# Lecture 14. Marine and cloud-topped boundary layers

*Marine Boundary Layers* (Garratt 6.3)

Marine boundary layers typically differ from BLs over land surfaces in the following ways:

(a) Near surface air is moist, with a typical RH of 75-100%

(b) The diurnal cycle tends to be weak (though not negligible), since surface energy fluxes get distributed over a considerable depth (10-100+) of water, which has a heat capacity as much as hundreds of times as large as the atmospheric BL.

(c) Air-sea temperature differences tend to be small, except near coasts. The air tends to be 0-2 K cooler than the water. This is because the BL air is usually radiatively cooling, and some of this heat is supplied by sensible heat fluxes off the ocean surface. However, if the air temperature is much lower than the SST, vigorous convection will reduce the temperature difference, and except where there are large horizontal gradients in SST, horizontal advection cannot maintain the imbalance. Hence the surface layer is nearly neutral over almost all of the oceans.

(d) Due to the small air-sea temperature difference, the Bowen ratio tends to be small (typically 0.1 in the tropical oceans, and more variable in midlatitudes); latent heat fluxes are 50-200 W $m^{-2}$, while (except in cold air outbreaks off cold landmasses) sensible heat fluxes are 0-30 W $m^{-2}$.

(e) Over 95% of marine boundary layers contain cloud. The only exceptions are near coasts, where warm, dry continental air is advected over a colder ocean, and in some regions (such as the eastern equatorial Pacific cold tongue and some western parts of the major subtropical oceans) in which air is advecting from warmer to colder SST, tending to produce a more stable shear-driven BL which does not deepen to the LCL of surface air. Cloud profoundly affects the BL dynamics, as we discuss below.

Many large field experiments have studied marine BLs. Particular focus areas, and particularly seminal field experiments, have included:

(i) Tropical BLs associated with deep convection (GATE 1973, tropical E Atlantic; TOGA-COARE 1992, tropical W Pacific)

(ii) Trade cumulus boundary layers (BOMEX 1969, Caribbean; ATEX 1973, tropical E Atlantic)

(iii) Subtropical stratocumulus-capped BLs (FIRE-MSC 1987, California; ASTEX 1992, NE Atlantic; DYCOMS-II 2001, NE Pacific; EPIC-2001, SE Pacific)

(iv) Midlatitude summertime BLs (JASIN 1978, NE Atlantic)

(v) Midlatitude wintertime BLs (AMTEX 1974, S China Sea; MASEX 1983, Atlantic Coast)

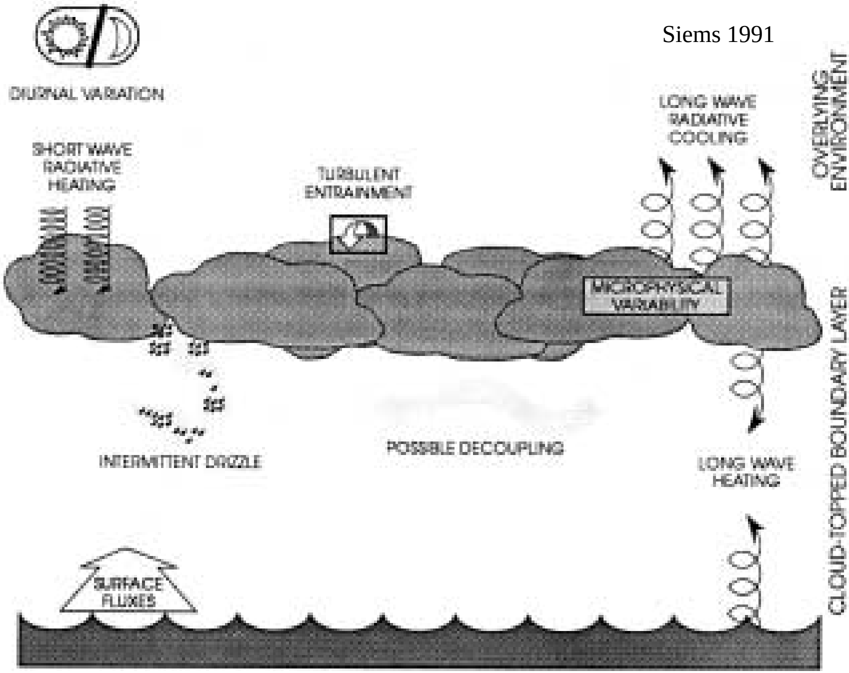
(vi) Arctic stratus (Arctic Stratus Experiment 1980, BASE 1994, SHEBA/FIRE.ACE 1997-8)

While there are interesting issues associated with the formation of stable cloudless marine boundary layers due to advection of air off a continent (see Garratt 6.4), the study of marine boundary layers largely comprises an important subset of the study of cloud-topped boundary layers, to which we turn now.

## Cloud-topped boundary layers (Garratt, Ch. 7)

### *Regimes and geographical distribution*

Over much of the globe, and in particular over most of the oceans, low-lying cloud plays a key role in BL dynamics. Cloud affects boundary layer dynamics through latent heating, evaporation of precipitation into layers beneath the cloud, and through large changes in the radiative balance of both the BL itself and the underlying surface




Processes affecting convective cloud-topped BLs

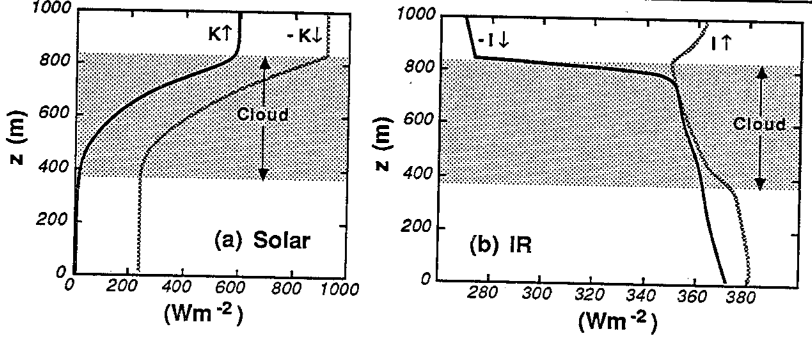



**Fig. 13.4** Average (a) solar, K, and (b) IR, I, radiation fluxes. The extent of the stratocumulus cloud layer is shown by the shading. (After Nicholls, 1984).

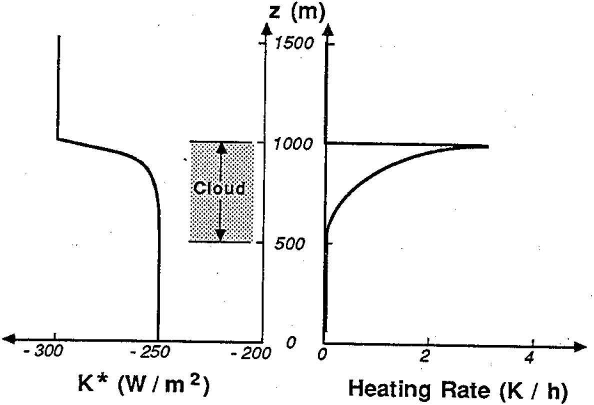
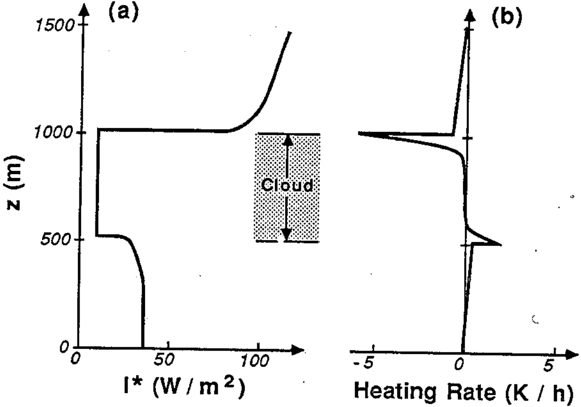



**Fig. 13.5**
Profiles of net shortwave radiative flux and the corresponding heating rate in an idealized stratocumulus deck. (After Hanson, 1987).

**Fig. 13.7**
Profiles of net longwave radiative flux and corresponding heating rate in an idealized stratocumulus deck. (After Nicholls and Leighton, 1986).



The most commonly seen cloudy BL types include:

(i) Shallow cumulus (Cu) boundary layers, ubiquitous over oceanic trade-wind regimes, but often seen over land and midlatitude oceans as the later phase of cold air outbreaks. These are driven primarily by clear-air radiative cooling

(ii) Stratocumulus (Sc)-capped BLs, typically found in anticyclonic flow over the subtropical and midlatitude oceans, and often seen during the cool season over moister landmasses. These BLs may include Cu below or rising into the Sc, and are driven in large part by radiative cooling at the tops of the clouds, and secondarily by surface cold advection.

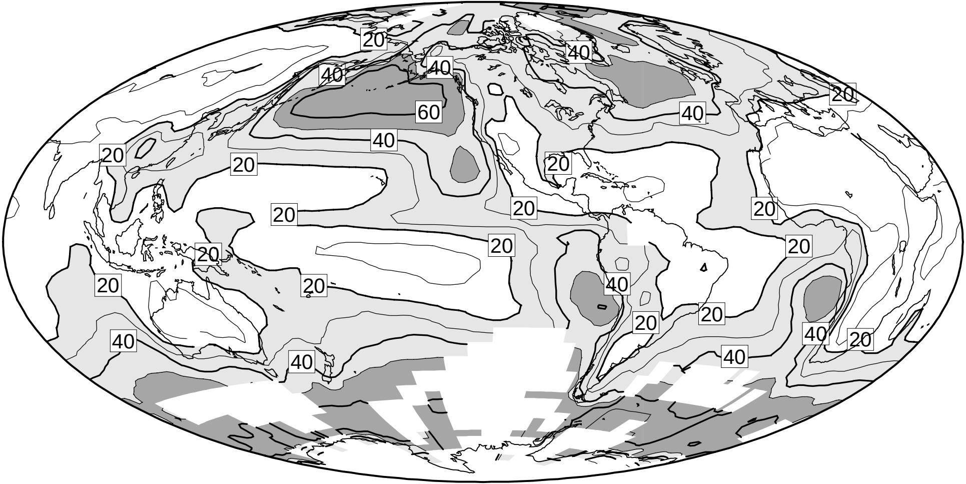
(iii) The progression in a wintertime cold air outbreak from shallow cloud streets to broader patches and lines of Sc and finally polygonal arrays of Cu. The BL is driven by strong surface heat fluxes of up to several hundred W $m^{-2}$.

(iv) Shear-driven shallow stratus layers, often seen in midlatitudes in warm advection. Here the dynamical and radiative effects of the cloud are probably secondary, since there are often overlying clouds that reduce the radiative impact of the low cloud, and the BL is not deep enough for the latent heating in the clouds to be important. There may be low cloud and rain that does not have a clear associating with BL processes associated with synoptic-scale lifting.

(v) Summertime arctic stratus under a weak anticyclone, in which there may be multiple cloud layers driven by surface chilling of and cloud top radiative cooling of moist, warm air advected over cold pack ice.

The global distribution of low cloud (at heights of 2 km or less above the surface) is best documented in routine synoptic observations of cloud type and cover by untrained surface observers using a simple classification scheme from WMO. These have been archived over the past 50 years, and were compiled by Warren et al. (1988). Below are shown the annually averaged cloud cover (frequency of occurrence multiplied by fractional sky cover when cloud type is present) for low lying 'stratus' (stratus+stratocumulus+fog), which encompasses the most radiatively important cloud types, and for cumulus cloud.  These cloud layers are typically 100-500 m thick, with a cloud base anywhere from the surface to 1500 m, and tend to be nonprecipitating. Over much of the midlatitude oceans and parts of the eastern subtropical oceans, stratus cloud cover exceeds 50%.

# Annual Stratus Cloud Amount

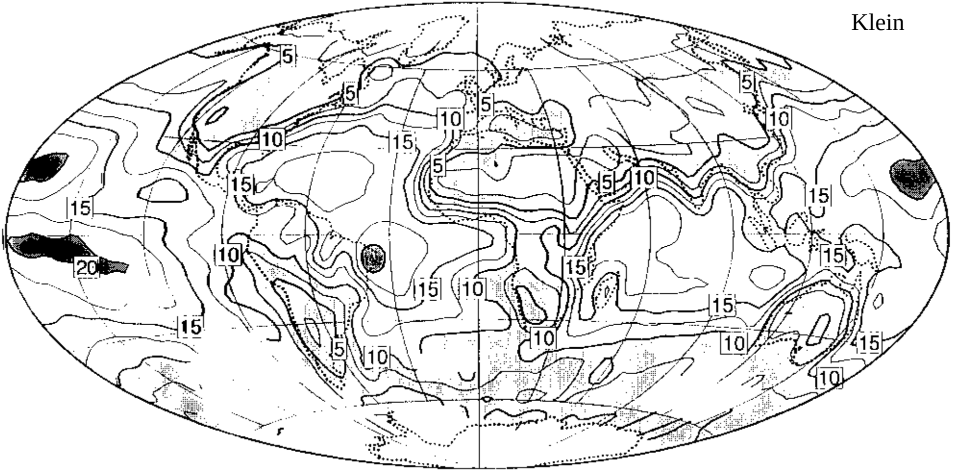


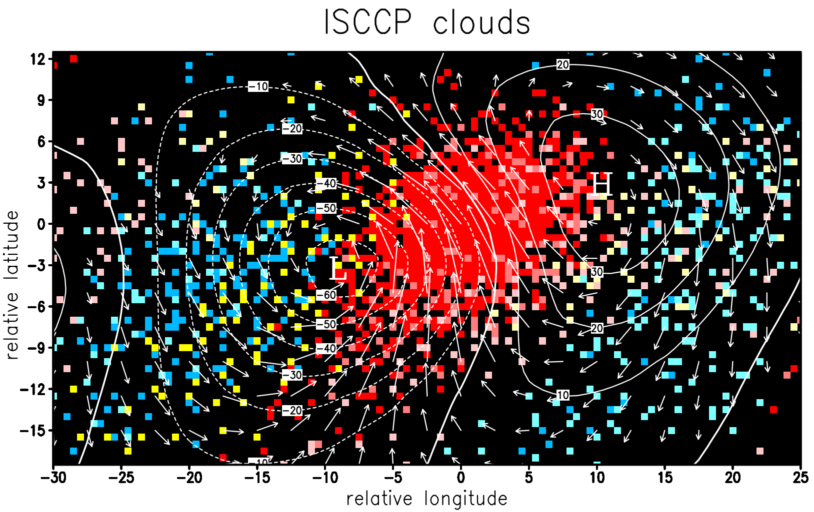

Klein and Hartmann (1993), from surface observations

# Cumulus Cloud Amount

cumann.2

Klein




ISCCP clouds
relative latitude
relative longitude
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H
-10
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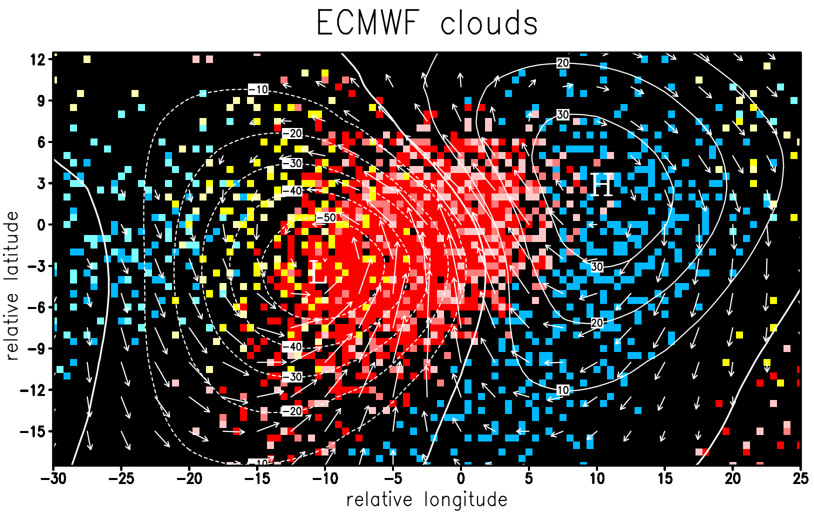
ECMWF clouds
relative latitude
relative longitude
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-10
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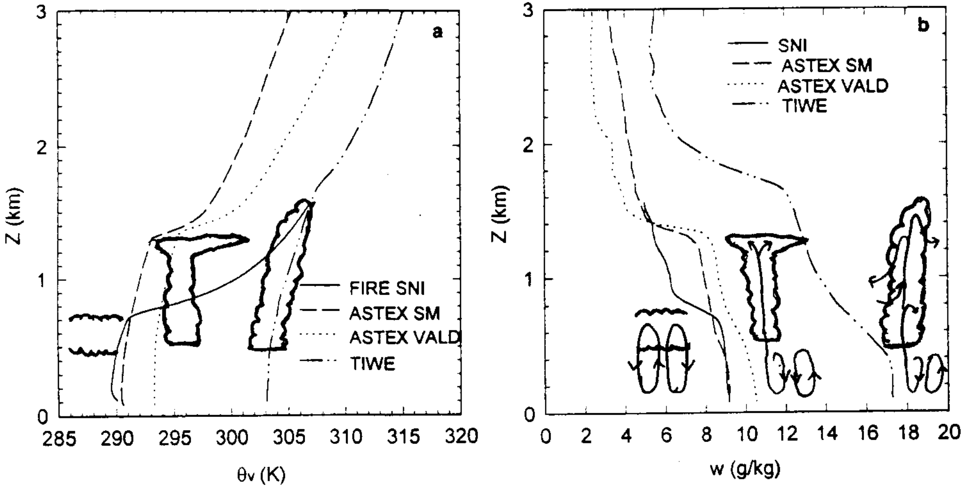
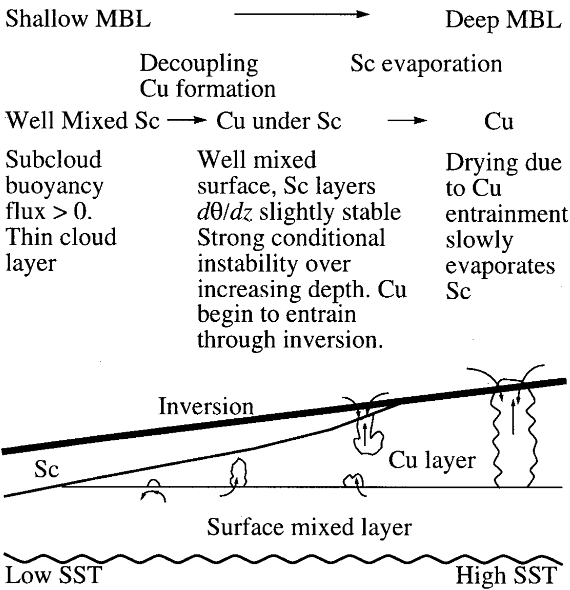
Klein and Hartmann (1993) showed that the cloud cover in these regions is highest when the sea-surface is coldest compared to the air above the boundary layer, which tends to occur in the summertime. In some parts of the Aleutian Islands, the average stratus cloud cover in June, July and August is 90%...a dreary sky indeed. Over land, there is much less stratus cloud due to the lesser availability of surface water. In most of the tropical and subtropical oceans, stratus clouds are rare. There is a very strong correlation between TOA cloud radiative forcing and stratus cloud amount due to the high albedo of these clouds, coupled with the smallness of their greenhouse effect since being low clouds, they are at a similar temperature to the underlying surface. There is an obvious correlation between cumulus cloud and a relatively warm surface. Note that cumulus cloud amount is everywhere low, even though over much of the trade wind belts, the frequency of occurrence is 70-90%. More than 100-200 km offshore, a complete lack of BL cloud is rare, occuring 1-2% of the time in most ocean locations.

*BL structure of subtropical convective CTBLs*

The figure above shows composite soundings from four field experiments that studied marine subtropical and tropical CTBLs (Albrecht et al. 1995). The experiments were conducted over locations with very different sea-surface temperature (SST).The typical observed boundary layer cloud structure and circulations are sketched. The experiments are FIRE SNI (July 1987, 33 N, 120 W, SST = 289 K, Cloud Fraction = 0.83), ASTEX (June 1992, SM: 37 N, 25 W, SST = 291 K, CF = 0.67; VALD: 28 N, 24 W, SST = 294 K, CF = 0.40), ), and TIWE (December 1991, 0 N, 140 W, SST = 300 K, CF = 0.26).




Composite $\theta_v$ and $q_t$ from four CTBL experiments (Albrecht et al. 1995)



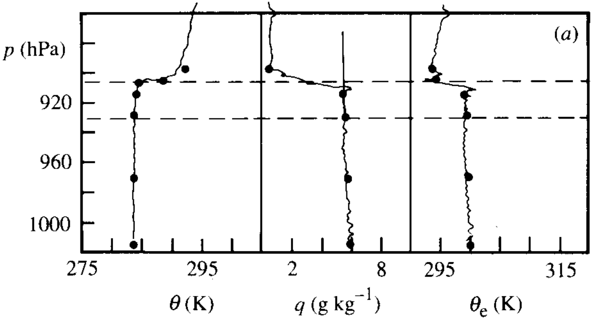
Shallow MBL
Deep MBL
Decoupling
Cu formation
Sc evaporation
Well Mixed Sc
Cu under Sc
Cu
Subcloud buoyancy flux > 0. Thin cloud layer
Well mixed surface, Sc layers $d\theta/dz$ slightly stable Strong conditional instability over increasing depth. Cu begin to entrain through inversion.
Drying due to Cu entrainment slowly evaporates Sc
Inversion
Sc
Cu layer
Surface mixed layer
Low SST
High SST

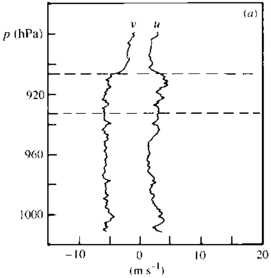
The deeper BLs tend to have less cloud cover, a weaker inversion, and a less well-mixed structure in the total water mixing ratio $q_t = q_v + q_l$ (which is conserved following fluid motions in the absence of mixing). The stratification of $\theta_v$ is roughly dry-adiabatic below cloud base. In the cloud layer, it is moist-adiabatic within the shallow FIRE stratocumulus cloud layer and conditionally unstable in the other cases. In general, one can identify three types of BL structure:

(i) well-mixed (e. g. FIRE-SNI). A specific example is shown on the next page

(ii) diurnally decoupled (some daytime shallow Sc layers), in which there are well-mixed surface and cloud layers separated by a stable layer across which there is no turbulent transport. An example is shown on next page.

(iii) conditionally unstable, in which a well-mixed subcloud layer is topped by cumulus clouds, and




Garratt

Well-mixed Sc layer

Garratt

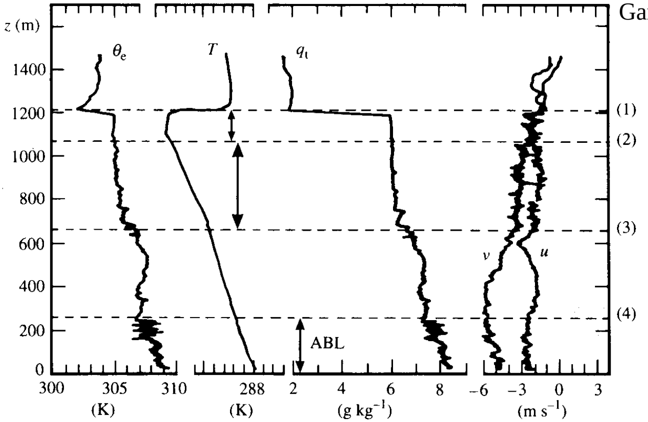
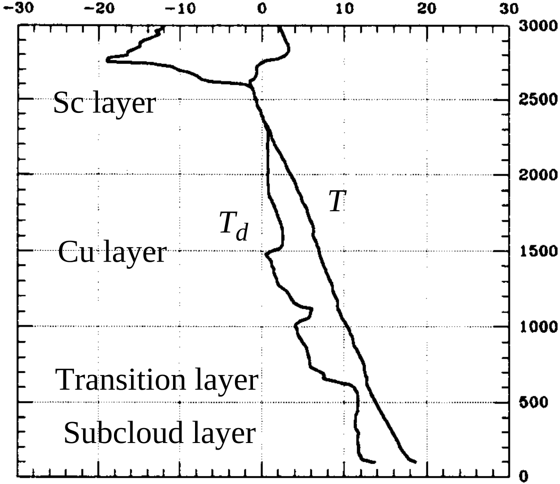



Fig. 7.5 Observed mean profiles of thermodynamic variables and wind components made in the CTBL over the ocean during JASIN, for a decoupled stratocumulus layer. The pecked horizontal lines delineate layer boundaries as follows: (1) cloud top; (2) cloud base; (3) bottom of subcloud layer; (4) top of the surface-related Ekman layer. After Nicholls and Leighton (1986), *Quarterly Journal of the Royal Meteorological Society*.

# Decoupled Sc layer

there may or may not be a thin stratocumulus layer below the capping inversion formed by detrainment from the cumuli. There is a very weak (< 1 K) inversion at the base of the cumuli called the transition layer that separates the region of subcloud convection below cloud base from the drier cumulus layer above. Essentially, the transition layer acts as a valve to allow only the strongest subcloud updrafts to form cumulus clouds. The capping inversion tends to be sharp if there is more Sc cloud (see figure on next page) and extends over 100-500 m if only Cu is present.

PORTO SANTO ASTEX, June 1 1992 (33 N, 16 W)




Conditionally unstable sounding with shallow Cu rising into an Sc layer

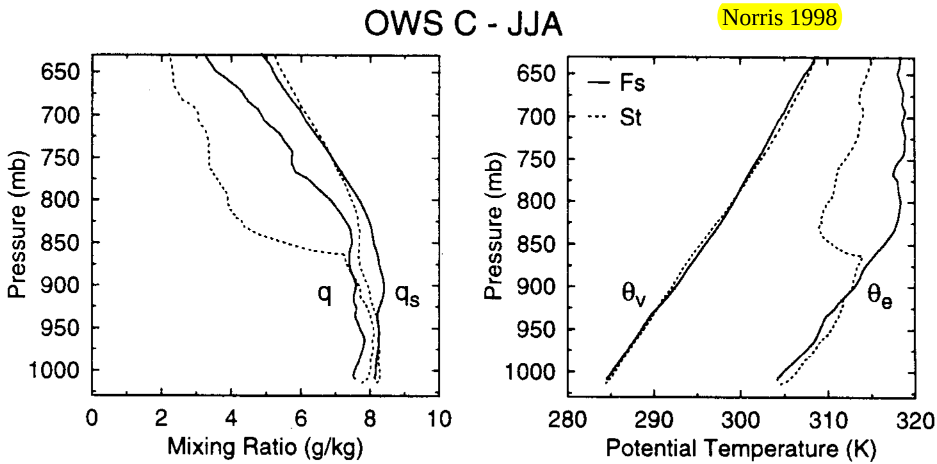
In the deep convective regions of the tropics, conditionally unstable cumulus boundary layers are also often seen extending up to around 800 mb when deep convection is suppressed. A capping inversion is not evident around deep convection; here the BL is complicated by internal BLs as shallow as 100 m due to cold dry outflow from deep convective systems. Even over a uniform sea-surface, mesoscale temperature variationsof 3-5 K are common in this situation. Surface fluxes restore the outflow air to a typical non-outflow thermodynamic state in 6-24 hrs.

Over midlatitudes, when stratocumulus or cumulus cloud is observed the soundings again fall into the above categories (Norris 1998). However, the RH of surface air may be lower and hence the depth of the subcloud layer may be as much as 1500 m, especially over land.

## *Stable CTBLs*

Some cloud types (such as stratus and fog) are associated with stable BLs. Norris (1998) has used soundings from ocean weather ships taken during the 1970s to form composites for different cloud types. In these cases, the sounding is absolutely stable and the presence of cloud just reduces the effective stability. We will not discuss these BLs more, as the impact of cloud on convective BLs is more profound, especially when surface sensible heat fluxes are weak as they usually are over the ocean

Norris 1998




Composite profiles for stratus (St) and fractostratus (Fs)-capped (stable) CTBLs.at Ocean Weathership C in the N Atlantic Ocean.