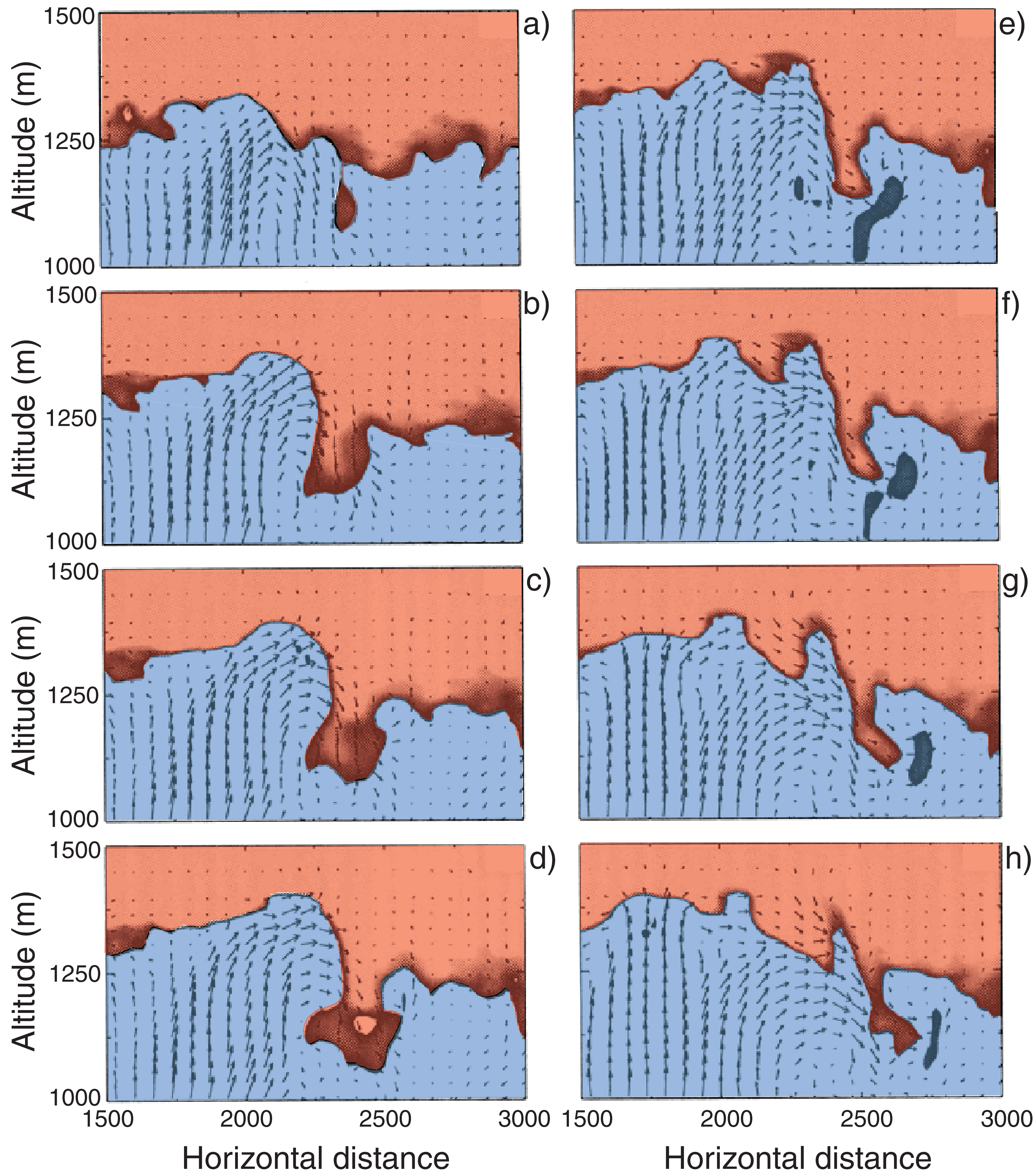
The Atmospheric Boundary Layer

- Turbulence (9.1)
- The Surface Energy Balance (9.2)
- Vertical Structure (9.3)
- ***Evolution (9.4)***
- Special Effects (9.5)
- The Boundary Layer in Context (9.6)

What processes control the depth of the boundary layer?

- Entrainment
- Large-scale vertical velocity
- Horizontal advection

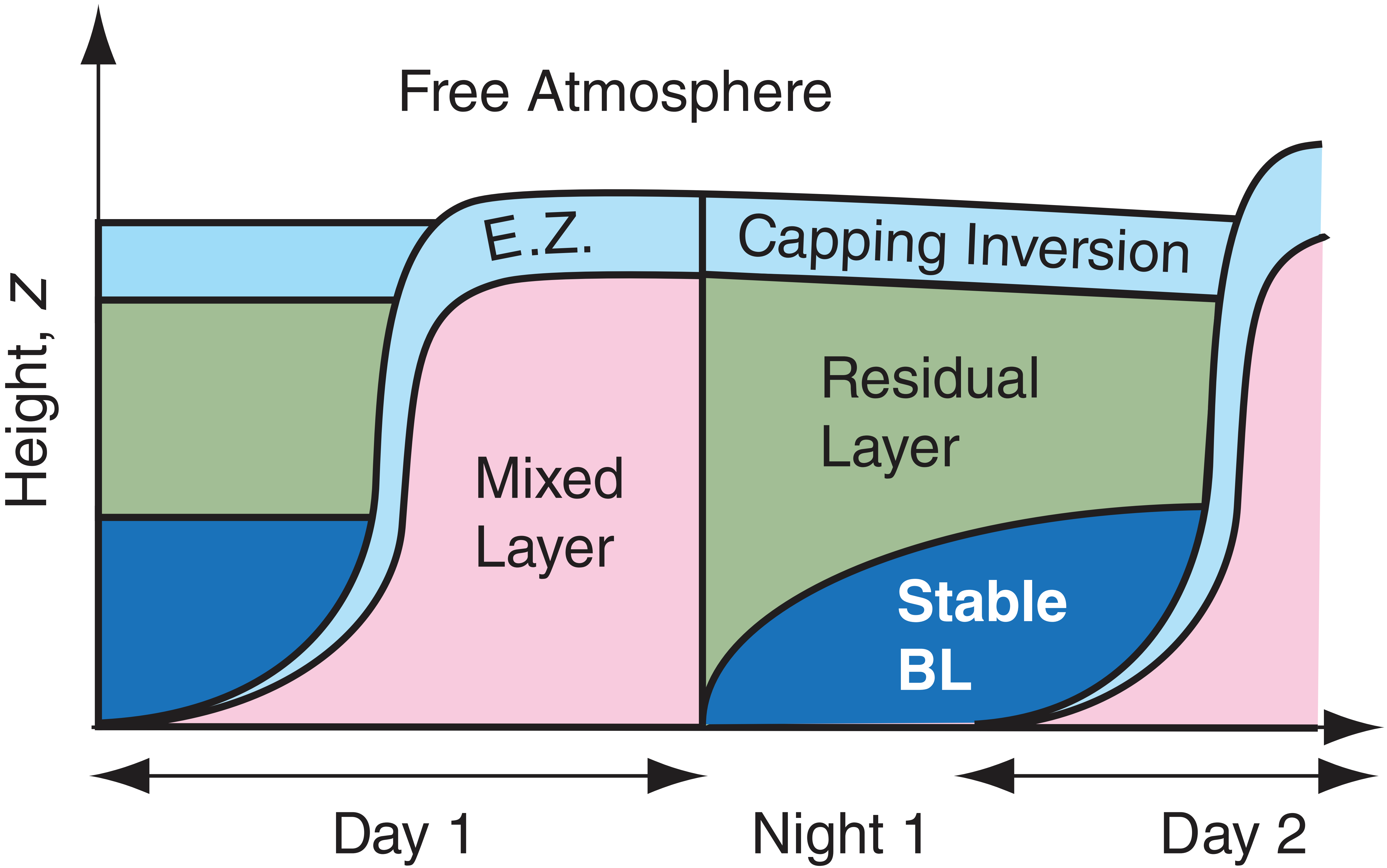
Entrainment



Entrainment

- *Entrainment* occurs whenever a non-turbulent volume is incorporated into a turbulent volume.
- Entrainment increases the depth of the boundary layer.
- *Detrainment* occurs whenever a turbulent volume becomes non-turbulent.

Entrainment



E.Z. = Entrainment Zone

Entrainment

In winter, the stable nocturnal BL is much deeper, and the daytime mixed layer is so shallow that the top of the stable BL persists day and night as the capping inversion.

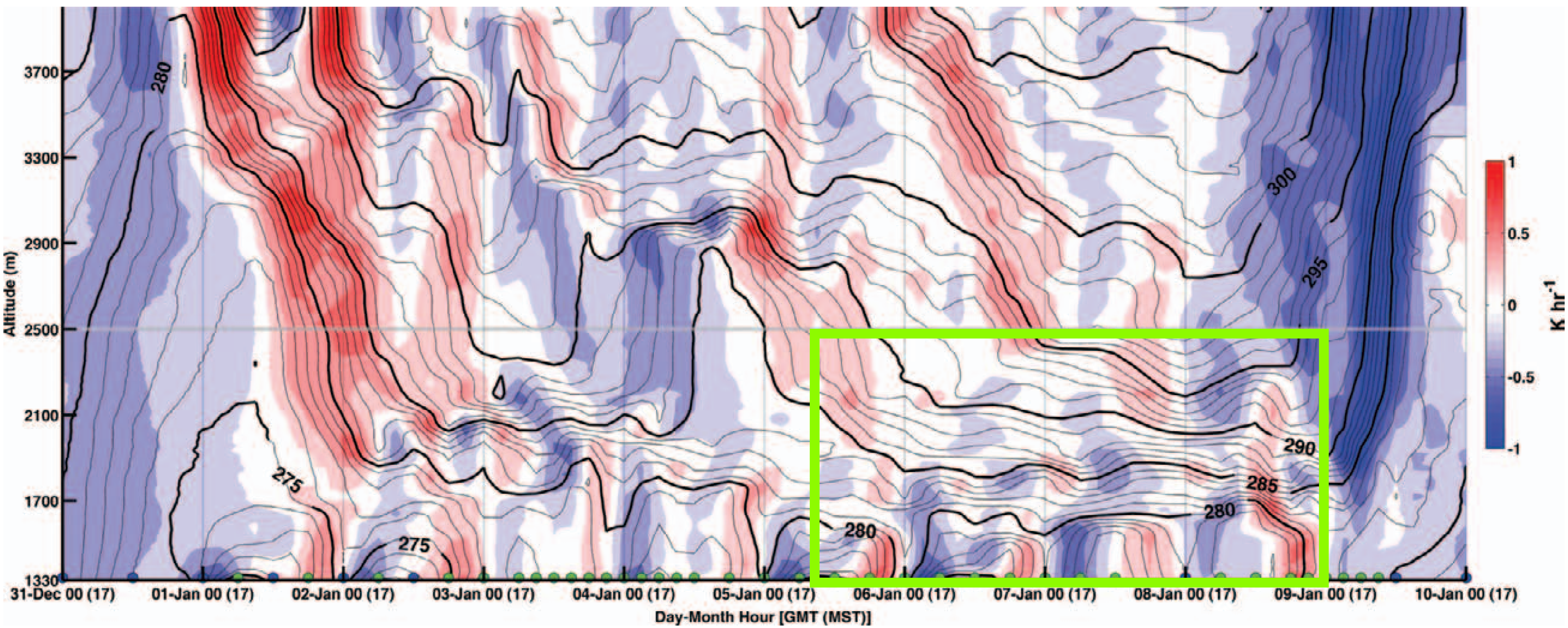
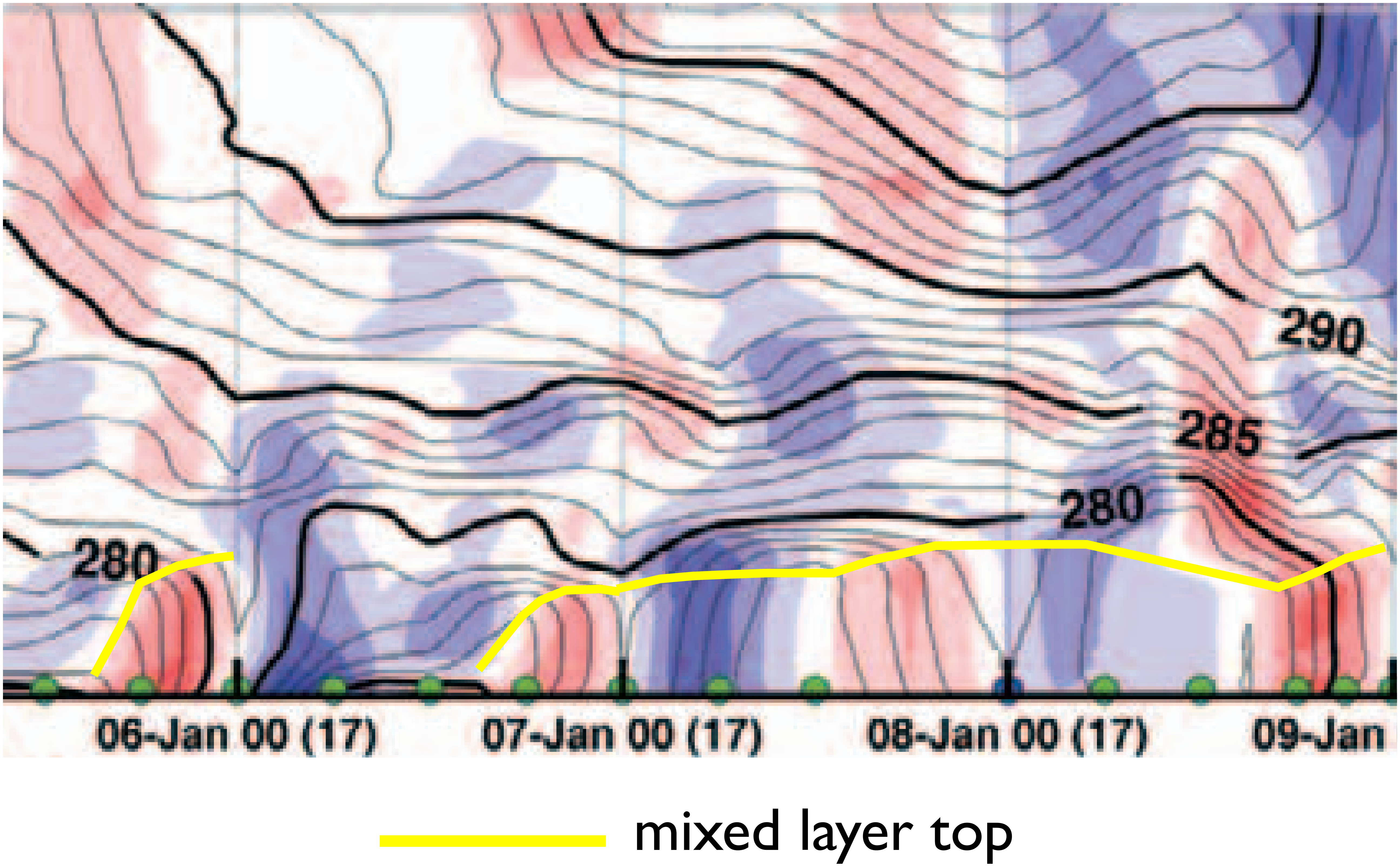
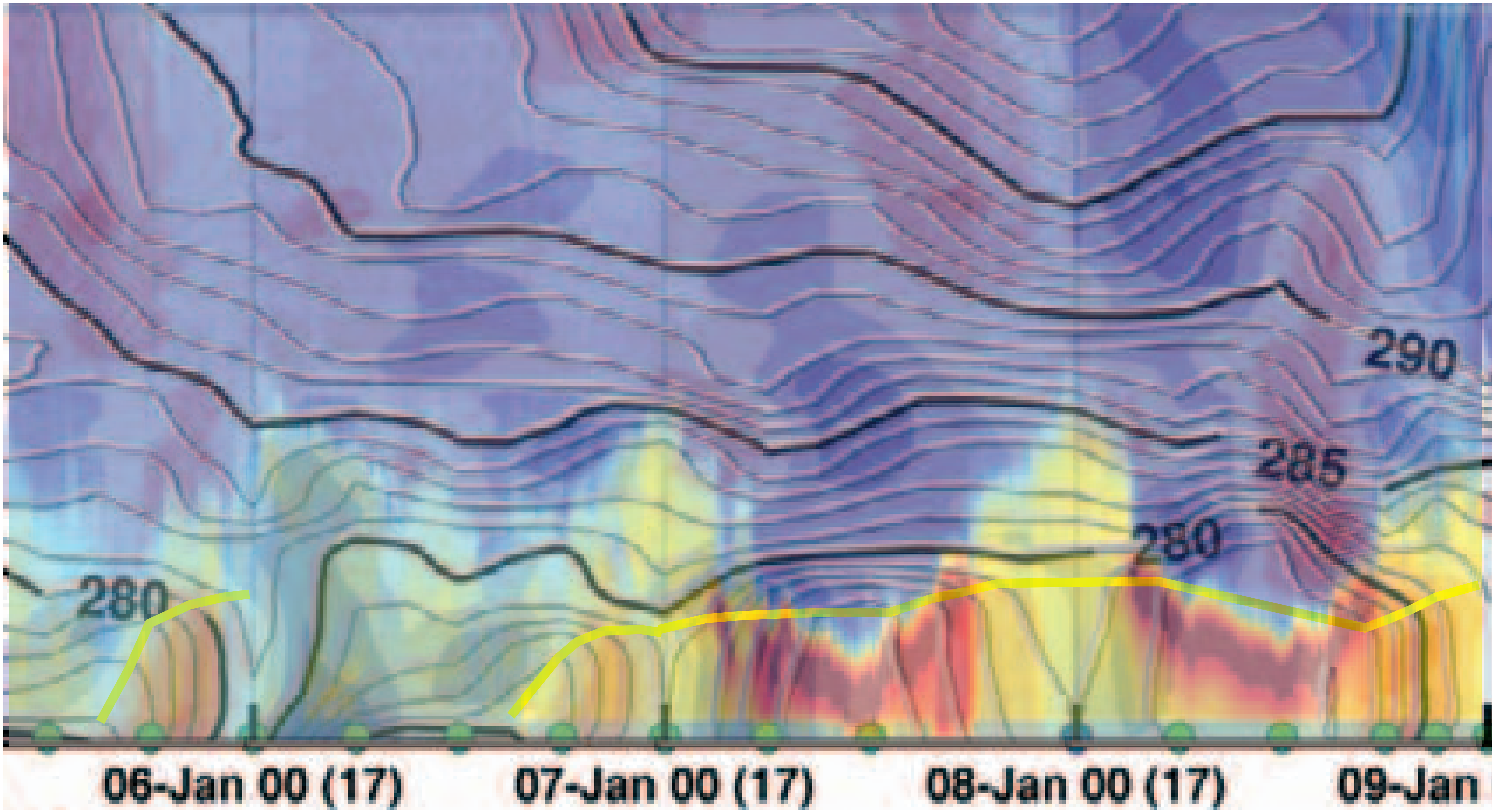


FIG. 6. Time–height plot of potential temperature during IOP 5. Isentropes are indicated by contours (bold contours every 5 K and light contours every 1 K). The 1-h change in potential temperature is indicated in shading to highlight periods of warming and cooling. The gray line at 2,500 m indicates the approximate elevation of the mountain crests that enclose the SLV. Green (blue) dots indicated the time of ISS (NWS) radiosonde launches.

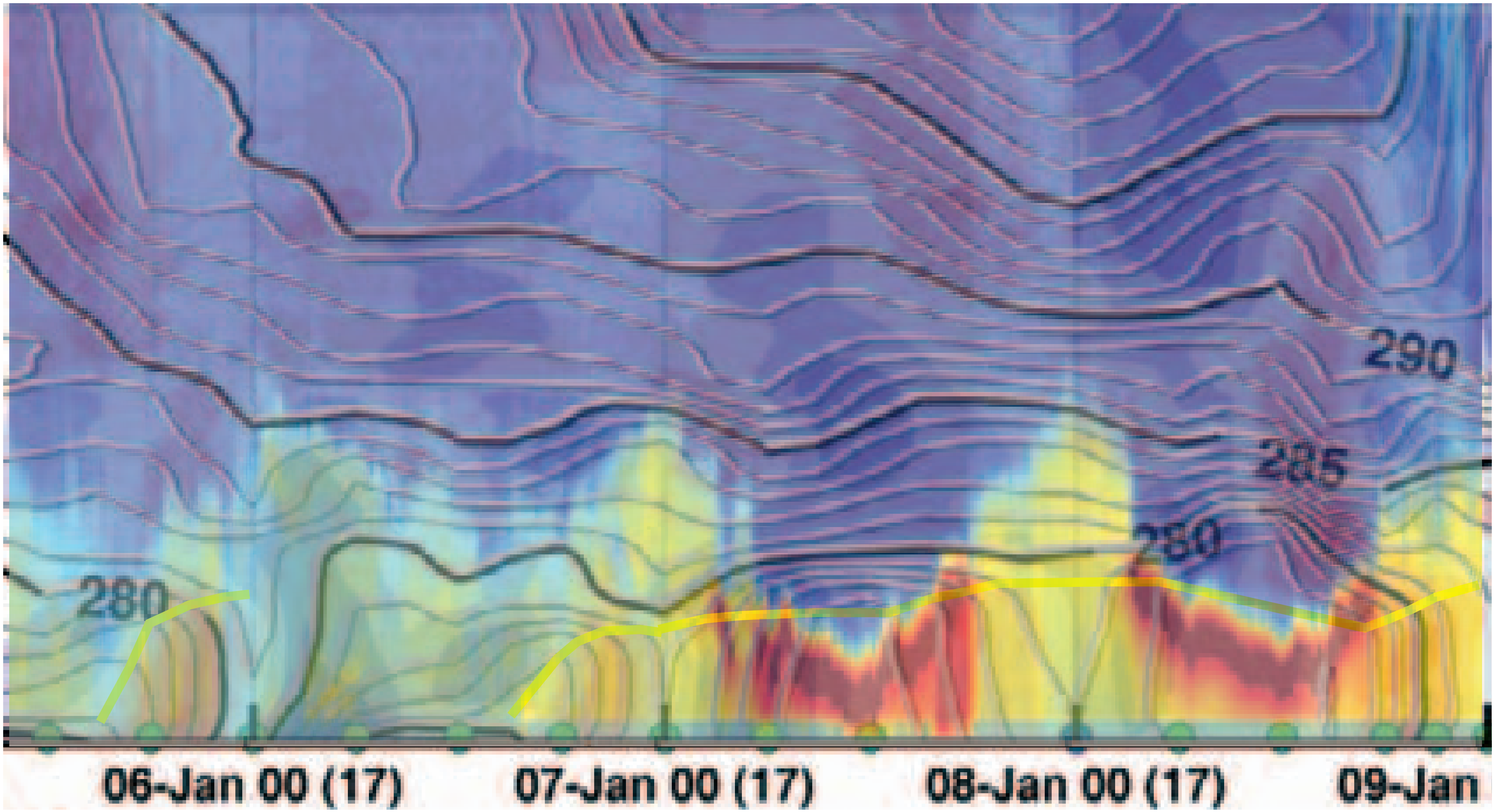
Entrainment



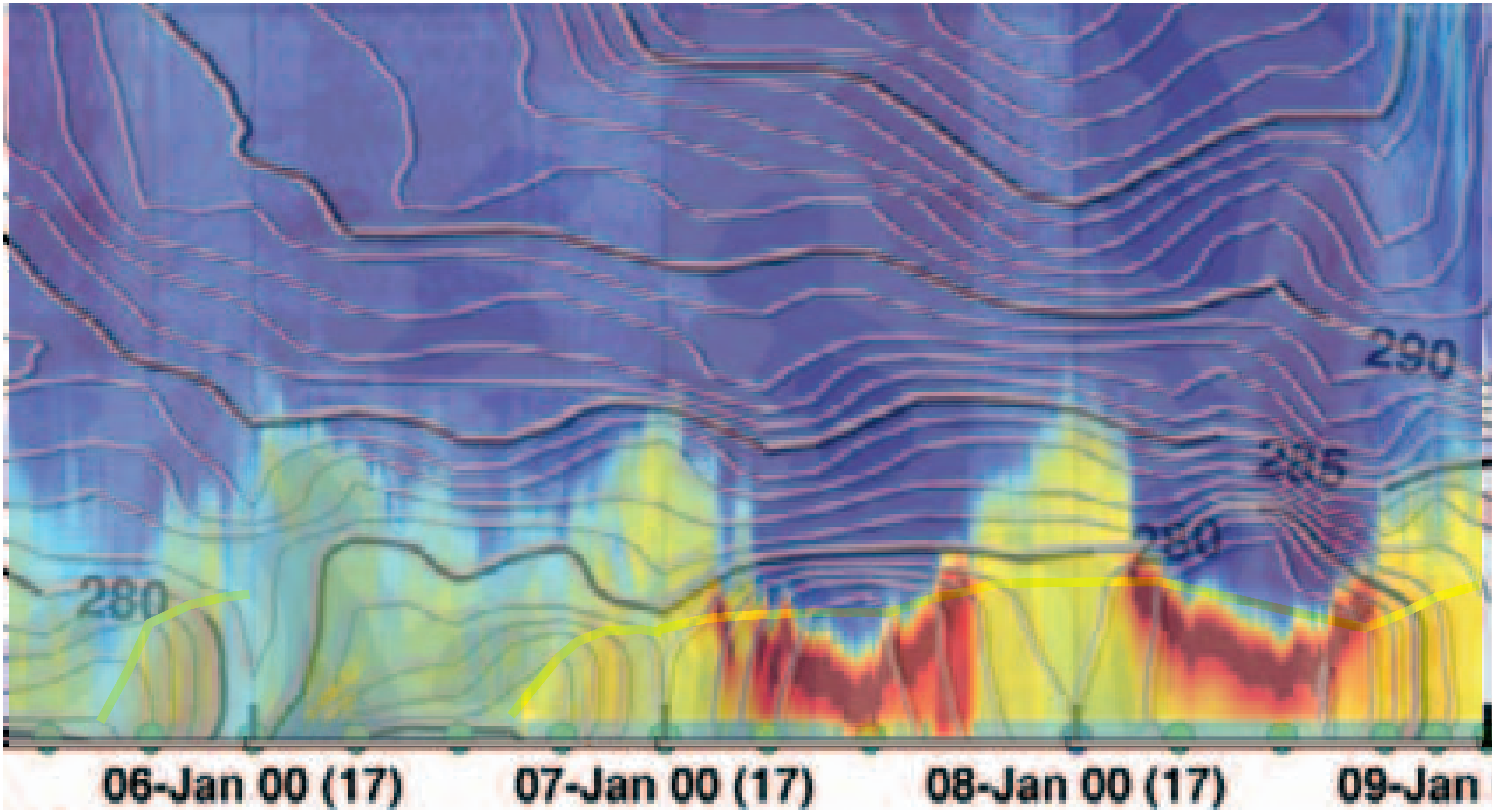
Entrainment



Entrainment

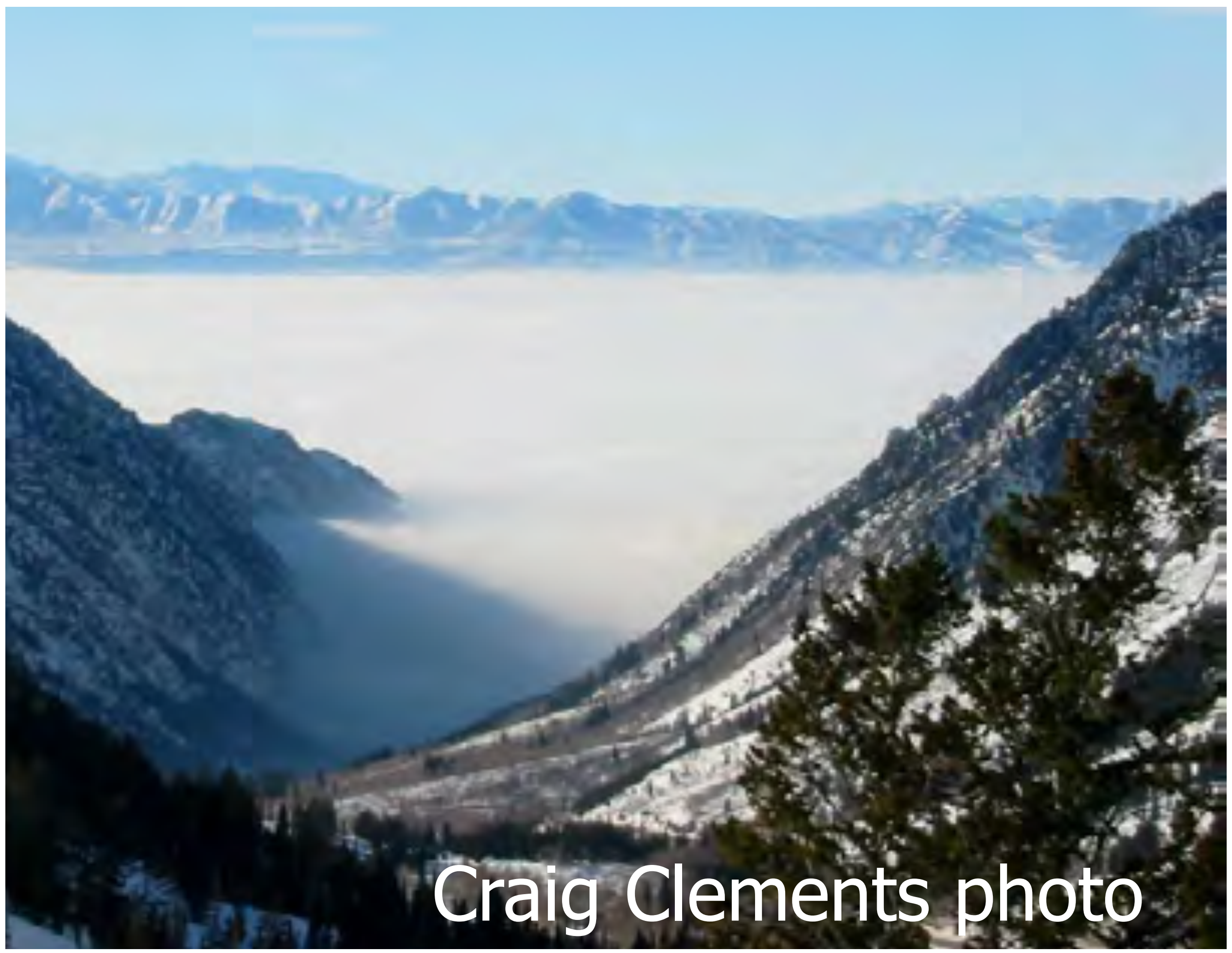


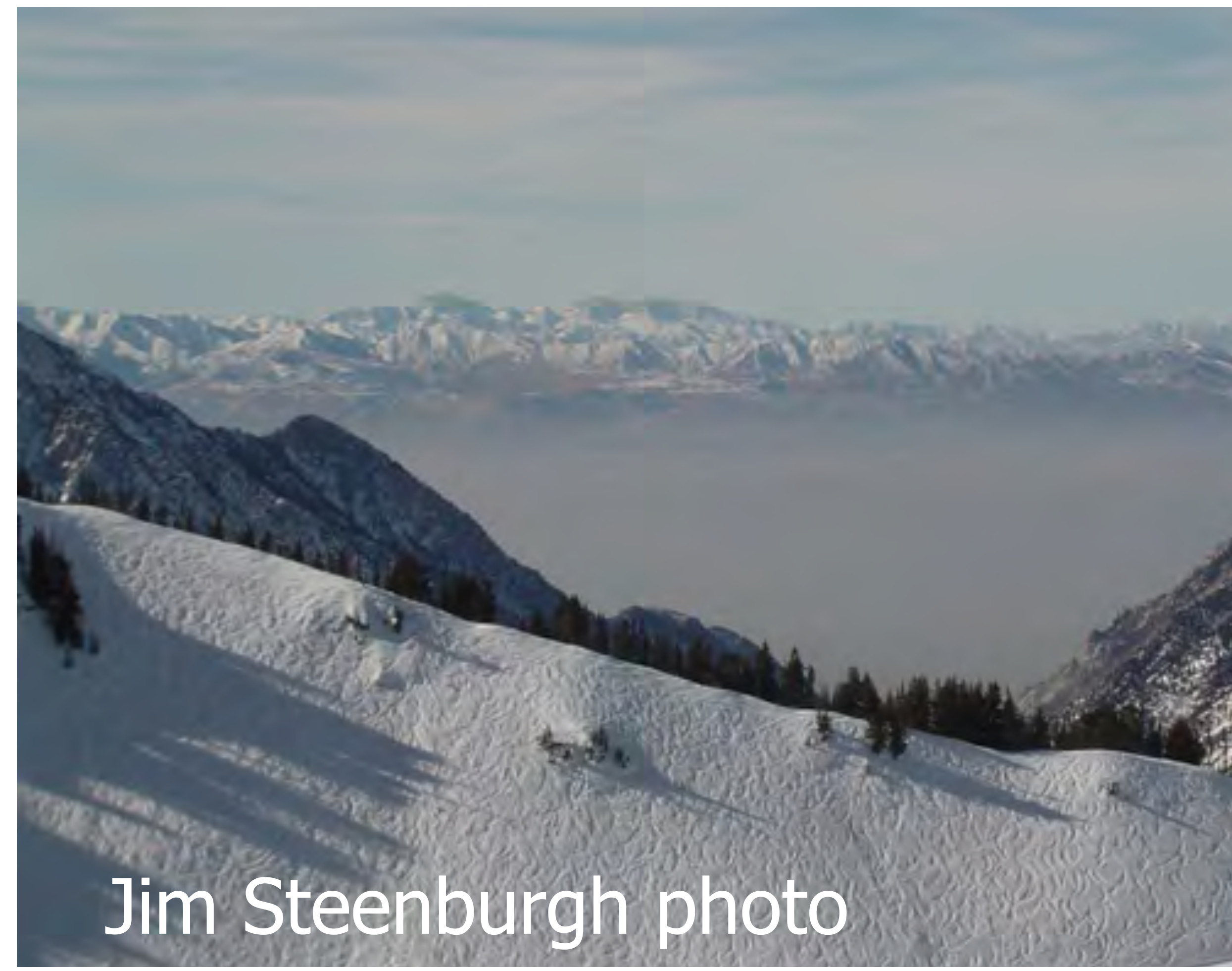
Entrainment



Entrainment

daytime stable boundary layers during winter





Boundary Layer Growth

What processes control the depth of the boundary layer?

- Entrainment
- Large-scale vertical velocity
- Horizontal advection

$$\frac{dz_i}{dt} = w_e + w_i$$

or

$$\frac{\partial z_i}{\partial t} = -\mathbf{V} \cdot \nabla z_i + w_e + w_i$$

where w_e is the *entrainment velocity* (volume per area and time) and w_i is the large-scale vertical velocity at $z = z_i$.

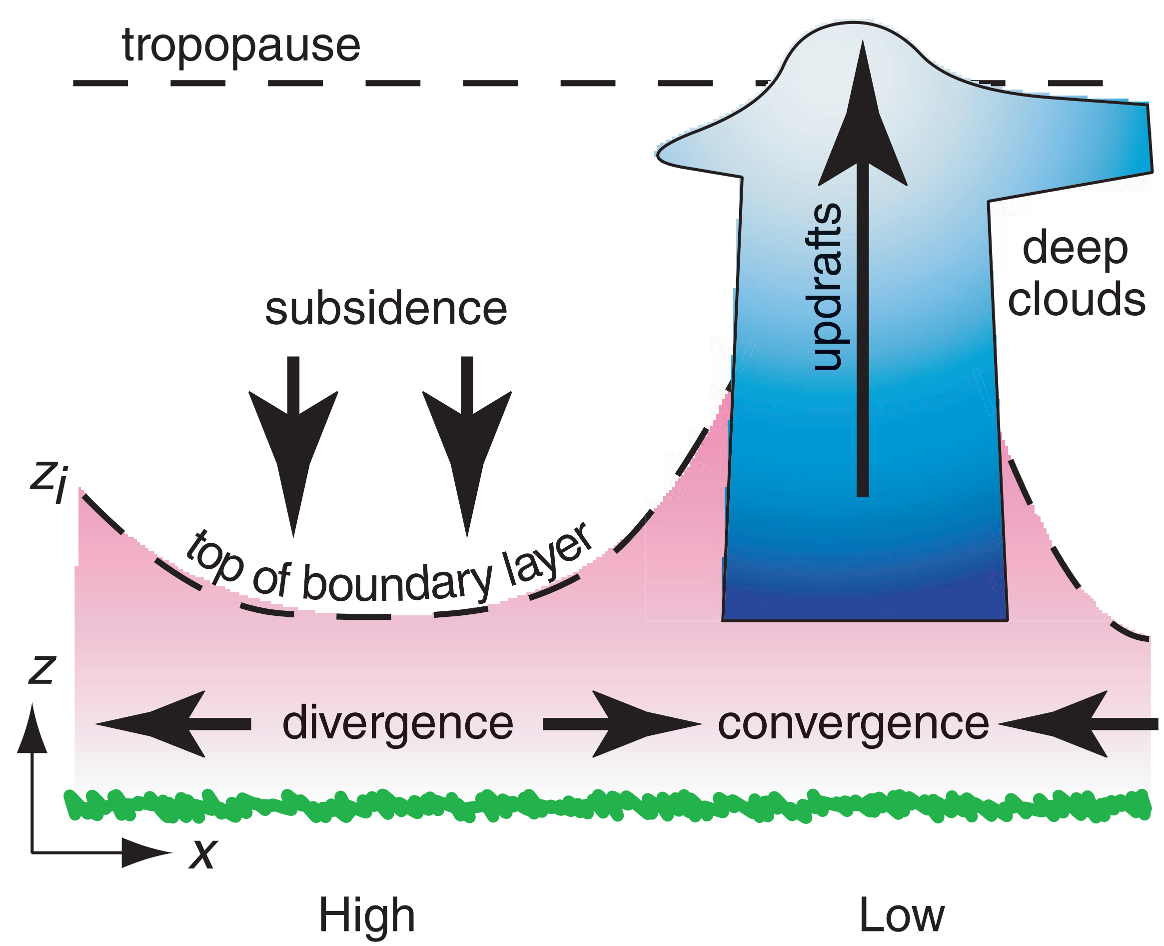
Boundary Layer Growth

Exercise 9.30 shows that

$$w_i = -z_i\{\nabla \cdot \mathbf{V}\}$$

where $\{\nabla \cdot \mathbf{V}\}$ is the mass-weighted horizontal divergence in the boundary layer.

In regions of fair weather, w_i is usually negative (downward) and tends to make the boundary layer shallower.



Boundary Layer Growth

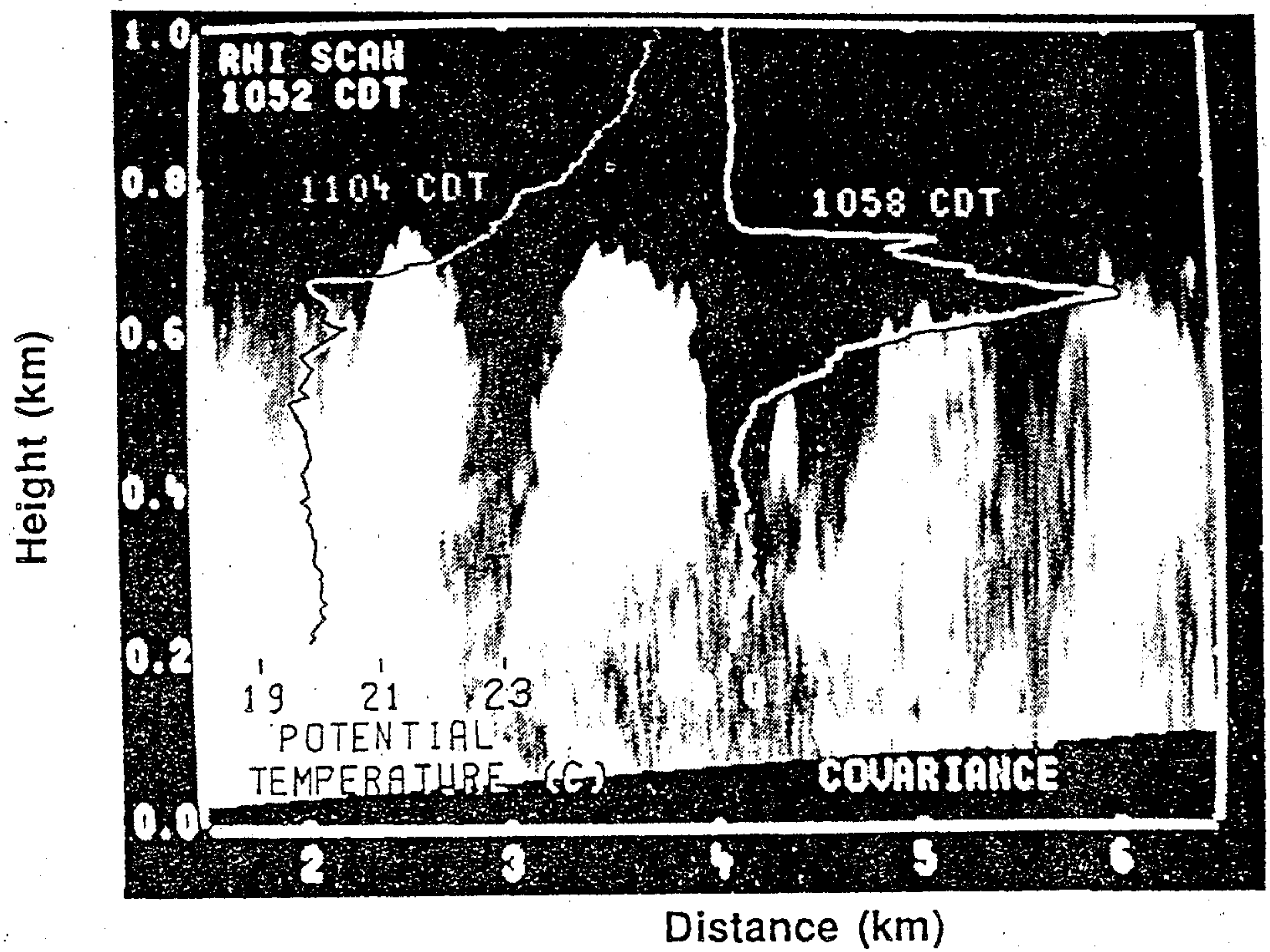
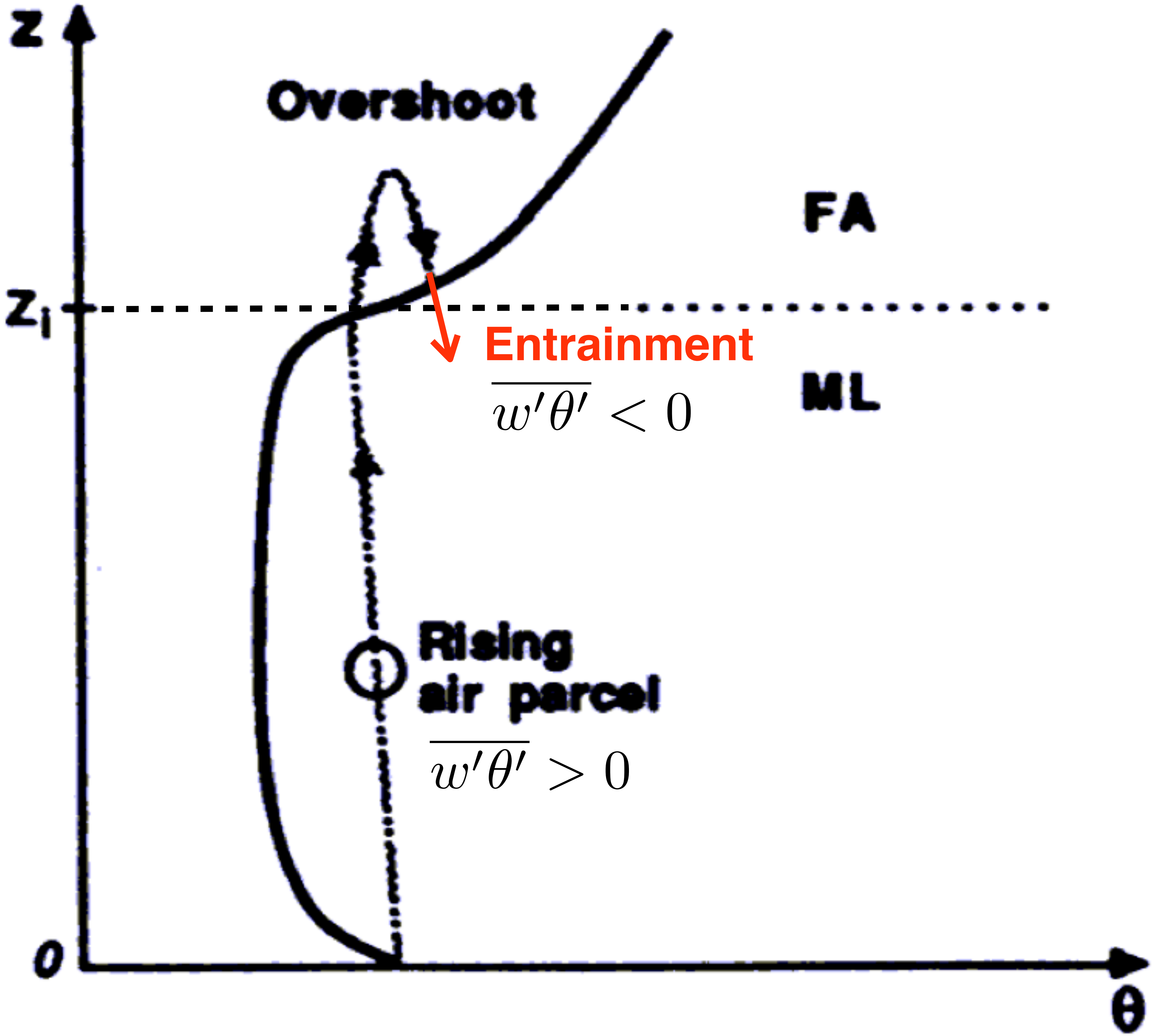


Fig. 11.24 RHI scan taken on 17 July at 1052 CDT. The light areas are areas of high aerosol concentrations carried aloft by rising convective plumes. The left overlay graph is the potential temperature profile at 1104 CDT. The right overlay is the normalized covariance profile of the aerosol density inhomogeneities. (After Hooper, 1982).

Boundary Layer Growth



Boundary Layer Growth

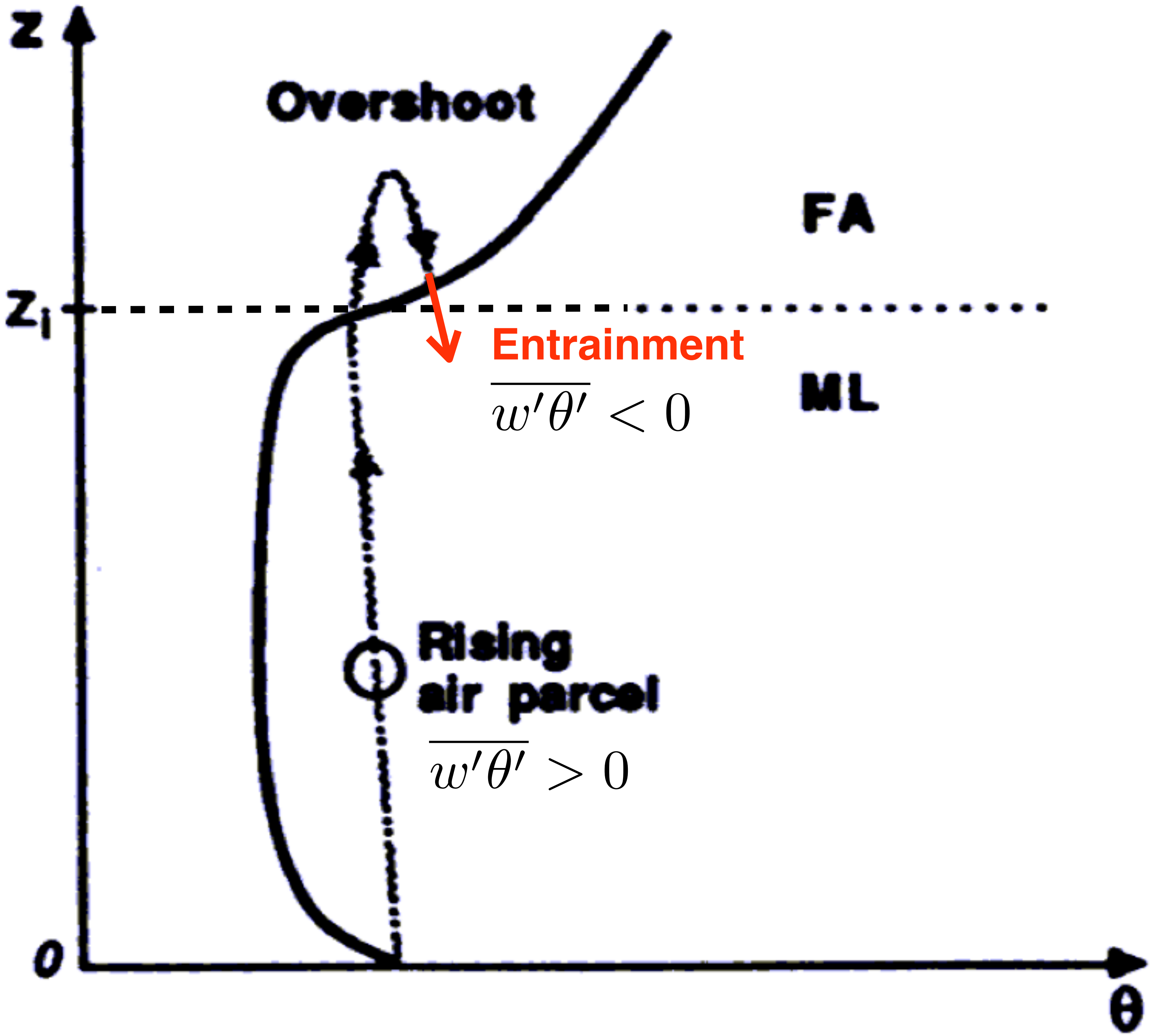
What controls w_e?

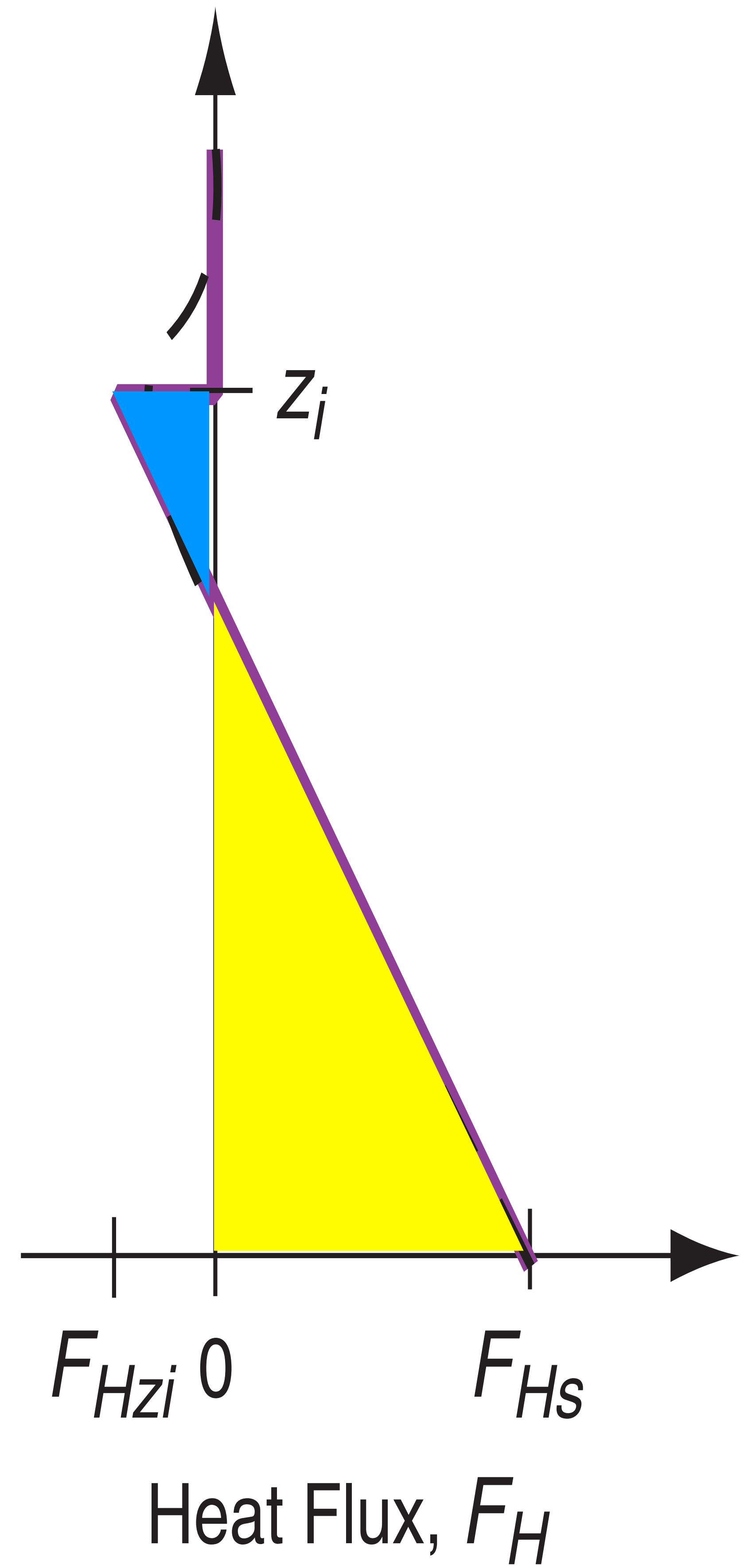
- Stronger turbulence (w_*) increases w_e.
- Greater stability ($\partial\bar{\theta}/\partial z$) at ABL top decreases w_e.

The *convective velocity scale* is

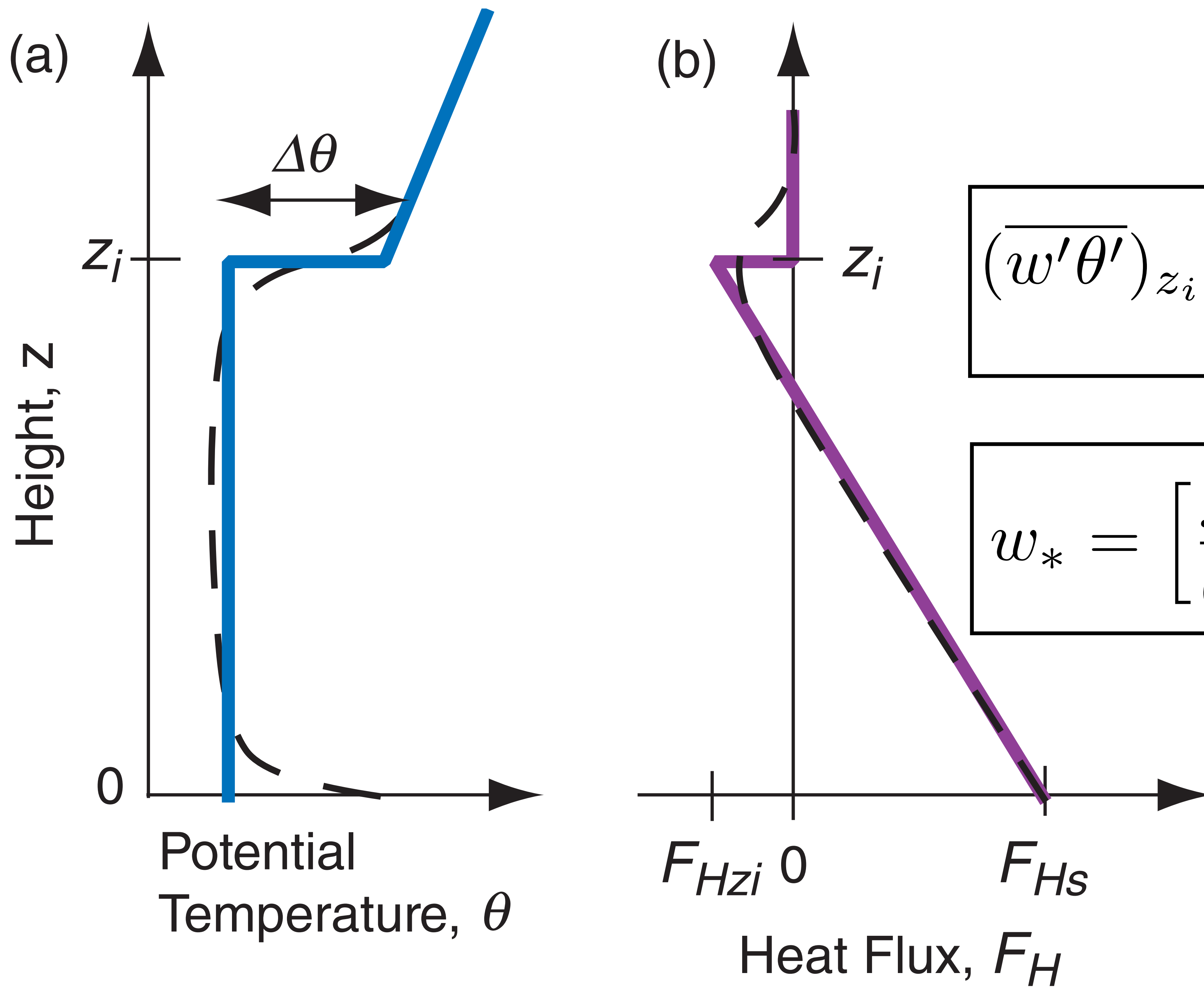
$$w_* = \left[\frac{g}{\theta}\,(\overline{w'\theta'})_s\, z_i\right]^{1/3}$$

Boundary Layer Growth





Boundary Layer Growth



$$(\overline{w'\theta'})_{z_i} = -w_e \Delta\theta$$

$$w_* = \left[\frac{g}{\theta}\,(\overline{w'\theta'})_s\, z_i\right]^{1/3}$$

$$-(\overline{w'\theta'})_{z_i} = A(\overline{w'\theta'})_s = w_e\Delta\theta \rightarrow w_e = \frac{A(\overline{w'\theta'})_s}{\Delta\theta}$$

Boundary Layer Growth

The average θ in the mixed layer, $\langle\theta\rangle$, is affected by the surface and entrainment sensible heat fluxes:

$$\frac{d\langle\theta\rangle}{dt} = \frac{F_{Hs} - F_{Hz_i}}{z_i}$$
$$= \frac{(1+A)F_{Hs}}{z_i}$$

$$\frac{dz_i}{dt} = w_e + w_i$$

$$w_e = \frac{AF_{Hs}}{\Delta\theta}$$

Boundary Layer Growth

- Under conditions of light winds, one can predict z_i without knowing w_e.
- Use the early morning $\theta(z)$ and a prediction of $F_{Hs}(t)$.
- $F_{Hs}(t)$ can be estimated from F^* (net downward radiation at the surface).
- The procedure is called the *thermodynamic method* or the *encroachment method*.

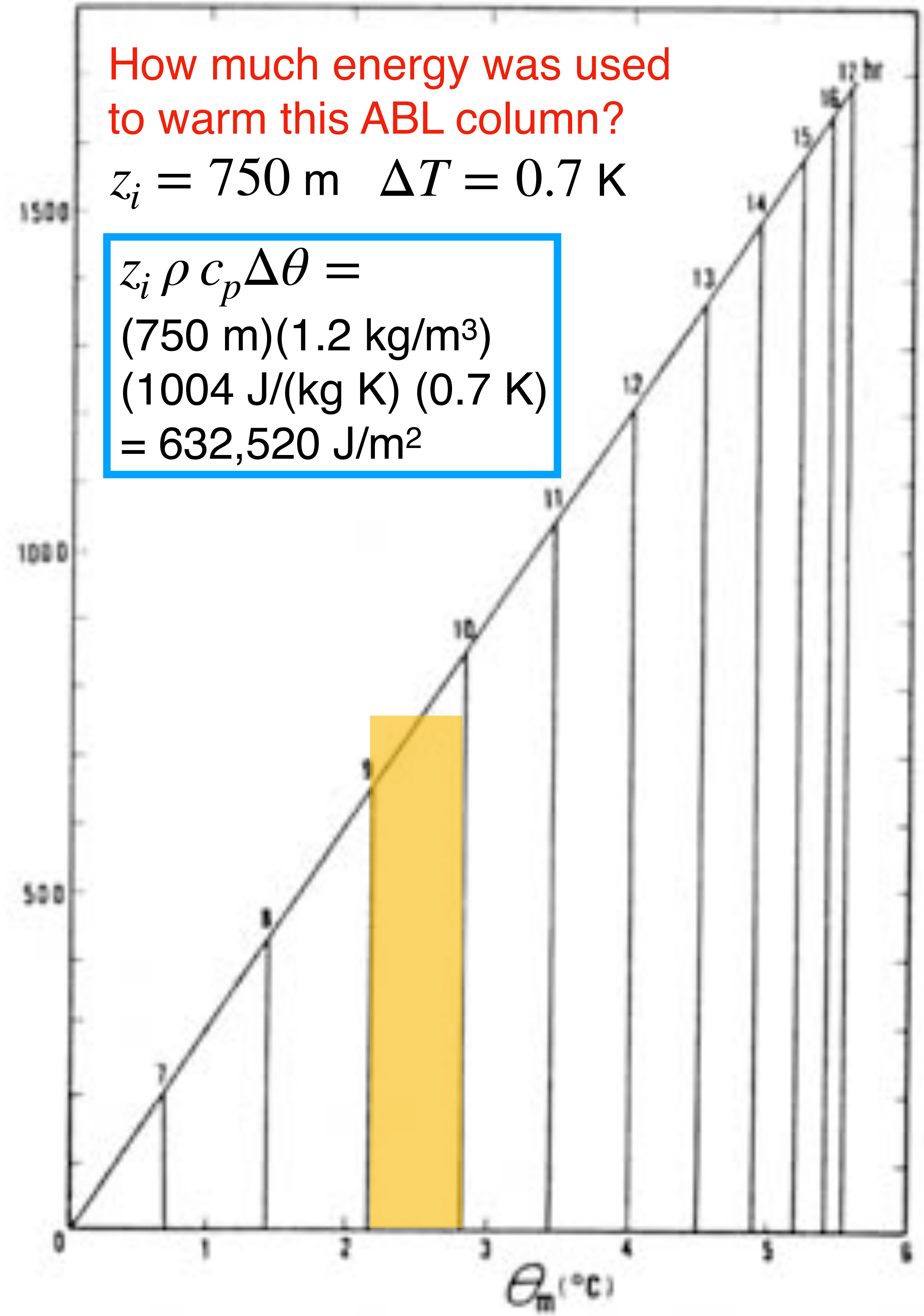
Boundary Layer Growth

How much energy (heat) is needed to change the average temperature of the ABL by 1 K?

Change in energy per unit mass is specific heat $= c_p \Delta T$ (J/kg).

Change in energy per unit volume $= \rho\, c_p \Delta T$ ($\mathrm{J/m^3}$).

Change in energy in the ABL per unit area ($\mathrm{J/m^2}$):
$= z_i\, \rho\, c_p \Delta T = z_i\, \rho\, c_p \Delta \theta$.



Boundary Layer Growth

Energy put into the ABL per unit area and time $= \rho\, c_p F_{Hs}$ (W/m^2)

Energy put into the ABL per unit area during a short time interval Δt

$$= \rho\, c_p F_{Hs}\, \Delta t \quad (\mathrm{J/m^2})$$

Equate energy used to warm the ABL column to energy put in by F_{Hs}

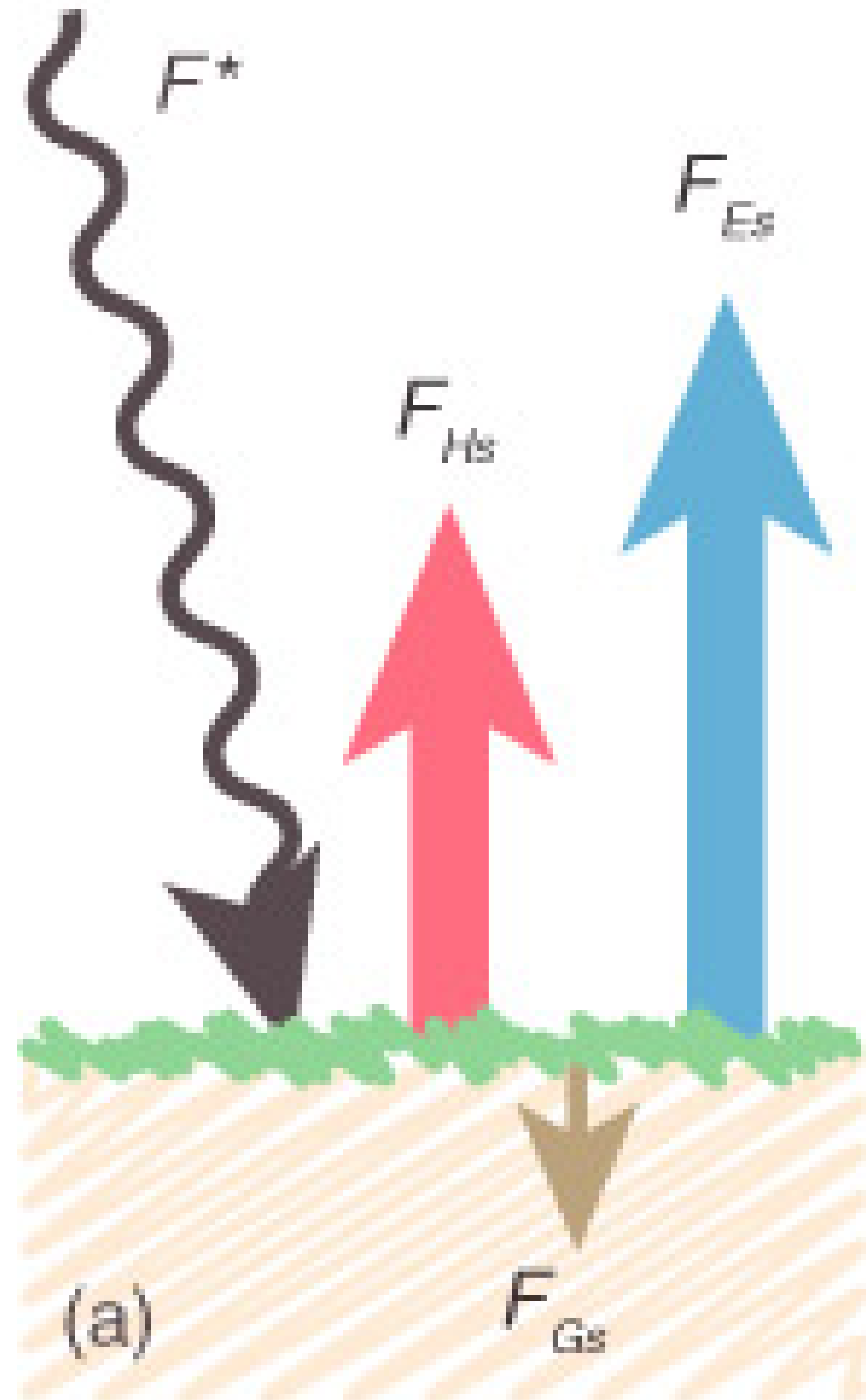
$$z_i\, \rho\, c_p \Delta\theta = \rho c_p F_{Hs}\, \Delta t$$

Simplify the condition for this equality to

$$z_i\, \Delta\theta = F_{Hs}\, \Delta t$$

$$\int_{\theta(t_1)}^{\theta(t_2)} z_i(\theta)\, d\theta = \int_{t_1}^{t_2} F_{Hs}(t)\, dt$$

General equality for variable z_i and F_{Hs}



Boundary Layer Growth

Exercise 9.6 (a) At sunrise, $\partial\theta/\partial z = \gamma$ in the stable BL and $z_i = 0$. What is $z_i(t)$ after sunrise if F_{Hs} is constant?

$$\int_{\theta(0)}^{\theta(t)} z_i(\theta)\, d\theta = \int_0^t F_{Hs}(t)\, dt$$

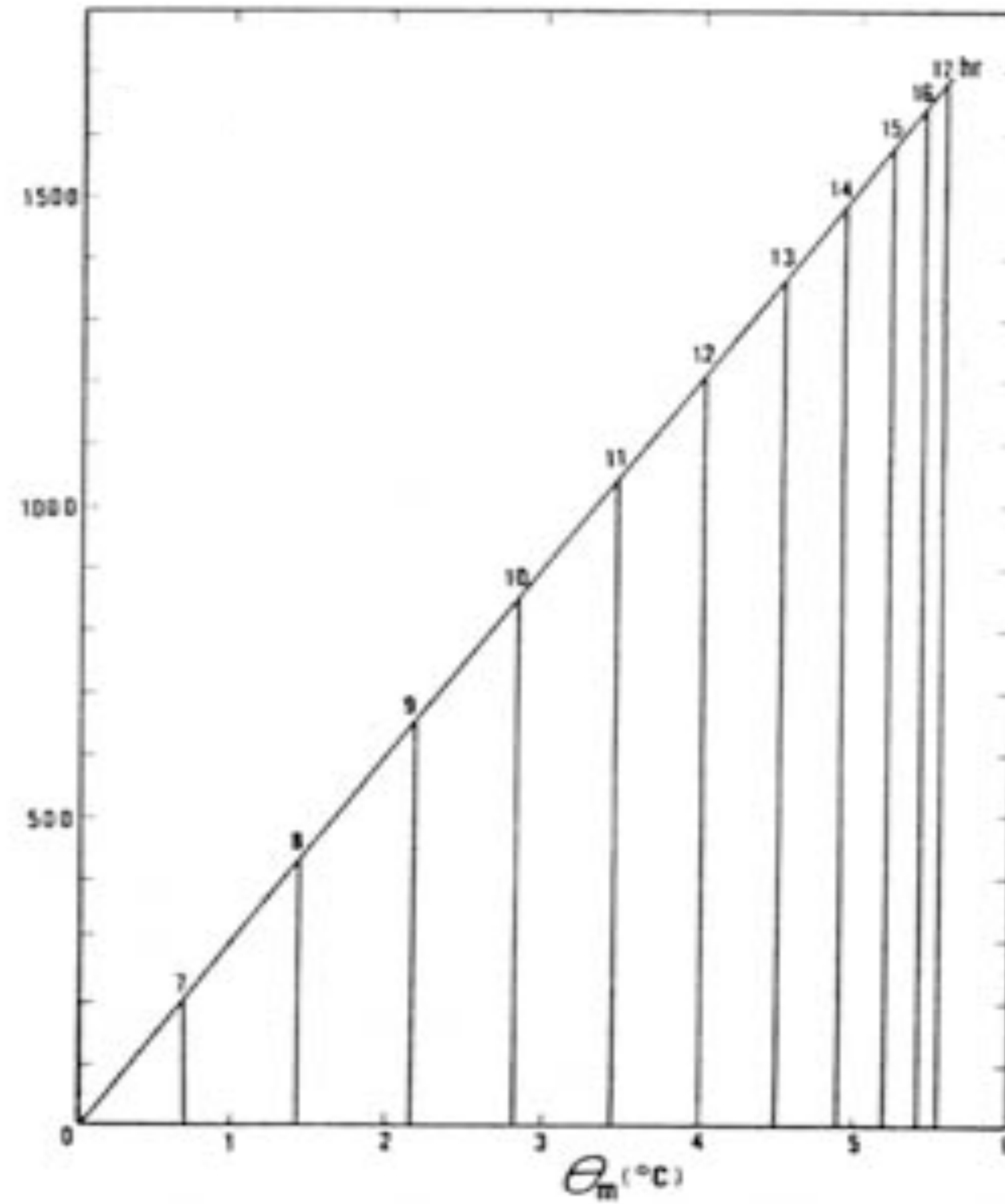
$$z_i(\theta) = \frac{\theta - \theta(0)}{\gamma}$$

$$\int_{\theta(0)}^{\theta(t)} \frac{\theta - \theta(0)}{\gamma}\, d\theta = F_{Hs} t$$

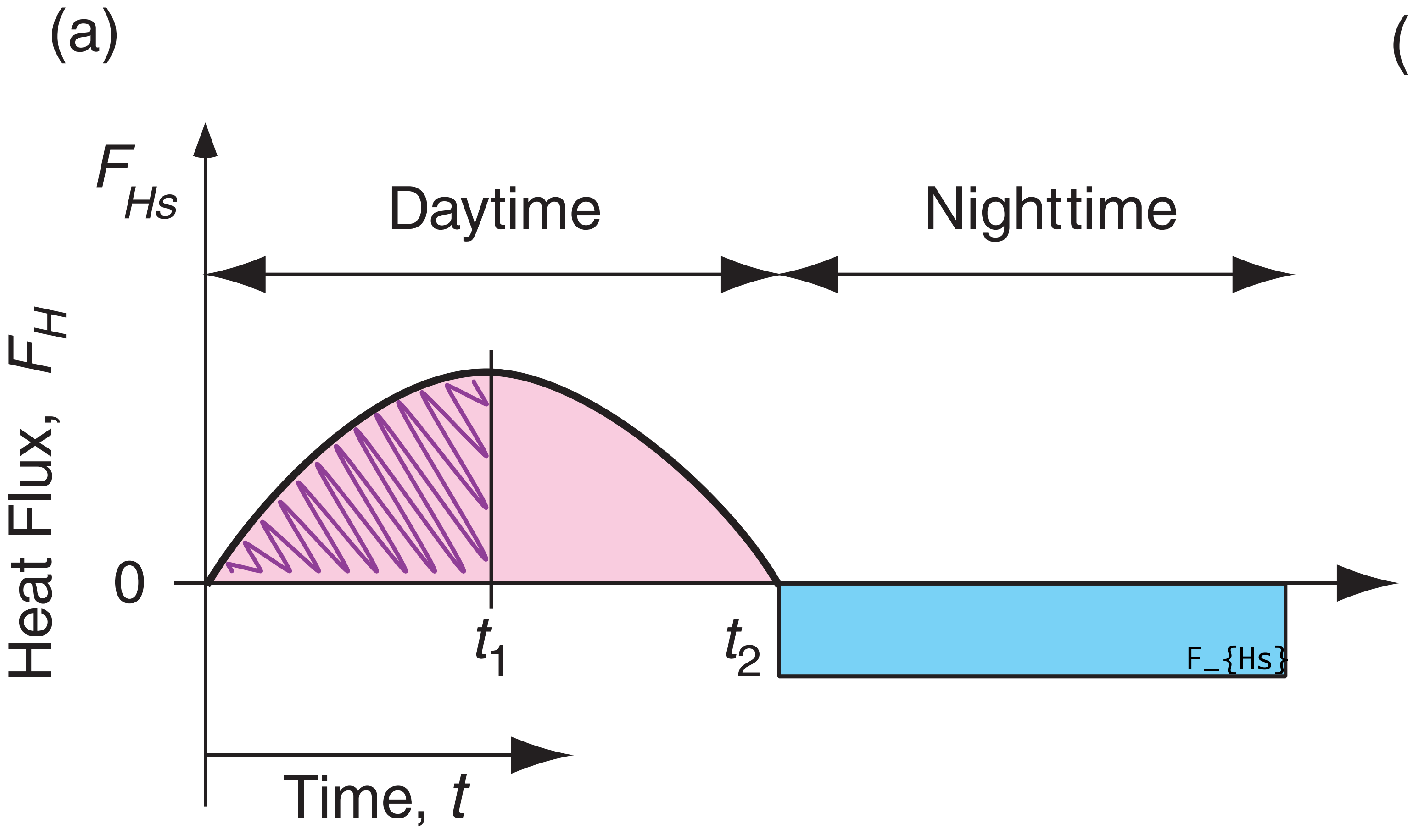
$$\frac{[\theta(t) - \theta(0)]^2}{2\gamma} = F_{Hs} t$$

$$\frac{[\gamma z_i(t)]^2}{2\gamma} = F_{Hs} t$$

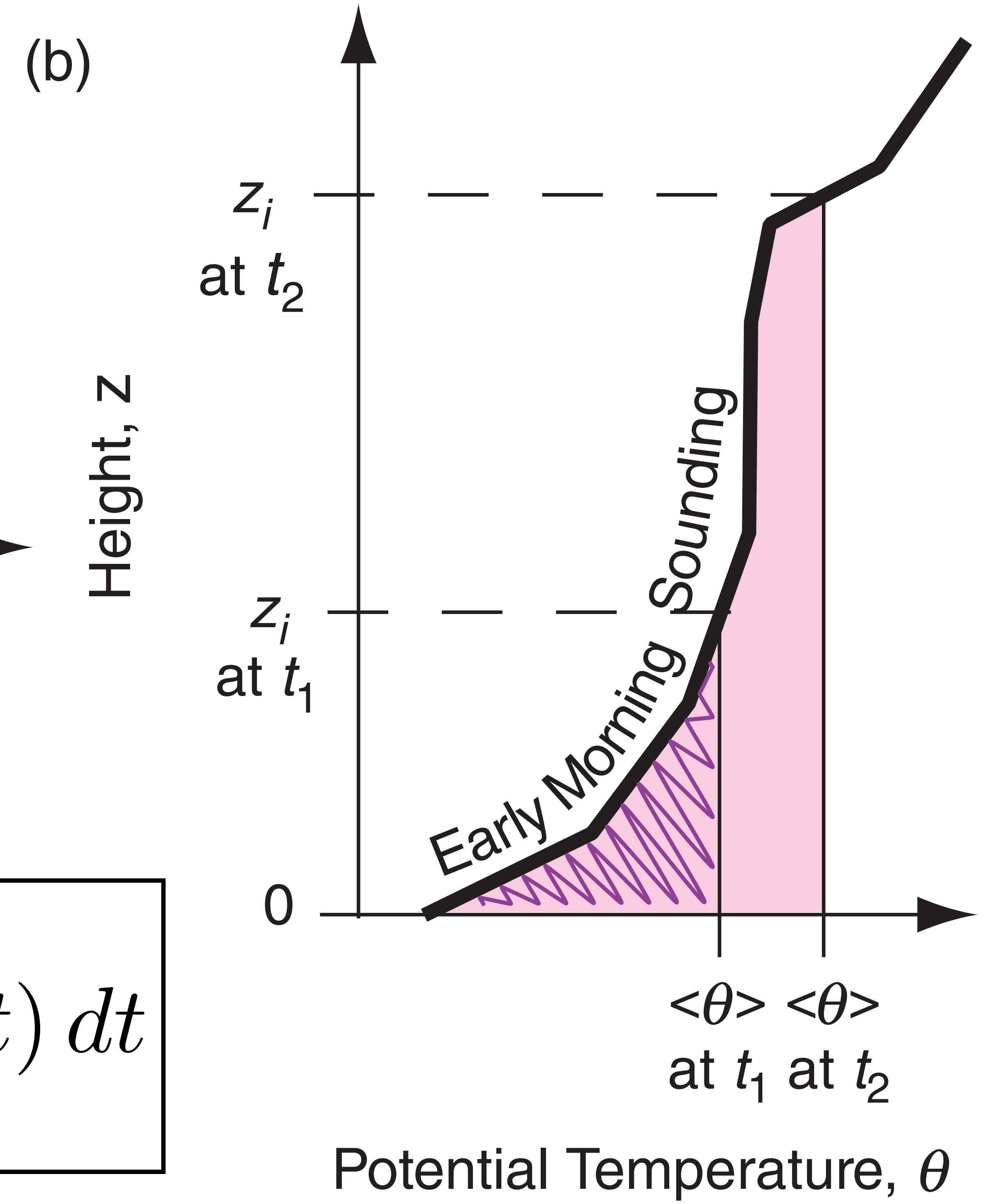
$$z_i(t) = [(2F_{Hs}/\gamma)\, t]^{1/2}$$



Boundary Layer Growth

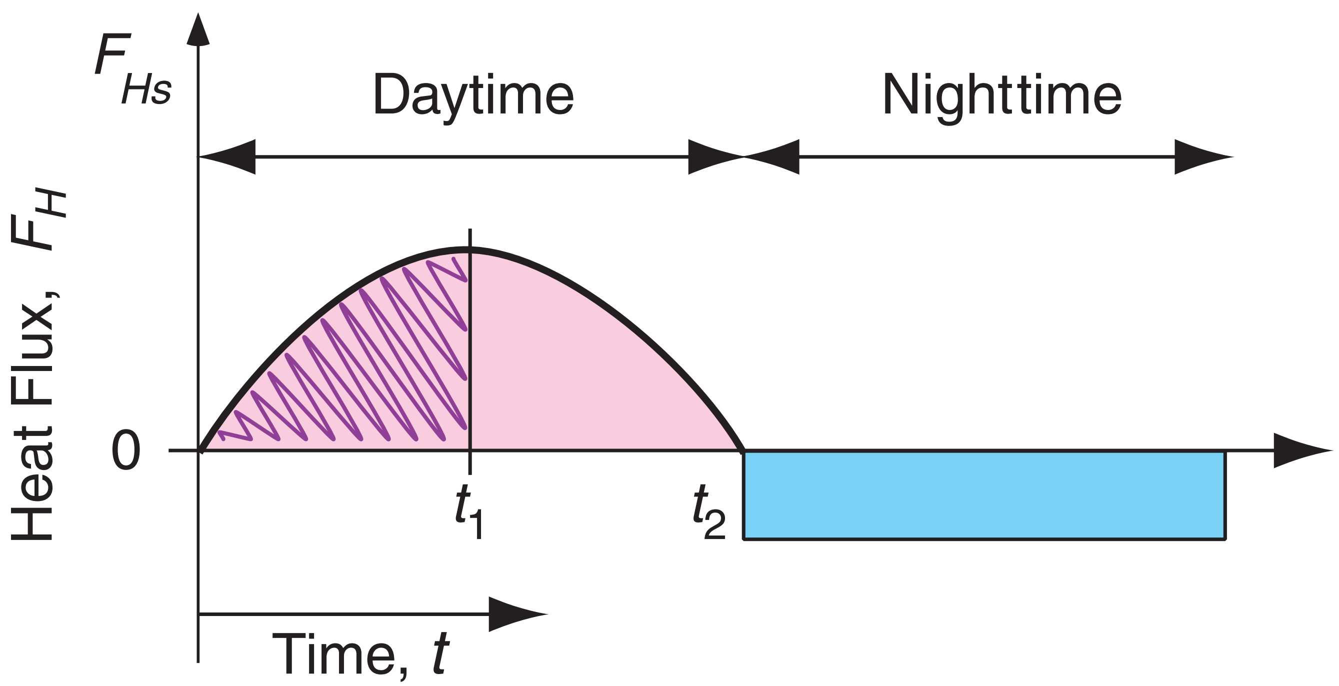


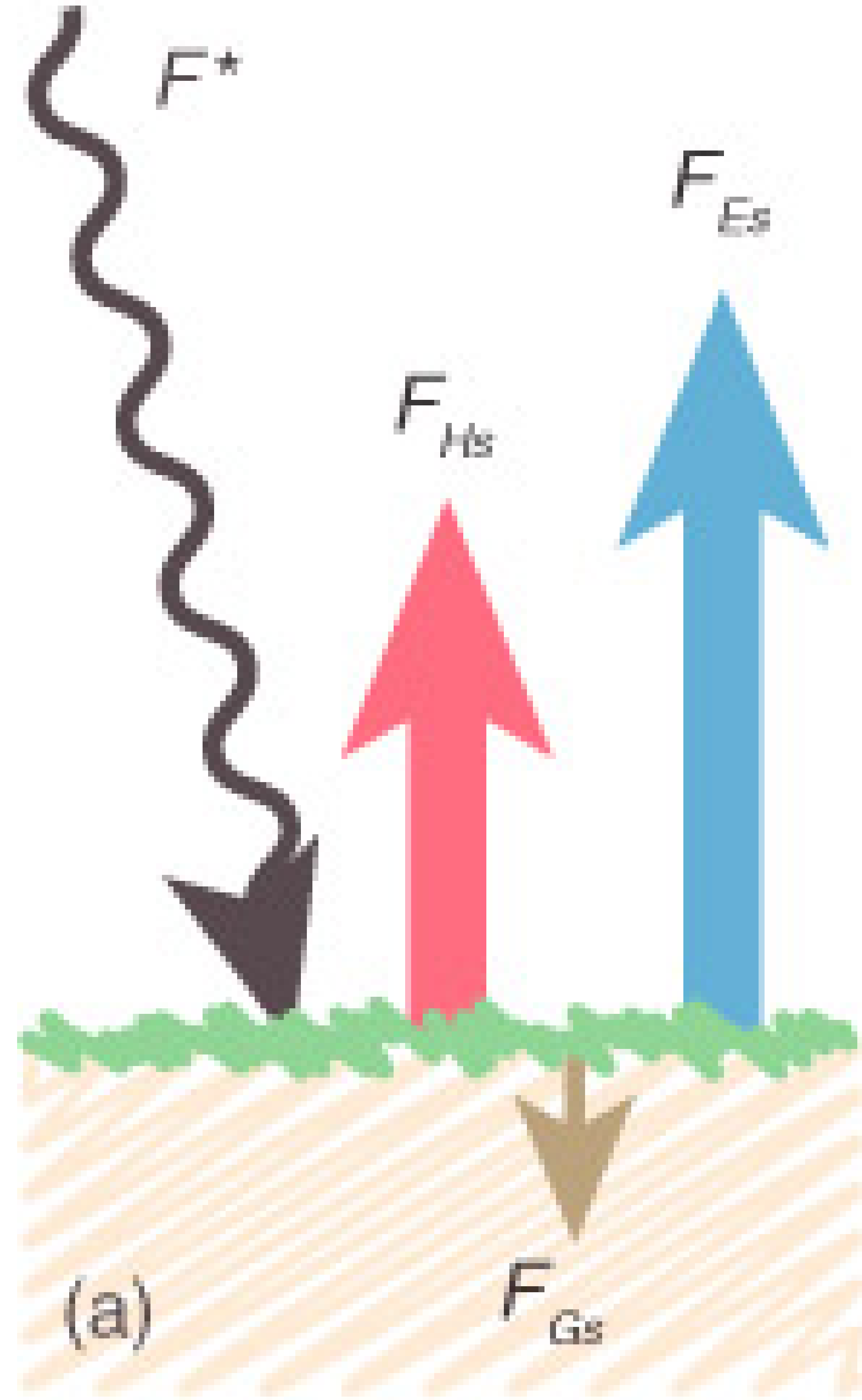
$$\int_{\theta(t_1)}^{\theta(t_2)} z_i(\theta)\, d\theta = \int_{t_1}^{t_2} F_{Hs}(t)\, dt$$



Boundary Layer Growth

How do we predict $F_{Hs}(t)$?

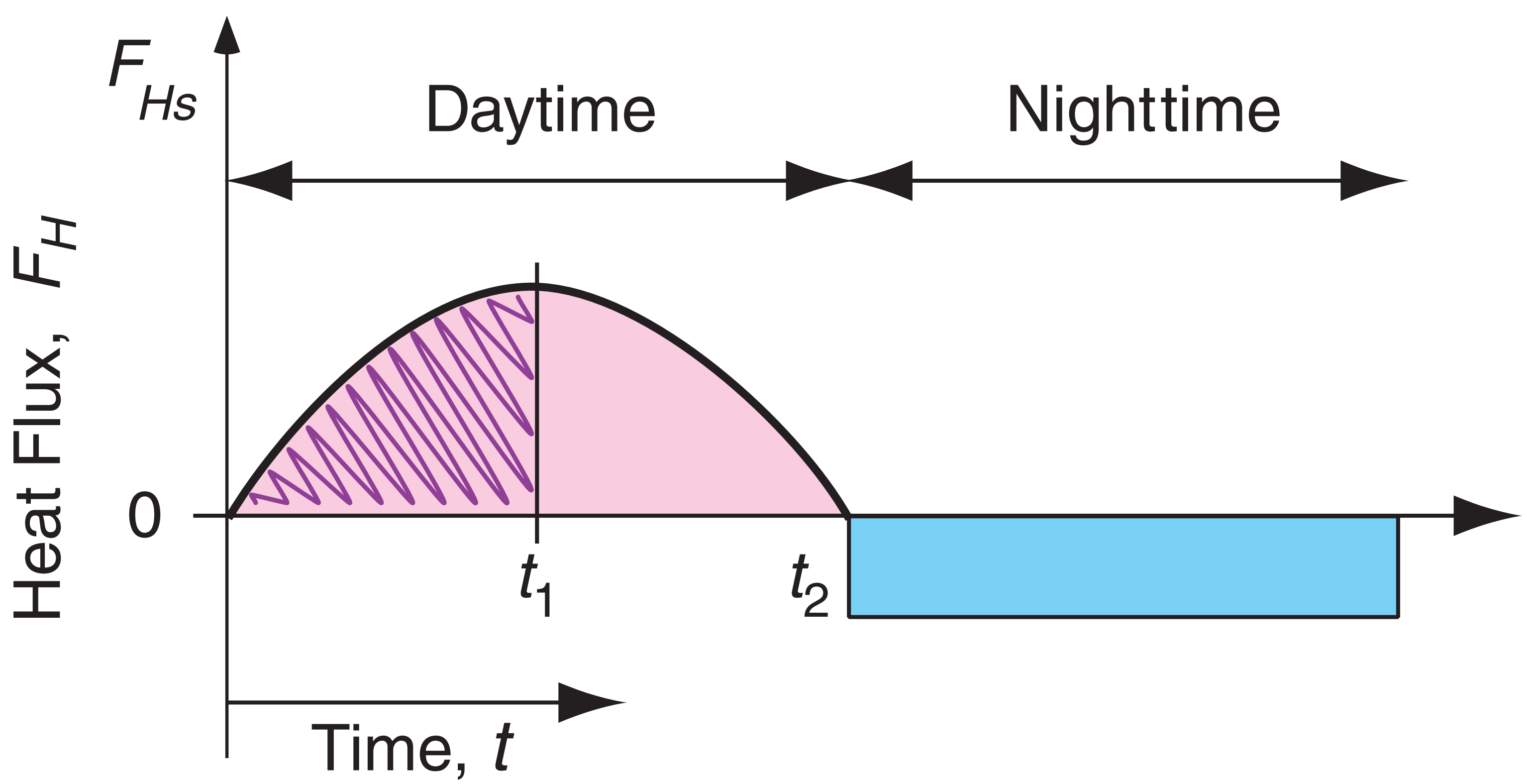


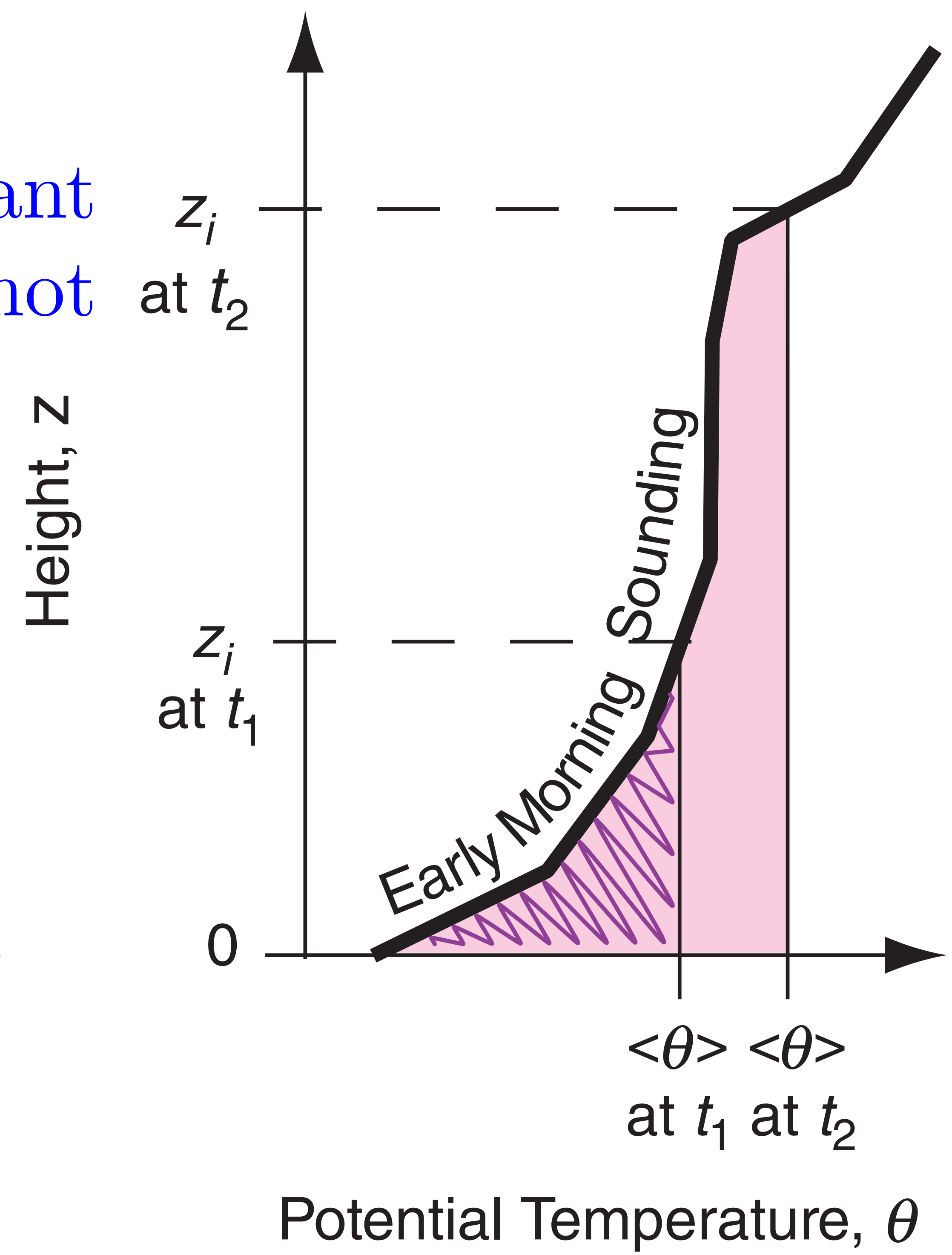


Boundary Layer Growth

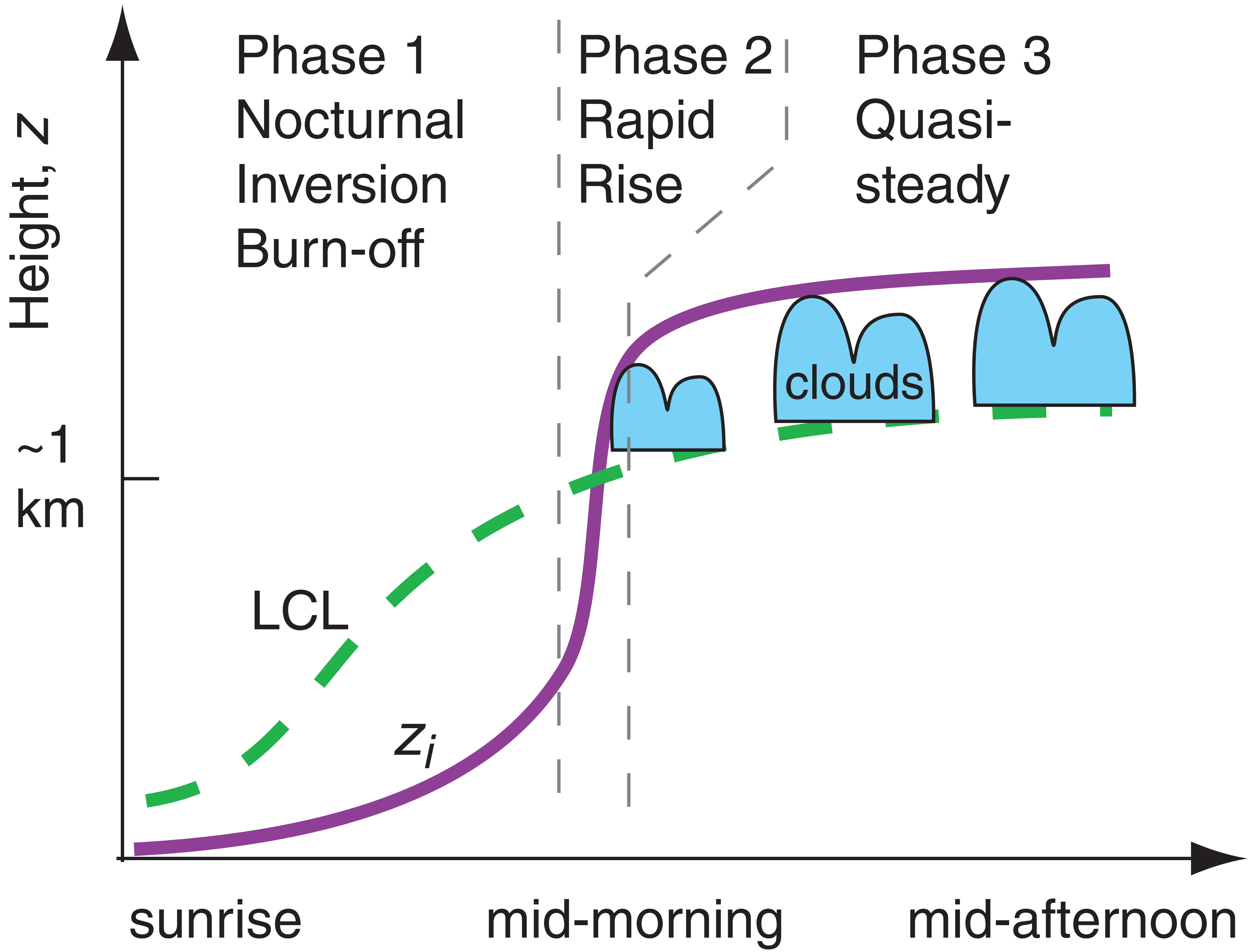
Exercise 9.6 (b) How does the shape of $F_{Hs}(t)$ relate to the shape of $z_i(t)$?

$z_i \sim t^{1/2}$ does not agree with $z_i \sim t^2$ which typically observed in the early morning because $F_{Hs}(t)$ is not constant but increases, and the initial $\theta(z)$ is not linear but exponential in shape.





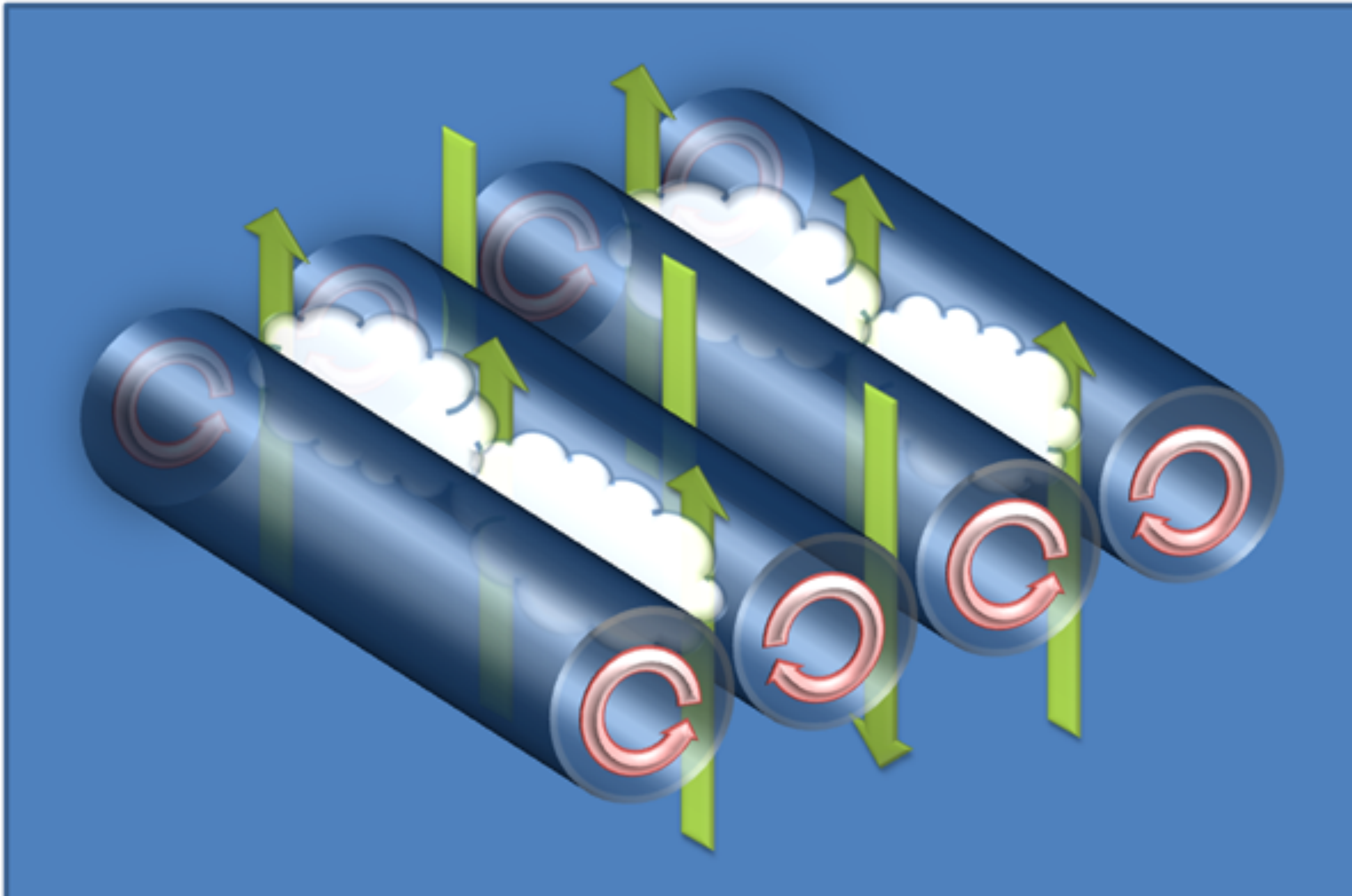
Cloud-topped Boundary Layer over Land



Cloud-topped Boundary Layer over Land

- *Horizontal roll vortices* may form under certain conditions.
- The roll axes are aligned with the mean wind direction.
- Roll diameter is comparable to the BL depth.
- Clouds may form in the updrafts and produce *cloud streets*.

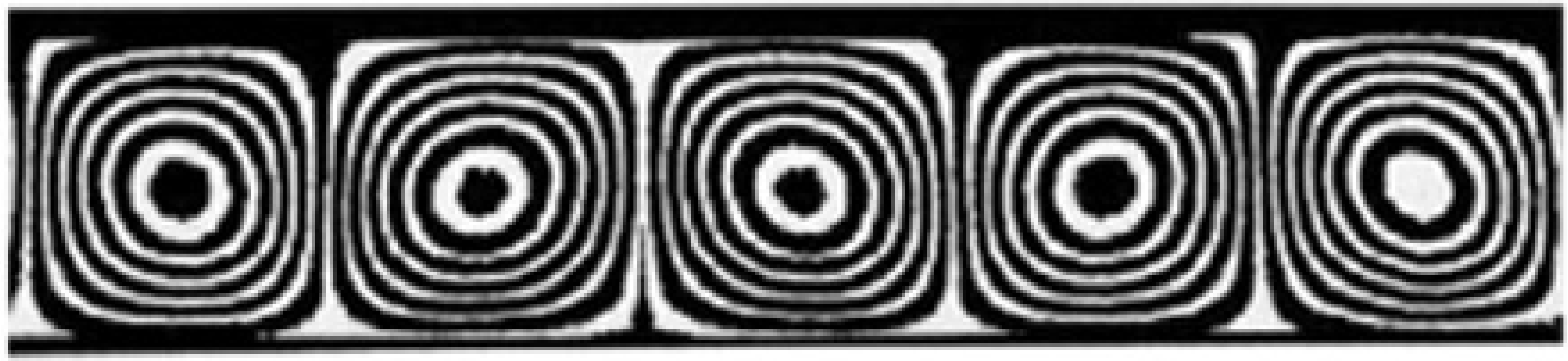
Cloud-topped Boundary Layer over Land



Cloud-topped Boundary Layer over Land

Cloud-topped Boundary Layer over Land

Vertical cross-section through laminar horizontal roll vortices



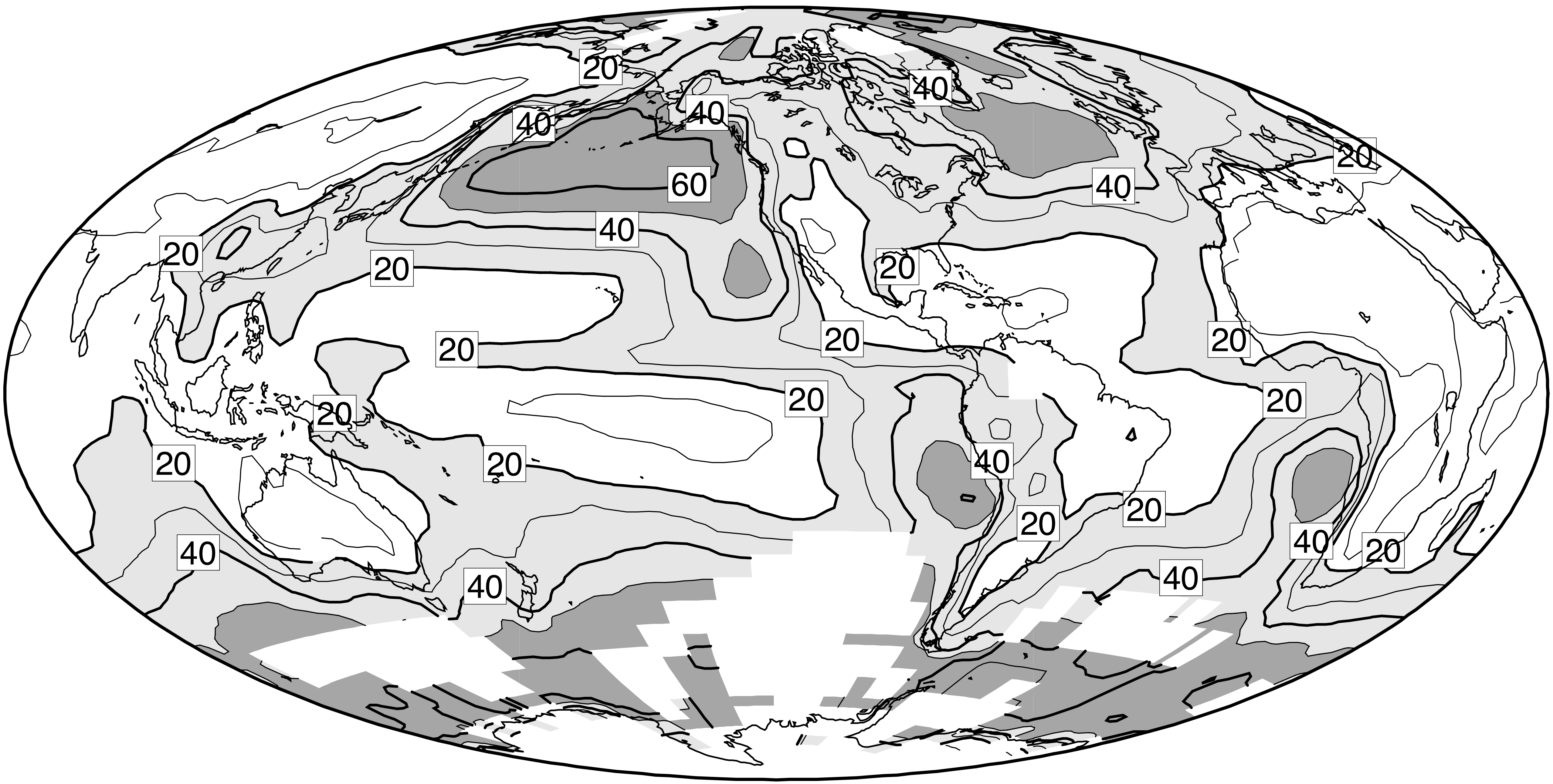
Satellite view of cumulus clouds aligned into cloud streets by turbulent horizontal roll vortices

The Marine Boundary Layer

Differs from the BL over land in several ways:

- The *diurnal cycle* is not as important.
- *Relative humidity* is greater.
- *Cloud cover* is more extensive.
- *Radiative heating* is more affected by clouds.
- *Drizzle* is significant in some regions.

Annual Stratus Cloud Amount

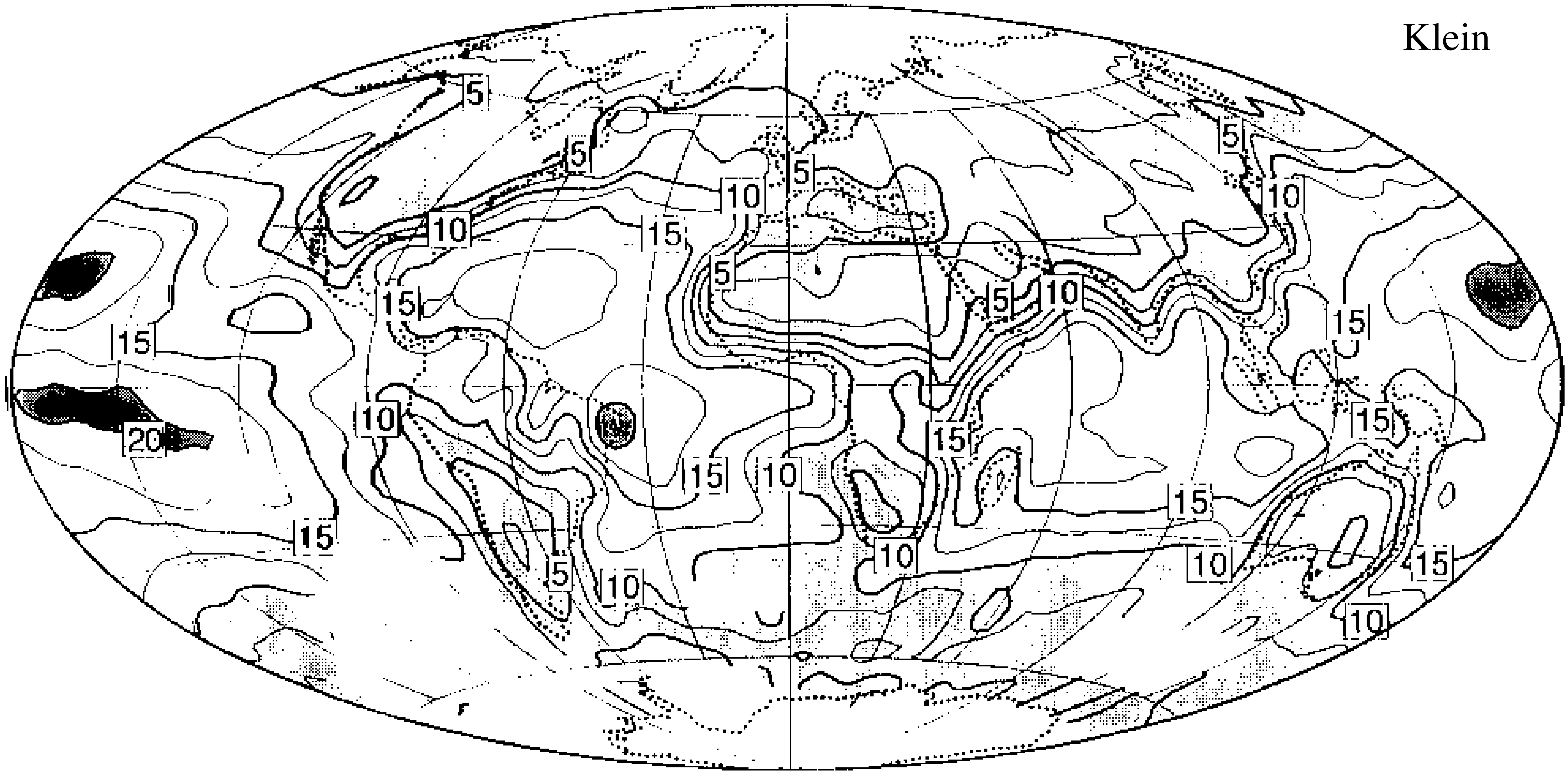


Klein and Hartmann (1993), from surface observations

Cumulus Cloud Amount

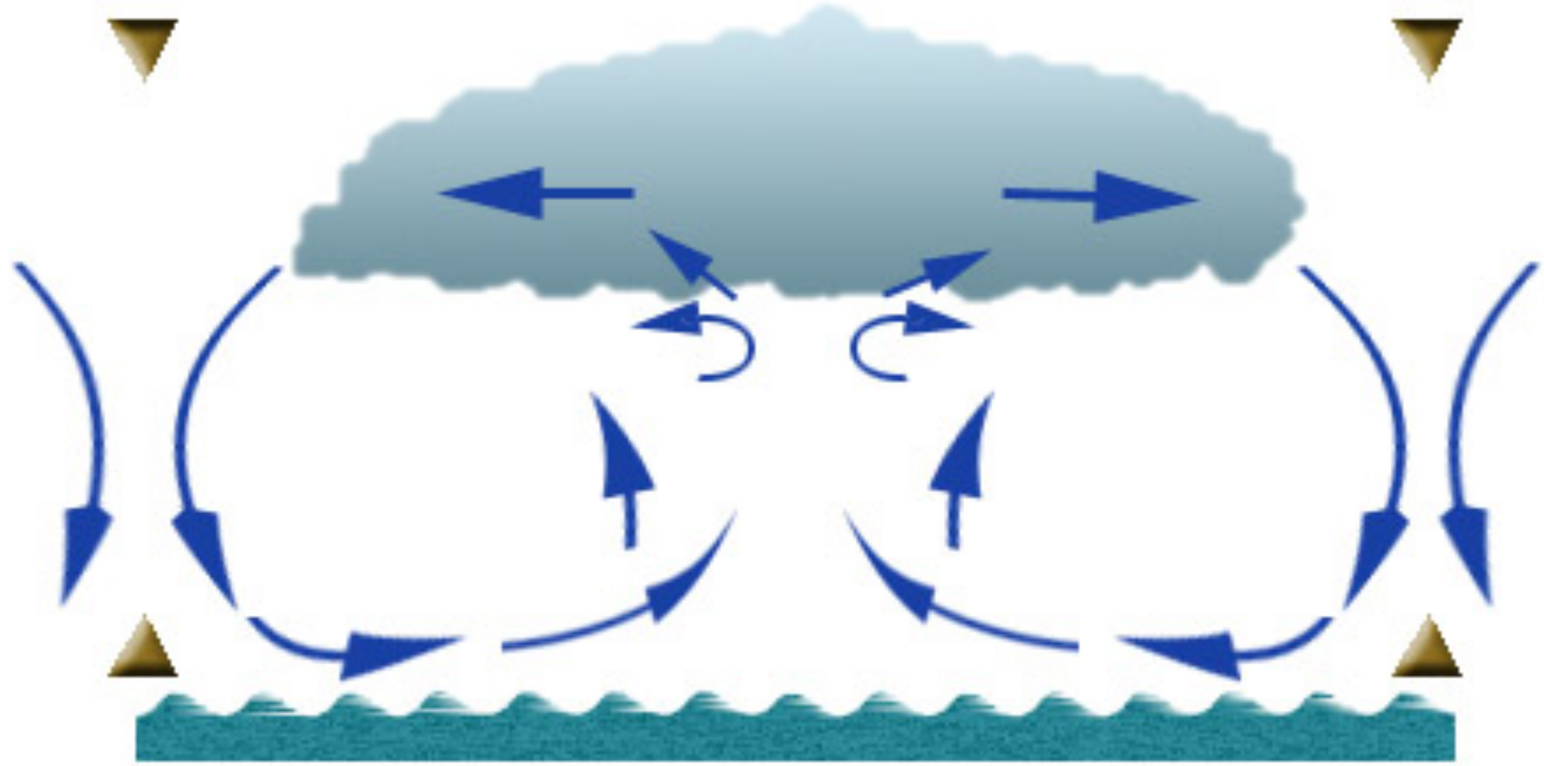
cumann.2

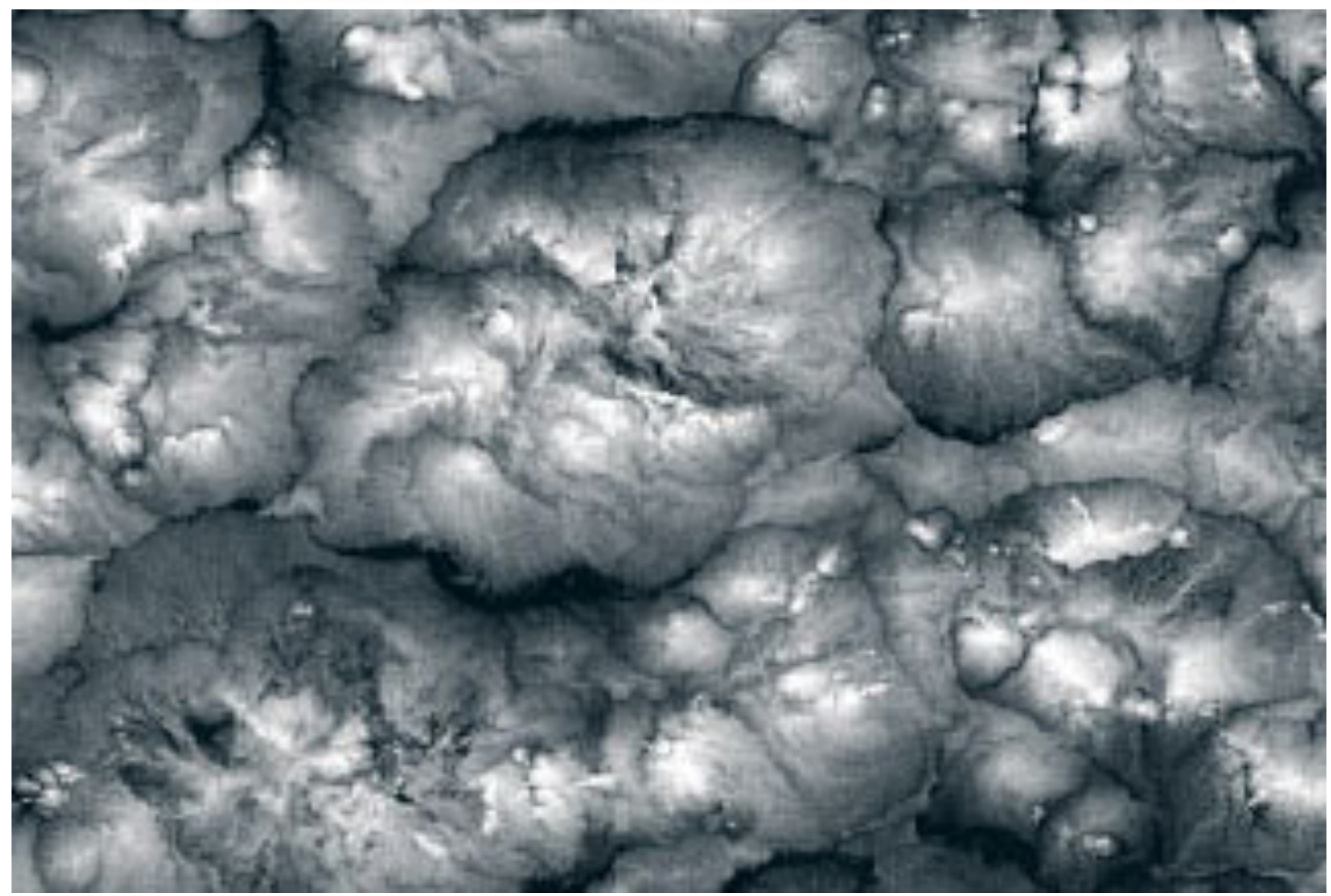
Klein



The Marine Boundary Layer

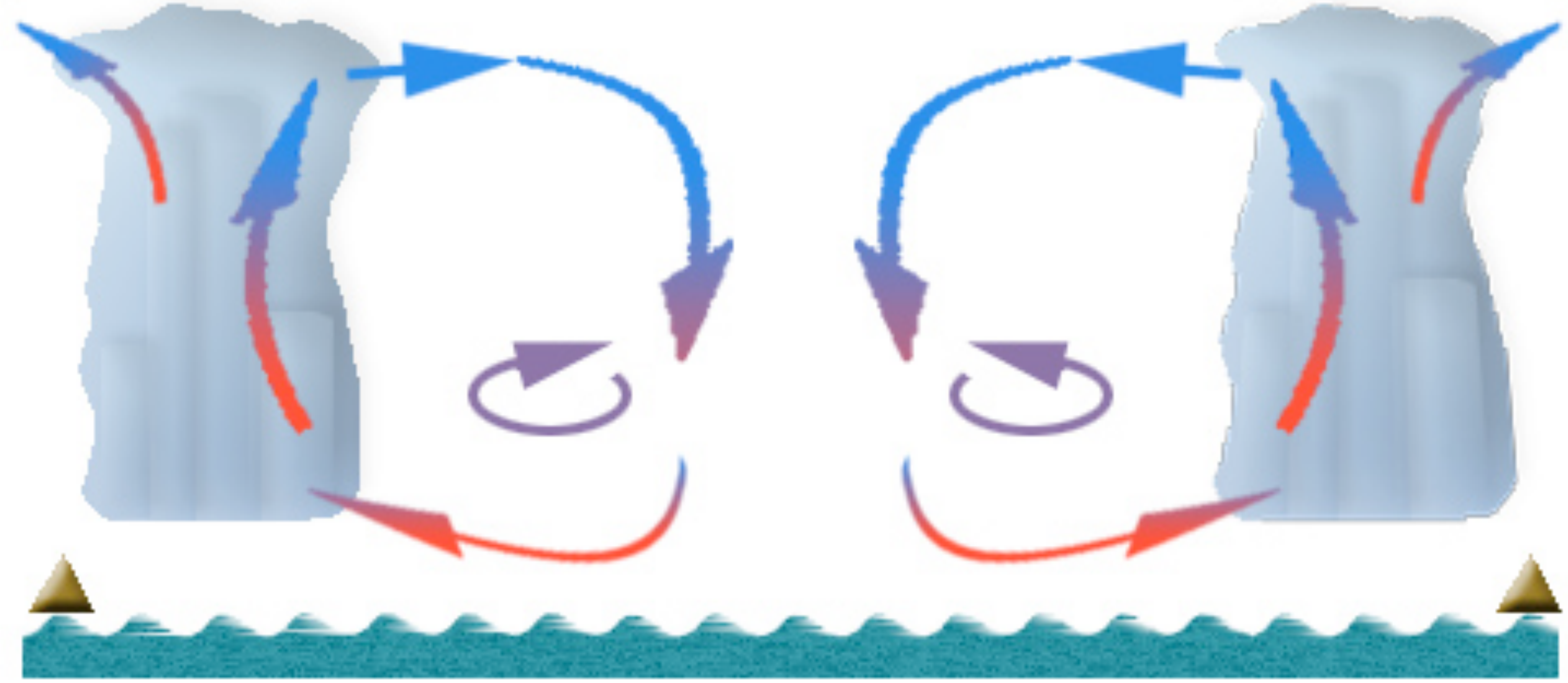
Closed cell convection is driven by cooling at the cloud top.

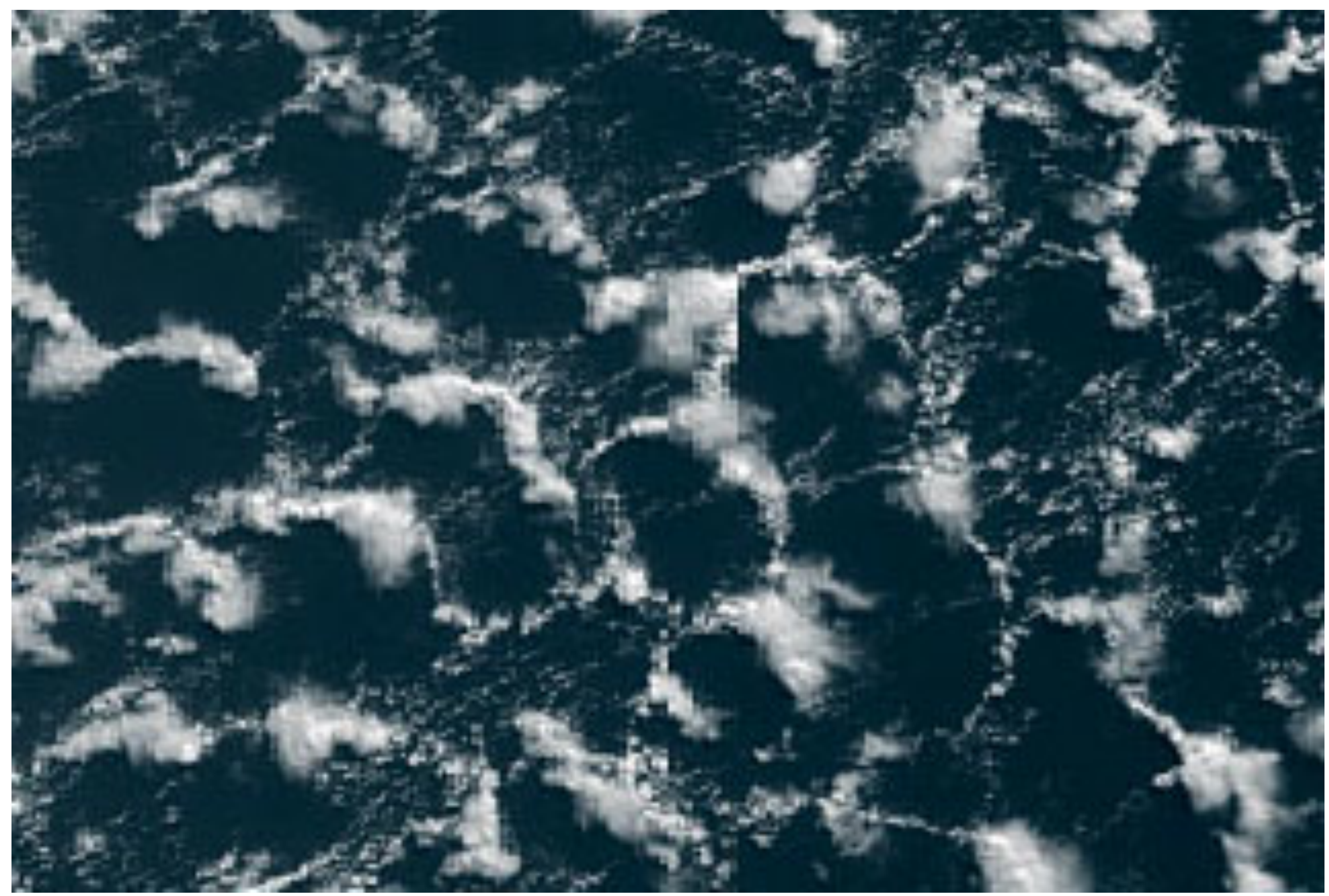




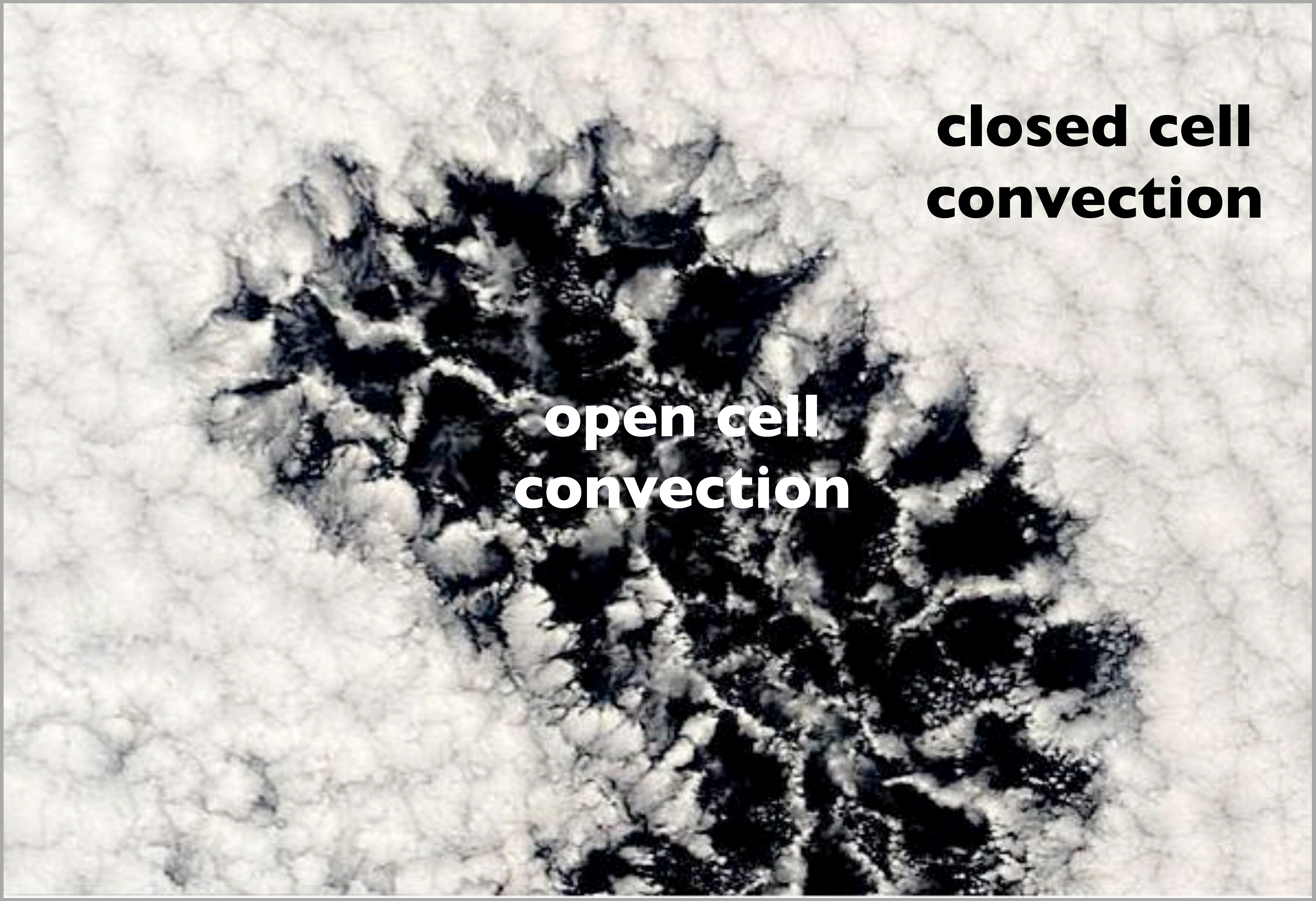
The Marine Boundary Layer

Open cell convection is driven by heating at the surface.





The Marine Boundary Layer



The Marine Boundary Layer

Stratocumulus-topped boundary layer

show simulation results

The Marine Boundary Layer

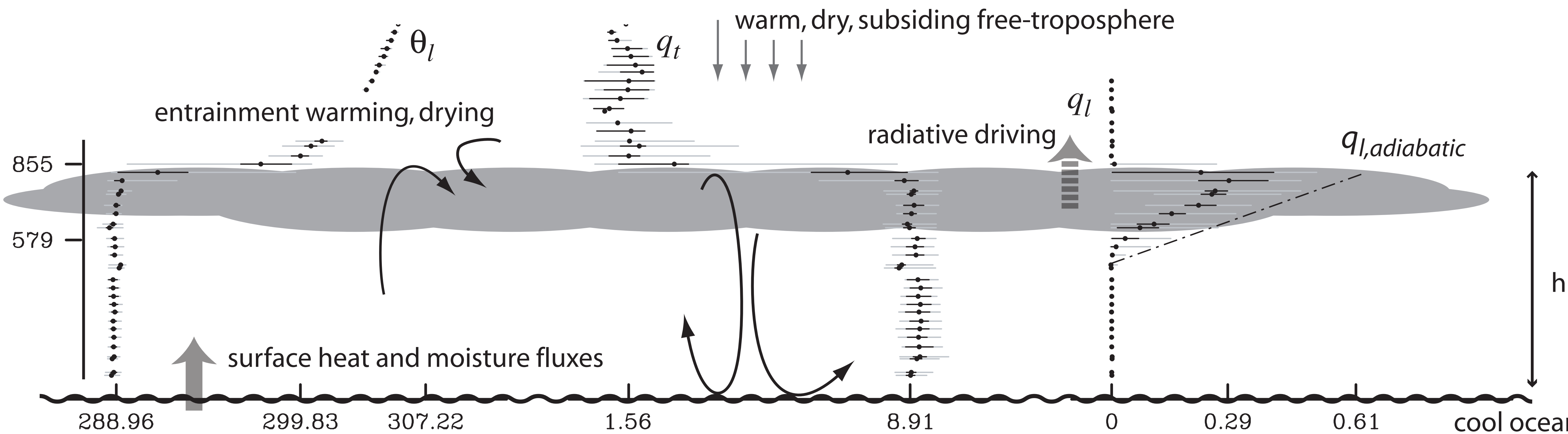


Figure 4: Cartoon of well mixed, non precipitating, stratocumulus layer, overlaid with data from research flight 1 of DYCOMS-II. Plotted are the full range, middle quartile and mean of θ_l, q_t and q_l from all the data over target region binned in 30m intervals. Heights of cloud base and top are indicated as is mixed layer values, and values just above the top of the boundary layer, of various thermodynamic quantities. The adiabatic liquid water content is indicated by the dash-dot line.

The Marine Boundary Layer

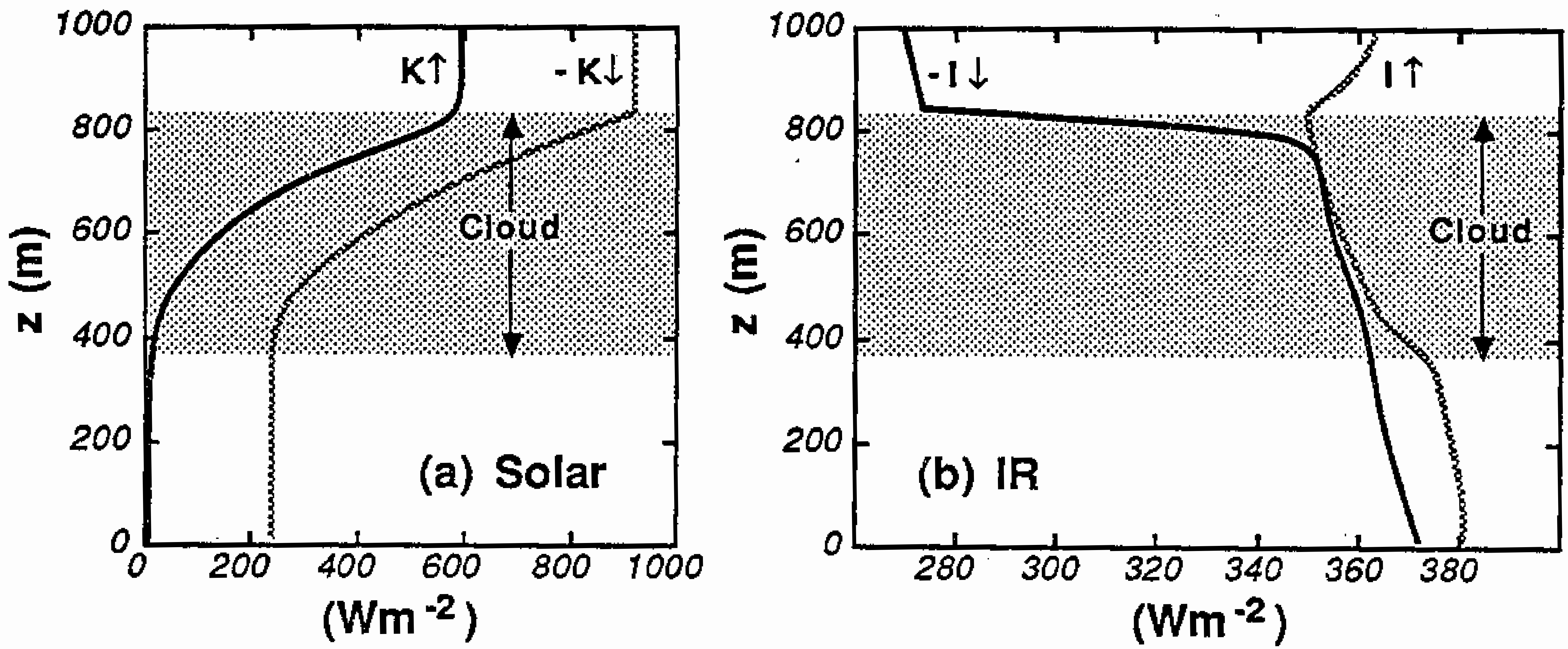


Fig. 13.4 Average (a) solar, K, and (b) IR, I, radiation fluxes. The extent of the stratocumulus cloud layer is shown by the shading. (After Nicholls, 1984).

Radiative fluxes in a stratocumulus cloud layer

The Marine Boundary Layer

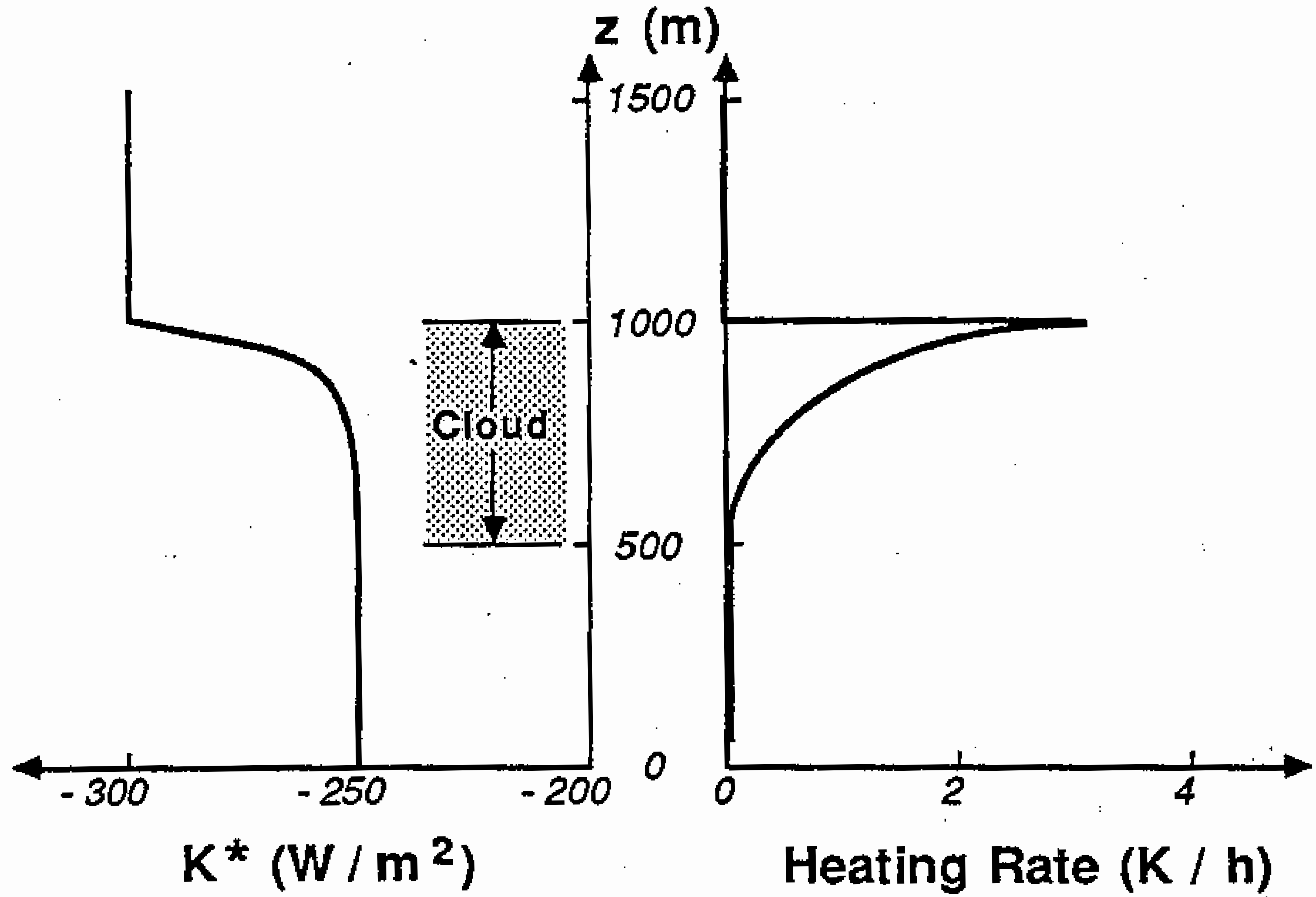
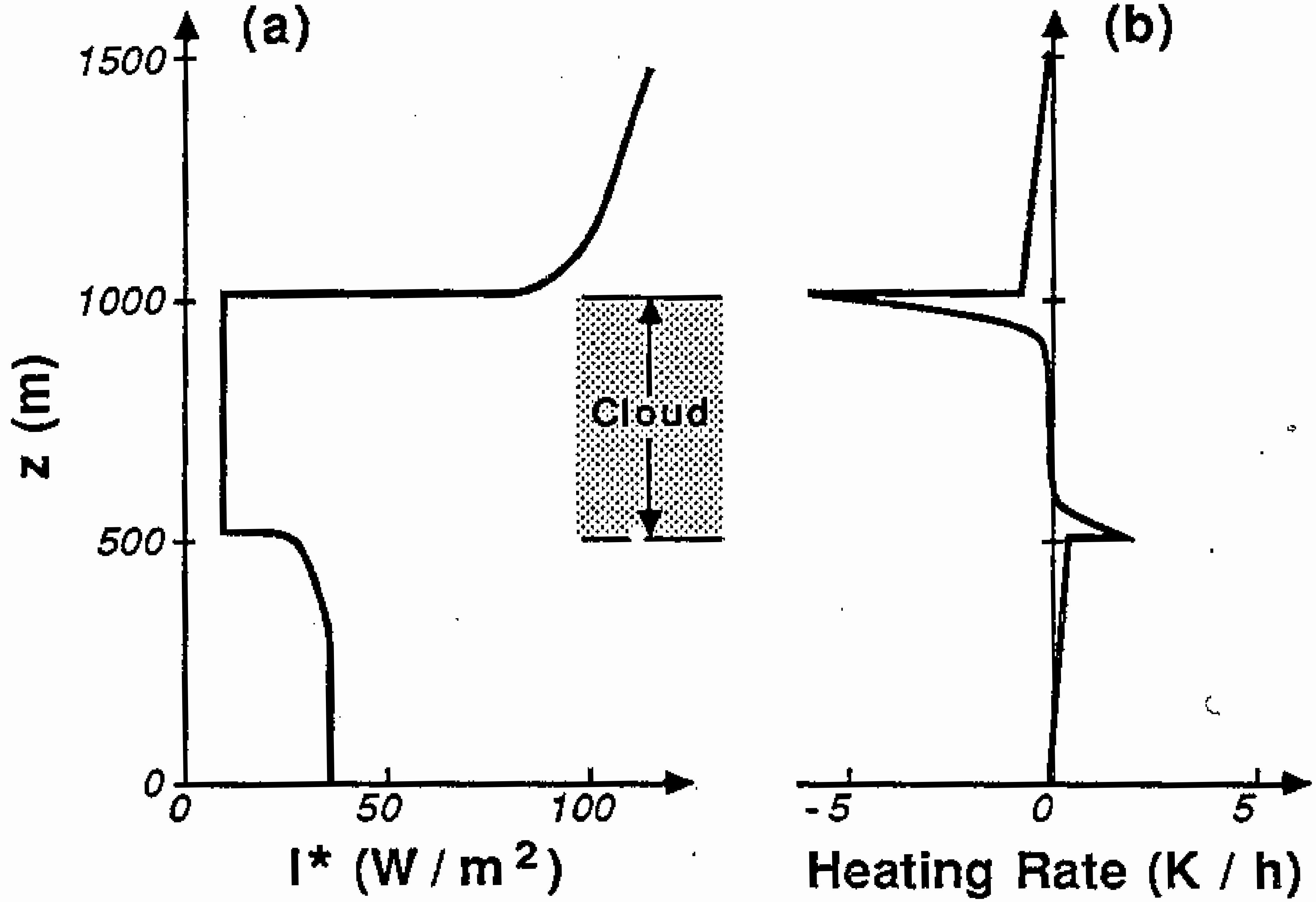


Fig. 13.5 Profiles of net shortwave radiative flux and the corresponding heating rate in an idealized stratocumulus deck. (After Hanson, 1987).

Shortwave (solar) net flux and radiative heating

The Marine Boundary Layer

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



Longwave net flux and radiative heating

The Marine Boundary Layer

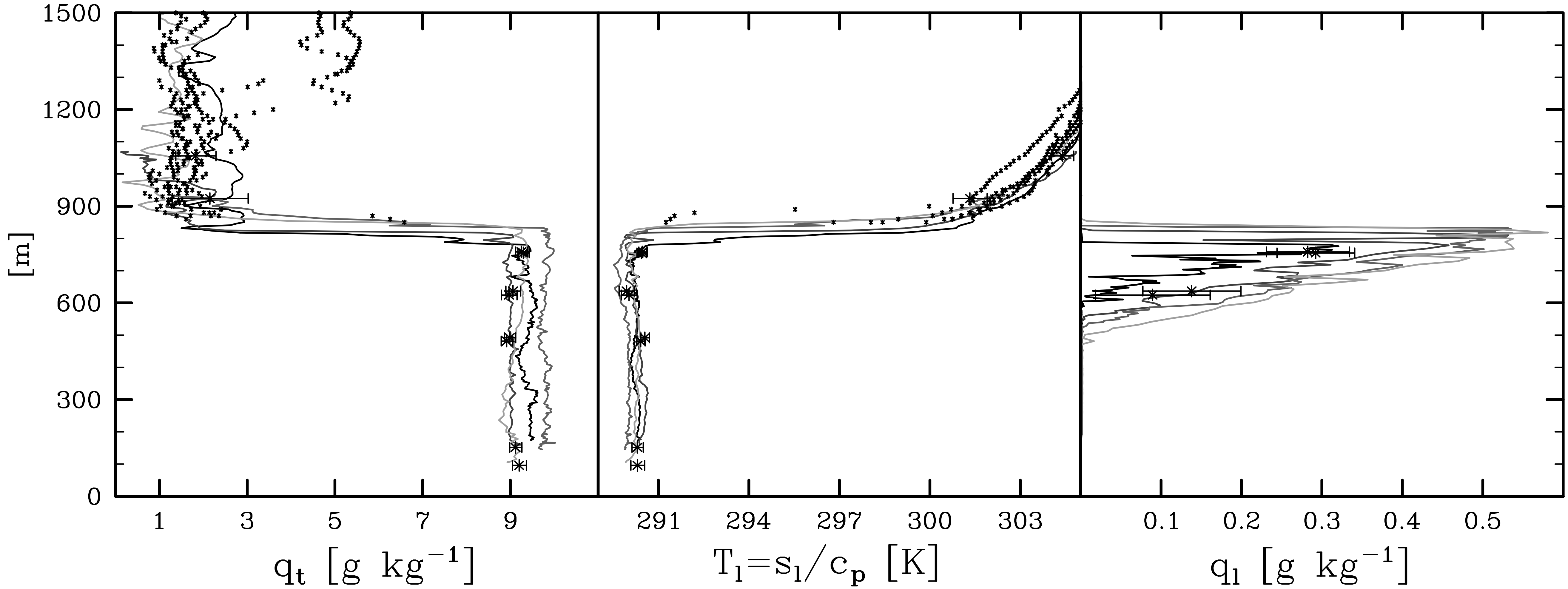


Figure 1. Cloud layer state as observed during RF01. From left to right, total water specific humidity, q_t, liquid-water static energy temperature, s_l/c_p, and liquid water specific humidity, q_l. Lines are from soundings, darker indicating earlier, filled circles and bars denote level leg means and standard deviations, and dots denote dropsonde data from the above-cloud portion of the descent.

Cloud layer maintains the capping inversion.

The Marine Boundary Layer

How does the cloud layer maintain the capping inversion?

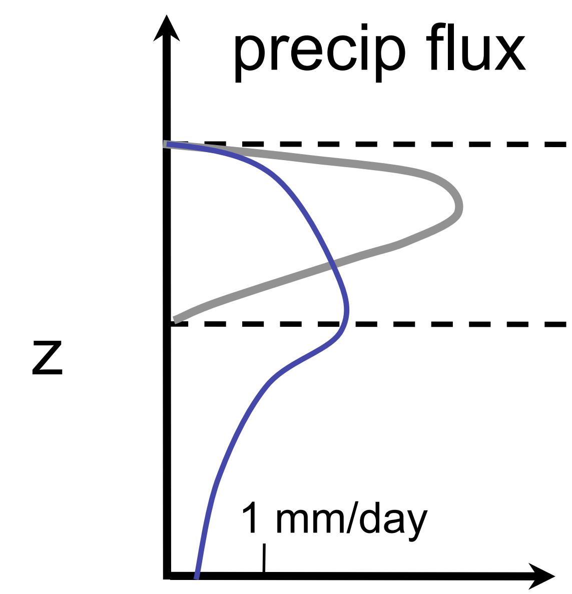
- *Radiation* cools the BL, while *subsidence* warms the air above the BL.

- The strong capping inversion reduces *entrainment*, which otherwise would tend to evaporate the cloud layer.

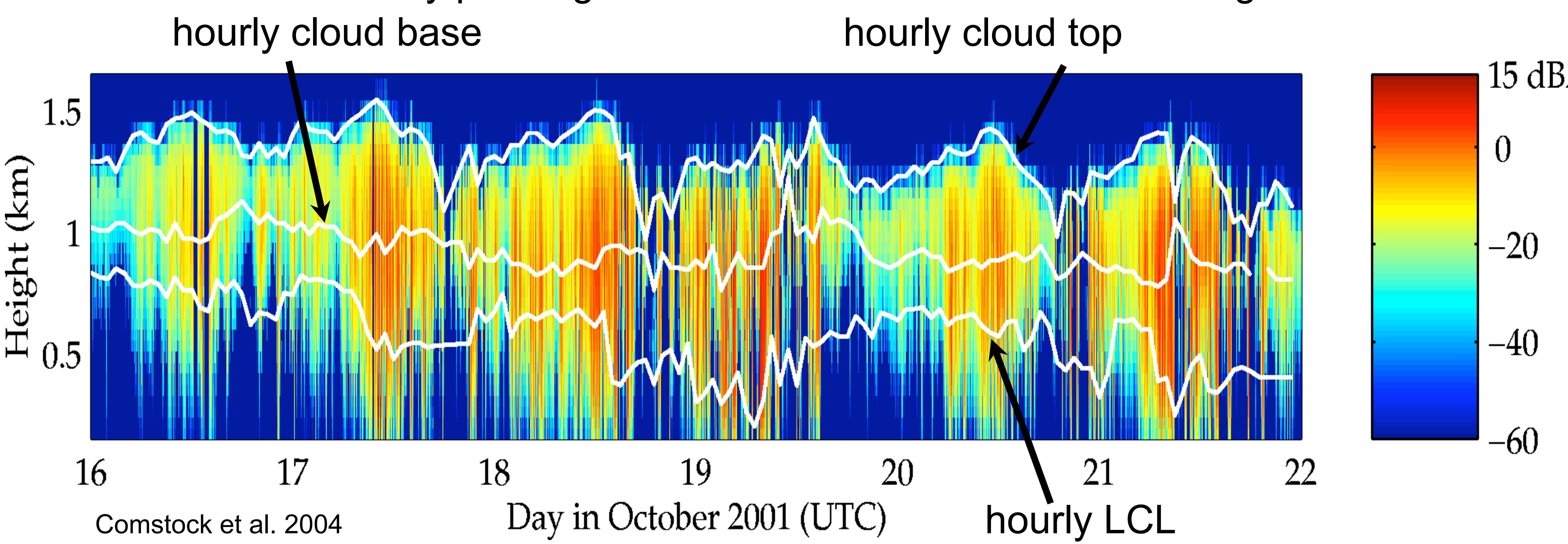
The Marine Boundary Layer

Sc physical processes: Precipitation

- Drizzle: Drops > 100 μm radius, falling ~ 1 m s^{-1}.
- Sedimentation (in cloud only): Cloud droplets less than 20 μm radius, falling a few cm s^{-1}.



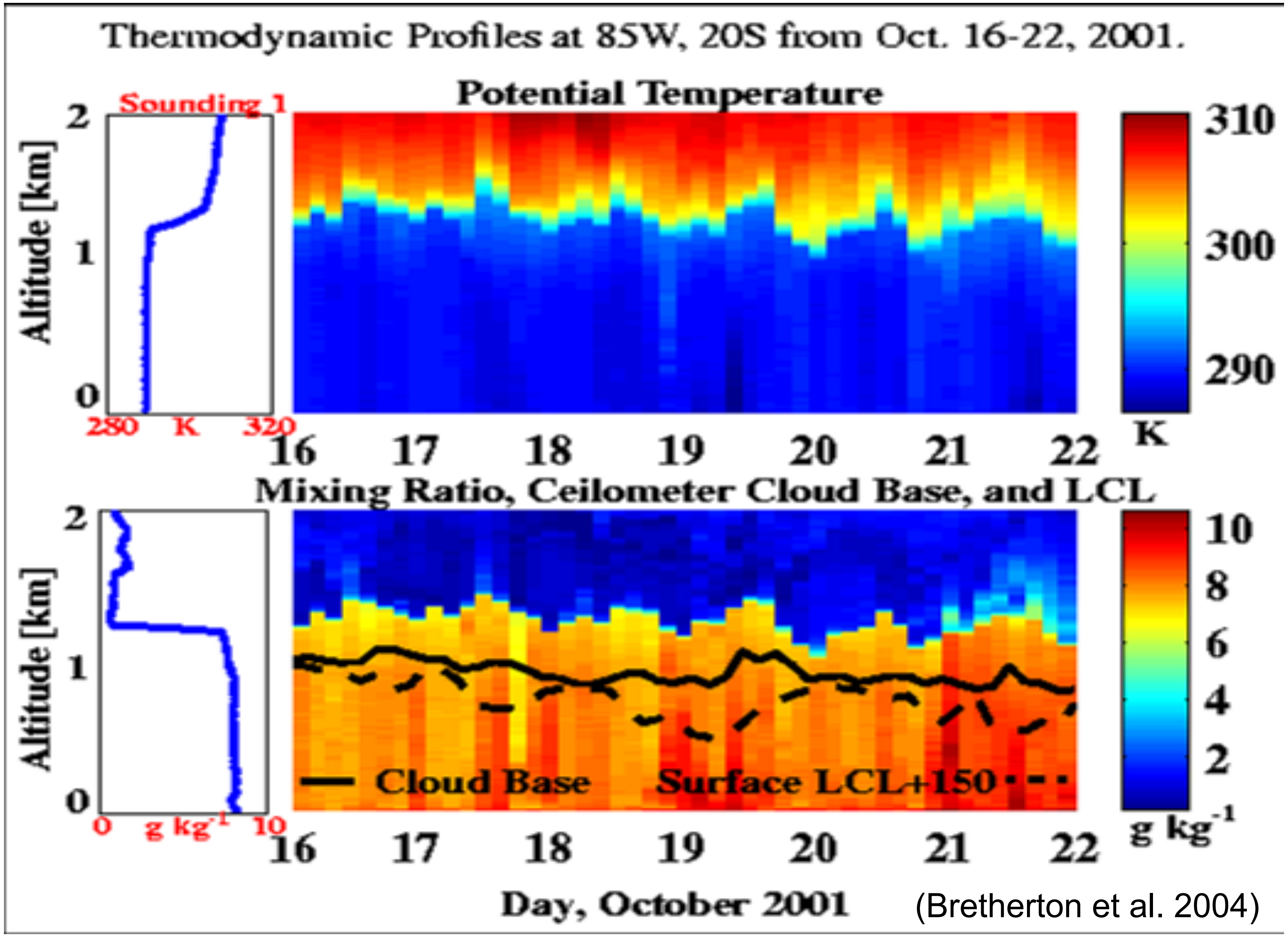
EPIC 8-mm vertically pointing ‘cloud radar’ observations of drizzling Sc



Comstock et al. 2004

The Marine Boundary Layer

SCBL diurnal cycle in SE Pacific sonde time series

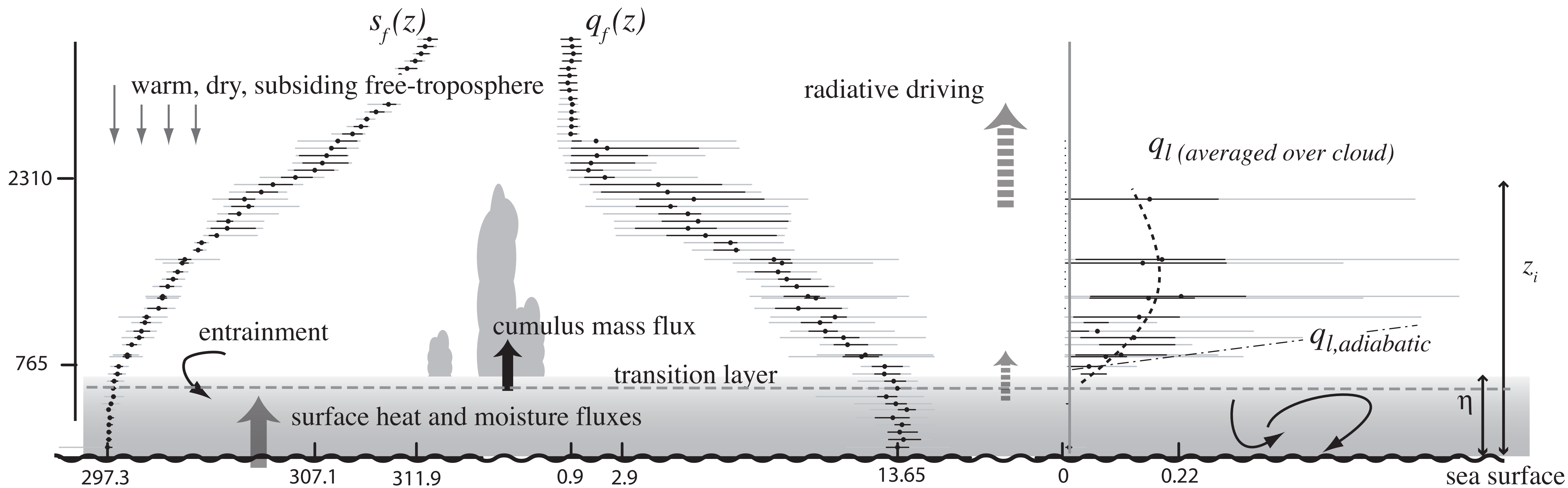


(Bretherton et al. 2004)

3-hourly sondes show:

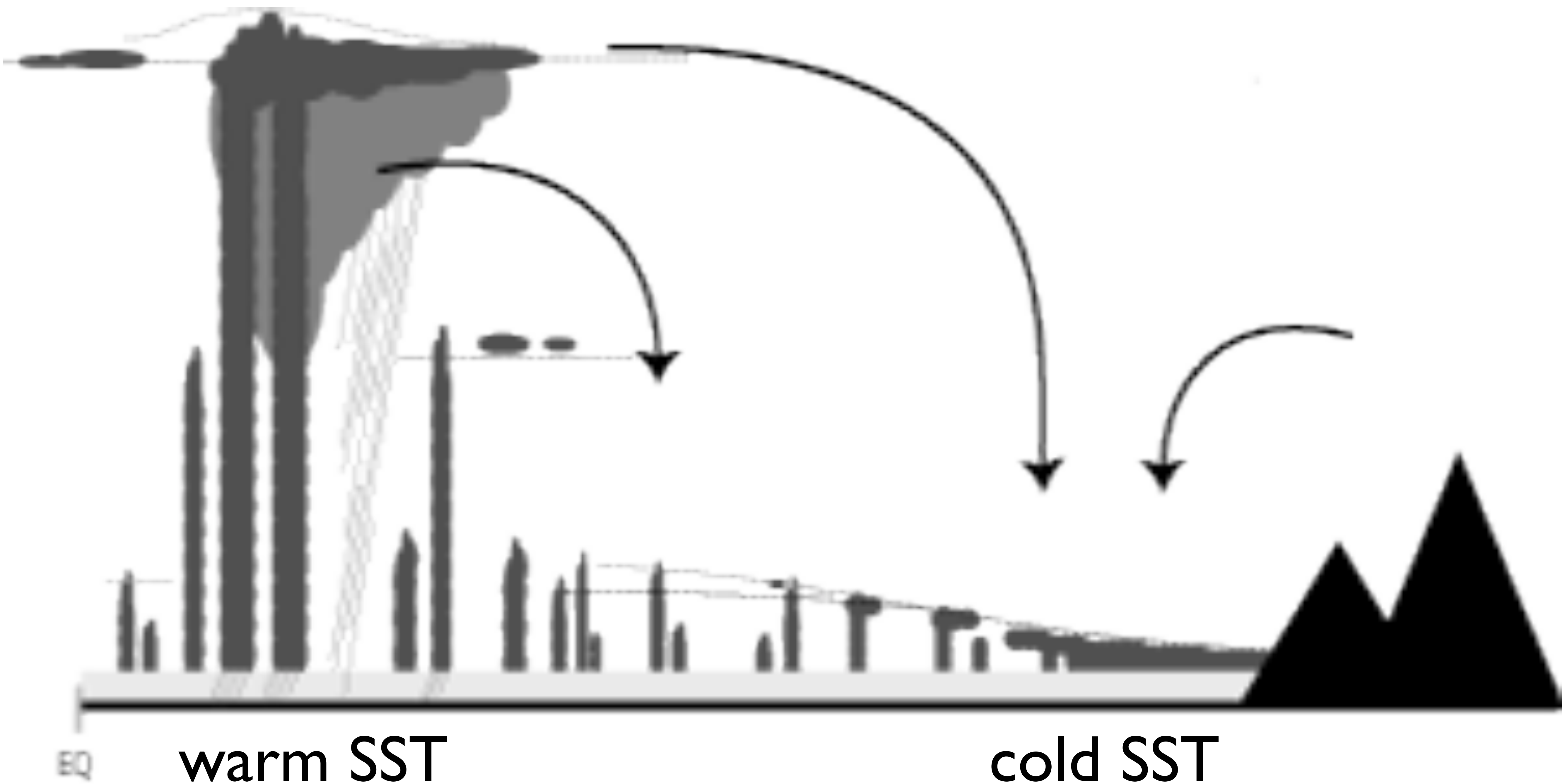
1. Mixed-layer structure with strong sharp inversion
2. Regular night-time increase in inversion height, cloud thickness.
3. Decoupling measured by cloud base - LCL increases during daytime and during periods of drizzle on 19, 21 Oct. (local noon = 18 UTC)

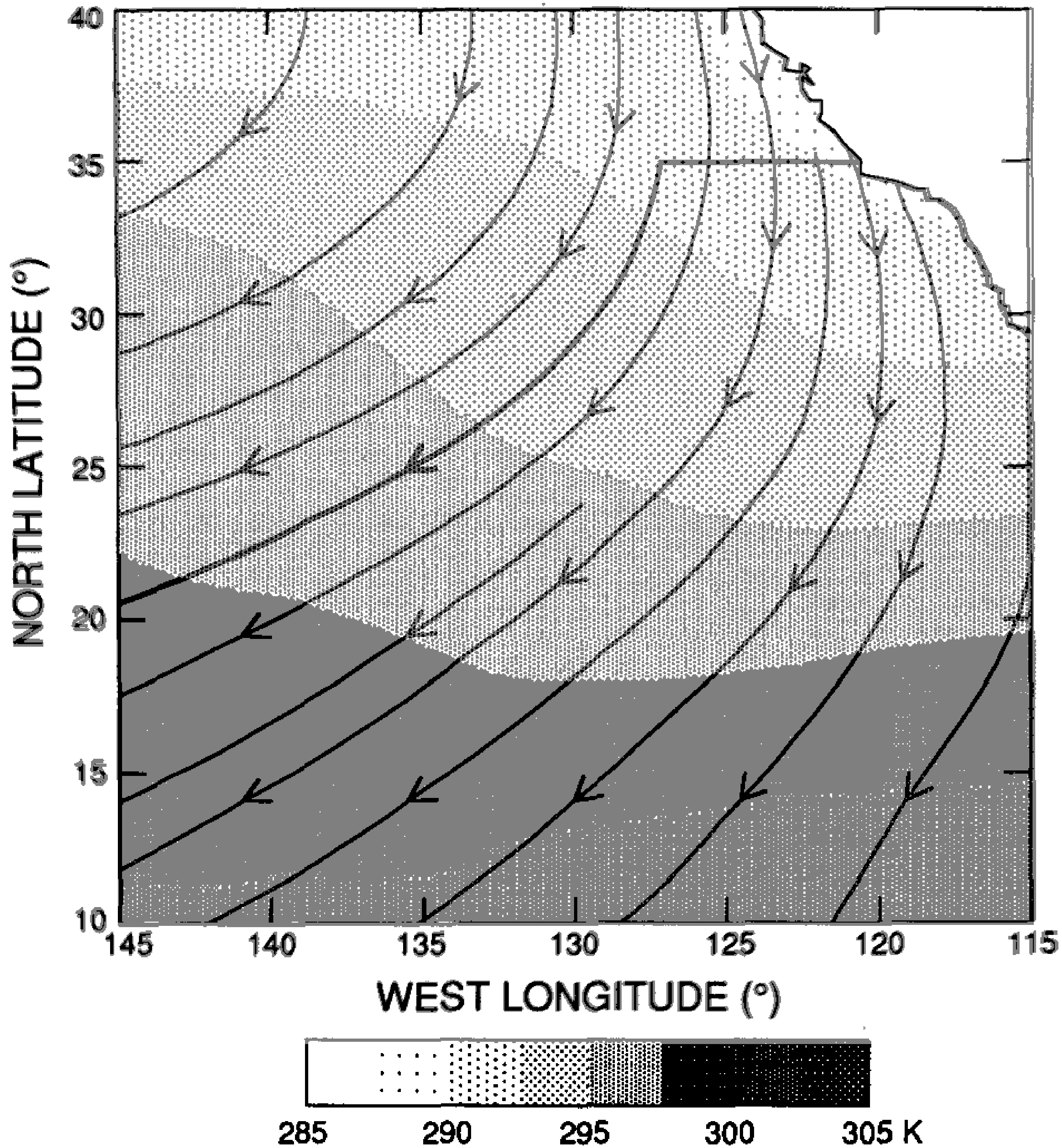
The Marine Boundary Layer



Structure of the cumulus topped boundary layer as observed during the 10th research flight of the Rain in Cumulus over the Ocean Field Study. The ordinate shows the top of the cloud layer and the LCL of the mean surface layer air. The values on the x-axis give s/cp averaged over the sub-cloud layer, at 2300 m and at 3500 m for the left panel; q at 3500 m, 2300 m and averaged over the sub-cloud layer for the middle panel; and the liquid-water specific humidity over cloud passes only (where cloud coverage is typically 5-10%) in the rightmost panel.

The Marine Boundary Layer





NORTH LATITUDE (°)
40
35
30
25
20
15
10
145
140
135
130
125
120
115
WEST LONGITUDE (°)
285
290
295
300
305 K

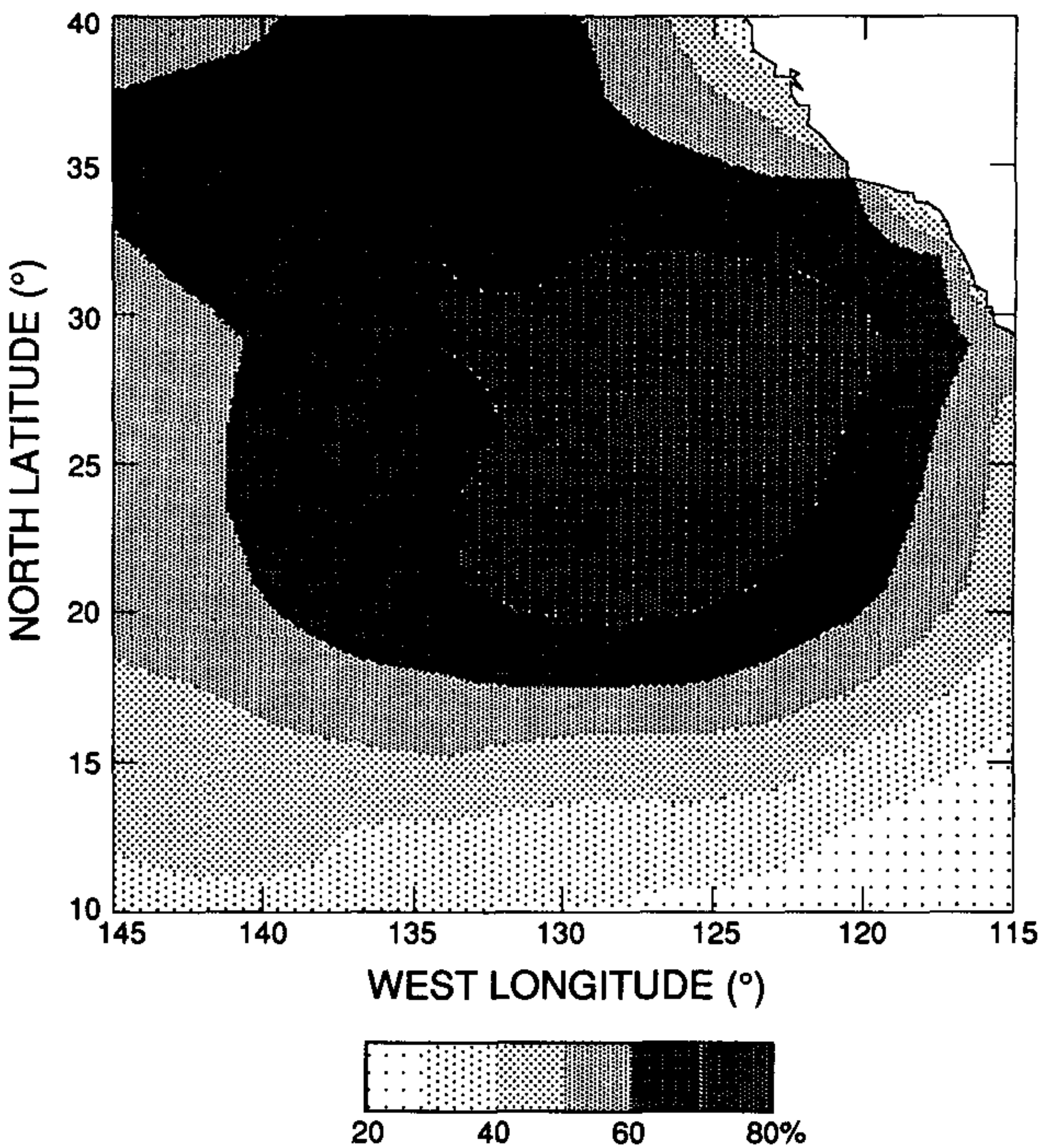


FIG. 3. Mean July low cloud cover from GOES (1983–87; from Heck et al. 1990).

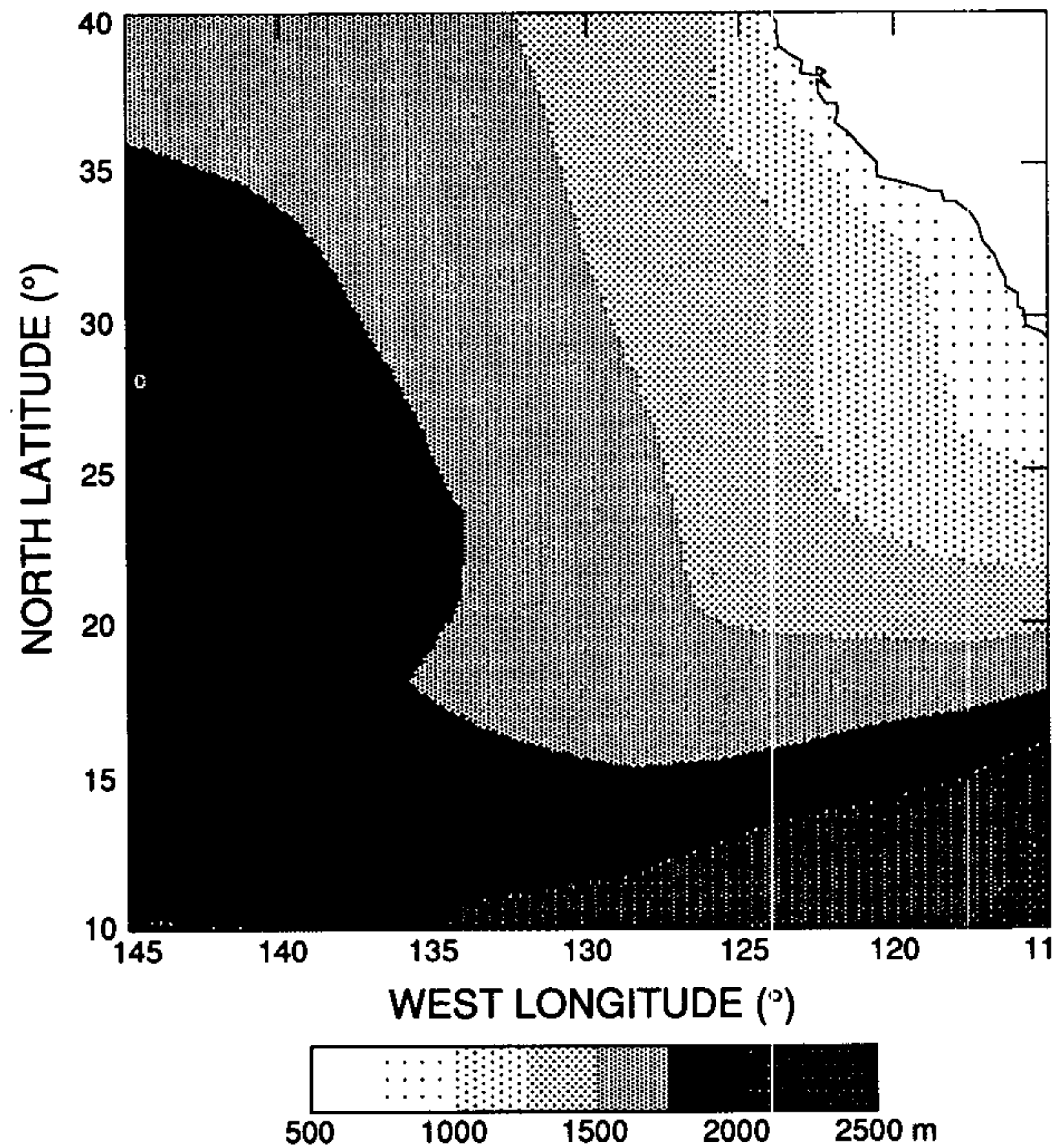


FIG. 5. Mean July low cloud-top heights from GOES (1983–87) using fixed lapse rate of 7.1 K km^{-1}.

The Marine Boundary Layer

- As the Sc-topped BL moves over warmer SSTs, it deepens and Cu clouds appear below the Sc layer.
- The Sc layer becomes increasing decoupled from the surface and gradually thins due to entrainment.
- The Sc layer completely evaporates leaving a trade-wind Cu BL.

The Marine Boundary Layer

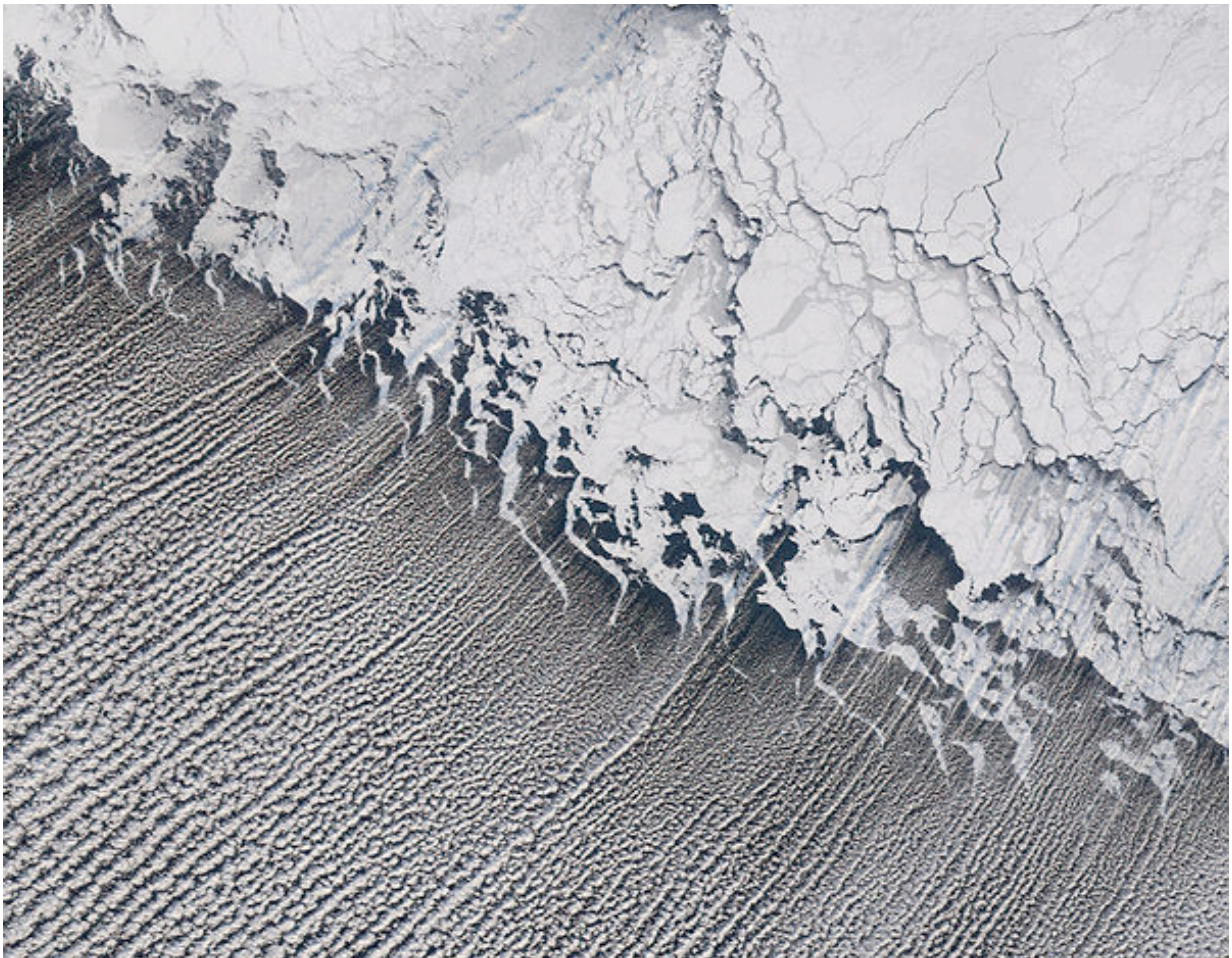
Cu under Sc

The Marine Boundary Layer

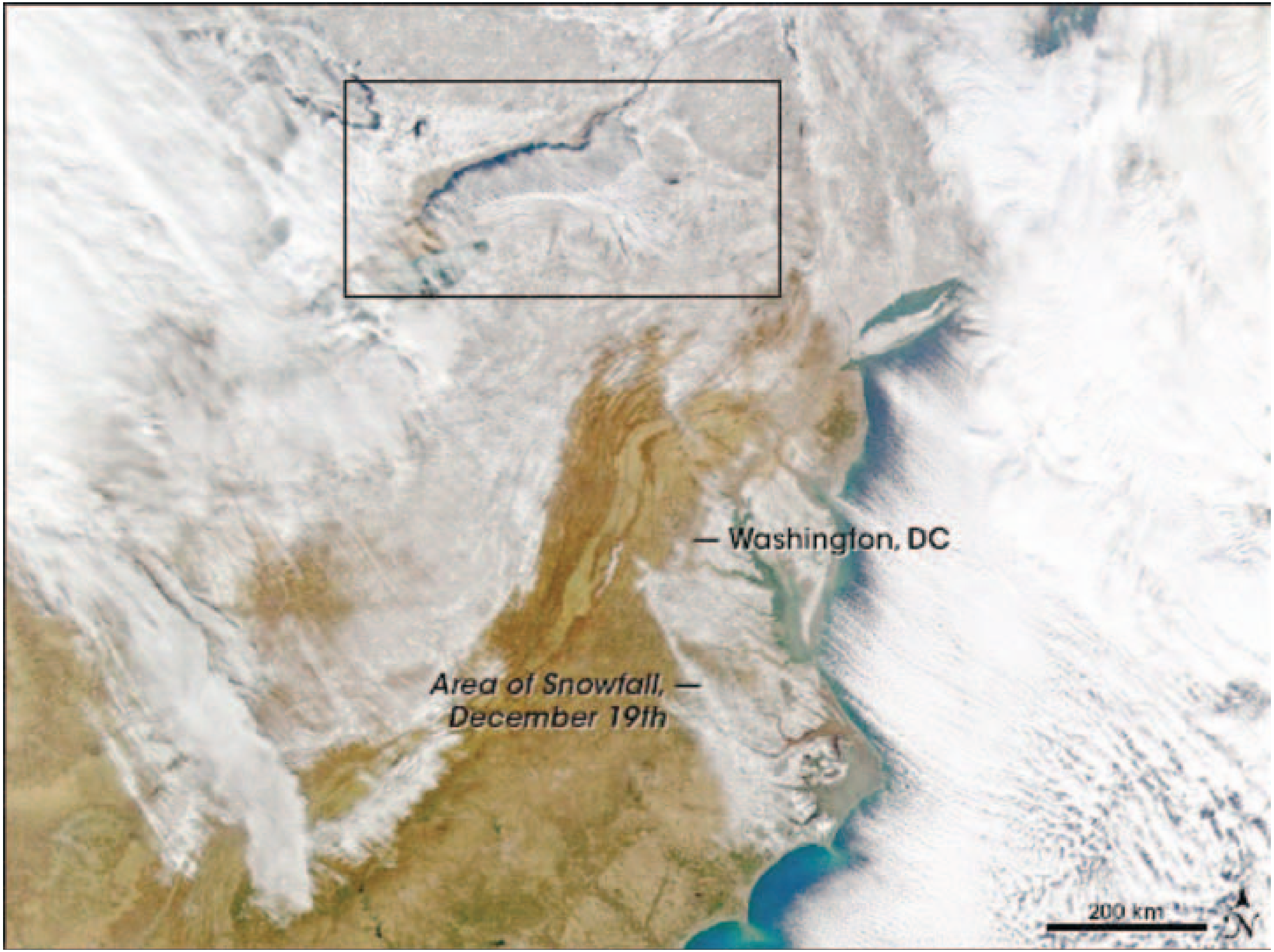
Cu under Sc

The Marine Boundary Layer

Cold air outbreak



The Marine Boundary Layer



The Marine Boundary Layer

The Marine Boundary Layer