Photo: A. Christen

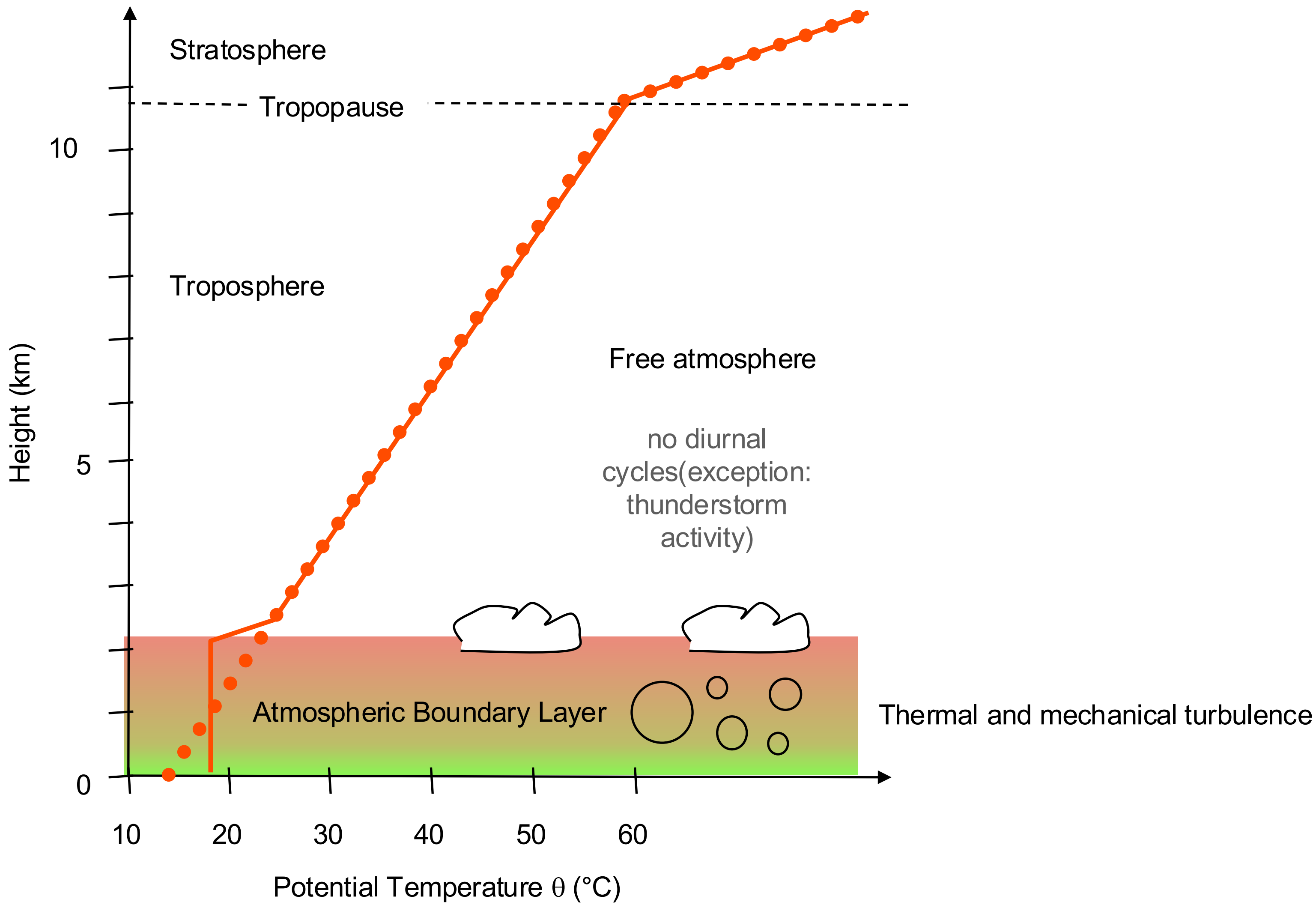
26 Convective and stable boundary layers

Learning objectives

- Review: explain what is different in the atmospheric boundary layer (ABL) compared to the rest of the atmosphere.
- Describe how the ABL responds to the surface energy balance over a day.
- Explain how sensible heat is mixed and distributed in the ABL (i.e. mixed layer growth and entrainment processes.)
- Describe how moisture is mixed in the ABL.

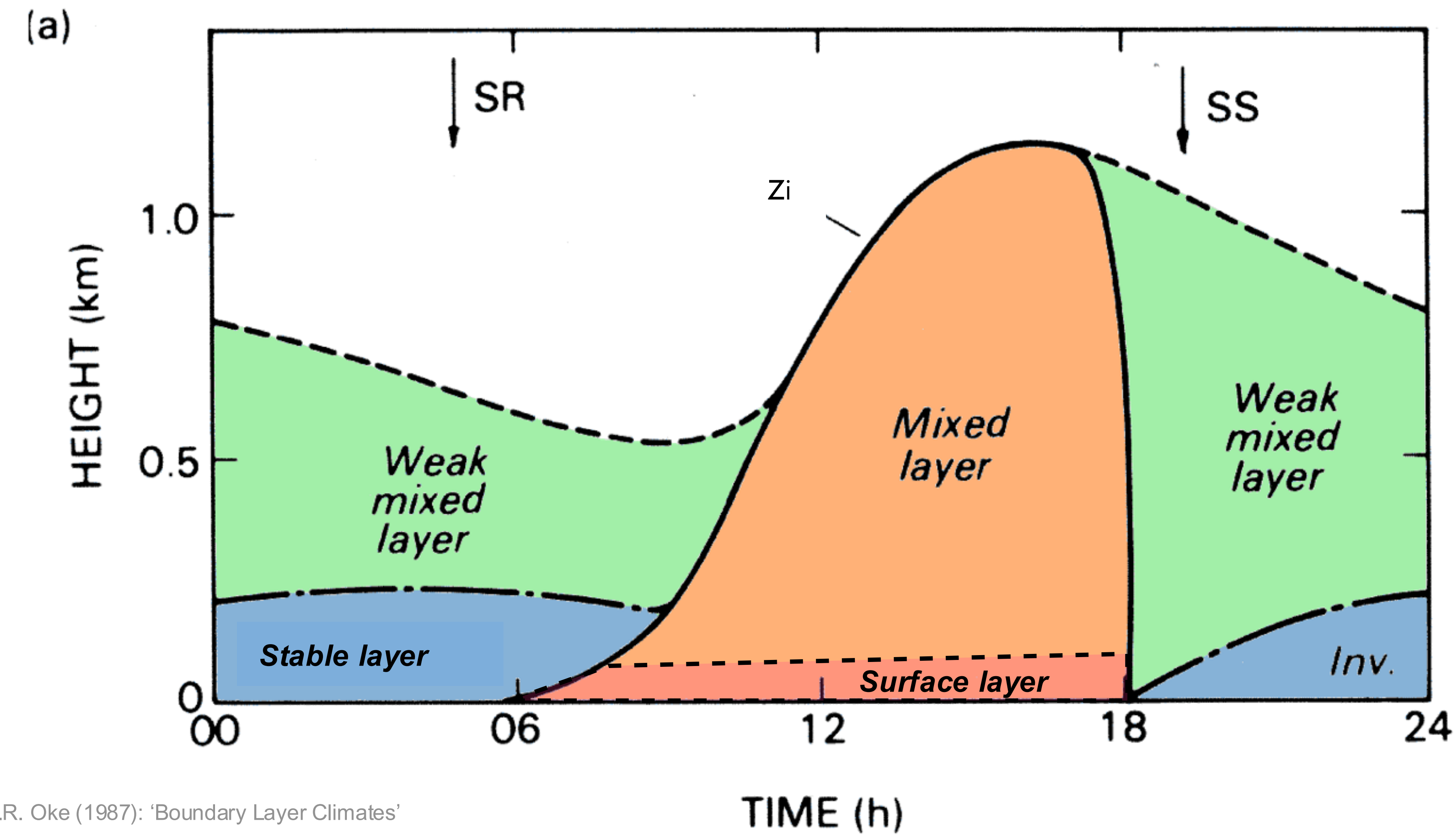
Photo: A. Christen

Thermal structure of the Atmospheric boundary layer



Potential temperature (θ) is the temperature that an air parcel would have **if it were moved adiabatically (no heat exchange) to a standard reference pressure**, typically **1000 hPa**. In practice, it isolates the effect of **compression/expansion due to pressure changes**.

Typical diurnal course of the Atmospheric boundary layer



T.R. Oke (1987): ‘Boundary Layer Climates’

Boundary layers.

CBL - convective boundary layer

- thermal plumes, convection cells and roll structures.
- surface layer, mixed layer and entrainment zone at top.
- deep, well mixed temperature profiles.

SBL - stable boundary layer

- inversion close to the ground.
- stable layer close to ground and residual layer above.
- inversion growth during night.
- waves.

Photos: A. Christen

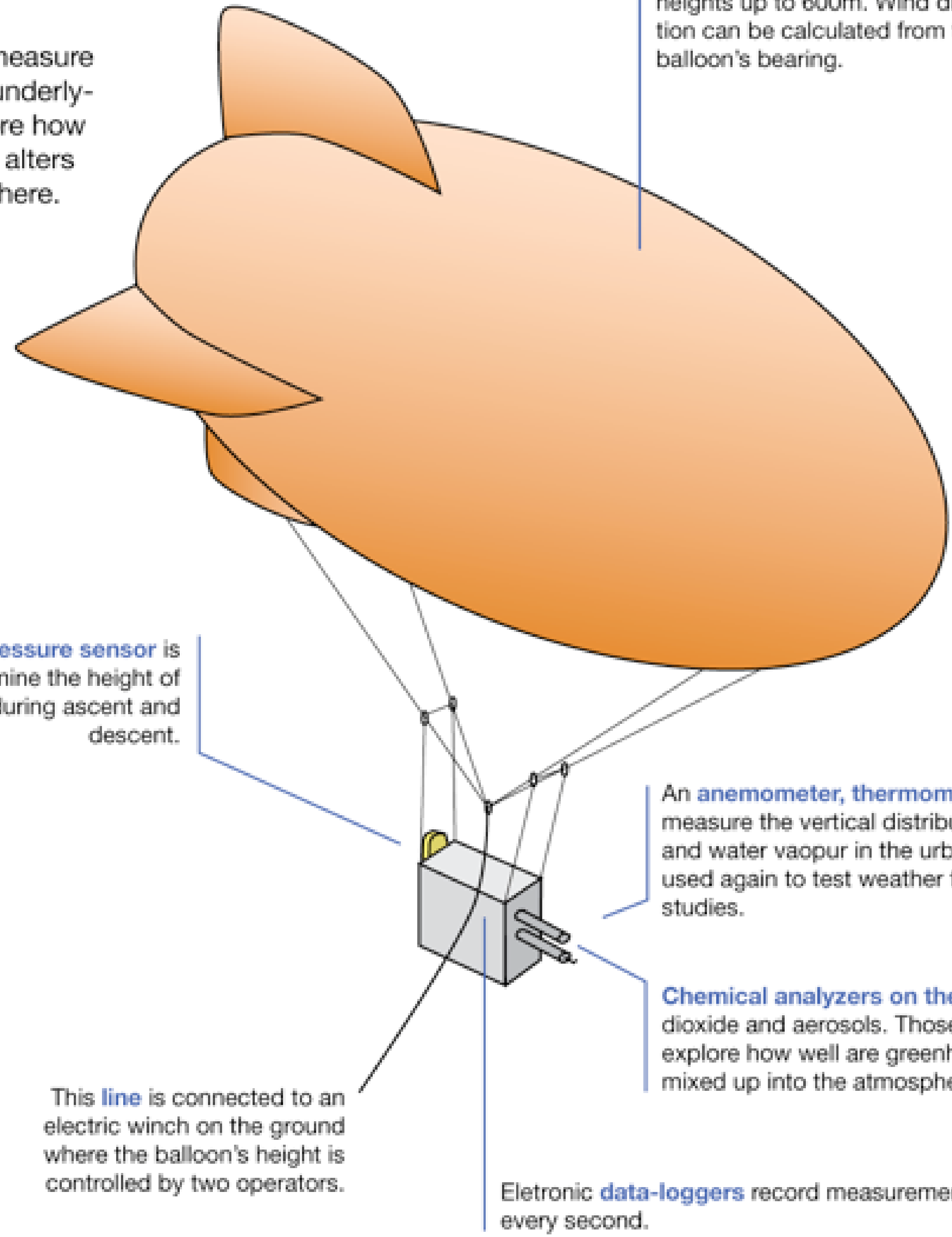
Photo: A. Christen

Photo: A. Christen

Photo: A. Christen

The tethered balloon is equipped with various instruments that probe the urban atmosphere above the height where towers can be errected.

In EPiCC, scientists use this balloon to measure how the atmosphere is modified by the underlying urban surface. For example, to explore how well pollutants are mixed or how the city alters temperature and humidity of the atmosphere.



Graph: A. Christen

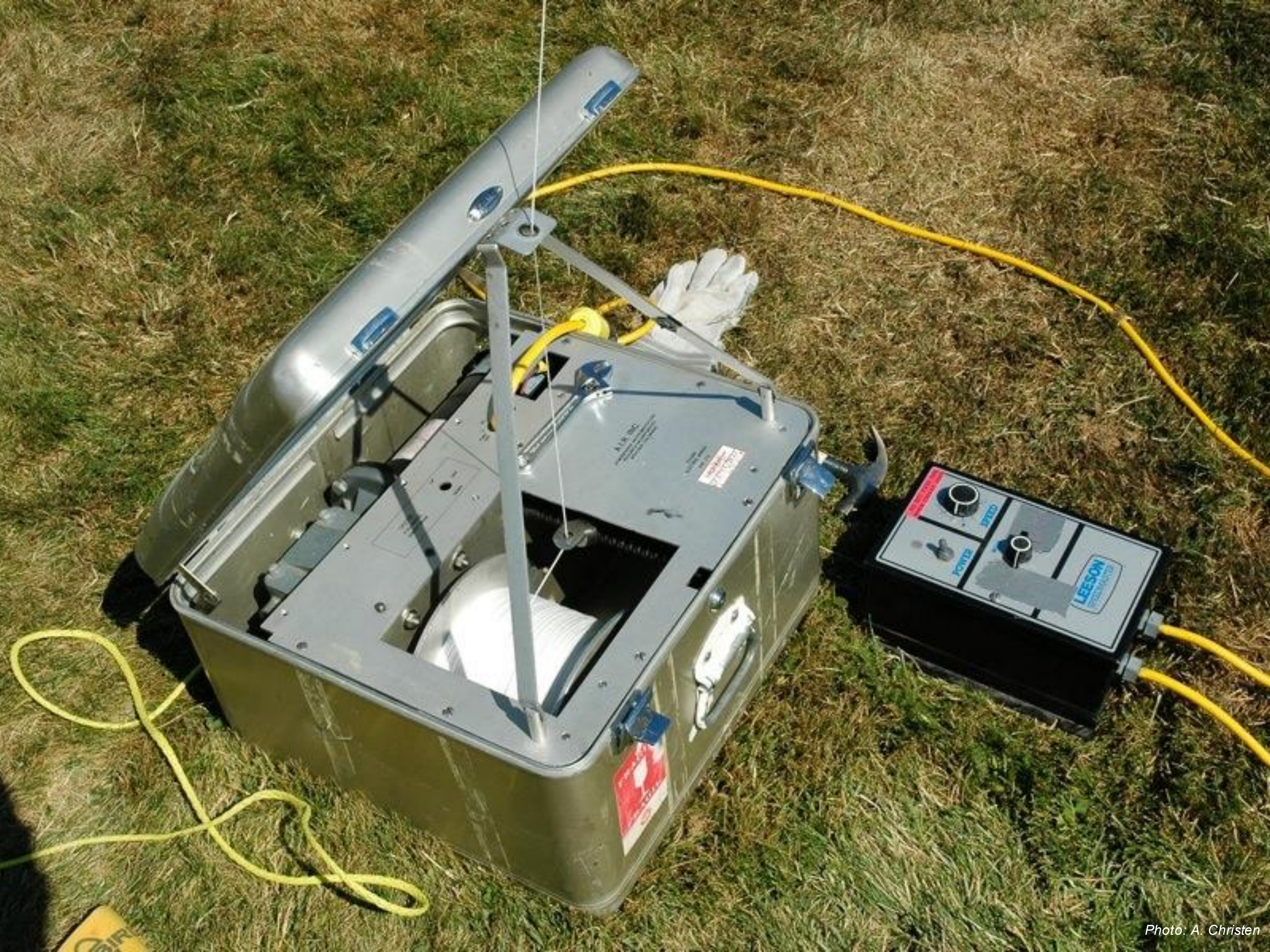
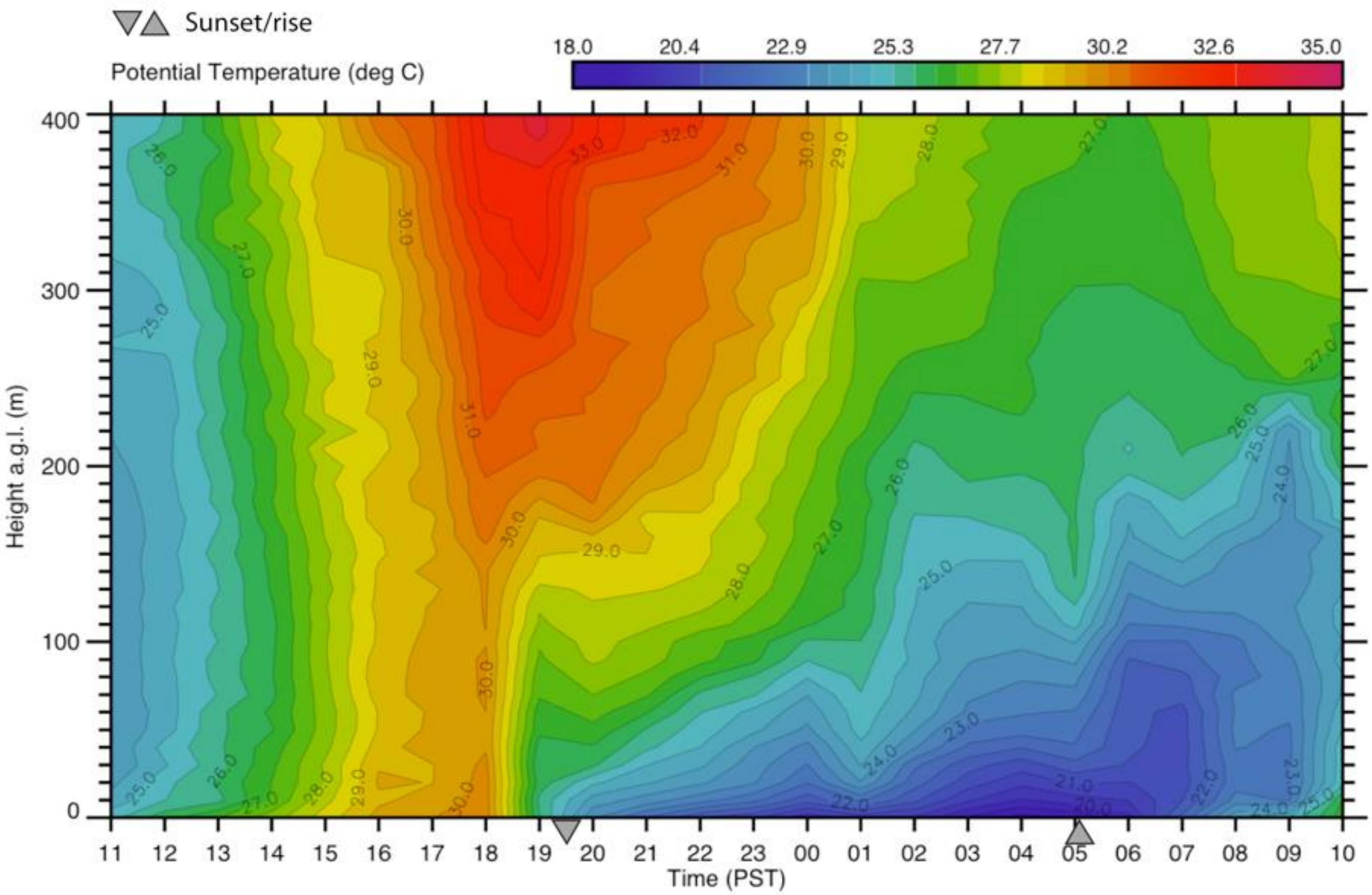
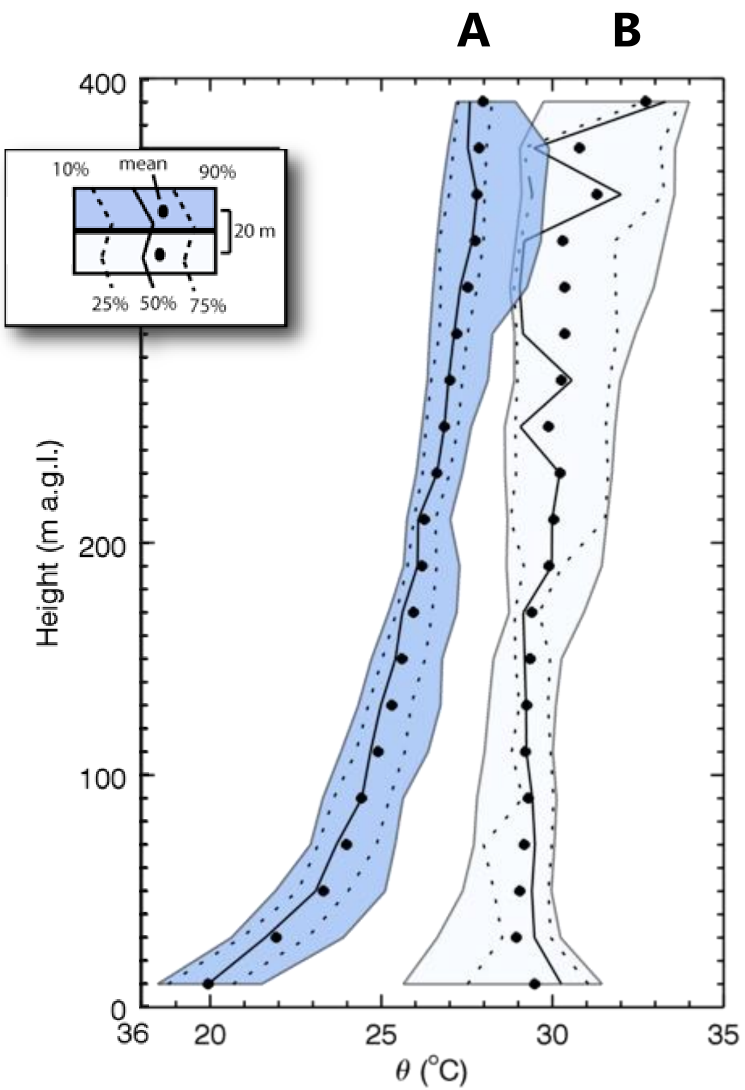


Photo: A. Christen

Temperature in the ABL over Vancouver



Potential temperature profiles day vs. night

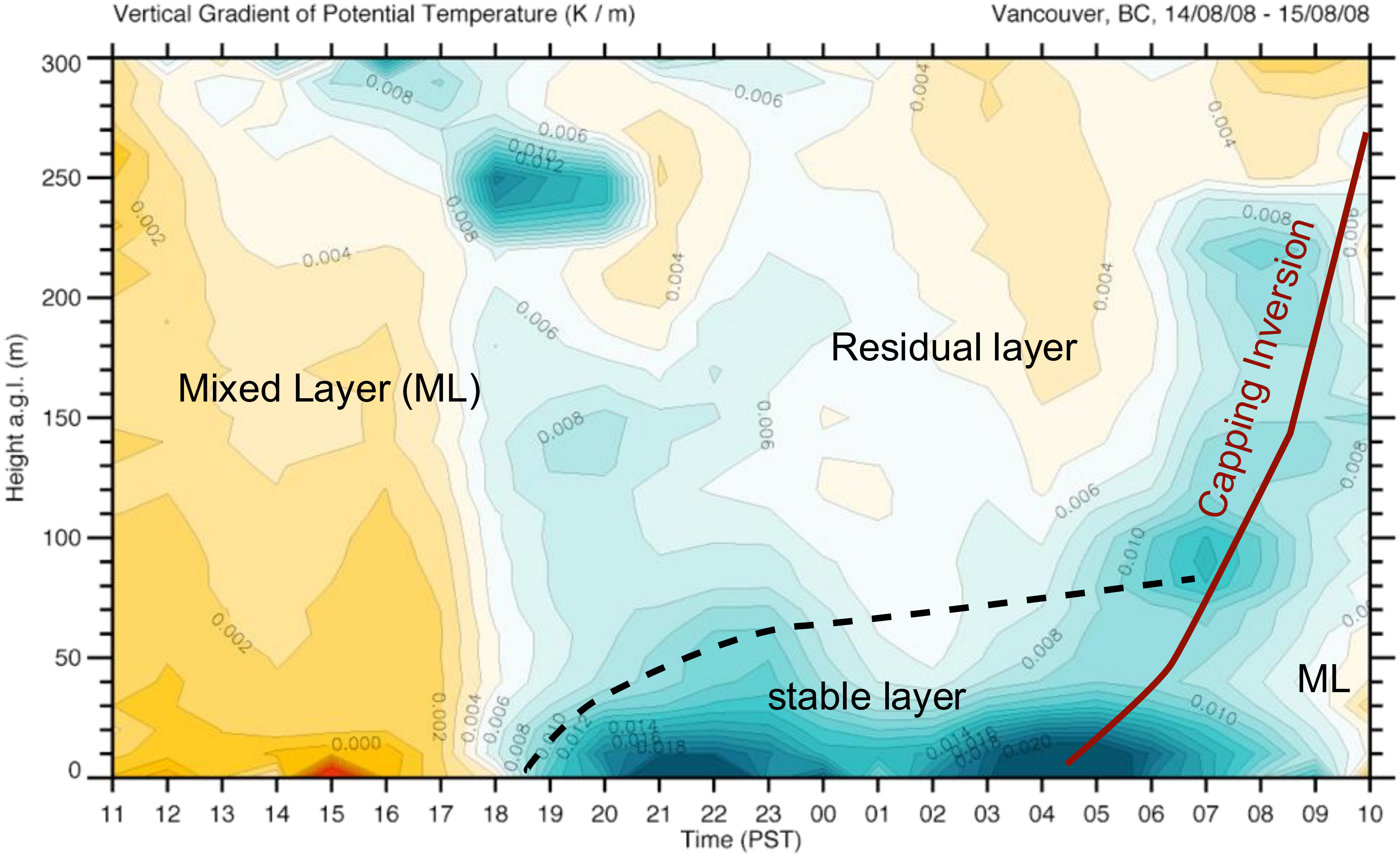


Which profile shows the **daytime** conditions?

B. Crawford, PhD Thesis in Geography, UBC, 2014

Join at
slido.com
#3273 402

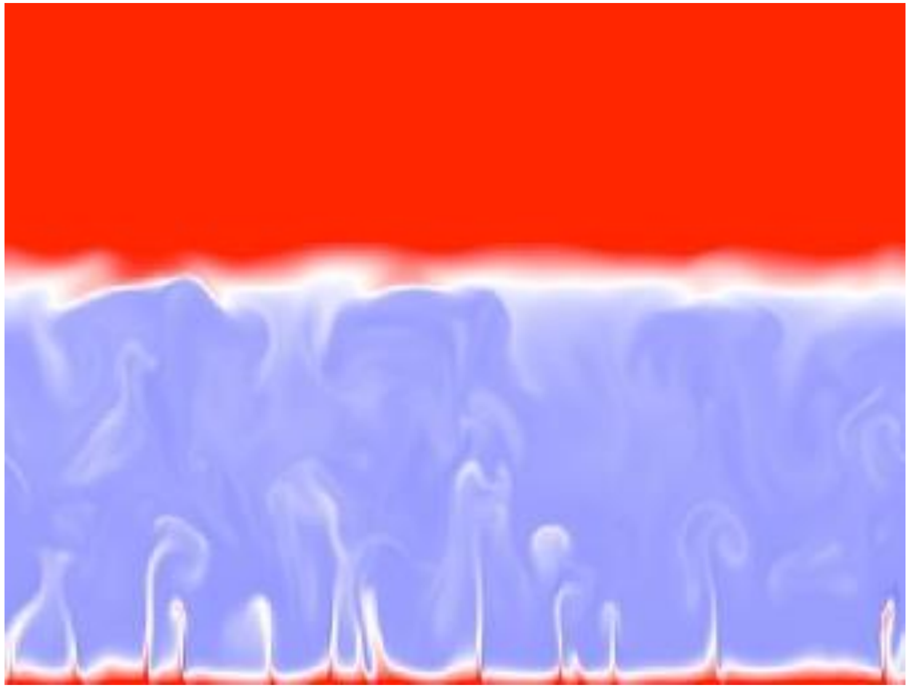
Temperature stratification over Vancouver



The Mixed Layer (ML)

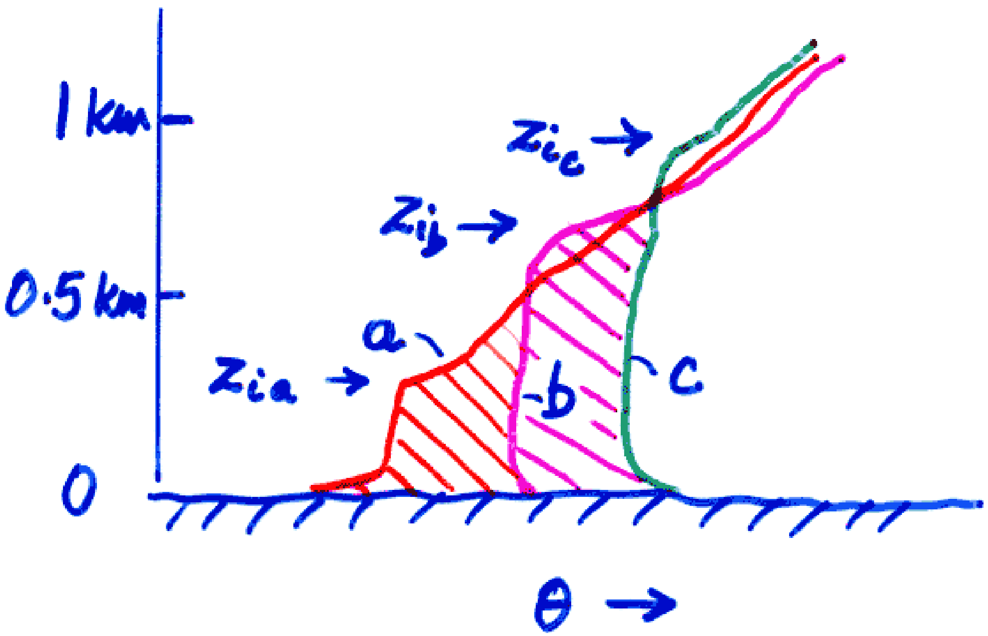
In the **convective boundary layer** apart from mechanical convection close to the surface (~lowest 100 m, surface layer), turbulence is driven solely by **thermal convection**.

Large plumes are originating from surface. These buoyancy driven cells need 10 to 15 minutes to turn over. Therefore, air is well mixed and θ is approximately constant with height - we call this layer from ~100 m up to 3 km the **mixed layer (ML)**.



Snapshot of the temperature field in a direct numerical simulation of convection in the ABL [Figure by Peter Sullivan (NCAR/MMM) and H. Jonker (Delft University, Netherlands)]

Daytime ML growth



Daytime progression

(a) soon after sunrise
(b) mid-morning
(c) later afternoon

Shaded area is total heat added between two times - integral of Q_H over z_i

Usually, growth depends on strength of Q_H at surface, but a CBL can be also formed by advection of stable air over a much warmer surface.

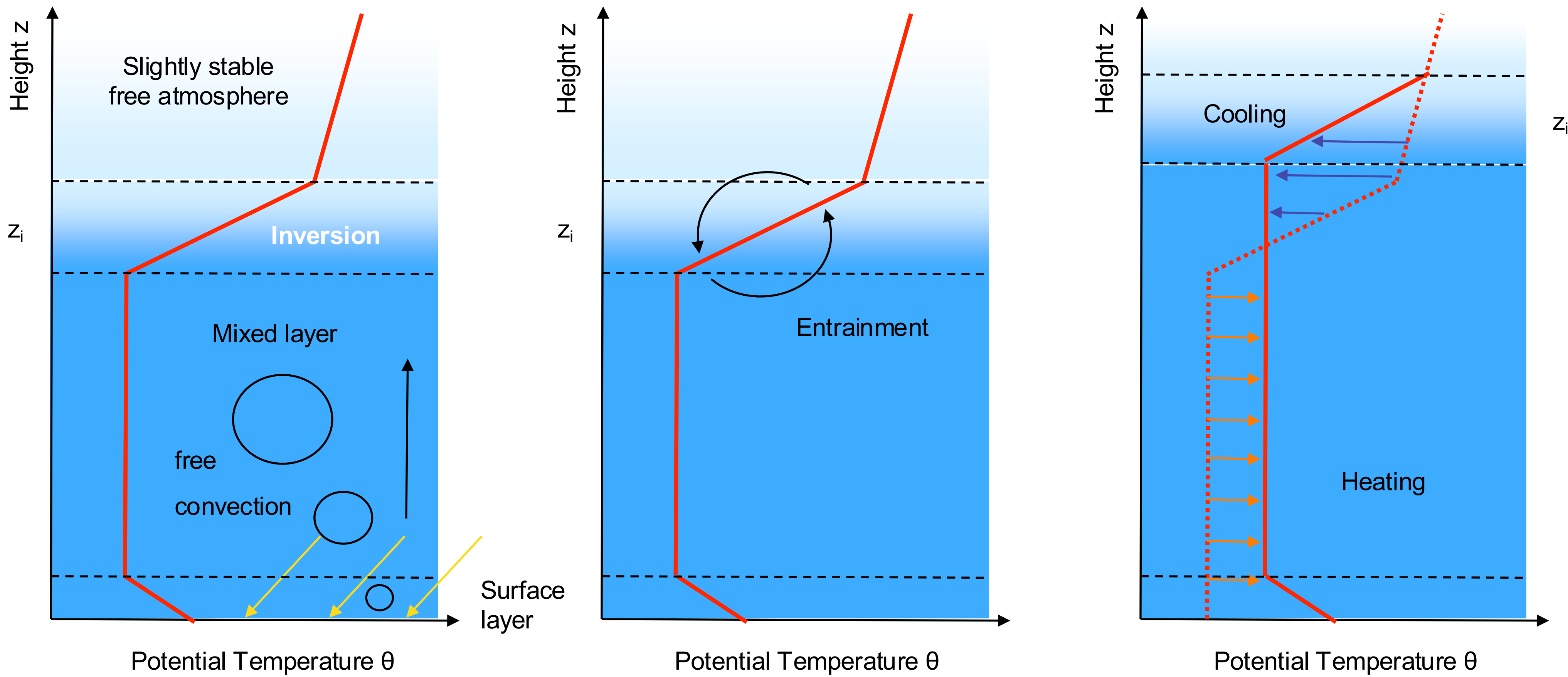
Entrainment zone

Thermals from surface layer and mixed layer overshoot into capping inversion at z_i (**entrainment zone**, EZ).

Acceleration due to buoyancy causes thermals to **penetrate some distance up into stable layer**, where they are repelled and returned to upper mixed layer. This brings downward flux of warmer, drier, cleaner, less turbulent air. This process is called entrainment.

▲ Capping inversion is typically at the height of fair-weather cumulus clouds (*cumulus humilis, A. Christen*).

Entrainment



Note, ABL growth is due to <u>both</u>, 'encroachment' from surface and 'entrainment' from free atmosphere above.

Discussion question

Briefly explain the difference between a convective boundary layer (CBL) and a stable boundary layer (SBL).

A. Free atmosphere

B. Surface Layer

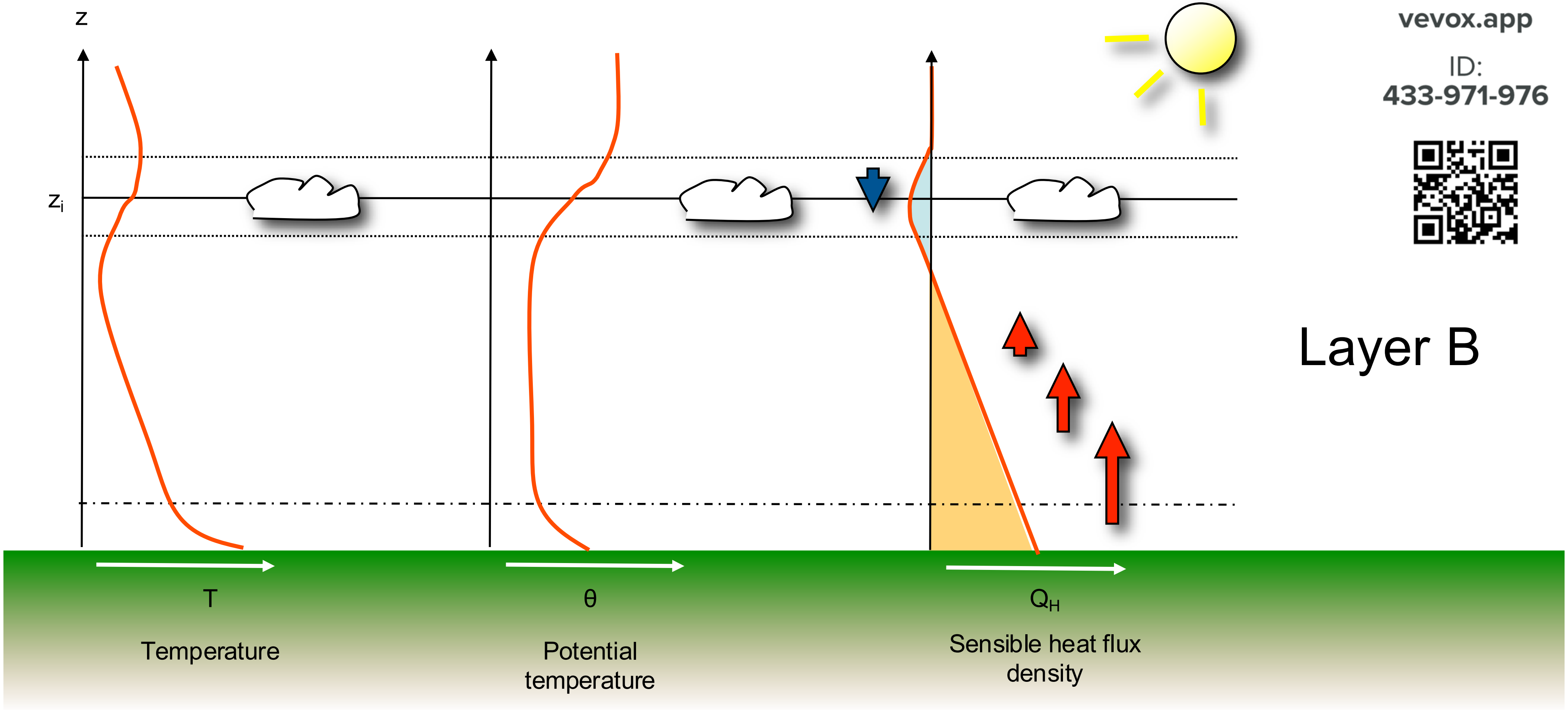
C. Mixed Layer

D. Entrainment Zone

What is layer B called?

Join at:
vevox.app

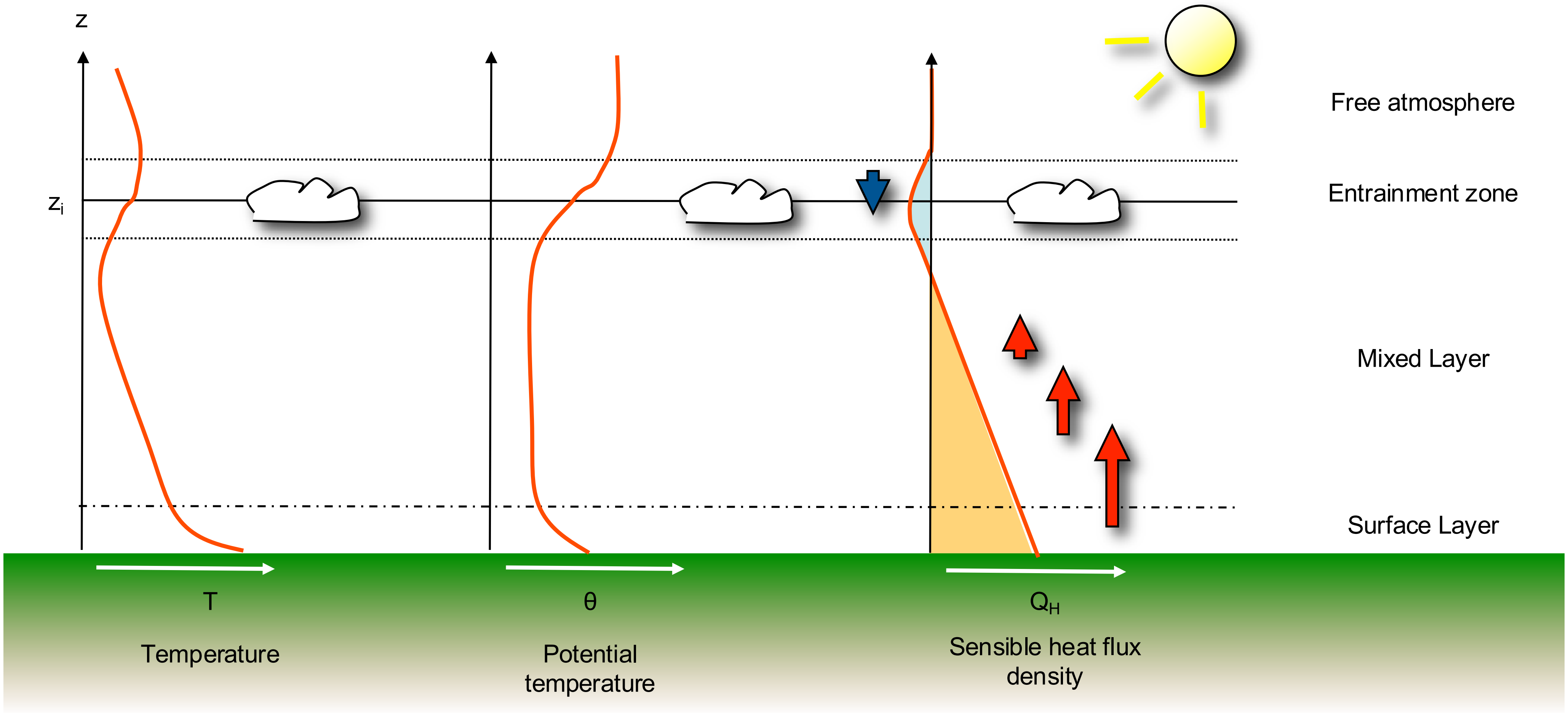
ID:
433-971-976



Layer B

Modified from R. B. Stull, 1997 'An Introduction to Boundary Layer Meteorology'.

Sensible heat flux density in the CBL



Modified from R. B. Stull, 1997 'An Introduction to Boundary Layer Meteorology'.

Surface to entrainment heat flux

During free convection (when winds are weak and thermal convection is strong), the entrained heat flux at top $Q_{H,ent}$ of the ABL is approximately 20% of the surface heat flux $Q_{H,0}$:

$$Q_{H,\text{ent}} = -A\,Q_{H,0}$$

Where A is the **Ball ratio**. This only works for sensible heat.

A measured vertical profile of daytime Q_H

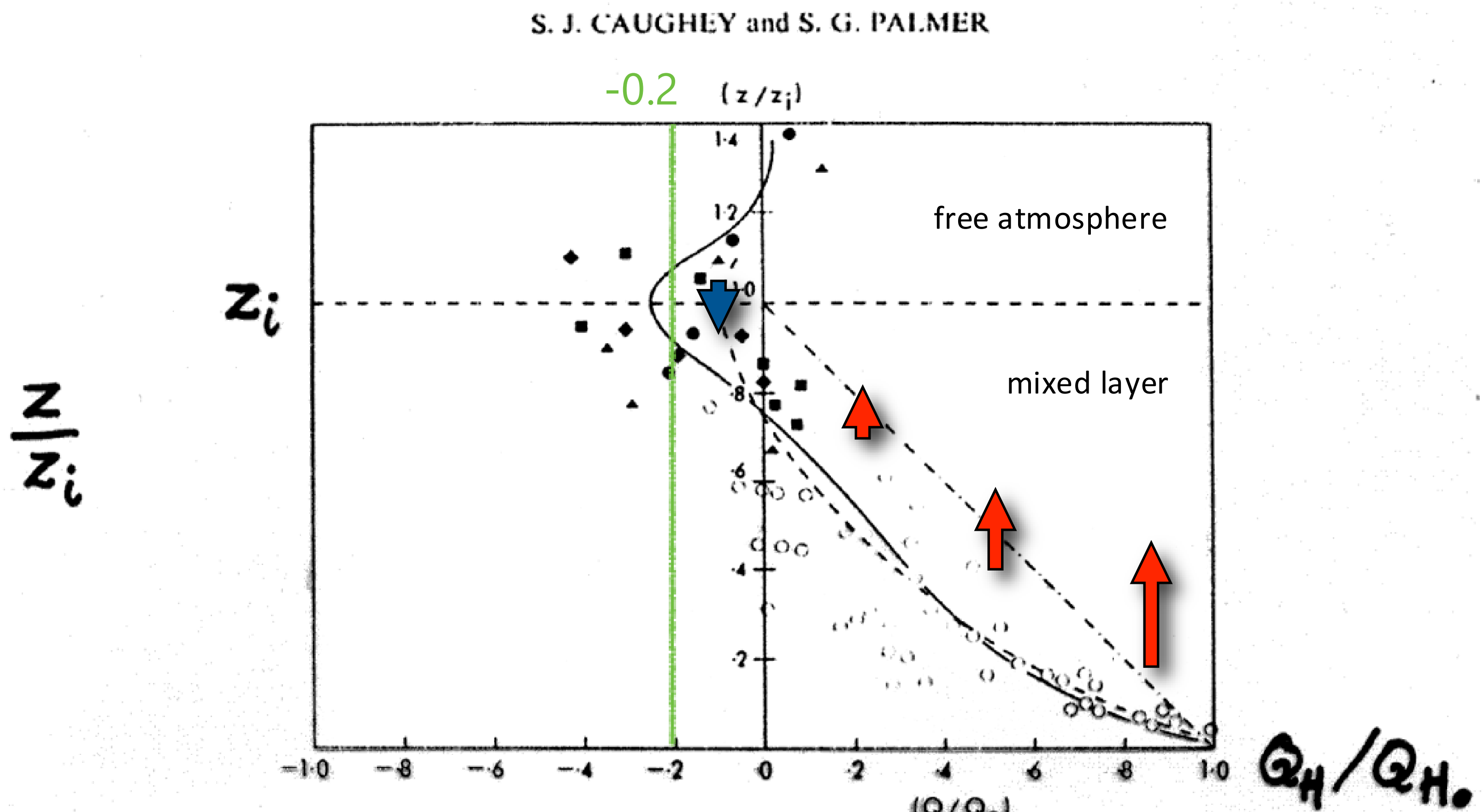
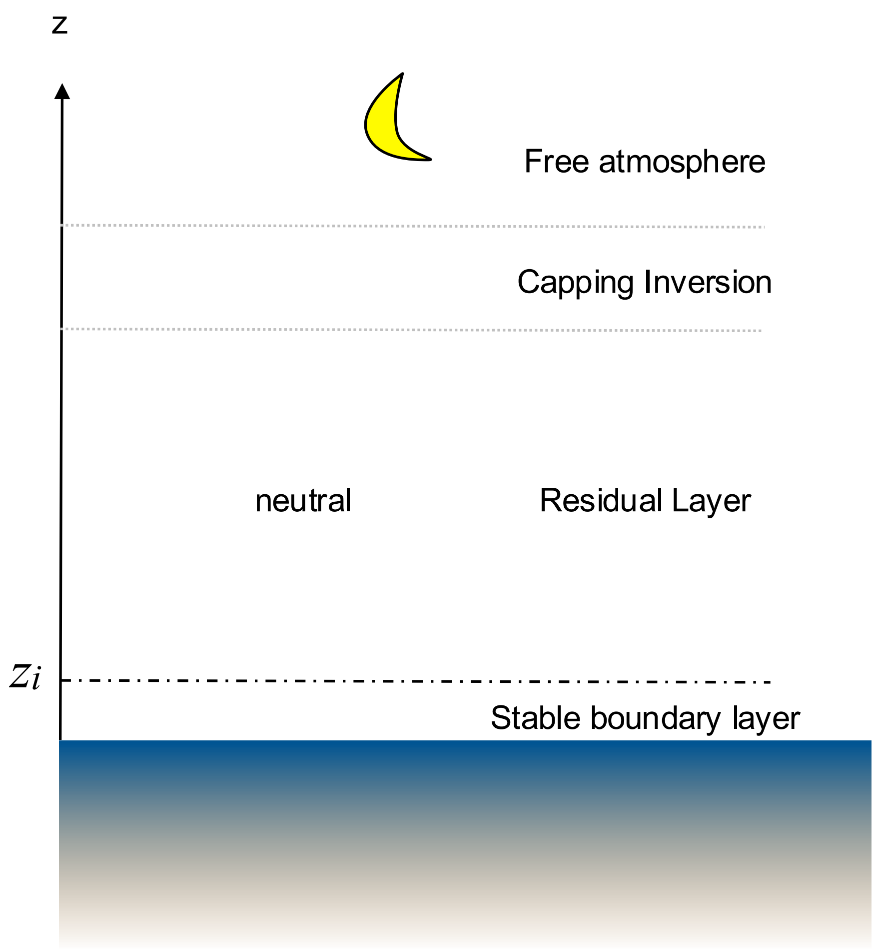


Figure 3. Normalized heat flux data from the Ashchurch and Minnesota experiments. The Ashchurch data are coded as in Fig. 2; the Minnesota data are shown by open circles. The dash-dot line indicates a linear fall-off with height; the dashed line represents Lenschow's (1970) aircraft results as presented by Deardorff (1972). The solid line is drawn through the Ashchurch + Minnesota data points.

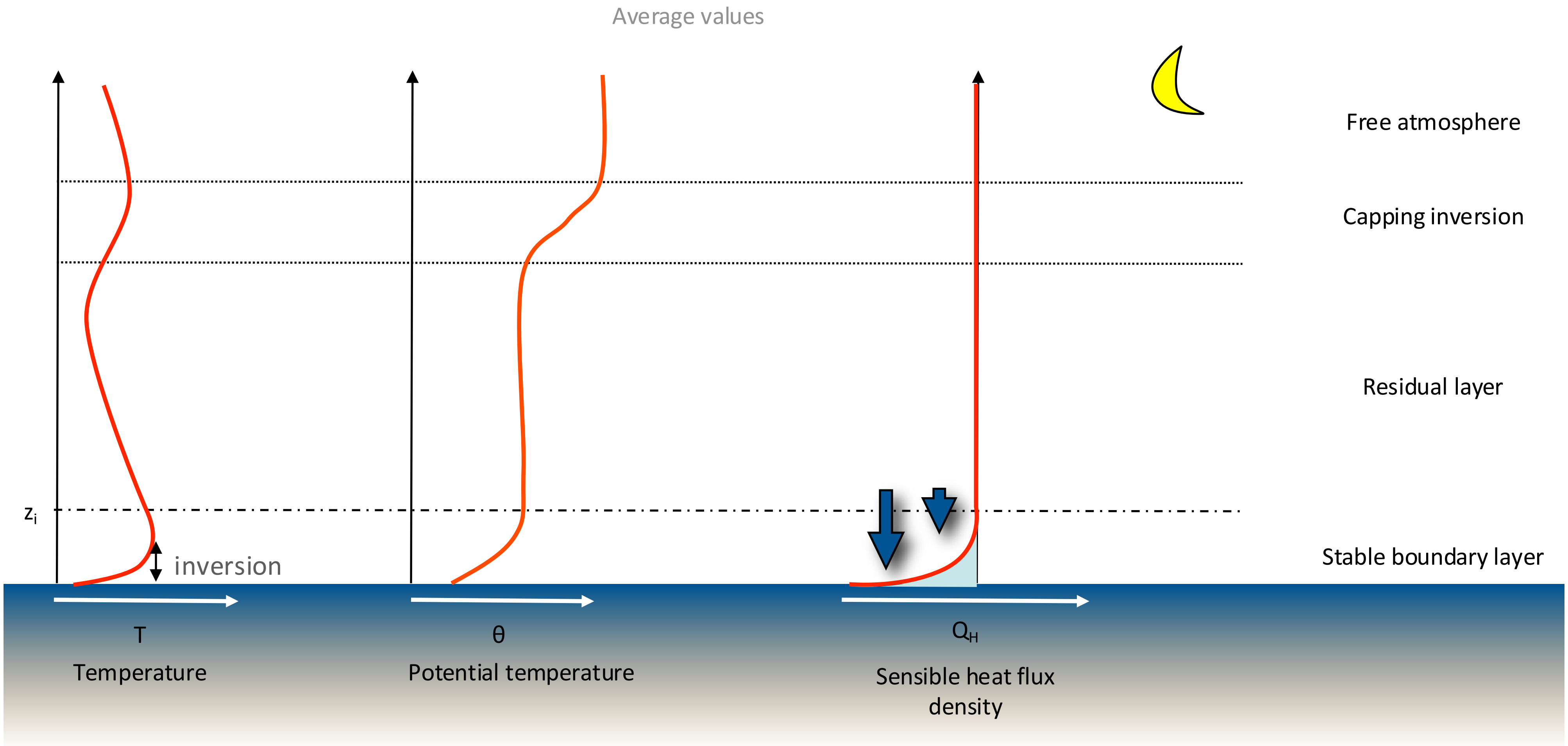
The vertical structure of the nocturnal boundary layer

Potential temperature profile defines the depth of the stable boundary layer, but may be hard to identify top (merges) - typically 100 - 300 m on a clear sky night.

In the ABL above the stable boundary layer we find the **residual layer**, remnants of previous day's CBL, weak mixing continues. It shows the properties of the decayed daytime mixed layer.



Temperatures in the nocturnal boundary layer

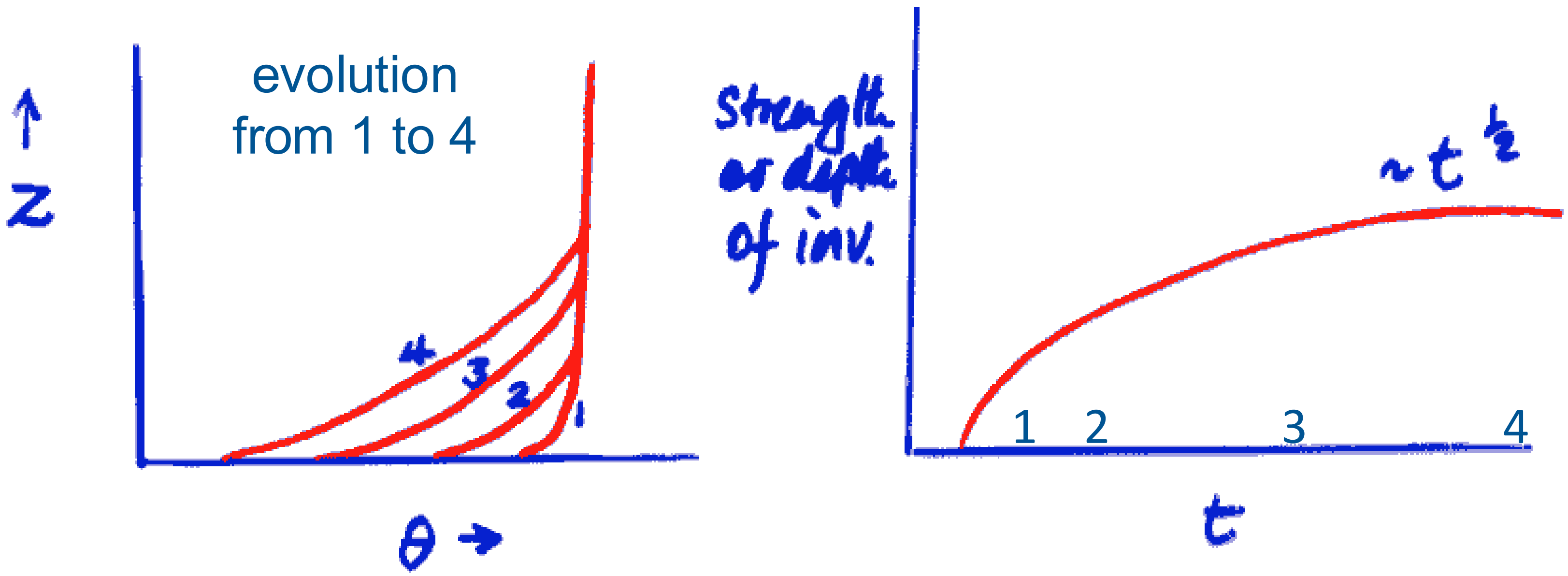


Modified from R. B. Stull, 1997 'An Introduction to Boundary Layer Meteorology'.

Stable boundary layer evolution

In the **stable boundary layer** surface radiative cooling invokes downward flux of sensible heat via inversion. Typically over land this is during night.

A stable boundary layer can also form over cold surfaces (e.g warm air masses advected over cold lake, glacier, snow).



Measured vertical profiles of moisture

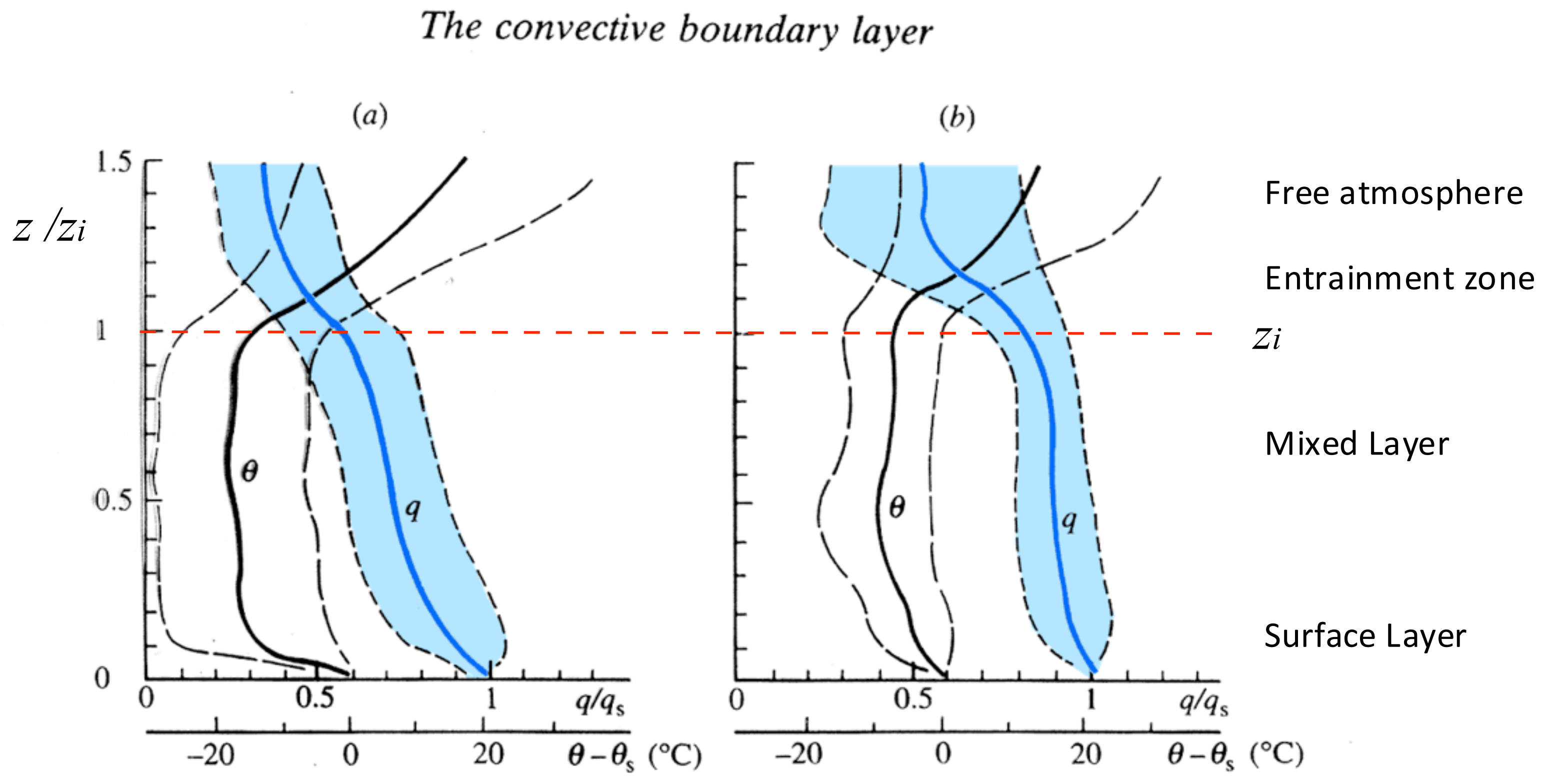
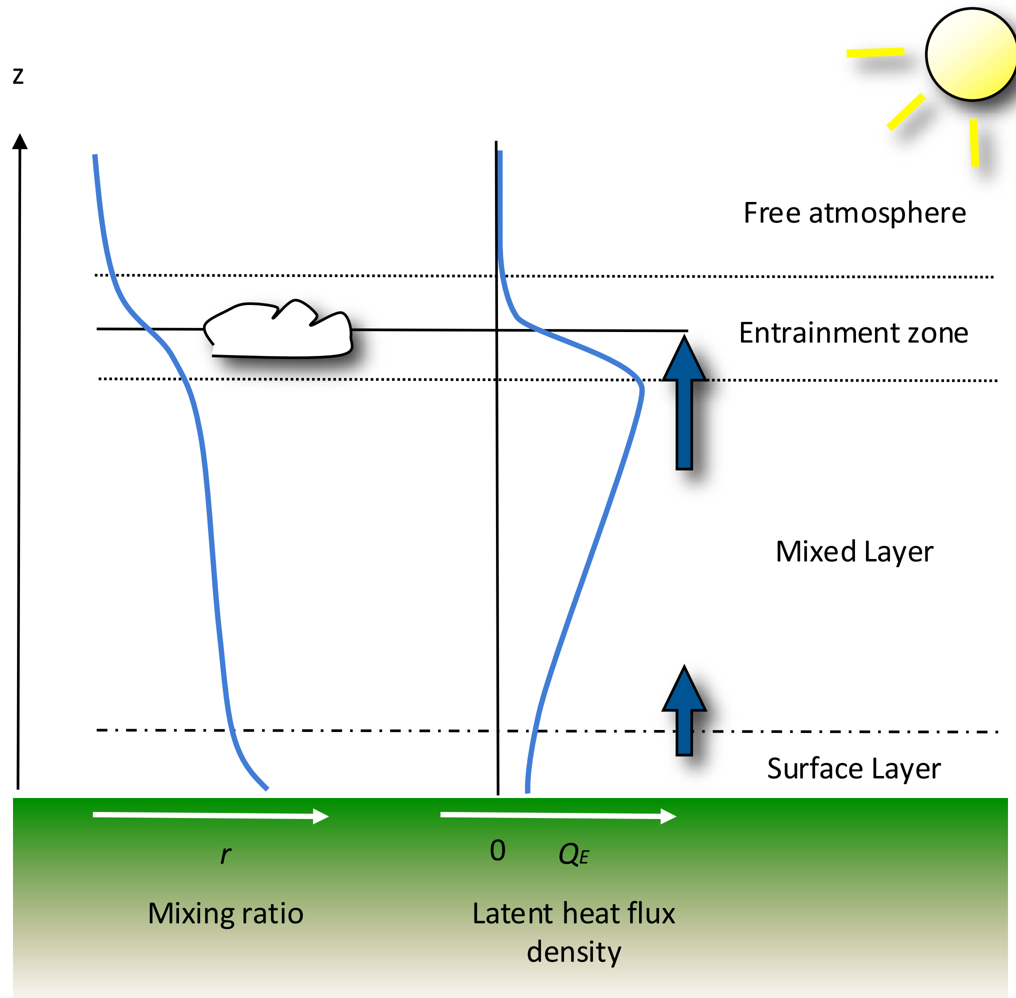


Fig. 6.8 Mean CBL profiles of θ and q observed in (*a*) north-east Colorado and (*b*) south-eastern Australia. Before averaging, q data were normalized by the screen-level value, and θ data were reduced by the screen-level value. In (*a*), mean $h = 1710$ m, mean $q_s = 0.0093$; in (*b*), mean $h = 915$ m and mean $q_s = 0.0041$. Pecked lines denote standard deviations about the mean profiles. After Mahrt (1976), *Monthly Weather Review*, American Meteorological Society.

Moisture in the daytime CBL

The drier free atmosphere produces a **drying flux through the entrainment zone**. So profiles of the mixing ratio *r* tend to decline through the mixed layer, and sharply above.

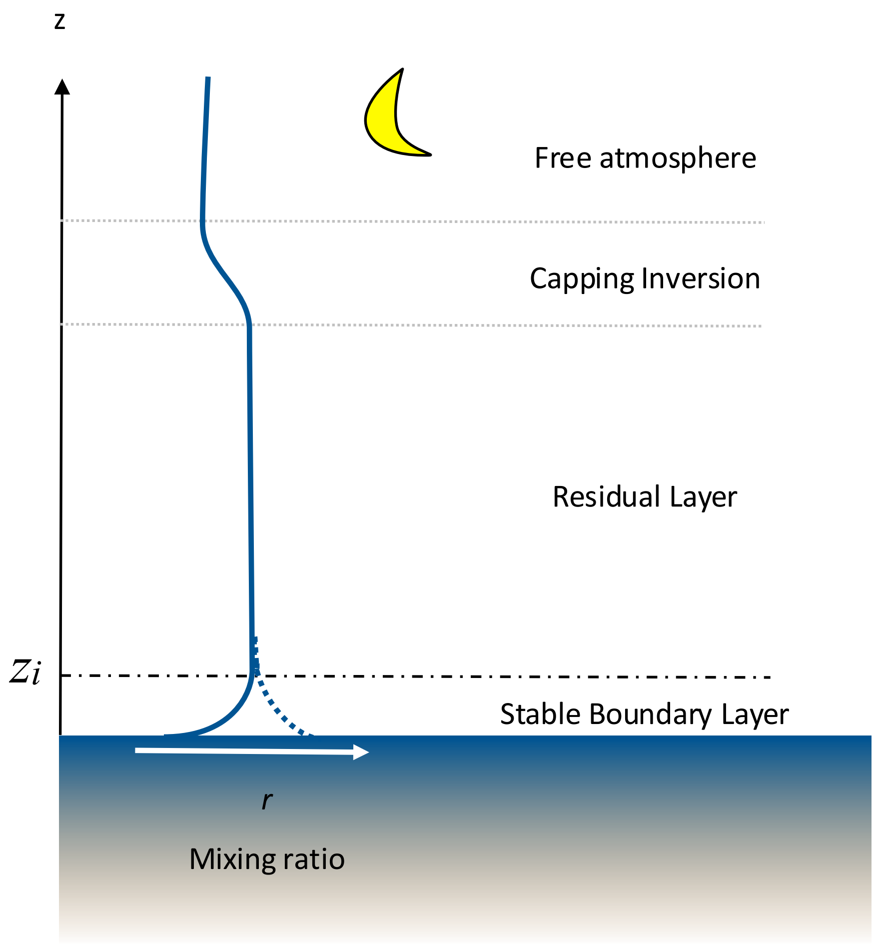
The amount of boundary layer moistening by day depends on relative strength of surface (moistening) and entrainment (drying) fluxes.



Moisture in the SBL

At night, the stable boundary layer shows relatively small gradients in the water mixing ratio *r* and can be of either sign:

Inversion → dewfall
lapse → evaporation



Take home points

- The Atmospheric boundary layer is responding to **energetic changes of the surface**, i.e.the surface energy balance.
- Thermal convection is the dominating mixing process in the daytime mixed layer. The ML grows due to **encroachment** and **entrainment**.
- A **stable boundary layer** with suppressed mixing develops during night and over cool surfaces (ice etc.).
- A drying flux through the entrainment zone is observed, as the free atmosphere is less humid that the ABL.