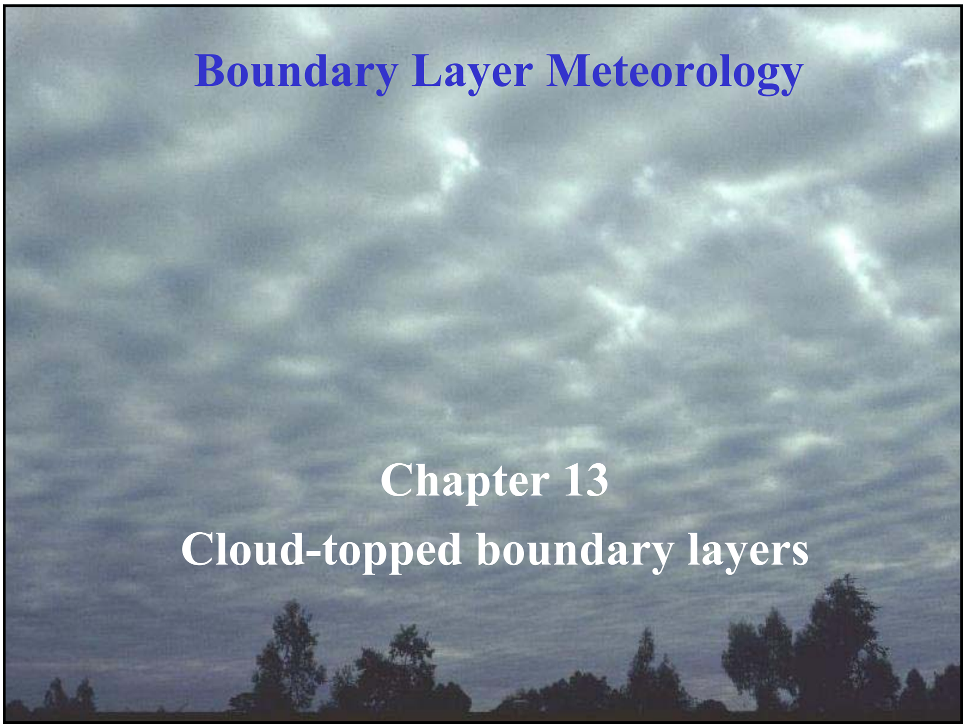


Boundary layer clouds

- **The presence of cloud has a large impact on BL structure.**
- **Clouds that are limited in their vertical extent by the main capping inversion are an intrinsic feature of the cloud-topped BL (CTBL) - they consist mainly of three types:**
  1) **Shallow cumulus (Cu) in the form of fair-weather cumulus (either as random fields or cloud streets);**
  2) **Stratocumulus (Sc); and**
  3) **Stratus (St).**
- **In addition, fog may exist in the lower regions of the BL in the form of radiation fog, frontal fog, advection fog and ice/snow fog.**

Fog

- Fog is defined as cloud in contact with the surface. For the present purposes, we exclude from this definition cloud in contact with hills or mountains.
- Over land, fog may form at night as a consequence of radiative cooling of the surface.
- Heat is lost from the air radialively and diffused downward into the surface by wind-induced turbulence. If the air near the ground is cooled to its dew-point temperature, condensation occurs, first near the ground and later at higher altitudes.
- Initially, the fog is thickest near the surface, with the cloud-water content falling off rapidly with altitude.

- If it does not achieve a thickness greater than a few meters by sunrise, it will remain in this state until absorption of sunlight by the surface and by the cloud itself raises the temperature enough to evaporate the cloud.
- Thin fog of this kind is not convective, because the cooling occurs from below.
- If the fog achieves a thickness greater than 5 or 10 m, a remarkable transition occurs.
- Fog of typical liquid water content strongly absorbs infrared radiation, to the extent that a fog bank of 100-m thickness is effectively opaque.

- Such cloud blocks infrared radiation from the surface and shuts down the cooling of the surface.
- At the same time, strong divergence of the infrared radiative flux at the top of the fog leads to rapid cooling there, thus destabilizing the fog layer.
- The fog convects and forms a cloud-filled mixed layer similar to the dry convective boundary layers

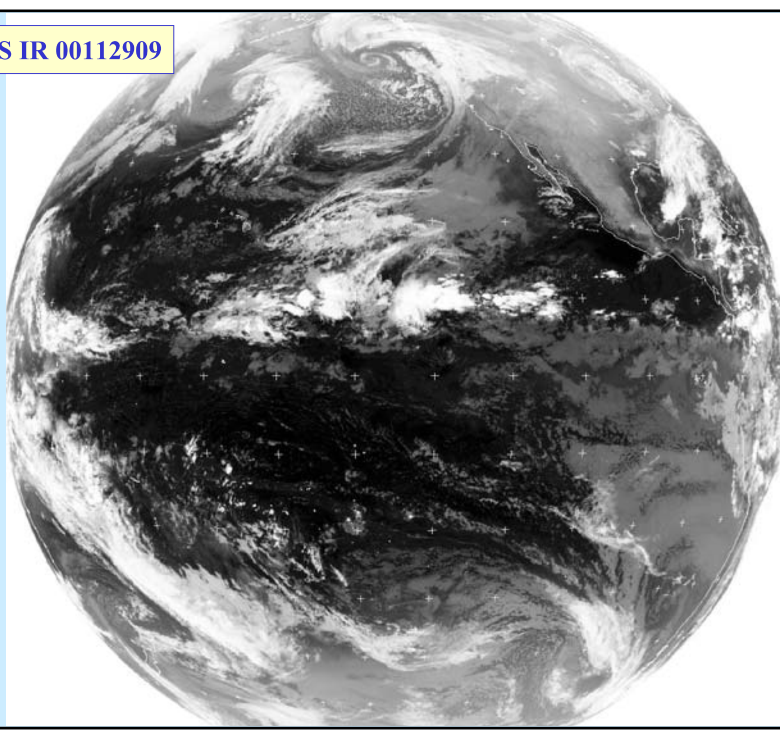
Complications with clouds

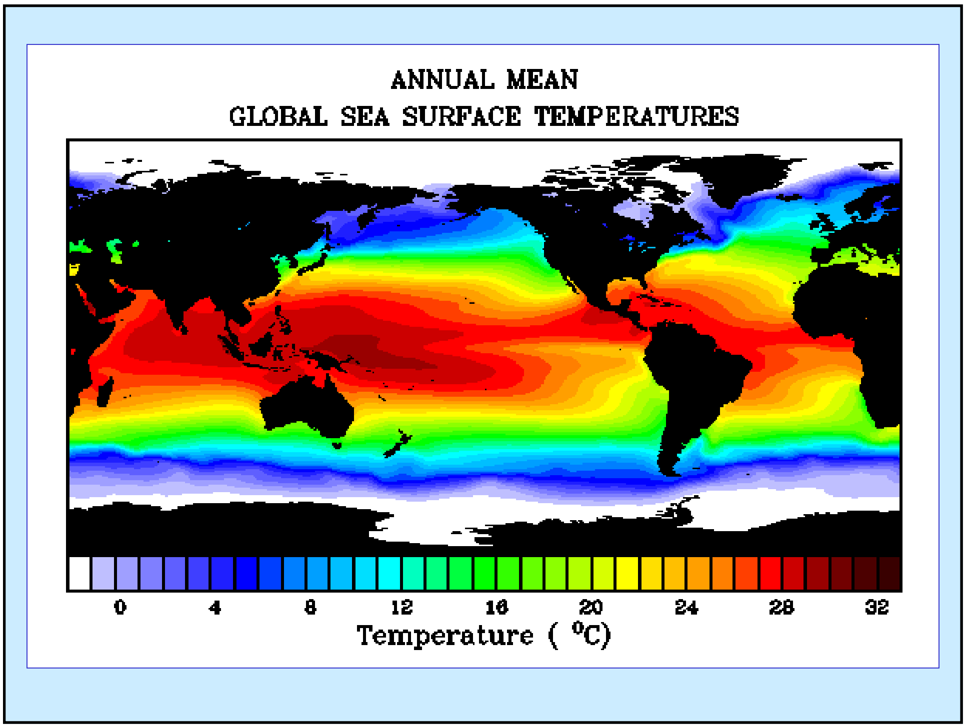
- Important role of radiative fluxes and phase changes.
- In a dry BL, the turbulent structure, the mean variables and their evolution with time are controlled by large-scale external conditions and by surface fluxes.
- In a cloudy BL, the surface fluxes may be important, but radiative fluxes produce local sources of heating or cooling within the interior of the BL and can greatly influence its turbulent structure and dynamics.
- The state of equilibrium of a CTBL is determined by competition between radiative cooling, entrainment of warm and dry air from above the cloud, large-scale divergence and turbulent buoyancy fluxes.

Cloud-topped boundary layer

- The cloud-topped boundary layer (CTBL) can be broadly identified with a turbulent region in which patterns and ensembles of stratus, stratocumulus and cumulus clouds reside inside the capping inversion.
- It is a dominant feature of the weather of the lower atmosphere and of the climate conditions of many areas of the globe, particularly over the sea, and has been recognized as an important component of the climate system.

GOES IR 00112909



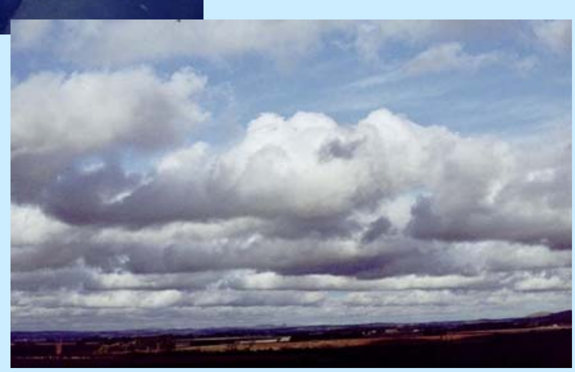

ANNUAL MEAN
GLOBAL SEA SURFACE TEMPERATURES
0
4
8
12
16
20
24
28
32
Temperature (°C)


Moist Convection
Trade Cumuli

Stratocumulus

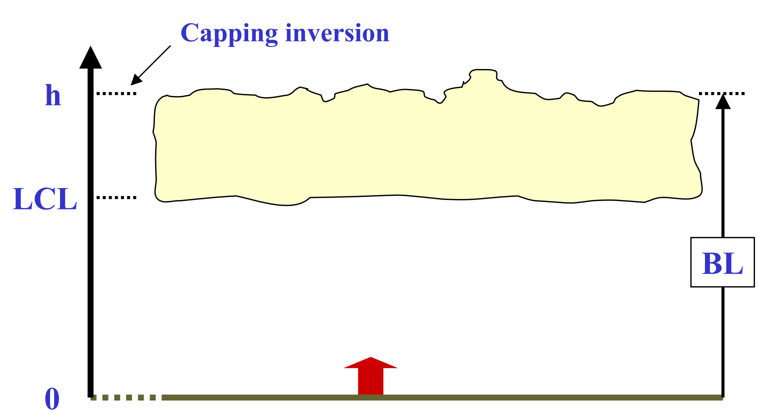






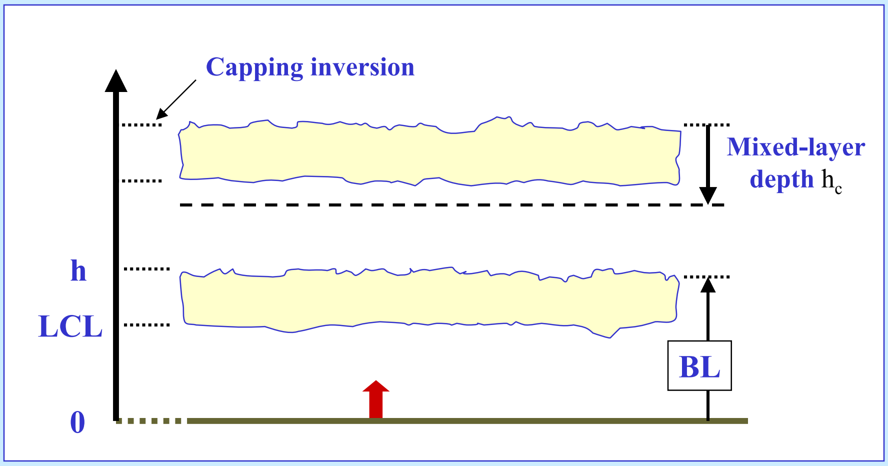

- In general, stratus clouds are found much closer to the surface than stratocumulus.
- Stratus may start life as low-level fog gradually developing into an elevated cloud layer (Hochnebel) of thickness anywhere between a few tens of metres to hundreds of metres.
- It is often (though not always) uniform and featureless with few undulations in cloud top.
- Stratocumulus is very much an elevated cloud layer often, though not exclusively, beneath the top of the BL at a subsidence inversion.
- Its thickness may vary between a hundred to several hundred metres.
- It has distinctive cellular patterns associated with convective motions within the cloud.

- Dynamically, **stratocumulus** is driven by convection, particularly that due to (negative) buoyancy generation near the cloud top related to strong radiative cooling.
- **Stratus** may be partly driven by convection due to cloud-top radiative cooling or it may be associated with strong winds and large vertical wind shear.
- It has distinctive cellular patterns associated with convective motions within the cloud.

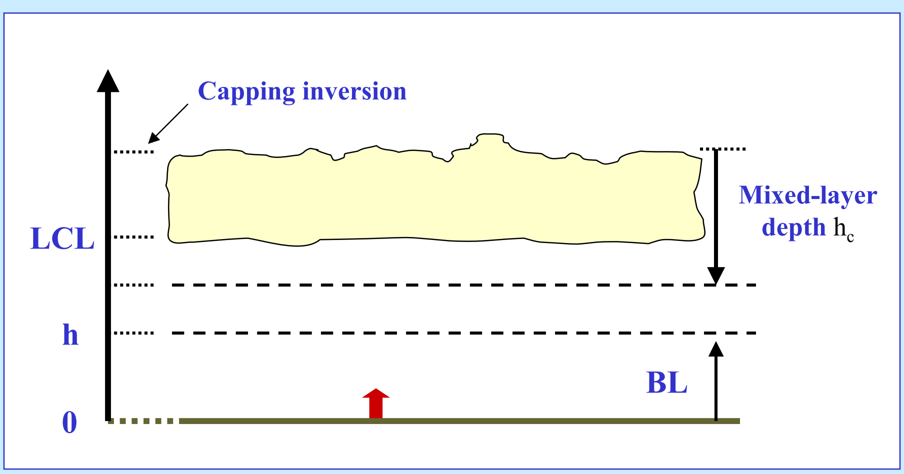


Schematic representation of the CTBL:
Fully coupled system, with a well-mixed layer from the surface to the cloud top.

N



Schematic representation of the CTBL:
Two cloud layers beneath the capping inversion, with a well-mixed layer of height h and an elevated mixed layer of height h_c.



Schematic representation of the CTBL:
Decoupled system and only one cloud layer, with weak surface fluxes and an elevated mixed layer of depth h_c.

Current knowledge of physical processes

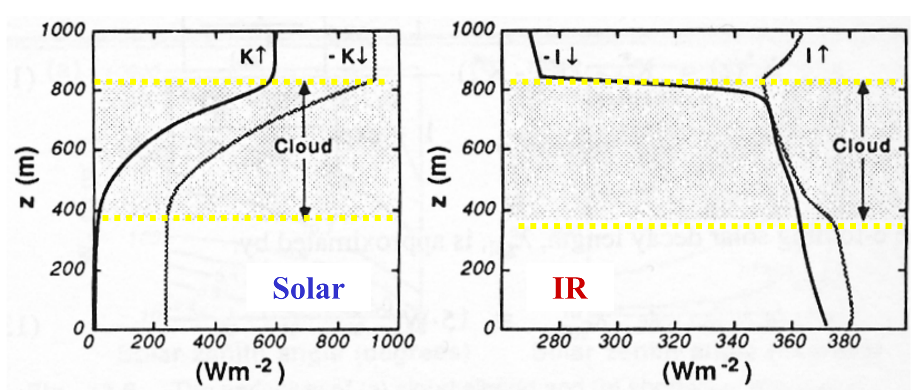
- Observational and modelling studies suggest that several processes are important in determining the formation, maintenance and dissipation of BL clouds.
- In general the internal structure of the CTBL depends strongly on the **dominant mechanism responsible for generating the turbulence.**
- Possibilities are:
  - **Convective**, from cloud-top radiative cooling or surface heating;
  - **Shear driven**, from surface stress or shear at cloud top.
- Radiative fluxes are affected by the cloud and produce local sources of heating and cooling that can influence the turbulent structure.

- It is generally considered that longwave radiative cooling extends only over the first 50 m or so beneath a stratocumulus cloud top, with solar heating extending deeper into the cloud layer.
- One main effect of the radiative cooling is the generation of an upward buoyancy flux across the BL that in turn drives entrainment at the cloud top.
- This entrainment brings warmer and drier air down into the BL (and into the cloud), and subsequently promotes evaporation of cloud droplets and so cooling.
- Under some circumstances, this evaporative cooling may lead to an instability process in which the parcel cools further, becoming negatively buoyant and sinking through the cloud. This may enhance the entrainment and promote the breaking up of a solid cloud deck.

Radiation

- The physics relevant for radiation within and between clouds requires knowledge of:
  - Liquid water content
  - Cloud droplet size distribution
  - Cloud temperature
  - Cloud surface shape
  - Fractional cloud cover
  - Solar zenith angle
  - And many more!
- Simplifications come from neglecting radiation from cloud sides and weighting the radiation budget by the fractional cloud cover.

Radiation fluxes in clouds

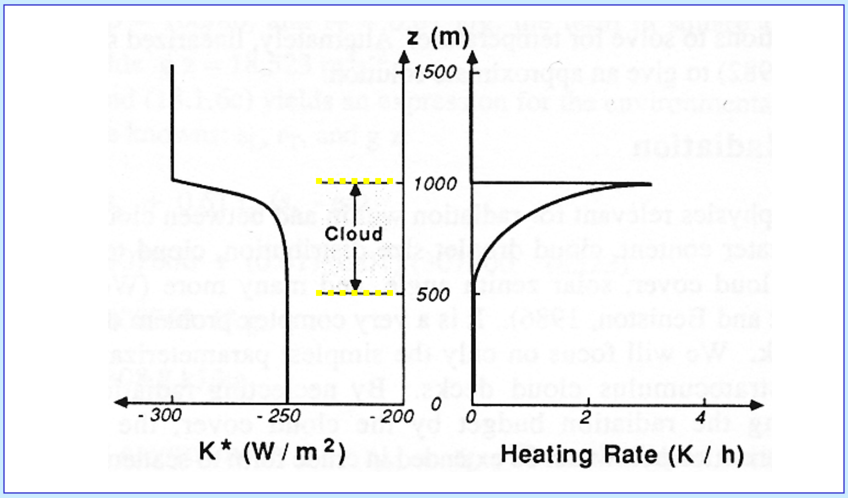


Average solar and IR radiation fluxes in a stratocumulus cloud.

From Nicholls, 1984

N

Solar radiation



Profiles of net ($K^* = K\downarrow + K\uparrow$) shortwave radiation flux and the corresponding heating rate in an idealized stratocumulus cloud.

From Hanson, 1987

N

Parameterization of solar radiation absorption

- **Hanson & Derr (1987) proposed the following simplification for solar radiation absorption, assuming that the cloud top height (z_T) and base (z_B) are known:**

$$K^*(z) = K_T^* - (K_T^* - K_B^*)\frac{1-\exp\left[-(z_T - z)/\lambda_{sol}\right]}{1-\exp\left[-(z_T - z_B)/\lambda_{sol}\right]}$$

$$\lambda_{sol} = 1.5 W_p^{0.335}$$

λ_{sol} **lies typically in the range 50 to 150 m**

- **The liquid water path is:**

m

$$W_p = \int_{z_B}^{z_T} \rho_{air} r_L dz \cong \frac{(z_T - z_B)^2}{880}$$ **g/m²**

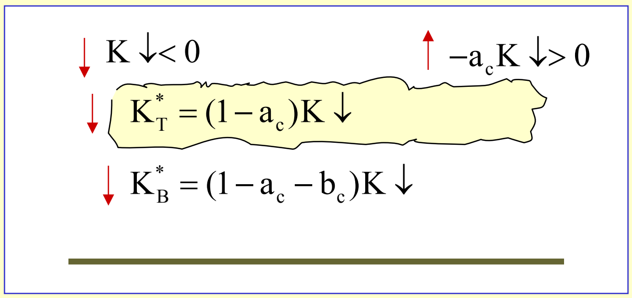
N

Albedo

- The **bulk cloud albedo**, a_c, and **absorption**, b_c, are used to find the net shortwave fluxes at the top and bottom of the cloud:

$$K_T^* = (1 - a_c)K\downarrow$$

$$K_B^* = (1 - a_c - b_c)K\downarrow$$



Describes the transmission of downward solar radiation through the cloud.

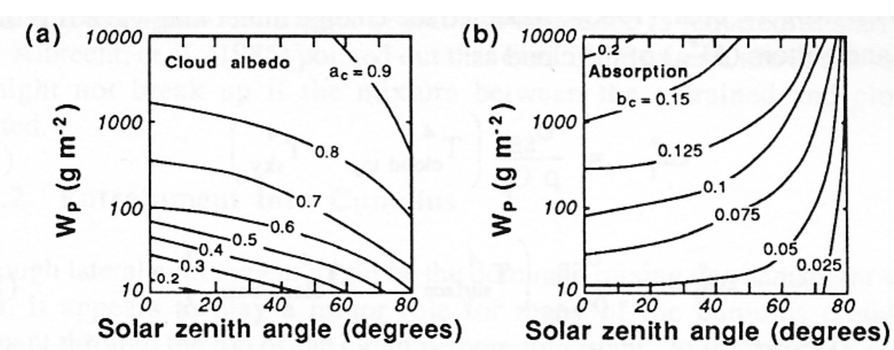
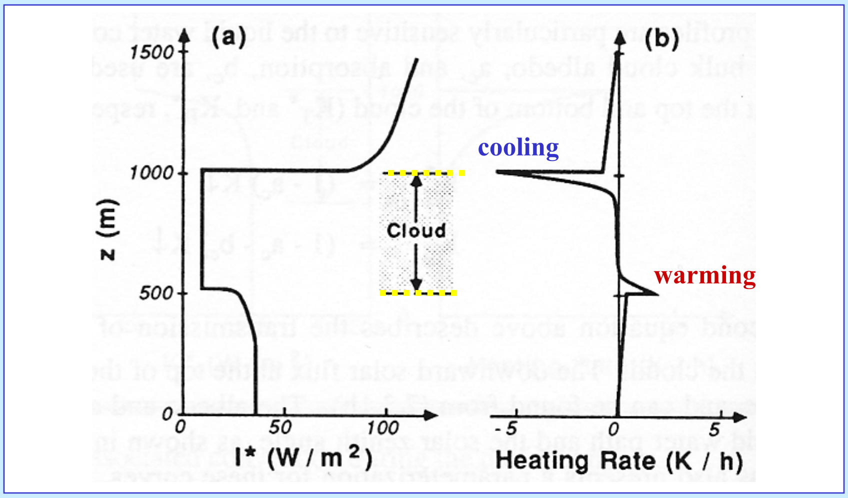


Fig. 13.6 The variability of (a) cloud albedo and (b) shortwave absorption as determined by a theoretical model for changes of solar incidence and liquid water path (W_P). The surface albedo is zero and a tropical moisture profile is assumed. The contours are the fraction of the incident downward flux at the cloud-top reflected or absorbed. (After Stephens, 1978).

- The albedo and absorption are a function of the liquid water path and the solar zenith angle.

Infrared radiation



Profiles of net ($I^* = I\downarrow + I\uparrow$) longwave radiation flux and the corresponding heating rate in an idealized stratocumulus cloud.

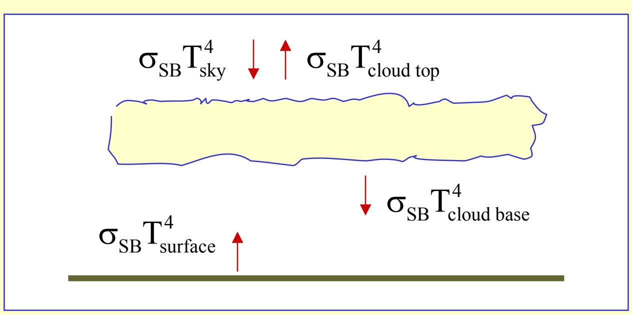
From Nicholls and Leighton, 1986

N

Parameterization of IR radiation

- Rogers et al. (1985) modelled the change in net longwave flux across the top (ΔI^*_T) and base (ΔI^*_B) of the cloud as:

$$\Delta I^*_T = \frac{\sigma_{SB}}{\rho c_p}(T^4_{\text{cloud top}} - T^4_{\text{sky}}) \qquad \Delta I^*_B = \frac{\sigma_{SB}}{\rho c_p}(T^4_{\text{surface}} - T^4_{\text{cloud base}})$$



N

Cloud entrainment mechanisms

Cloud-top entrainment instability in stratocumulus

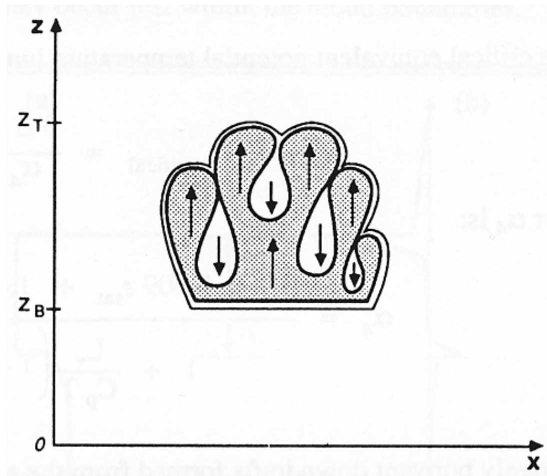
- **Lilly (1968) first suggested that the warm air entrained into the top of a stratocumulus cloud might cool and sink if it were initially dry enough to support considerable evaporative cooling of the neighbouring cloud droplets.**
- **Negatively buoyant downdraughts formed from the entrained air produce additional TKE that can enhance the mixing and entrainment.**
- **Then the newly entrained air can become unstable and sink also, resulting in even more TKE and entrainment.**
- **This positive feedback can cause a cloud to entrain large amounts of dry air, resulting in the rapid breakup and evaporation of the cloud.**

Cloud entrainment mechanisms

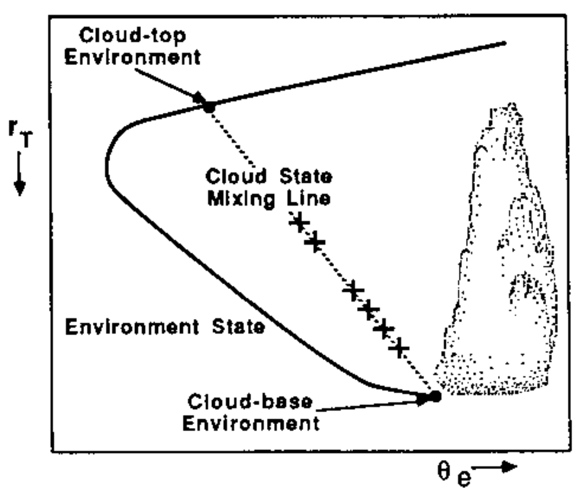
Entrainment into cumulus

- **Lateral entrainment appears to play a minor role in cumulus clouds – entrainment through the top of the cloud is more important.**
- **Entrained air at cloud top partially mixes with some of the cloudy air, and the evaporation of some of the droplets causes mixing, just like stratocumulus cloud-top entrainment instability.**
- **The result is a negatively buoyant updraught that sinks through the cloud and mixes with other cloudy air on the way.**

See figure



Idealization of the cloud-base and cloud-top entities that mix vertically within a cumulus cloud.



Idealization of data measured in the cloud (+) fall on a straight line connecting points representing the environmental state near cloud top and cloud base.

From Betts, 1985

N

Fair-weather cumulus

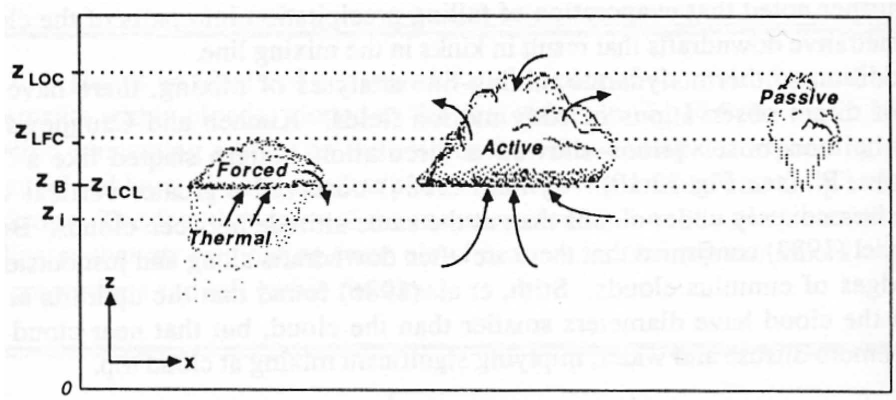


Fig. 13.11 Classes of fair-weather cumulus clouds. (After Stull, 1985).

N

Forced clouds

- These clouds form in the tops of mixed-layer thermals, and exist only while there is continued forcing from the parent thermal.
- Often, these clouds form in the negatively buoyant portion of the thermal that is overshooting into the capping inversion (entrainment zone).
- In spite of the latent heat release during condensation, there is insufficient heating for these clouds to become positively buoyant.
- As a result, the clouds behave as quasi-passive tracers of the top of the thermal: the cloud top never reaches its LFC.

- **Morphologically, these clouds are very shallow and often flat looking, and are usually classified as cumulus humilis.**
- **All of the air rising in the thermal up through the cloud base continues circulating through the cloud and remains within the ML (i.e., there is *no venting* of ML air out of the ML).**
- **In conditions of light wind shear, air in the cloud diverges from the center toward the lateral edges, where descending return flow into the ML is associated with droplet evaporation.**
- **In stronger wind shear, the cloud often appears as a breaking wave, with updrafts on the upshear side, and the return circulation and downdrafts on the downshear side.**

Active clouds

- **These clouds are also triggered by mixed layer thermals, but at some point a portion of the updraft reaches its LFC and the clouds become positively buoyant.**
- **The rising updraft induces its own pressure perturbations that affect its evolution and draw more air in through its cloud base.**
- **The lifetime of this cloud is controlled by its cloud dynamics and its interaction with the environment. It may persist longer than the mixed layer thermal that first triggered it.**
- **These clouds vent mixed layer air out into the free atmosphere.**
- **Their vertical dimensions are often on the same order, or slightly larger than their horizontal dimensions. Morphologically, they are the cumulus mediocris.**

Passive clouds

- **When active clouds cease withdrawing air from the mixed layer , we classify them as dynamically passive.**
- **The tops of the passive clouds might still be positively buoyant and may even be growing, but they no longer are venting mixed layer air.**
- **The bottoms of these clouds are diffuse as the droplets evaporate and mix with the environment.**
- **As a result, the original cloud base disappears, leaving the remaining portion of the cloud totally above the mixed layer and entrainment zone where it is not dynamically interactive with the mixed layer .**

Radiative Feedback of clouds

- **All classes of boundary-layer clouds shade the surface.**
- **Over a land surface this results in negative feedback, because less solar heating of the ground will trigger fewer or weaker thermals and will cause the mixed layer to grow more slowly, resulting in fewer new cumulus clouds being triggered.**
- **Thus on days over land where solar heating is the primary driving force for free convection (rather than cold air advection, ground thermal inertia, or forced mechanical convection), fair-weather cumulus clouds will tend to reach an equilibrium cloud cover that is scattered (**0.1 **to** 0.5 **coverage) or broken (**0.6 **to** 0.9**), but not overcast.**

Dynamic Feedback of clouds

- Active clouds withdraw some of the mixed-layer air, causing the mixed layer to grow more slowly or even not grow at all.
- This negative feedback limits the number of new thermals that can penetrate high enough to trigger new active clouds.
- The equation $\frac{dz_i}{dt} = (1-\sigma_c)w_e - \sigma_c w_c + w_L$ describes how active clouds can modify mixed-layer growth.
- Given typical values of entrainment velocity, subsidence, cloud base average updraft velocity, and mixed-layer growth rate (0.05, −0.01, 1.0, and 0.02 m/s, respectively), yields an active cloud cover of 2%.
- Active clouds rarely cover more than a few % of the area.

End