make clouds. Thus, the expected cloud coverage equals fraction of all air parcel points that are below and to the right of the sounding line.

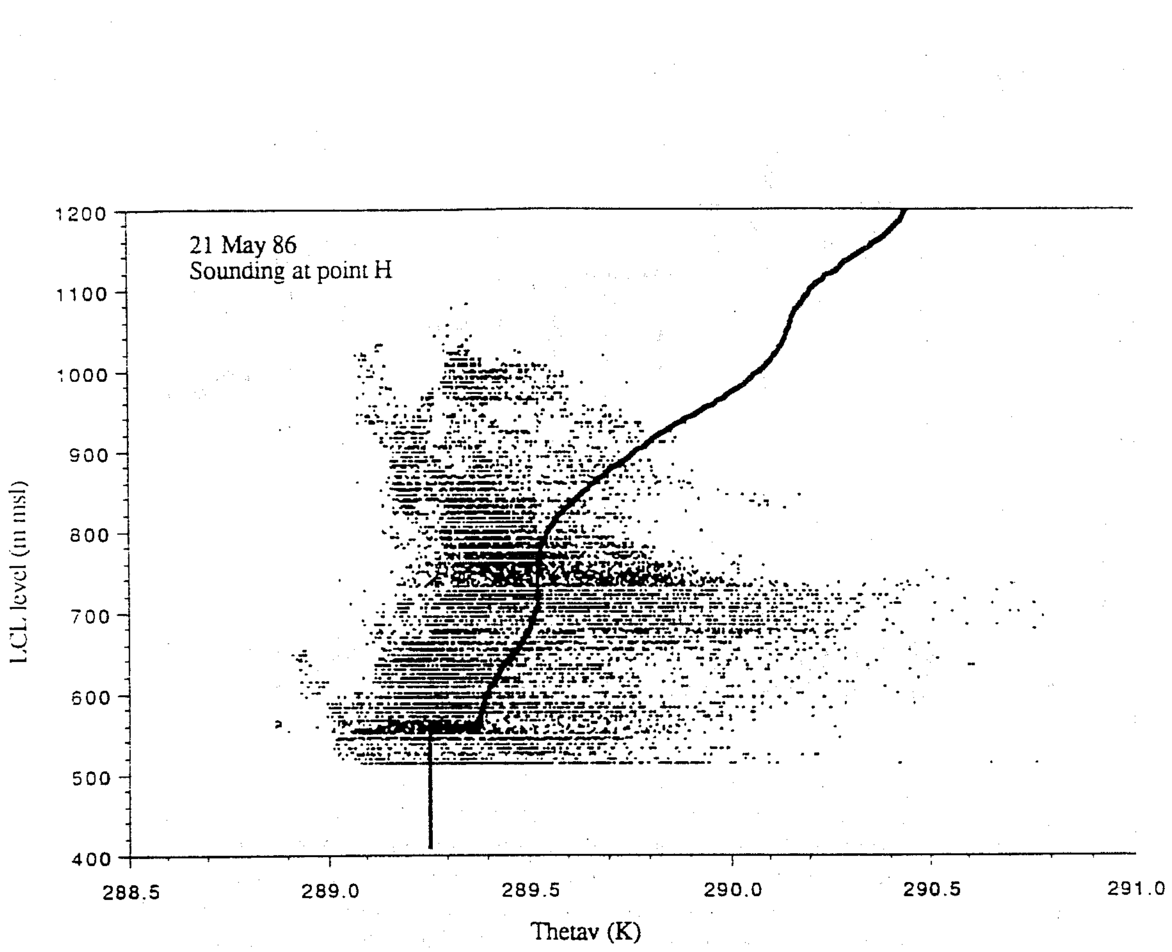


Fig 3. Each dot gives the LCL height and virtual potential temperature of an air parcel measured in the surface layer by aircraft during one of the flights in the HAPEX field experiment in southern France. They indicate the meteorological state of air parcels that have physical locations analogous to those surface-layer parcels in Fig 2. The heavy line superimposed is the nearest (in time and space) sounding of virtual potential temperature vs. height (not vs height of the LCL). Those data points to the left of the curve are not buoyant enough to reach their LCL, and would not make clouds. Thus, the fractional cloudiness associated with forced clouds during this particular flight leg equals the fraction of all the data points that are to the right of the sounding.

As the day evolves, the location of the cluster of "parcel" points moves and the mean sounding also changes, which results in changes to the cloud cover during the day. In early morning, the cluster might be totally above the sounding, implying no clouds. On some days the cluster might never begin to cross the sounding, if the air is dry enough and the ML is shallow enough. On other days the sky might become overcast with stratocumulus clouds, as indicated by a cluster that is totally to the right of the sounding. Luckily, the evolution of the mean sounding and movement of the cluster are relatively easy to predict, because they depend on mean ML characteristics.

8. Parameterizing the joint frequency distributions

The shape of these air-parcel clusters (i.e., the shape of the joint frequency distribution) might be expected to vary depending on the nature of the underlying surface. Namely, over land with vineyards there might be one distribution, while over a forest there might be another. For the HAPEX experiment in France, Fig 4 shows the five dominant land-use types, and the distribution of those types along a typical surface-layer flight track. Flight-track segment indices are defined in this figure.

Fig 5 shows the joint frequency distributions for each flight segment. None of the flight segments was over a perfectly-uniform surface, hence the joint distributions have some spread rather than being clustered at a single point. Nevertheless, each of these distributions is relatively mono-modal, suggesting that parameterization of the major characteristics of the distributions is possible.

We hypothesize that each joint-distribution cluster can be parameterized with simple bi-Gaussian probability distribution (Fig 6) with elliptical cross section having axes determined by the surface Bowen ratio and total energy available at the surface. Over a subgrid domain of diameter 20 km having a variety of land use subdomains, the total joint probability distribution is the superposition of many individual bi-Gaussian shapes for each subdomain. This total distribution can then be superimposed on the average sounding in the whole domain to diagnose subgrid cloud coverage of forced clouds as described in the previous section.

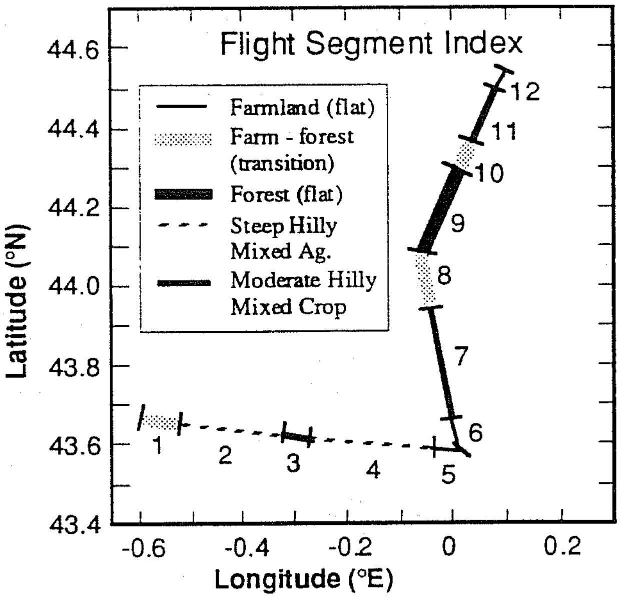
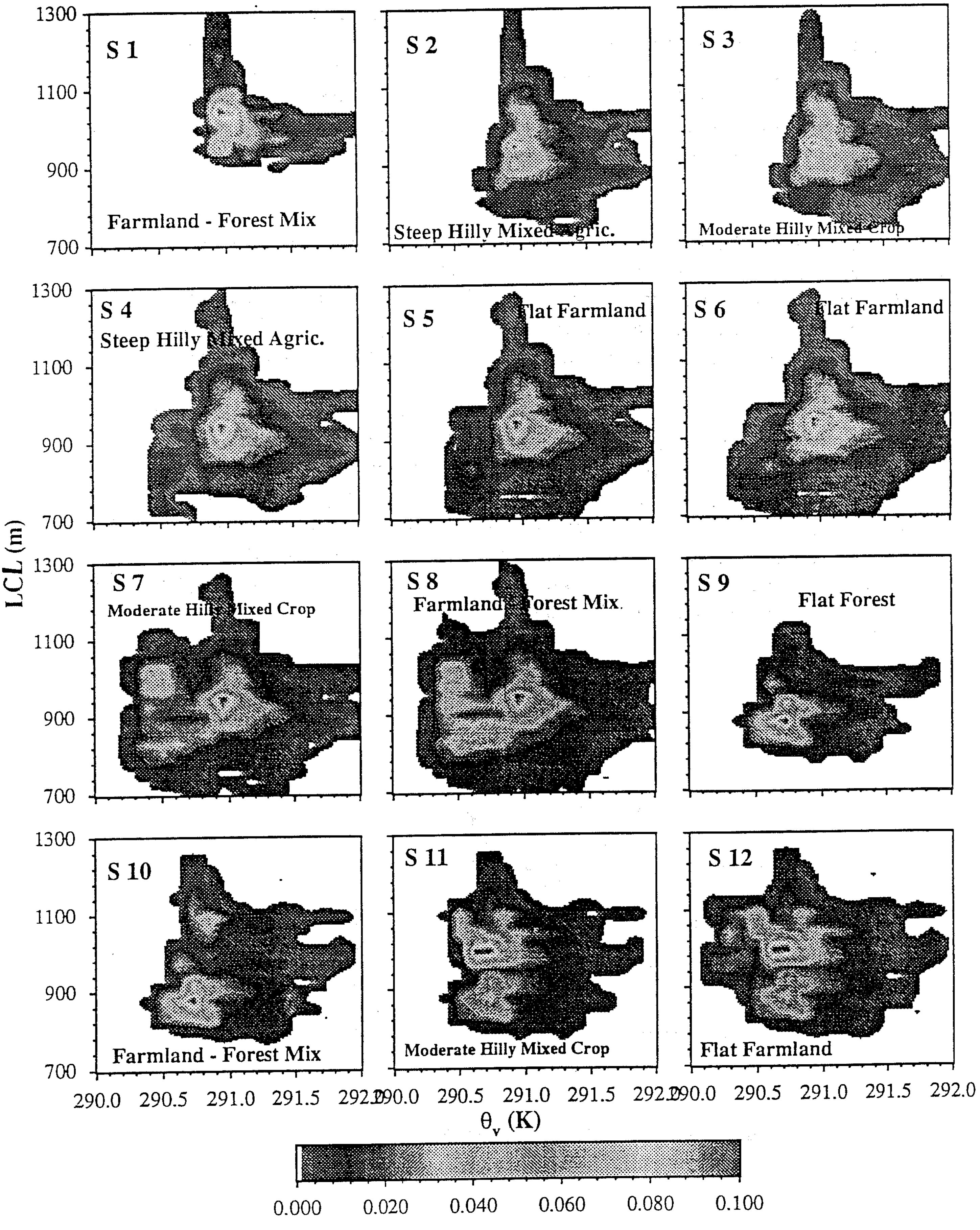
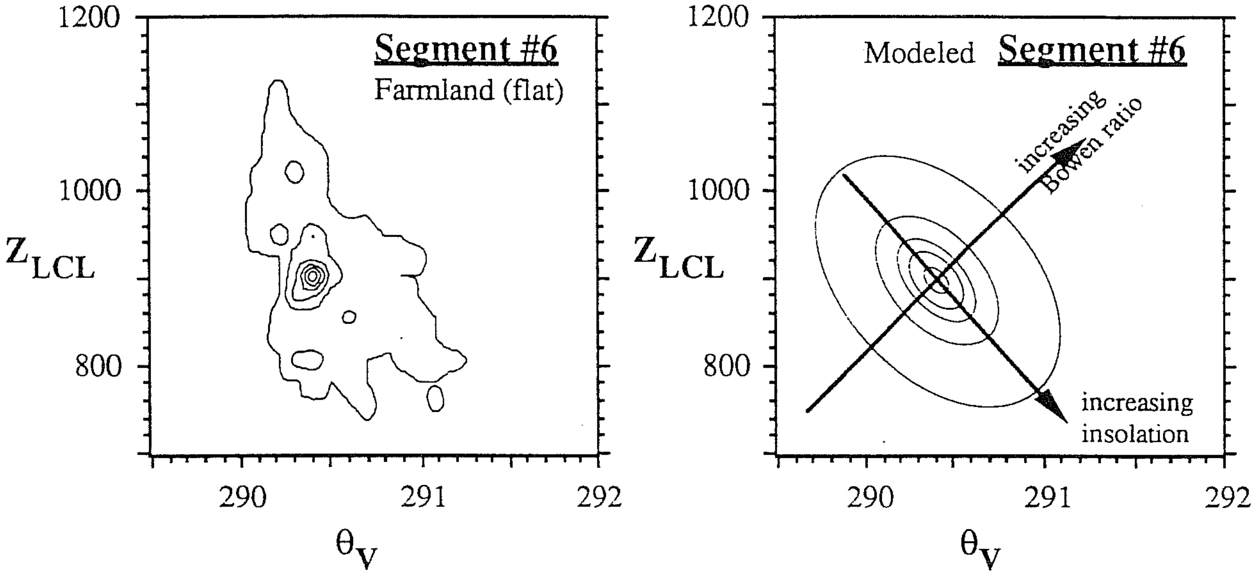


Fig 4. Land usage under HAPEX flight track.

Fig 5 . Joint frequency distributions of LCL heights vs virtual potential temperatures for air measured in the surface layer by aircraft during track 2 (about 1300 local summer time = UTC + 2h) of flight 6 (21 May 86). Data is segregated by dominant land use under the flight track, in the HAPEX field experiment in southern France.





(a) (b)

Fig 6. (a) Discrete relative frequency distribution of virtual potential temperature, θ_V(K), and height of the lifting condensation level, z_{LCL}(m), as observed in surface-layer air during segment 6, track 1, flight 1 of HAPEX. Tic marks indicate the sorting bin size. Contours drawn every 0.02, except first contour at 0.001; max. relative freq. = 0.12. (b) Parameterized model of the joint distribution data which approximates the measured distribution of (a).

9. Rate models for active and passive clouds.

The subset of forced clouds that reach their level of free convection (LFC) can continue to rise vertically as active clouds. This subset is found in a manner similar to that described in section 7, except that a cluster of surface-layer data points of z_{LFC} vs θ_v is plotted superimposed on the mean sounding. The fraction of data points from the cluster that lay below and to the right of the sounding indicate the fraction of thermals that become active clouds. The rate of formation, Y_1, of active clouds is just this coverage divided by the time scale for parcels to rise from the surface, $t_* = z_i / w_*$.

Active clouds have their own lifetime, based on their continued buoyant rise up to their limit of convection (LOC). Eventually, they stop actively withdrawing air from the ML, and are classified as passive clouds. The rate of transformation from active to passive is Y_2.

A simple rate model (Stull 1981, 1983a, 1986b) can be employed to approximate the coverage of a field of active clouds, σ_A:

$$\frac{\partial \sigma_A}{\partial t} = Y_1 - Y_2$$

Passive clouds have their own rate equation:

$$\frac{\partial \sigma_P}{\partial t} = Y_2 - \frac{\sigma_P}{\tau}$$

where the loss time scale, τ, for passive clouds depends on the relative humidity of the cloud environment and on the turbulence.

10. Other tidbits

Lopez (1977) suggested that the size characteristics of a field of cumulus clouds are lognormally distributed. We also found lognormal distributions of forced cumulus clouds based on the BLX83 field data (Stull 1984), based on photogrametric analyses from automatic airborne cameras.

Humidity, a necessary ingredient of clouds, is somewhat difficult to measure with fast response such as needed on airborne platforms. The Lyman-alpha hygrometer measures absorption of ultraviolet light by water vapor, and has the desired fast response. However, it has no absolute accuracy and must be frequently calibrated. Eloranta et al (1989) designed a calibration collar that can be inserted over the Lyman-alpha hygrometer while the aircraft is on the ground. By filling the ultraviolet path with different gases injected into this collar, one can calibrate the instrument before and after each flight (Crum et al 1986).

It became clear during the HAPEX experiment that the calibration changes significantly during a single flight, due to changes in aircraft voltage, ultraviolet radiation source strength, contamination of the windows in the radiation path, and other factors. To correct for this, calibration must also be made against other humidity measurements made during each flight, such as from dew point hygrometers. Unfortunately, the dew point hygrometer is a very slow response instrument (e-folding response time of a few seconds), with unequal response rates for dry and moist air. As a result, in the region near the top of the mixed layer (i.e., in the entrainment zone and just below cloud base) where moist thermals are adjacent to dry entrained air, the dew point instrument has difficult giving even the correct mean humidity (Otles, 1990) during a horizontal flight leg.

11. Summary

For nonprecipitating fair-weather cumulus clouds over land, we have found the following:

- BLCu can be categorized by dynamic activity as forced, active, or passive.
- A stochastic / phenomenological model can be used for subgrid cloudiness.
- The distribution of mixed layer air in the entrainment zone can be described by a double-exponential function
- The thickness of the entrainment zone has a hysteresis effect
- The variation of LCLs can be described by an LCL zone
- The top of the mixed layer might be multi-valued during the rapid growth phase in late morning
- Thermal buoyancy causes a natural filtering of the surface-layer air that rises to form clouds
- LES models have numerical problems with moisture at the top of the ML
- Lateral entrainment into thermals does not reach the core, which remains undiluted. The zone of entrainment has been called the intromission zone.
- Cloud base is equal to the LCL computed from surface-layer air
- "Reported" cloud base height by the USA civilian and military weather services are unreliable for scattered clouds. LCL is a better measure.
- Cloud sizes have lognormal distributions
- Large variations of cloud coverage and base height exist across the mesoscale
- Net effects of Cu coverage can be quantified using "cover hours".
- Local ML depth and LCL height are positively correlated
- Stratus clouds are not BL clouds
- Cloud / boundary-layer feedbacks include radiative, dynamic, kinematic
- Forced cloud coverage can be modeled using the joint probability distribution of z_{LCL} and virtual potential temperature, superimposed on a sounding.
- Rate modes can be used for active and passive cloud coverage

Details on these conclusions can be found in the references.

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