AOSC400-2015
November 05, Lecture # 18

Chapter 9:

- Connection between Chapter 4 and Chapter 9
- Components of the Surface Energy Budget (S**E**B)-in addition to radiation also fluxes of *heat and moisture*
- Fluxes of heat and moisture are transported by turbulence
- What is Planetary Boundary Layer (PBL)? Capping Inversion
- What is turbulence? How do we represent it? Reynolds Averaging

*Sources of information used for this lecture are listed in updated Syllabus.

Components of the Surface Energy Budget (SEB):

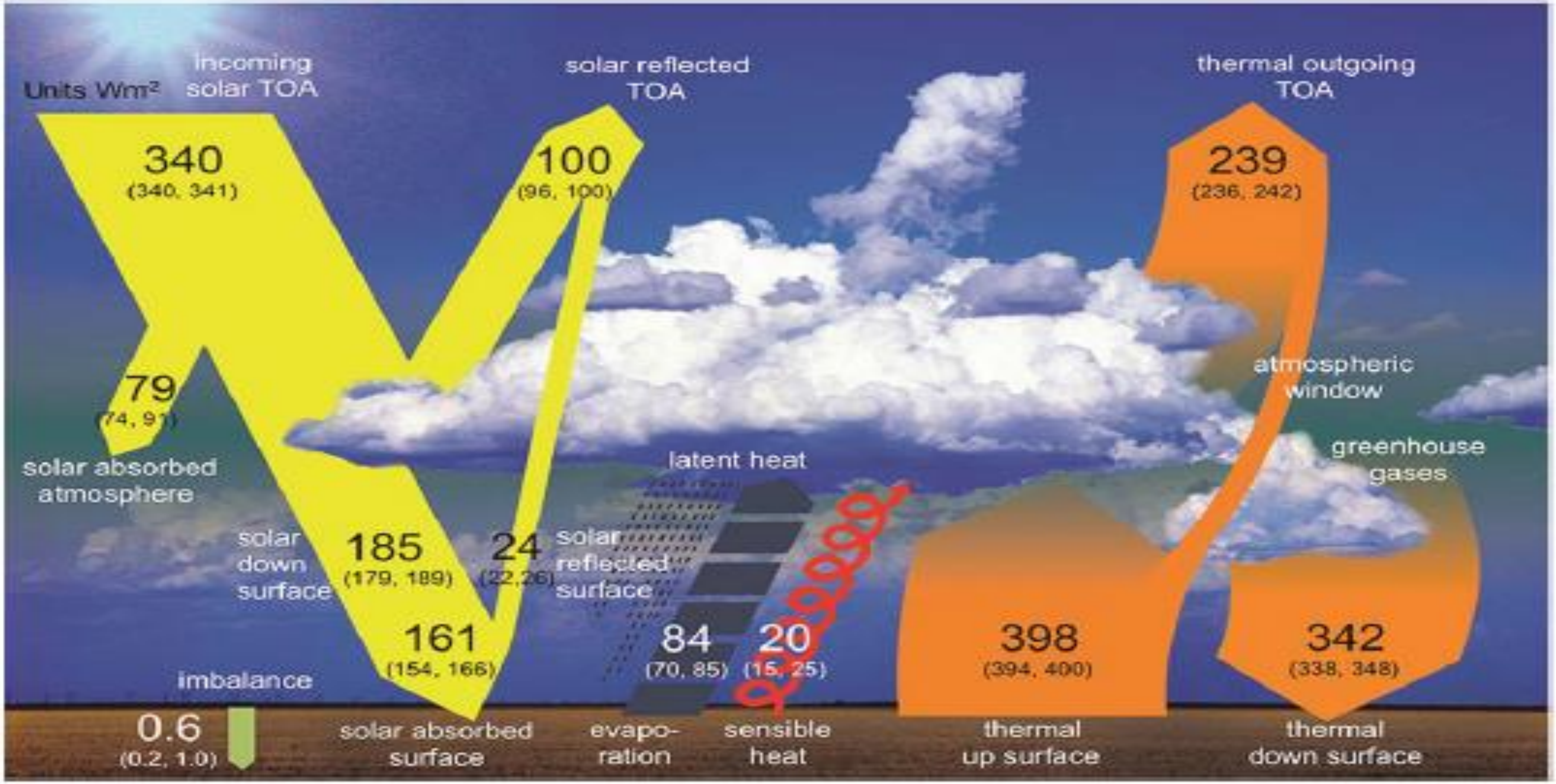
One Component of SEB: Surface Radiation Budget

Other components:

- Surface *Turbulent Fluxes of heat and moisture*
- Heat into ground

So far, in the following slide we have discussed only the radiative fluxes. We will continue to discuss the additional terms, namely sensible and latent heat.

Global mean energy budget under present day climate conditions (from IPCC 2013)



Radiation Balance at the Earth Surface

The net flux of radiation at the earth's surface results from a balance between the solar and terrestrial

Radiative fluxes:

$$F^{sfc}rad = F_{SW} + F_{LW}$$

The short-wave and long-wave radiation balance can be expressed:

$$F_{SW} = F_{SW}\downarrow - F_{SW}\uparrow$$

$$F_{LW} = F_{LW}\downarrow - F_{LW}\uparrow$$

The net radiation balance being:

$$F^{sfc}_{rad} = F_{SW}\downarrow - F_{SW}\uparrow + F_{LW}\downarrow - F_{LW}\uparrow$$

- The incident solar radiation $F_{SW}\downarrow$ is the sum of the direct and diffuse solar radiation.
- It has a pronounced diurnal and seasonal variation, and is also strongly affected by clouds.
- The outgoing short-wave solar radiation is the part reflected by the surface $F_{SW}\uparrow = A_{sfc}F_{SW}\downarrow$, where A_{sfc} is the surface albedo so that the net short-wave radiation is:

$$F_{SW} = (1 - A_{sfc})\, F_{SW}\downarrow$$

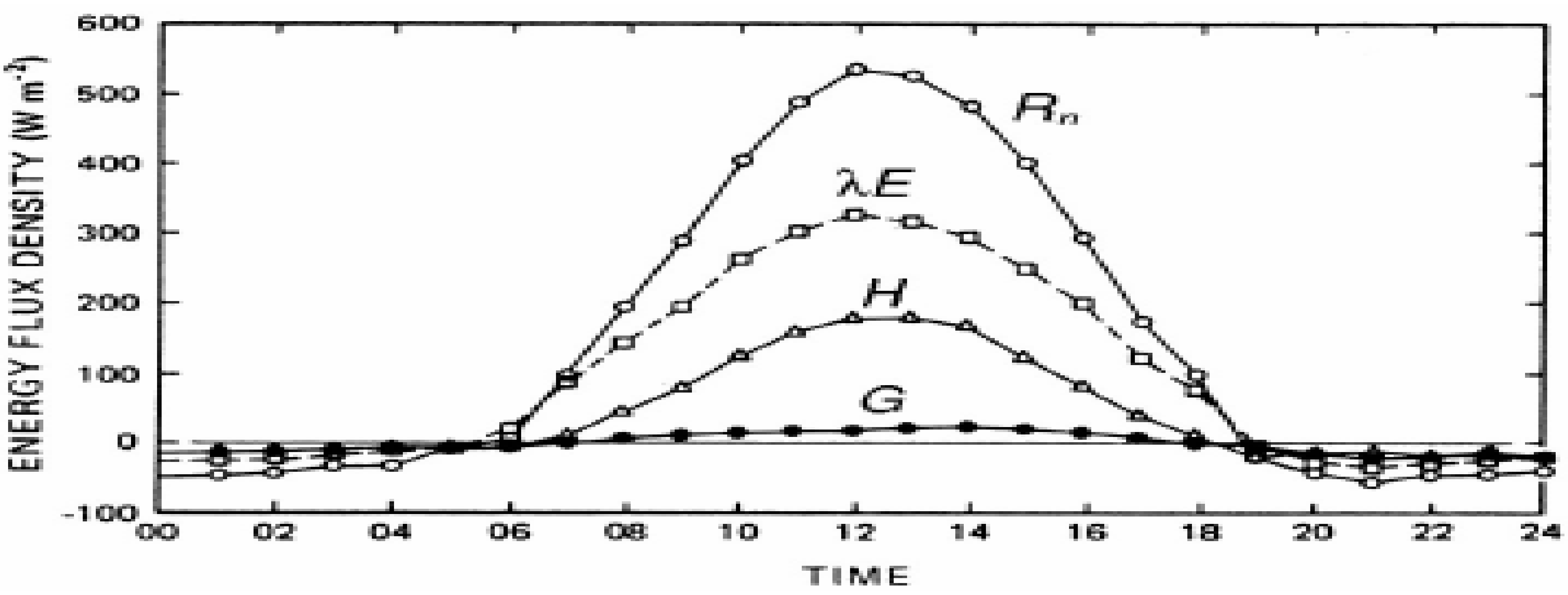
- The outgoing long-wave radiation $F_{LW}\uparrow$ is given by the Stefan-Boltzmann law, assuming a given emissivity ϵ for the earth's surface.
- The net radiation flux at the surface is then given by :

$$F^{sfc}{}_{rad} = F_{SW}\downarrow (1 - A_{sfc}) - \sigma\epsilon T^4{}_{sfc} + F_{LW}\downarrow$$

Energy Balance at the Earth Surface

- The main part of the energy absorbed at the surface is used to evaporate water,
- Another part is lost to the atmosphere as sensible heat, and a smaller part is lost to the underlying layers or used to melt snow and ice.
- There are essentially four types of energy fluxes at the earth's surface. They are the net radiation flux F_{rad}, the sensible heat flux $F_{SH}\uparrow$, the latent heat flux $F_{LH}\uparrow$, and the heat flux into the subsurface layers $F_G\downarrow$.
- Under steady conditions the balance equation for the energy is given by:

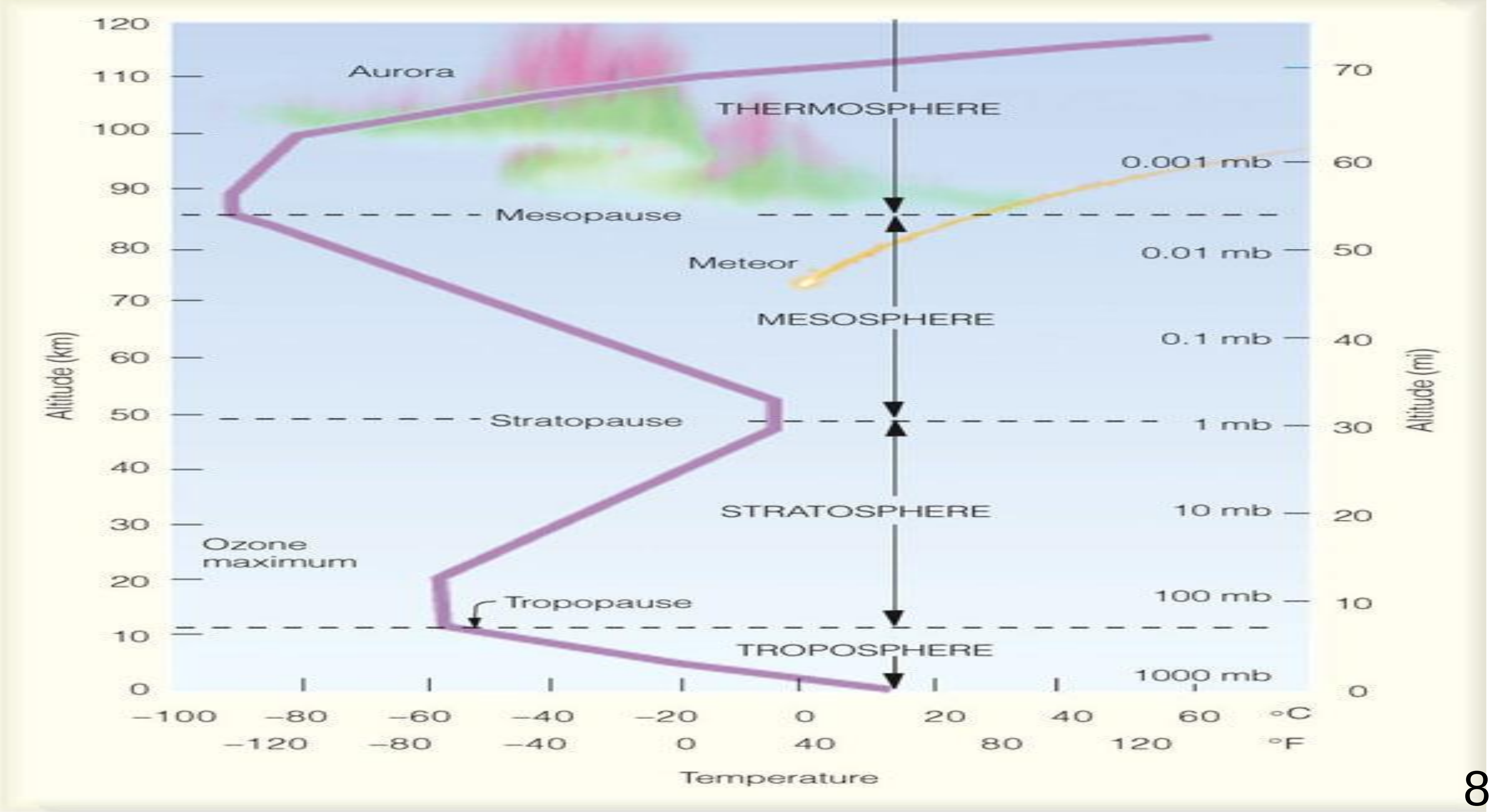
$$F^{sfc}_{rad} - F_{SH}\uparrow - F_{LH}\uparrow - F_G\downarrow - F_M = 0$$



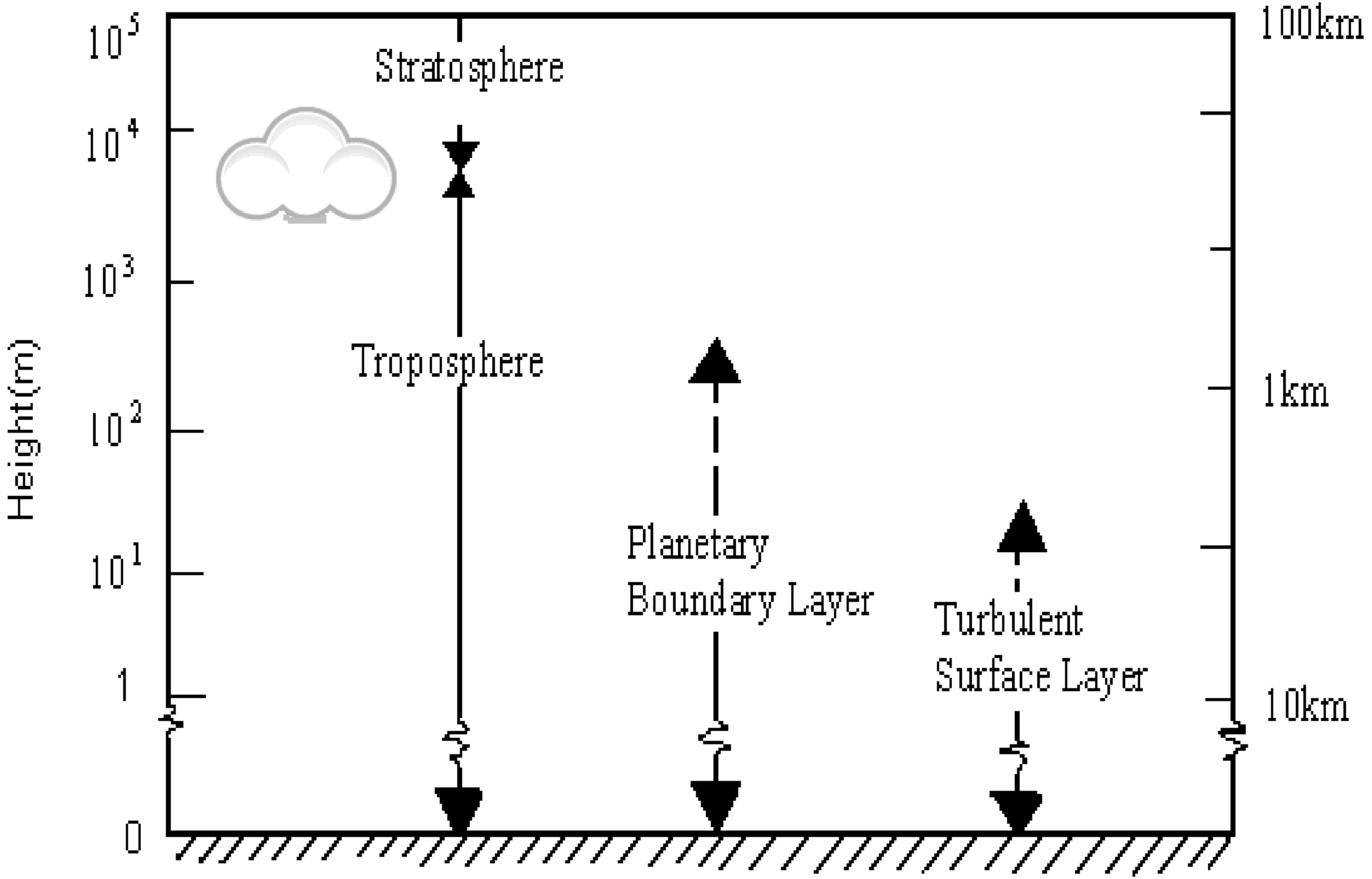
Diurnal variation of the components of the surface energy budget in cloudless conditions at a rural mid-latitude site.

Main layers of the atmosphere were identified previously:

Troposphere, Stratosphere, Mesosphere, Thermosphere

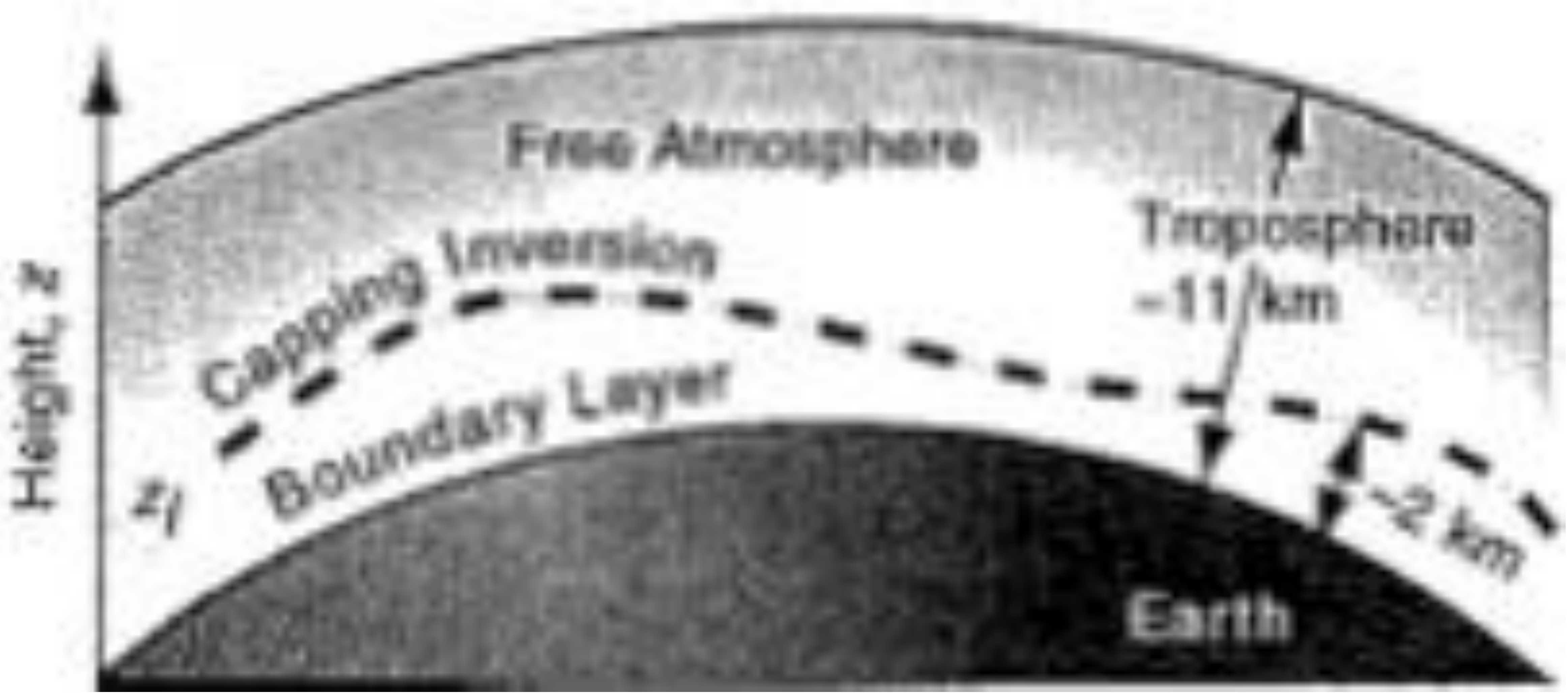


The troposphere can be subdivided as follows:



- The Earth's surface is the bottom boundary of the atmosphere.
- The portion of the atmosphere most affected by that boundary is called the Atmospheric Boundary Layer (ABL)
- The thickness of the boundary layer is quite variable in space and time. Normally -1 or 2 km thick (i.e., occupying the bottom 10 to 20% of the troposphere), it can range from tens of meters to 4 km or more.
- Turbulence and static stability conspire to sandwich a strong stable layer (capping inversion) between the boundary layer below and the rest of the troposphere above (called the free atmosphere).
- This stable layer traps pollutants, moisture and prevents the surface friction from being felt by the free atmosphere.

From the Textbook:



How if heat transported?

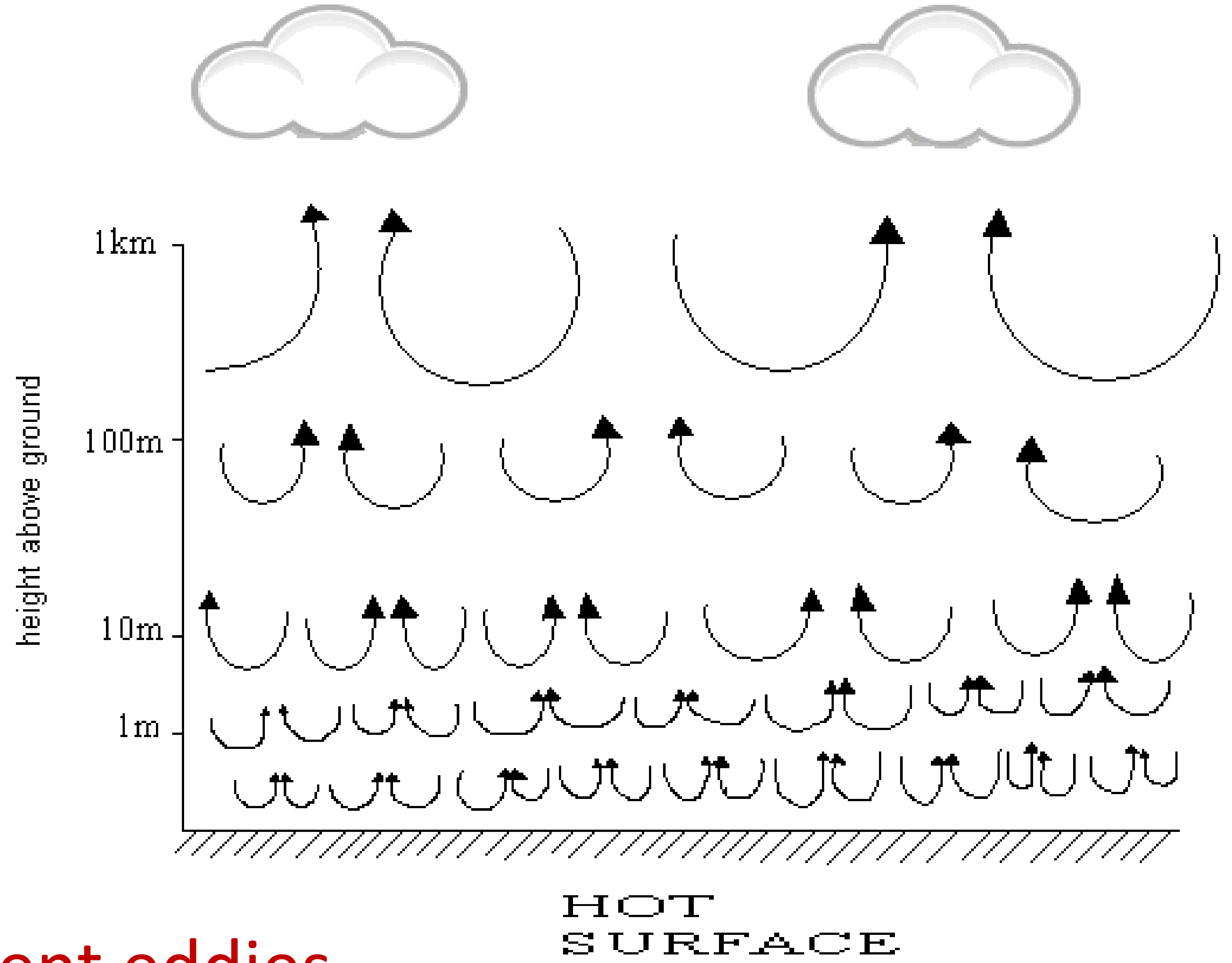
Conduction – principal method of heat transfer in ground.

Air temperature – determined principally by –

a) Radiative flux divergence
b) Advection
c) Convection
d) Latent heat exchanges by evaporation and condensation

Heat transfer from soil to air (and vice versa) in surface near air – a complex process. We can distinguish a three-layer structure:

1) A laminar boundary layer without turbulence (heat transfer by Brownian motion < 1mm).
2) A transitional boundary layer with incipient convection 1mm – 2cm.
3) Upper boundary layer with turbulent transfer that at its upper limit has fully free flow



Turbulent eddies.

- Turbulence is responsible for efficiently dispersing the pollutants
- However, the capping inversion traps these pollutants within the boundary layer,
- Turbulent communication between the surface and the air is quite rapid, allowing the air to quickly take 'on characteristics of the underlying surface.
- In fact, one definition of the boundary layer is that portion of the lower troposphere that feels the effects of the underlying surface within about 30 min or less.

Leonardo da Vinci's view of turbulence

View of turbulence by Leonardo da Vinci (1452-1519) who recognized the multi-scale nature of turbulence.

Three kinds of turbulence recognized:

- Mechanical turbulence
- Turbulence caused by shear
- Turbulence caused by buoyancy

Mechanical turbulence is caused by air flowing over rough features, such as hills or buildings.

https://www.meted.ucar.edu/EUMETSAT/at_dust/media/video/mech_turbulence.mp4

Note: In order to be able to view the clip, you need to register on the NCAR site. It is very simple. Once you do so, you will have access to educational resources of NCAR. They have many interesting presentations.

Turbulence from shear can result from differences in wind speed and/or direction.

https://www.meted.ucar.edu/EUMETSAT/at_dust/media/video/shear_turbulence.mp4

Sometimes clouds show these patterns known also as Kelvin-Helmholtz vortex patterns

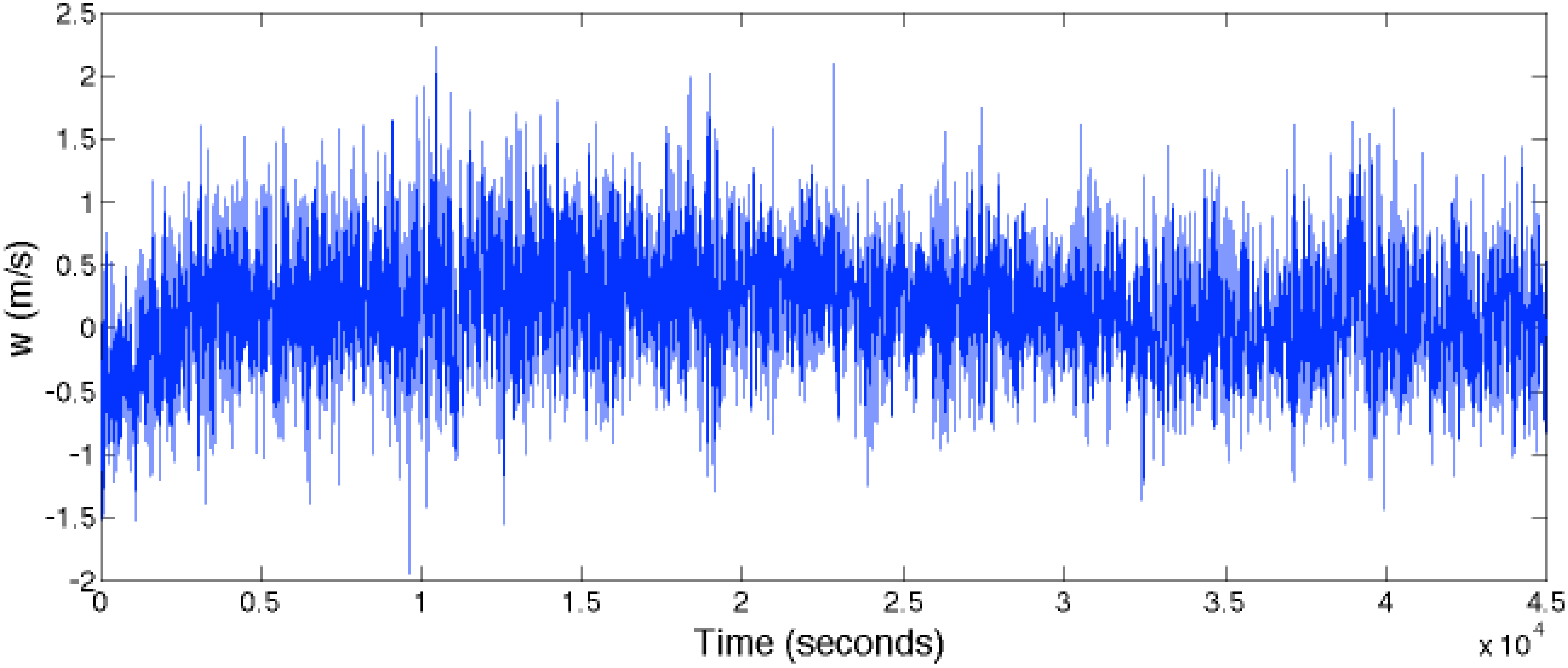
Buoyancy turbulence can be caused by a parcels of air rising during the diurnal heating of the surface.

In such case, buoyancy is governed by the stability of the atmosphere.

https://www.meted.ucar.edu/EUMETSAT/at_dust/media/video/buoy_turb.mp4

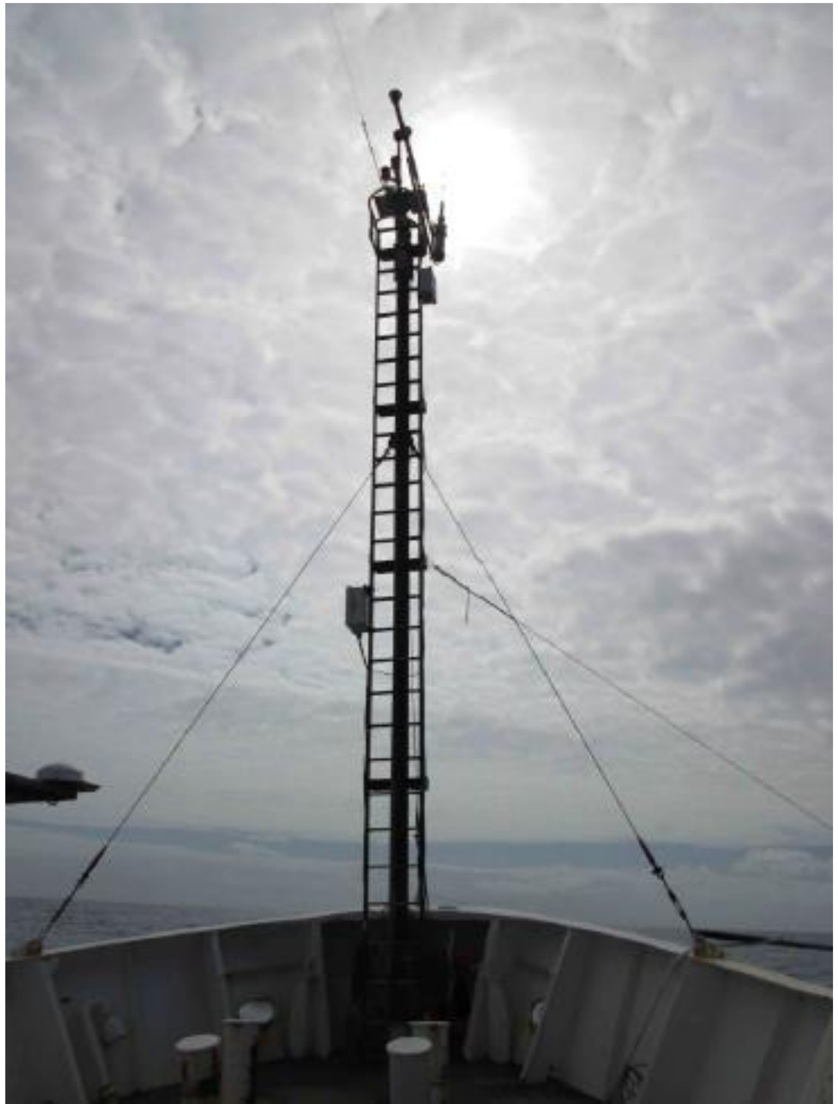
- Turbulence is very complex, consisting of a superposition of swirls called eddies that interact nonlinearly to create quasi-random, chaotic motions.
- An infinite number of equations is required to fully describe these motions.
- A complete solution has not been found.
- But when averaged over many eddies, we can observe persistent patterns.

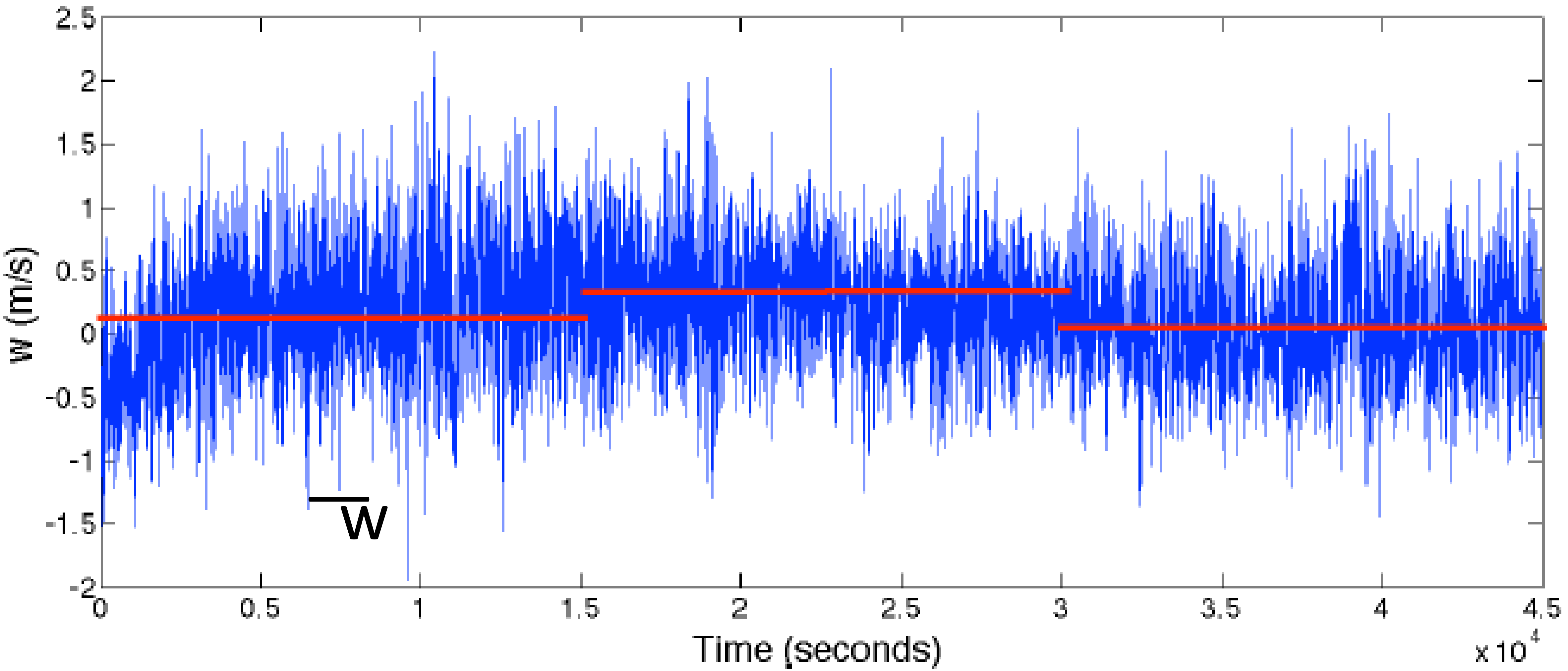
Sonic anemometer recording at 25 Hz



30 minute

- Need: fast response instrument
- For winds: a sonic anemometer





$$w' = w - \overline{w}$$

Another example of turbulent fluctuations. Most turbulent close to the ground.

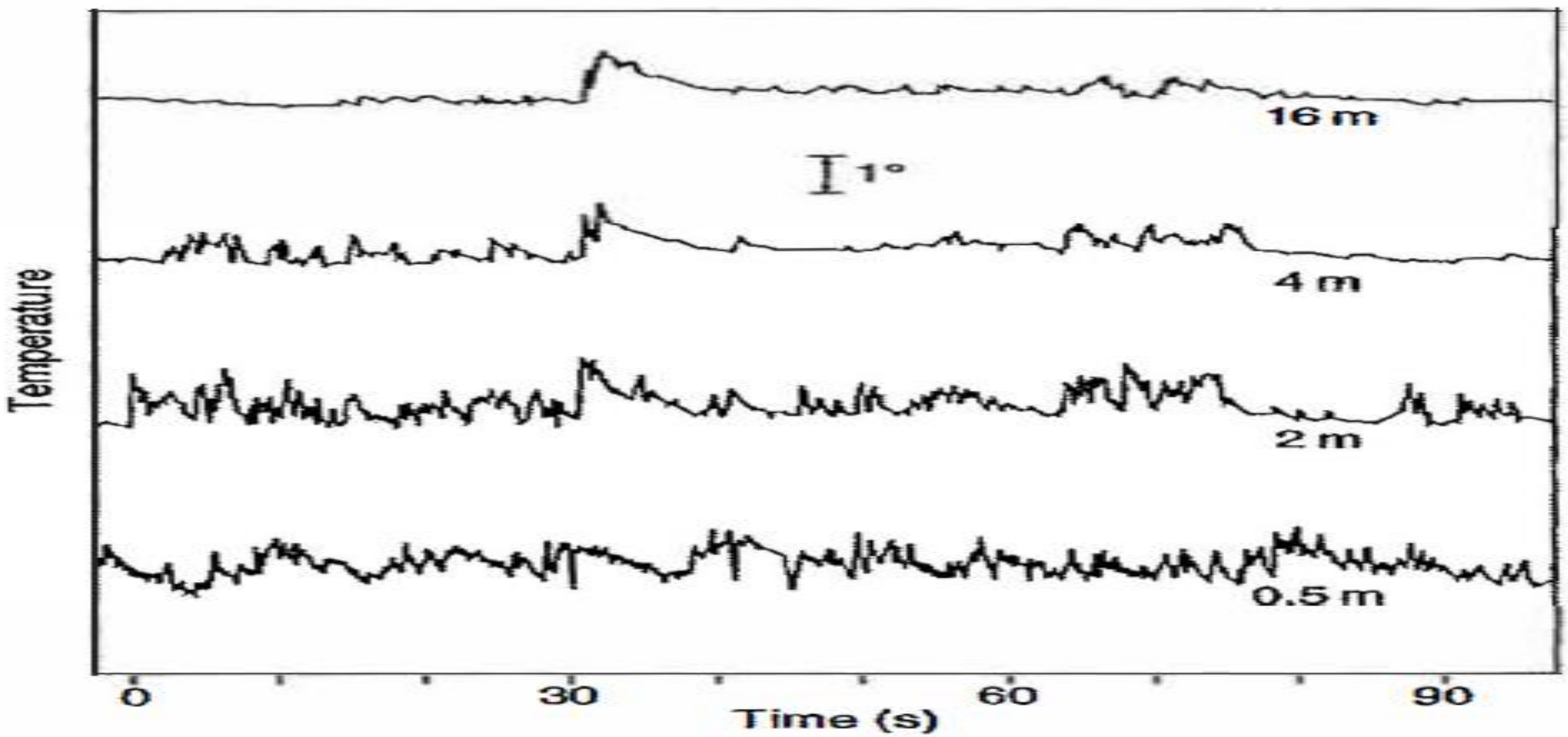


Fig. 9.6 Simultaneous time series of temperature (°C) at four heights above the ground showing the transition from the *surface layer* (bottom 5–10% of the mixed layer) toward the *mixed layer* boundary layer (upper levels of the boundary layer). Observations were taken over flat, plowed ground on a clear day with moderate winds. The top three temperature sensors were aligned in the vertical; the 0.5 m sensor was located 50 m away from the others. [Courtesy of J. E. Tillman.]

- Despite the difficulties of deterministic descriptions of turbulence, scientists have been able to create a statistical description of turbulence.

- The goal of this approach is to describe the net effect of many eddies, rather than the exact behavior of any individual eddy.

From Textbook:

Based on an average over a time period T (say half an hour):

$$\overline{u} = \frac{1}{N}\sum_{i=1}^{N} u_i \qquad (9.2)$$

In the atmosphere, this mean value can change from one half-hour period to the next, resulting in a slow variation of the mean-wind components with time.

Subtracting the mean from the instantaneous component u gives just the fluctuating (gust) portion of the flow (indicated with a prime)

$$u_i' = u_i - \overline{u} \qquad (9.3)$$

The intensity of turbulence in the u direction is then defined by the variance:

$$\sigma_u^2 = \frac{1}{N}\sum_{i=1}^{N}[u_i - \overline{u}]^2 = \frac{1}{N}\sum_{i=1}^{N}[u_i']^2 = \overline{[u']^2} \quad (9.4)$$

In the atmosphere, fluctuations in velocity are often accompanied by fluctuations in scalar values such as temperature, humidity, or pollutant concentration.
For example, in a field of thermals there are regions where warm air is rising (positive potential temperature ϑ' accompanies positive vertical velocity w'), surrounded by regions where cold air is sinking (negative ϑ' accompanies negative w'). One measure of the amount that ϑ and w vary together is the covariance (cov) .

If warm air parcels are rising and cold parcels are sinking, as in a thermally direct circulation, then $\overline{w'\theta'} > 0$. Covariances can also be negative or zero

$$\text{cov}\,(w,\theta) = \frac{1}{N}\sum_{i=1}^{N}[(w_i - \overline{w}) \cdot (\theta_i - \overline{\theta})]$$

$$= \frac{1}{N}\sum_{i=1}^{N}[(w'_i) \cdot (\theta'_i)] = \overline{w'\theta'} \qquad (9.5)$$

Reynolds Averaging

Will also help to explain how eq. 9.5 in Textbook was derived.

http://twister.caps.ou.edu/MM2002/Chapter2.2.pdf

Such averaging was first proposed by Reynolds, and is therefore named after him.

We use overbar to denote the mean value and prime to denote the perturbation.

For any quantity A (could be e.g., vertical velocity w and potential temperature θ), we have

$$A = \overline{A} + A'$$

where $$\overline{A} = \frac{1}{T}\int_0^T A(x,t)dt \qquad (2.1)$$

for a continuous function A, or

$$\overline{A} = \frac{1}{N}\sum_{n=1}^{N} A_n(x) \qquad (2.2)$$

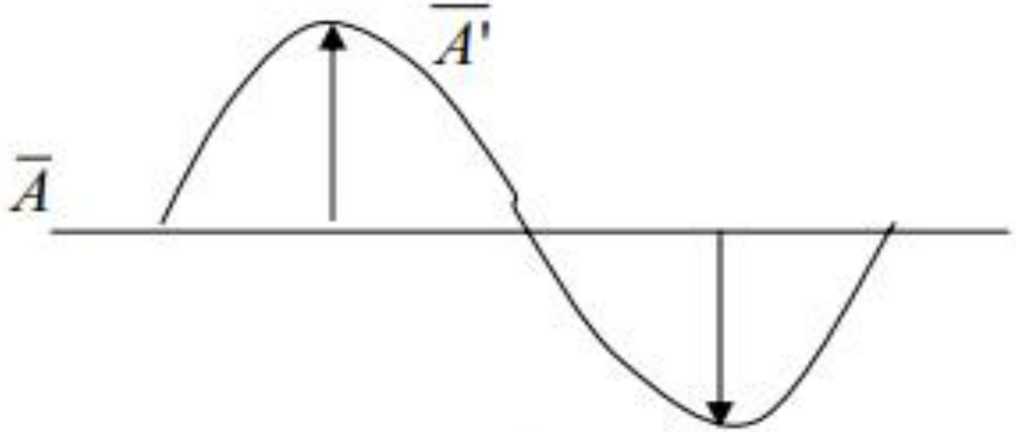
if we have discrete values of A. Here N is the number of points in the time series in time the chosen time interval T.

Note that $\overline{(\quad)}$ can be thought of as the integration operator, thus we can apply it as follows:

$$\overline{(A)} = \overline{(\overline{A} + A')} = \overline{\overline{A}} + \overline{A'} = \overline{A} + \overline{A'}$$

→ $$\overline{A'} = 0 \qquad \text{(mean of the fluctuation is zero).} \qquad (2.3)$$

Why $\overline{\overline{A}} = \overline{A}$? It's just the average of the average, which is the average (for a given time averaging interval, the average is no longer a function of time therefore further averaging has no effect). The statement that $\overline{A'} = 0$ means that as much area lies above the $\overline{A}$ line as blow it. Consider a since wave:



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Now let's examine the mean of the product of two variables, A and B, each of which can be split into the mean and perturbation parts, therefore:

$$
\begin{aligned}
\overline{AB} &= \overline{(\bar{A} + A')(\bar{B} + B')} \\
&= \overline{(\bar{A}\bar{B} + A'\bar{B} + \bar{A}B' + A'B')} \\
&= \overline{(\bar{A}\bar{B})} + \overline{(A'\bar{B})} + \overline{(\bar{A}B')} + \overline{(A'B')} \\
&= \bar{A}\bar{B} + 0 + 0 + \overline{A'B'} \\
&= \bar{A}\bar{B} + \overline{A'B'}
\end{aligned} \tag{2.9}
$$

In the above, $\overline{(A'\bar{B})} = \overline{A'}\bar{B} = 0 \cdot \bar{B} = 0$.

We call AB a nonlinear term since both A and B are time-dependent variables. A'B' is also a nonlinear term whose average is not necessarily zero!

$\overline{A'B'}$ is called the covariance of A and B (defined as $\overline{A'B'} \equiv \frac{1}{T}\int_0^T A'B'dt$ for continuous A' and B' and $\overline{A'B'} = \frac{1}{N}\sum_{n=1}^{N} A'_n B'_n$ for discrete values of A' and B'). This term is actually extremely important for boundary layer studies, as we will see later. For example, when A is w (vertical velocity) and B is θ (potential temperature), the $\overline{w'\theta'}$ represent vertical turbulent flux of potential temperature (heat).

When A' = B', then the covariance becomes variances $\overline{A'^2}$.

Terms like $\overline{A'B'}$, $\overline{A'^2}$, and $\overline{B'^2}$, are called second-order moments because they are covariances or variances .

In the above, we have chosen the averaging to be performed in time. If a turbulence field is measured simultaneously by many sensors distributed in space, then a spatial mean should be used. For statistically stationary turbulence, the time mean is equal to the spatial mean.