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)

Fair Weather over Land

- Associated with high pressure centers
- Diurnal cycle is prominent
  - Night: cool and calm
  - Day: warm and gusty
- *Unstable:* surface is warmer than the air
  - ABL state: *free convection*
- *Stable:* surface is cooler than the air
  - ABL state: *forced convection*

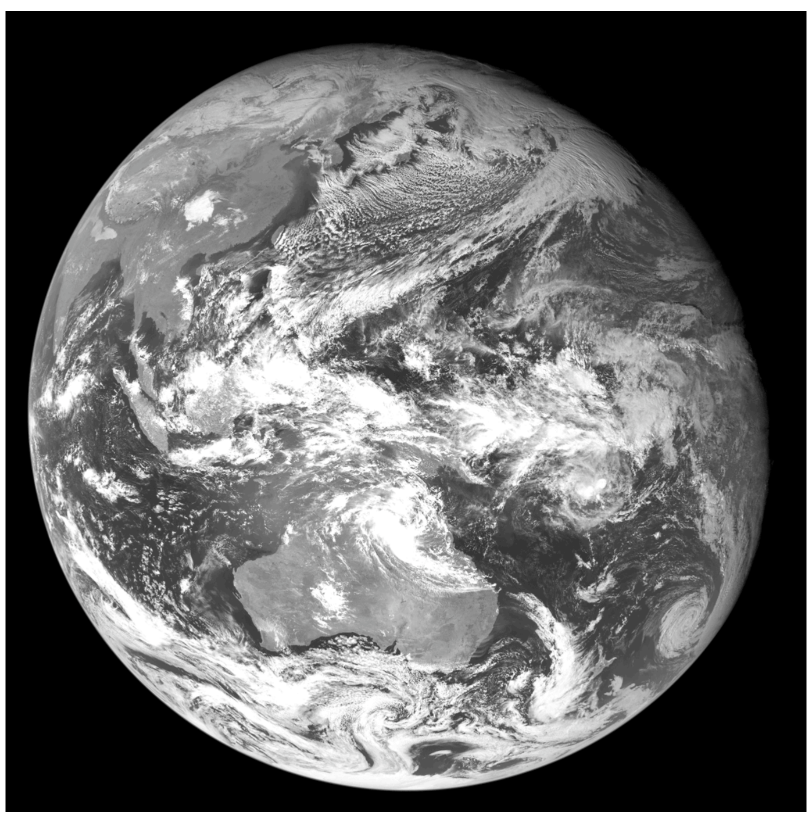
Turbulence

- Ubiquitous in ABL
- Efficiently *mixes* pollutants that are trapped in the ABL by the *capping inversion*
- *Dissipates* the kinetic energy of large-scale wind systems in the ABL.
- Consists of *eddies* of a large range of sizes

Scales of Atmospheric Motion

10,000 km	1000 km	100 km	10 km	1 km	100 m	10 m
Planetary waves	Extratropical Cyclones	Mesoscale Convective Systems	Cumulonimbus clouds	Cumulus clouds	Turbulence =>	

Global Climate Model (GCM)	Cloud System Resolving Model (CSRM)	Large Eddy Simulation (LES) Model



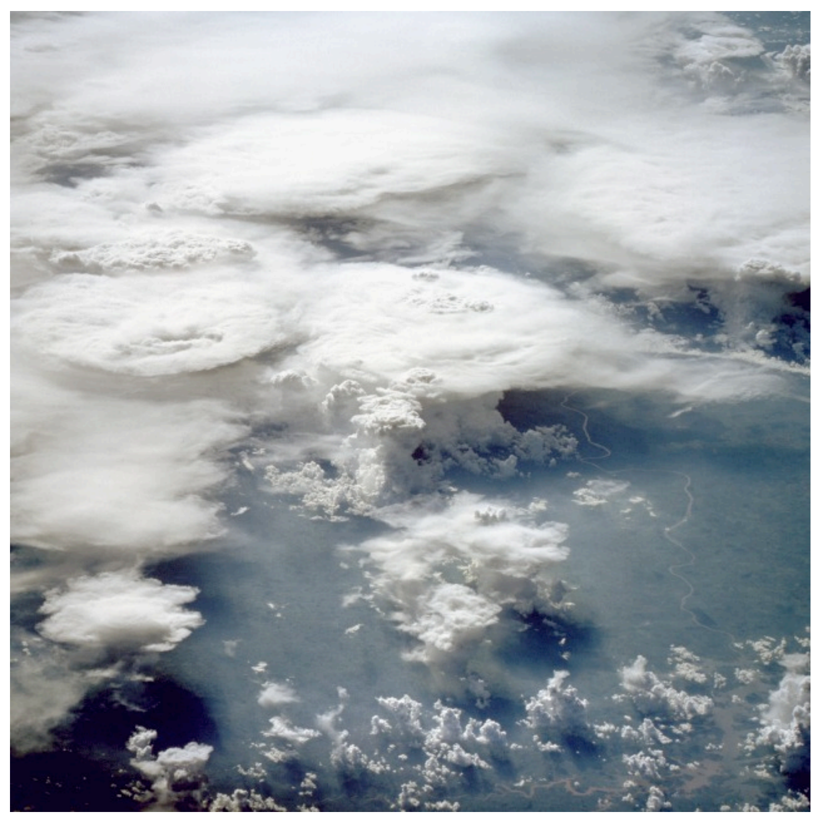


Table 9.1 Scales of horizontal motion in the atmosphere

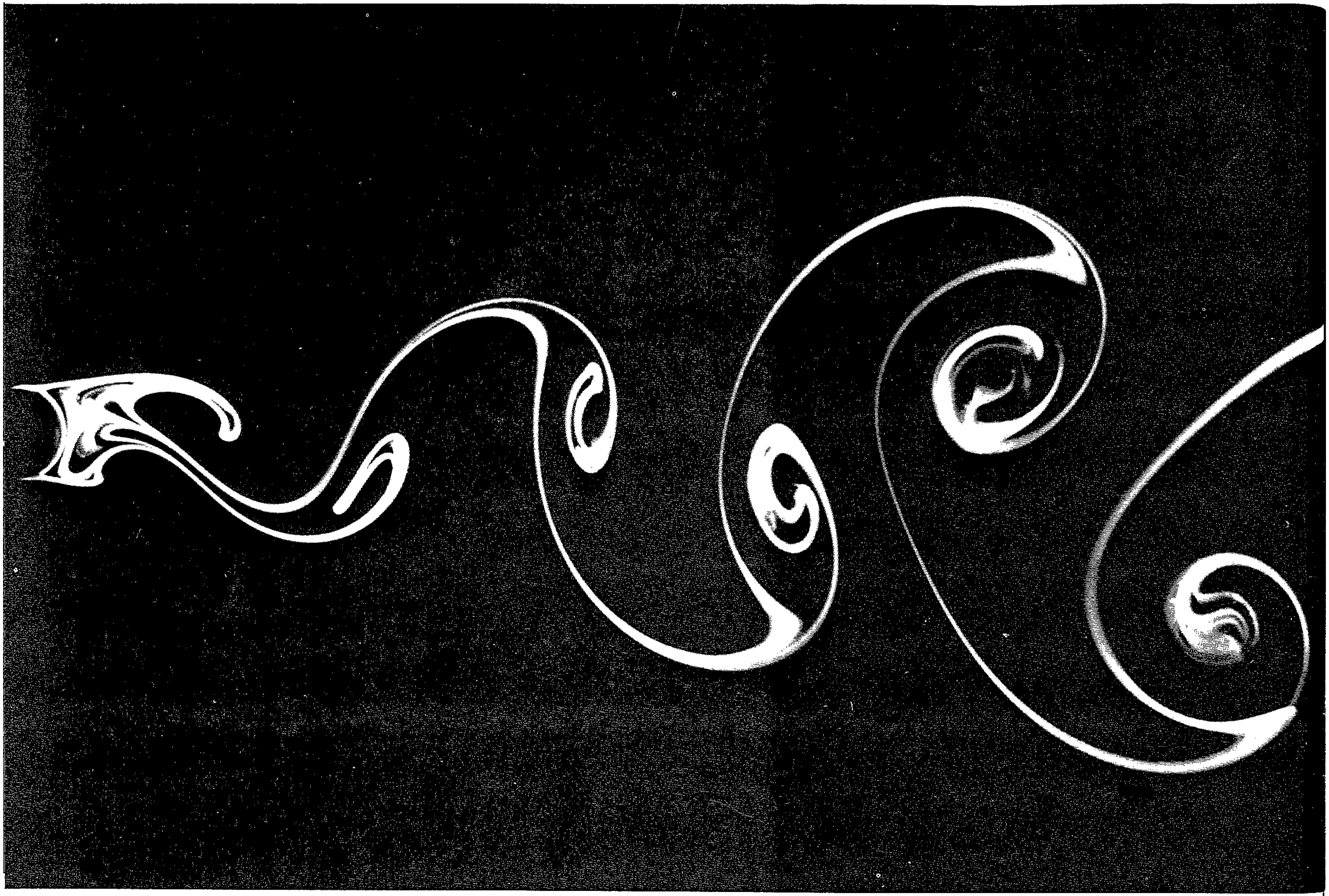
Larger than	Scale	Name
20,000 km		Planetary scale
2,000 km		Synoptic scale
200 km	Meso-α	Mesoscale
20 km	Meso-β	Mesoscale
2 km	Meso-γ	Mesoscale
200 m	Micro-α	Boundary-layer turbulence
20 m	Micro-β	Surface-layer turbulence
2 m	Micro-γ	Inertial subrange turbulence
2 mm	Micro-δ	Fine-scale turbulence
Air molecules	Molecular	Viscous dissipation subrange

Turbulence

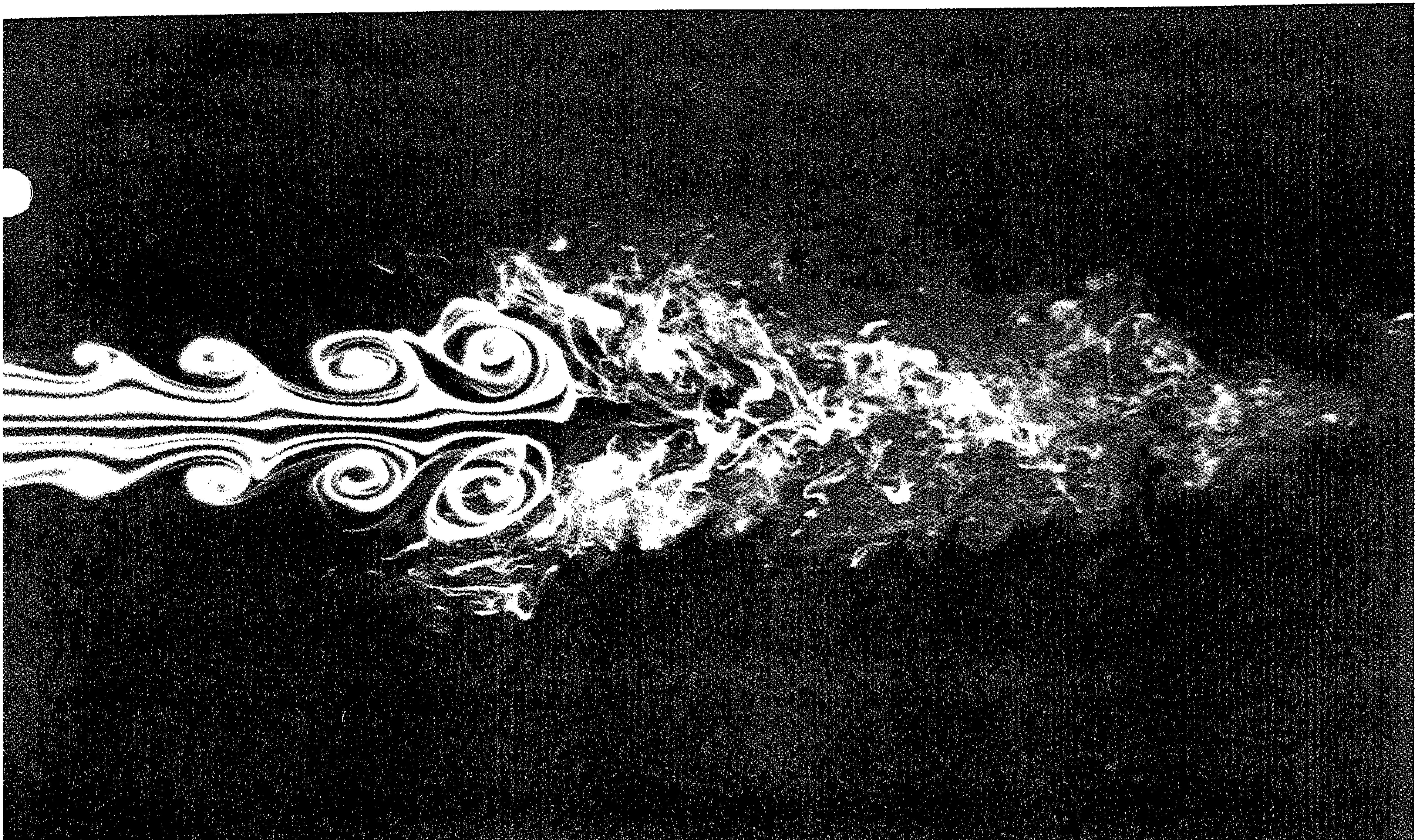
- Turbulent flow is irregular, quasi-random, and chaotic.
- Laminar flow is smooth and regular.
- Turbulence be generated *mechanically*, *thermally* (via *buoyancy*), and *inertially*.

Turbulence

- *Mechanical turbulence* (*forced convection*) is generated by wind shear.
- Shear can produce flow instabilities.
- Shear occurs
  - Near the surface due to *frictional drag*
  - In *wakes* behind obstacles
  - In the jet stream in the free atmosphere

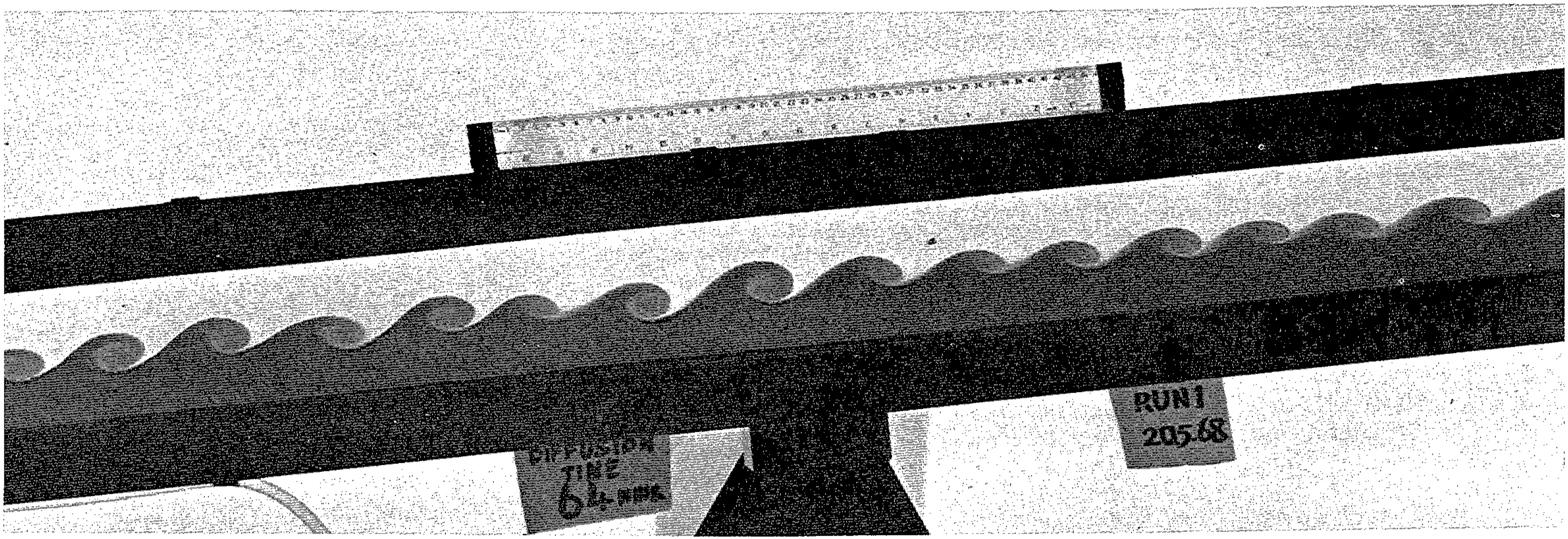


94. Kármán vortex street behind a circular cylinder at R**=140.** Water is flowing at 1.4 cm/s past a cylinder of diameter 1 cm. Integrated streaklines are shown by electrolytic precipitation of a white colloidal smoke, illuminated by a sheet of light. The vortex sheet is seen to grow in width downstream for some diameters. *Photograph by Sadatoshi Taneda*



102. Instability of an axisymmetric jet. A laminar stream of air flows from a circular tube at Reynolds number 10,000 and is made visible by a smoke wire. The edge of the jet develops axisymmetric oscillations, rolls up into vortex rings, and then abruptly becomes turbulent. *Photograph by Robert Drubka and Hassan Nagib*

Kelvin-Helmholtz instability of stratified shear flow



145. Kelvin-Helmholtz instability of stratified shear flow. A long rectangular tube, initially horizontal, is filled with water above colored brine. The fluids are allowed to diffuse for about an hour, and the tube then quickly tilted six degrees, setting the fluids into motion. The brine accelerates uniformly down the slope, while the water above similarly accelerates up the slope. Sinusoidal instability of the interface occurs after a few seconds, and has here grown nonlinearly into regular spiral rolls. *Thorpe 1971*

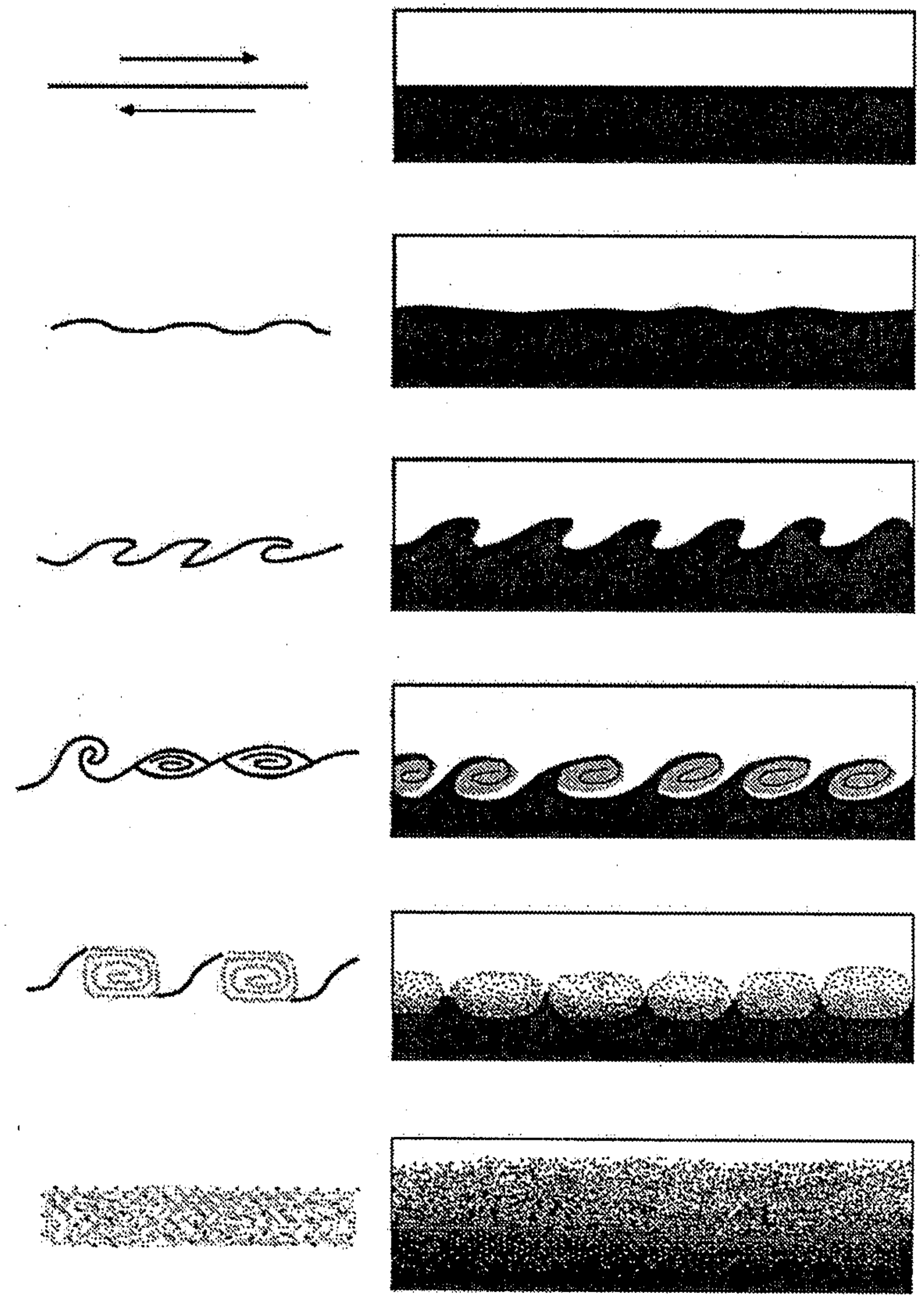


Fig. 5.18 Schematic diagram of Kelvin-Helmholtz instability in a laboratory experiment where shear flow has been generated. The upper layer, water, flows to the right, and the lower more dense fluid, dyed brine, flows to the left. The figures are about half a second apart. After Thorpe (1969,1973) and Woods (1969).

2D numerical simulation of Kelvin-Helmholtz instability

Turbulence

- *Thermal or convective turbulence* (*forced convection*) consists of *plumes* or *thermals* that are generated by *buoyancy*.
  - *Buoyancy* accelerates a parcel upwards or downwards depending on its density perturbation.
  - *Plumes* are curtains or sheets of updrafts near the ground with diameters ~ 100 m.
  - Higher in the ABL, plumes merge into larger diameter (~ 1000 m) *thermals*.

The top of a thermal may be visible as a cumulus cloud.

Cumulus time-lapse videos on class web page

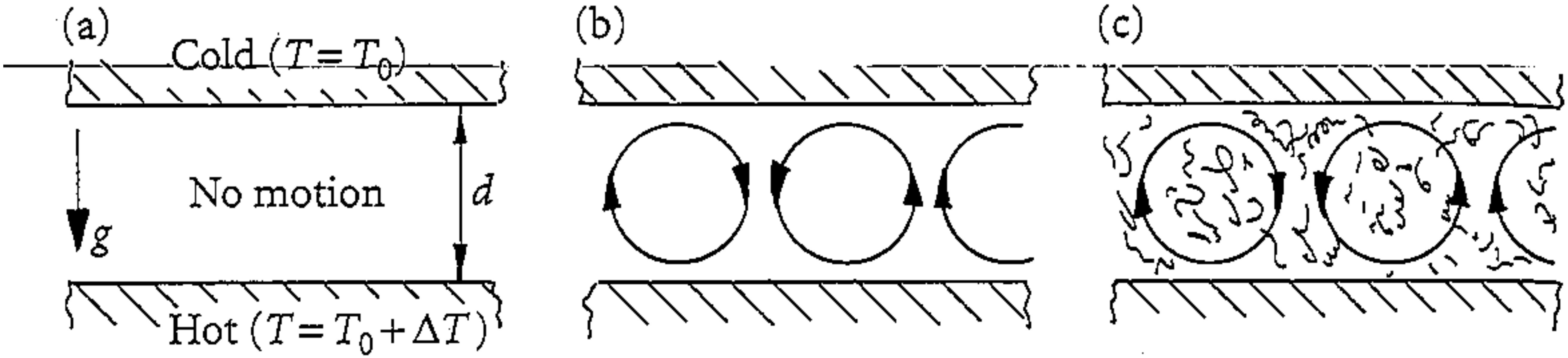
Cumulus humilis time-lapse movie (Mar 3, 2011)

Cumulus humilis time-lapse movie (Nov 8, 2011)

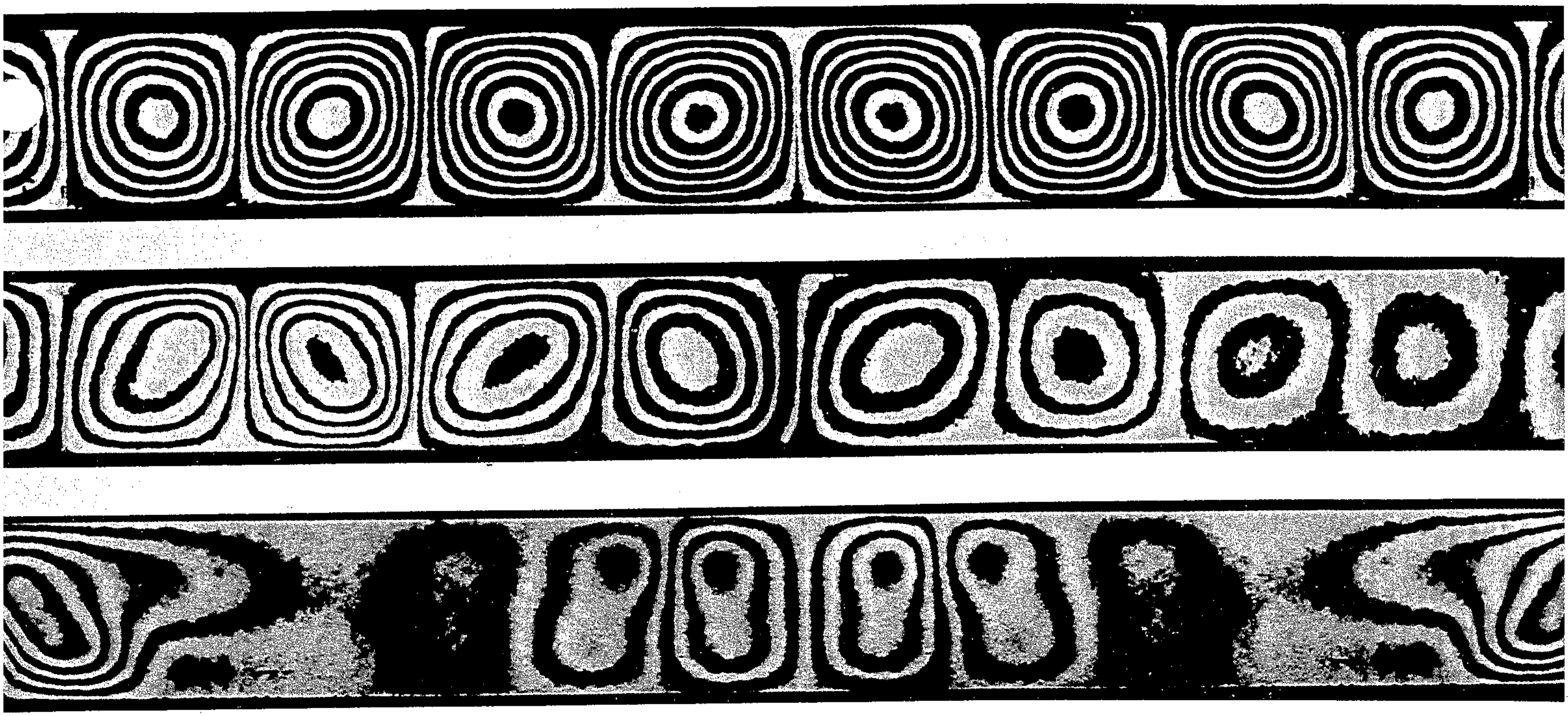
Cumulus congestus time-lapse movie (Aug 16, 2002, Santa Catalina Mts, Arizona)

Global convective instability

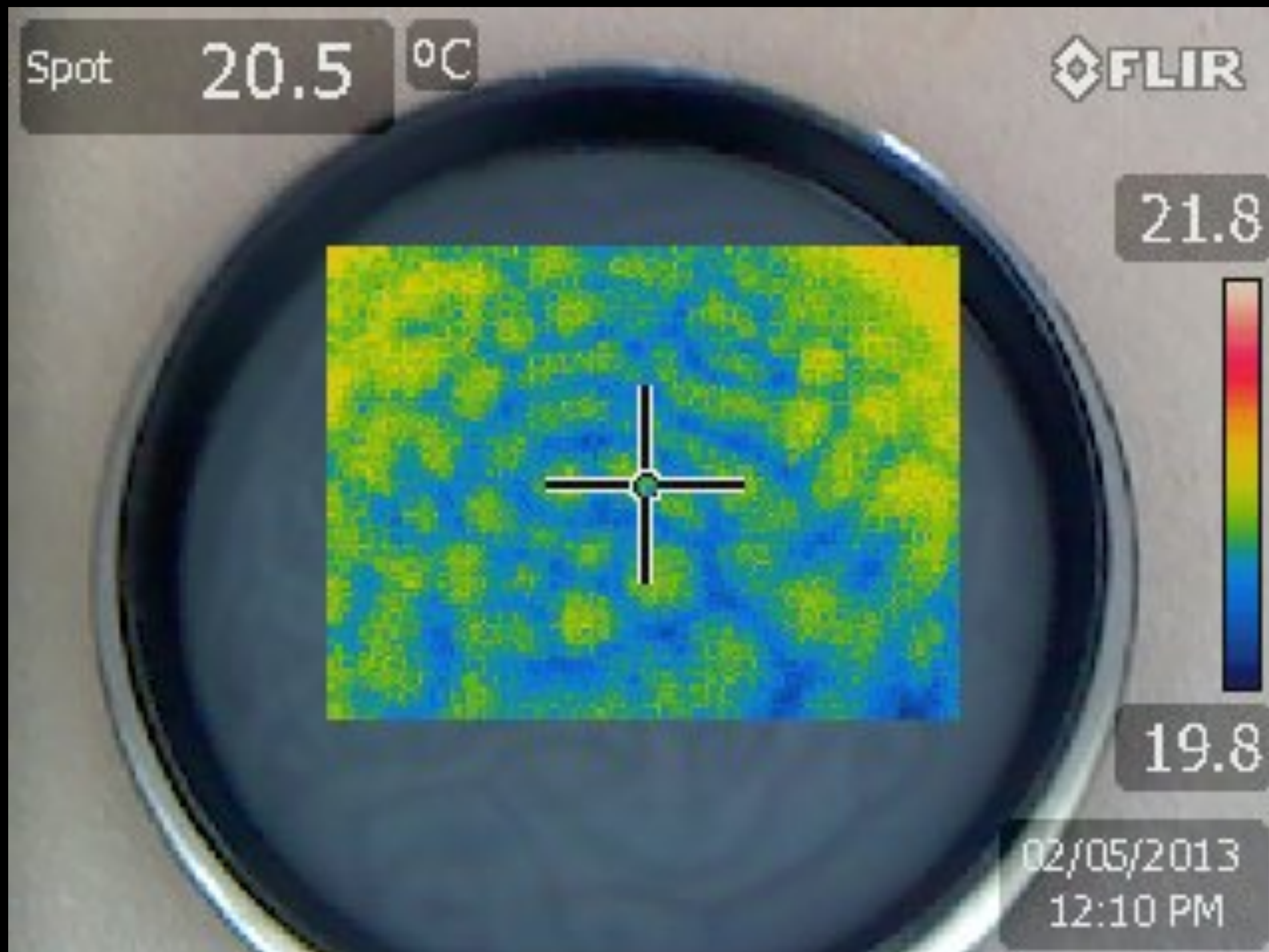
Figure 1.3 Fluid is held between two flat, parallel plates. The lower plate is heated. At low values of ΔT the fluid is quiescent. As ΔT is increased natural convection sets in, first in the form of regular convection cells and then in the form of turbulent flow.



Low ΔT | Bénard cells | Turbulent convection (High ΔT)



139. Buoyancy-driven convection rolls. Differential interferograms show side views of convective instability of silicone oil in a rectangular box of relative dimensions 10:4:1 heated from below. At the top is the classical Rayleigh-Bénard situation: uniform heating produces rolls parallel to the shorter side. In the middle photograph the temperature difference and hence the amplitude of motion increase from right to left. At the bottom, the box is rotating about a vertical axis. *Oertel & Kirchartz 1979, Oertel 1982a*


Spot 20.5 °C
FLIR
21.8
19.8
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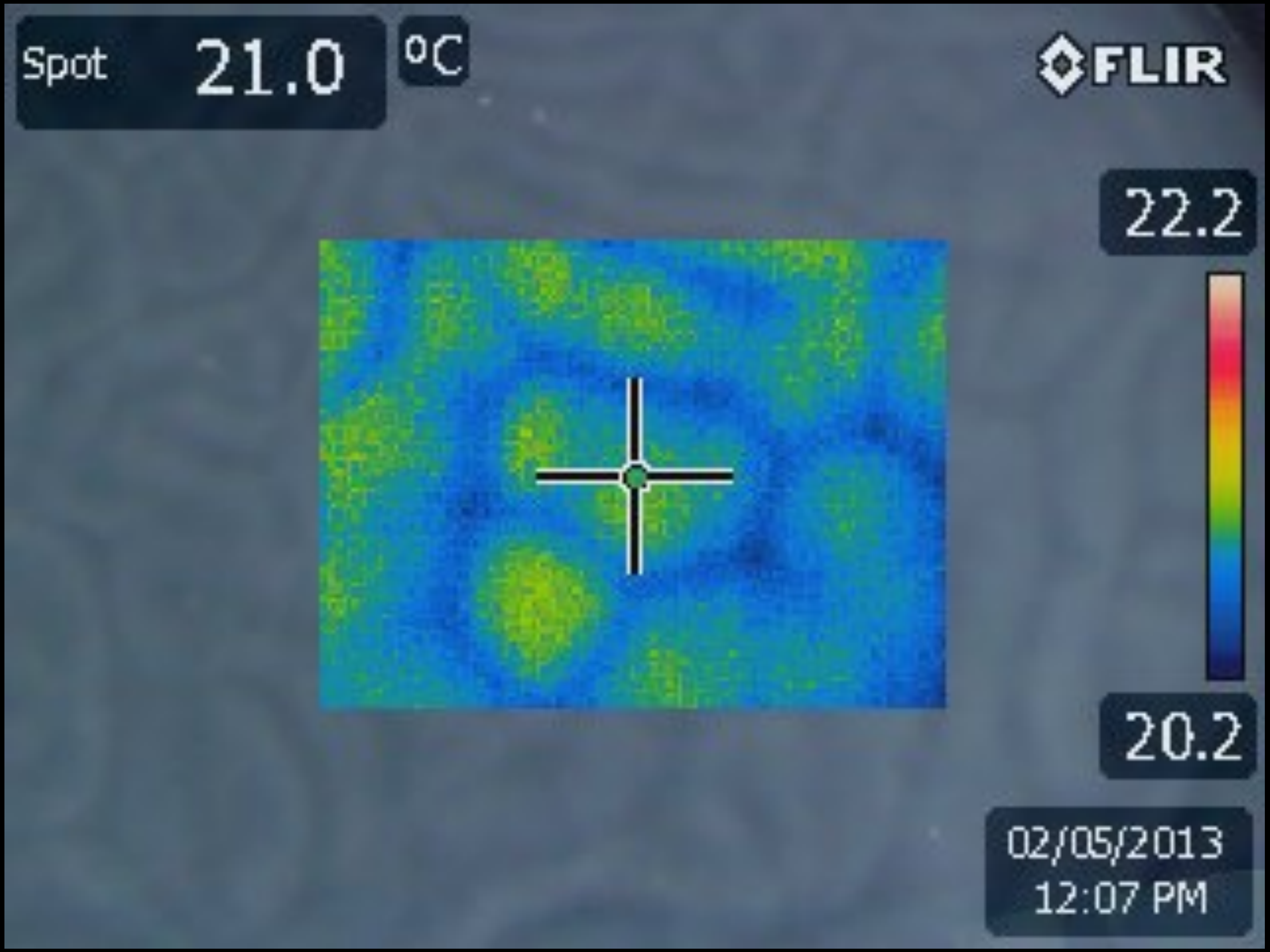
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Boundary layer cloud 'streets'

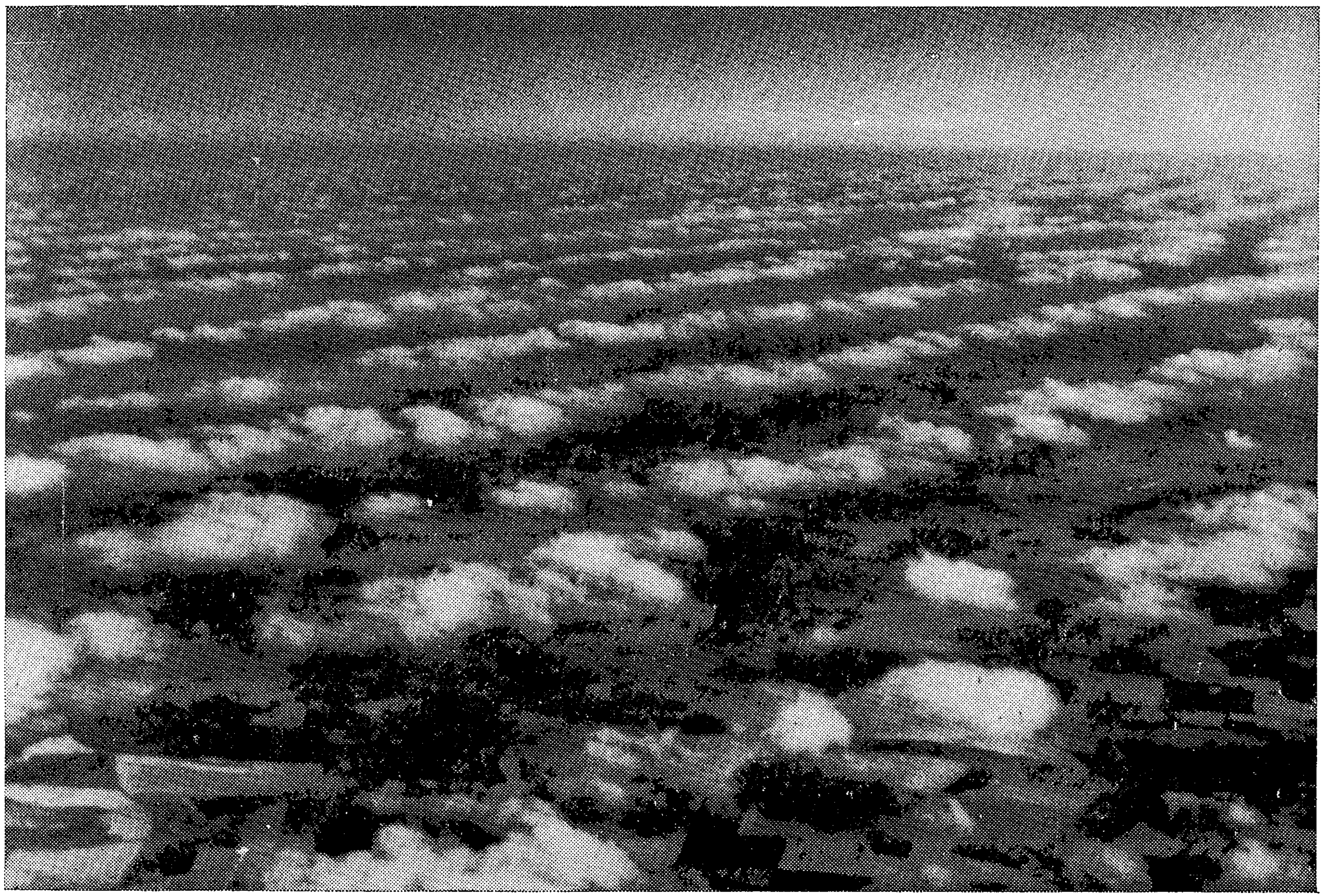


Fig. 7.2. Convective clouds in an unstable layer, aligned in 'streets' along the direction of shear. (Compare with fig. 4.14 pl. x, which shows clouds formed by a shear instability and aligned across the flow. The form of 'billow' clouds can vary widely according to the relative importance of shear and convection.) (Photograph: R. S. Scorer.)

Turbulence

- The shear at the edges of large eddies produces smaller eddies.
- This process is the *turbulence energy cascade*.
- Some of the *inertial energy* of the larger eddies is transferred to the smaller eddies, as described by Richardson's poem.

> Big whorls have little whorls
>
> That feed on their velocity,
>
> And little whorls have lesser whorls
>
> And so on to viscosity.

Turbulence

- *Turbulence kinetic energy* (TKE) is continually *dissipated* (converted) into internal energy by molecular viscosity. [rubber band experiment]
- Dissipation occurs only in the smallest (~1 mm) turbulent eddies.
- Because of dissipation, there must continual generation of TKE (by shear and/or buoyancy) for turbulence to exist.

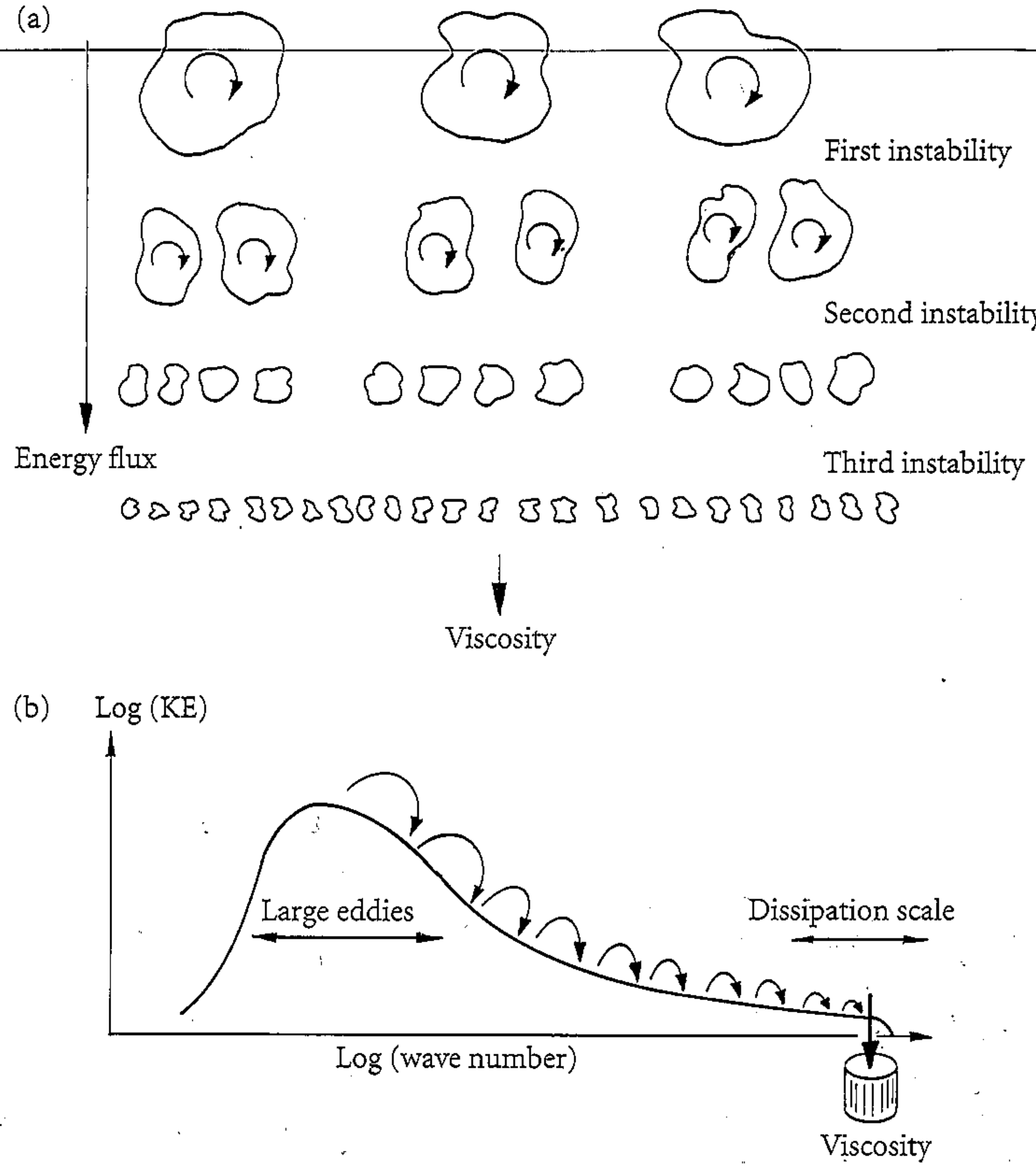
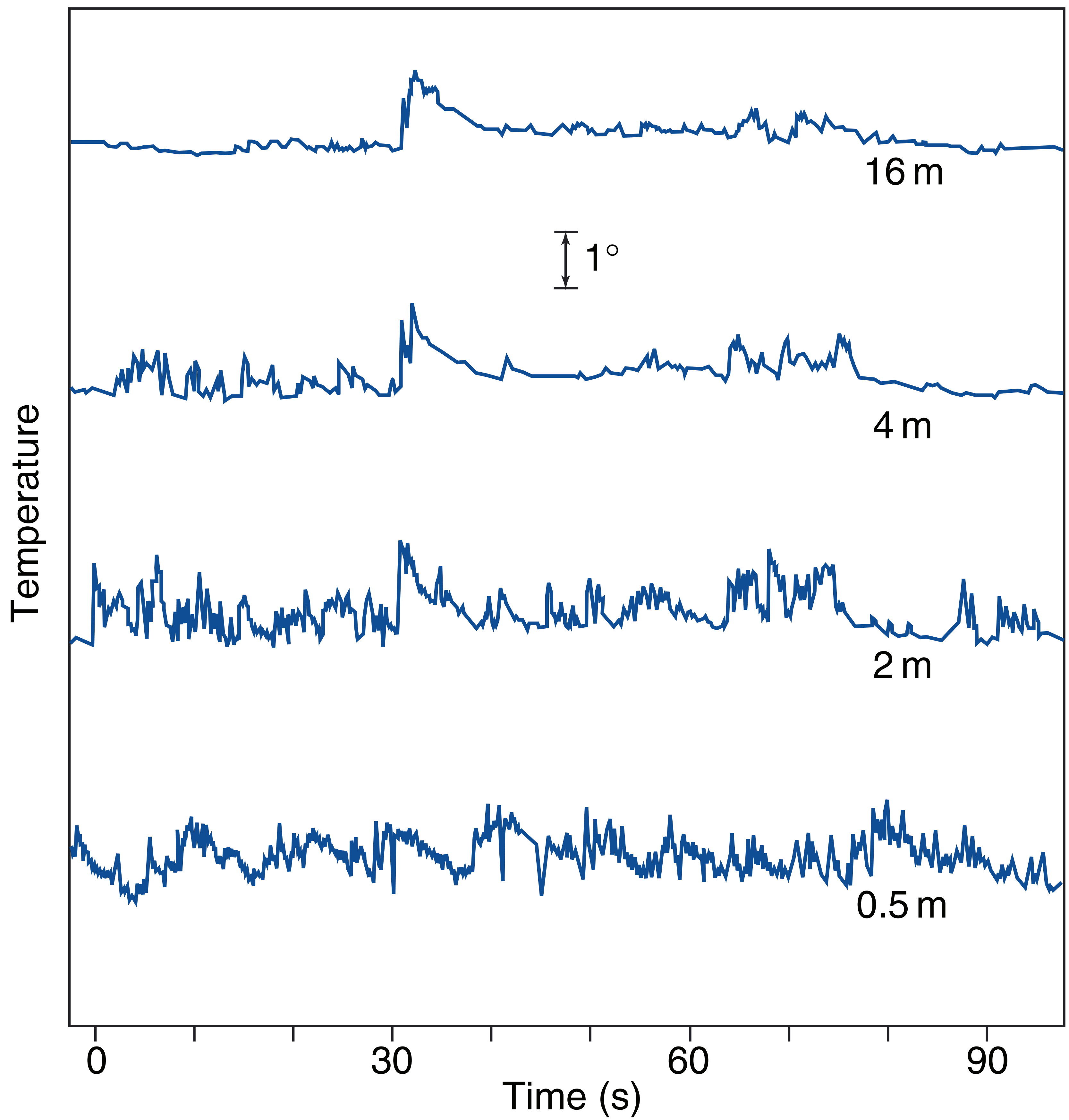


Figure 3.9 (a) A schematic representation of the energy cascade (after Frisch). (b) The energy cascade in terms of energy versus wave number.

Describing Turbulence

- Unlike synoptic-scale weather systems, turbulence cannot be predicted *deterministically* for useful periods of time.
- The time scale for the break-down of a turbulent eddy is T ~ L / U, where L is the eddy size, and U is the eddy velocity.
    - Large eddy: L ~ 1000 m, U ~ 1 m/s, T ~ 1000 s ~ 15 min.
    - Small eddy: L ~ 1 m, U ~ 0.1 m/s, T ~ 10 s.
- Turbulence can be described *statistically*.

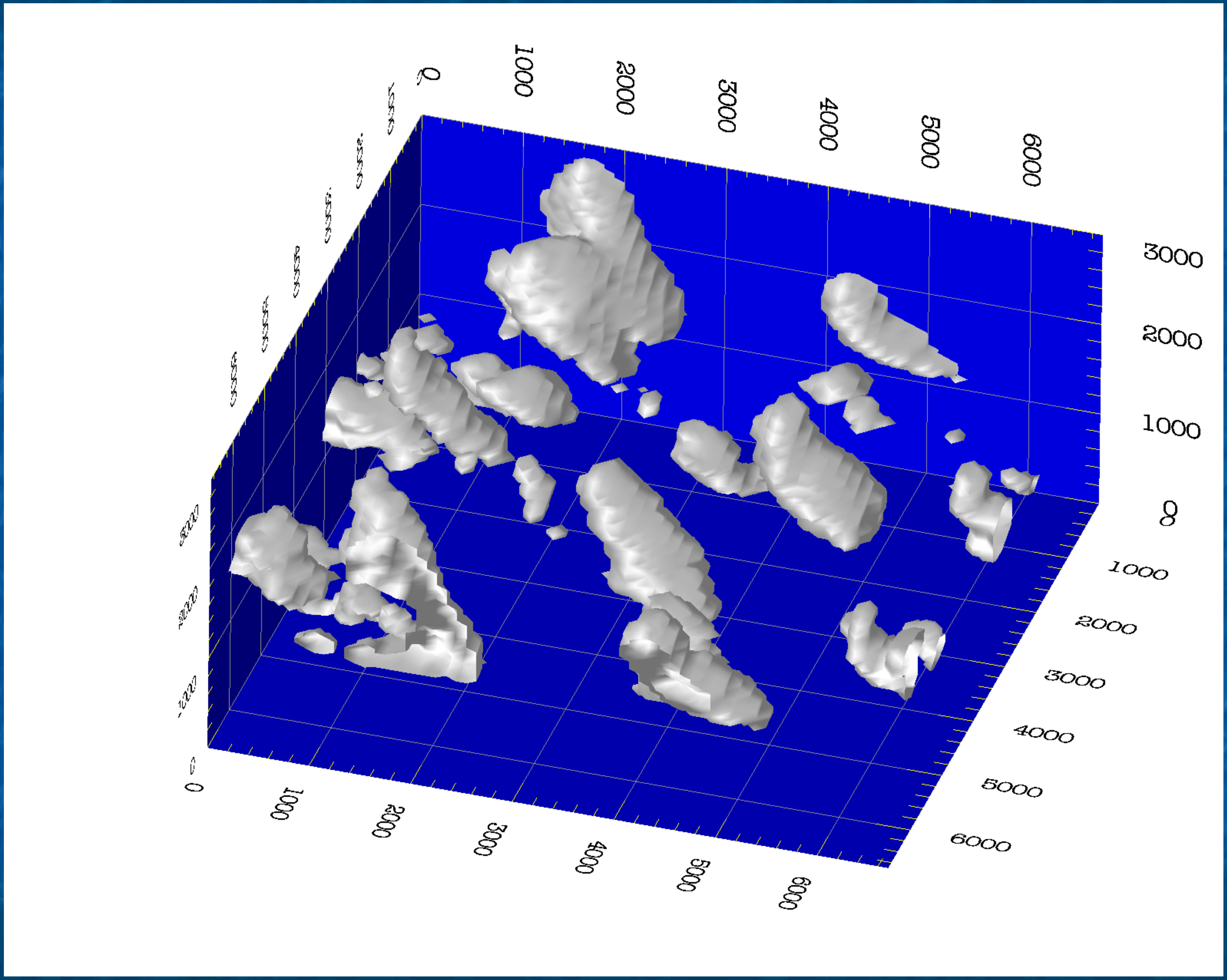
Time series at four heights over flat, plowed ground on a clear day with moderate winds



- A *probability density function* (PDF) describes the distribution of the values of a property in a population.

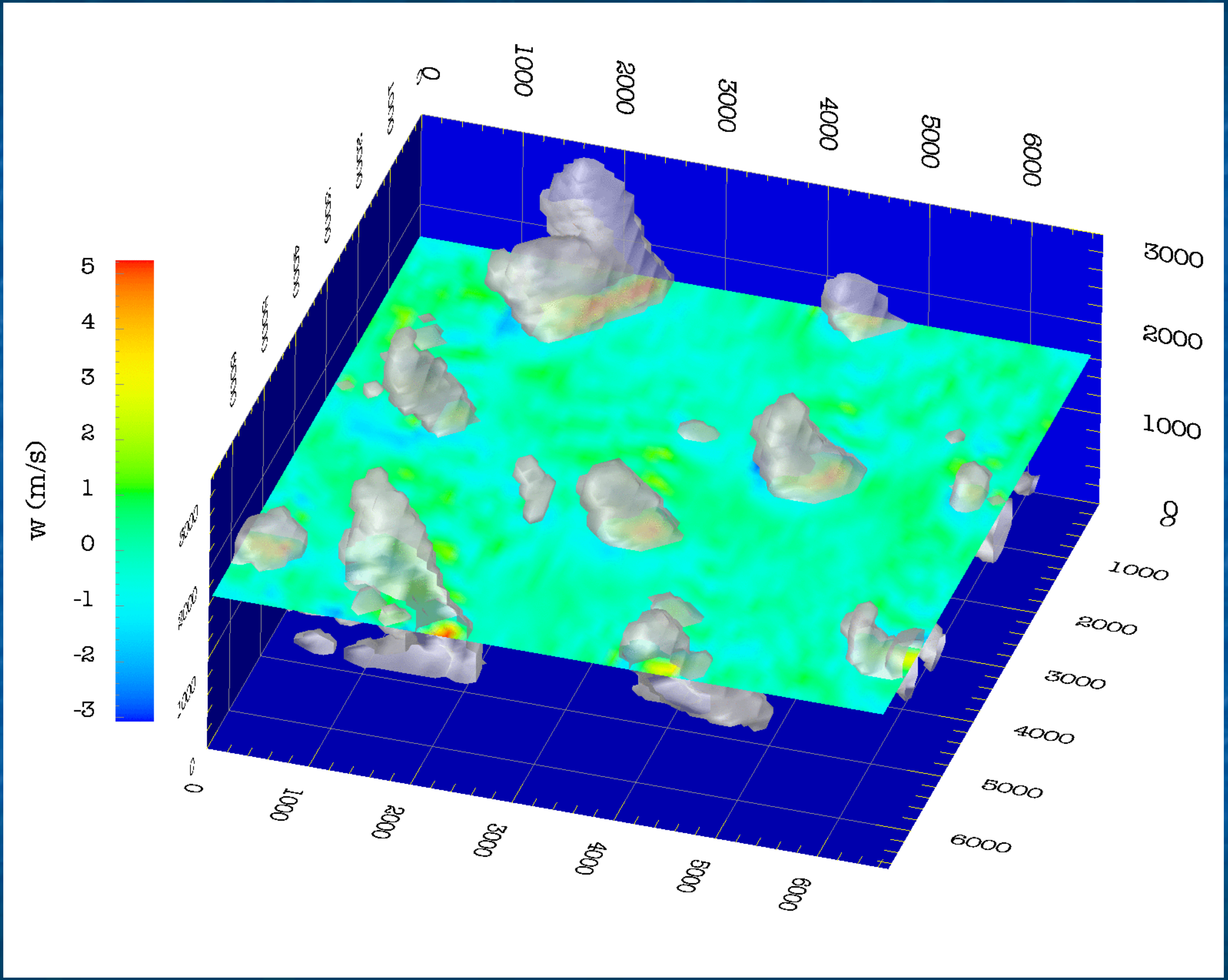
- It is closely related to a frequency distribution or histogram.

PDFs of cumulus clouds



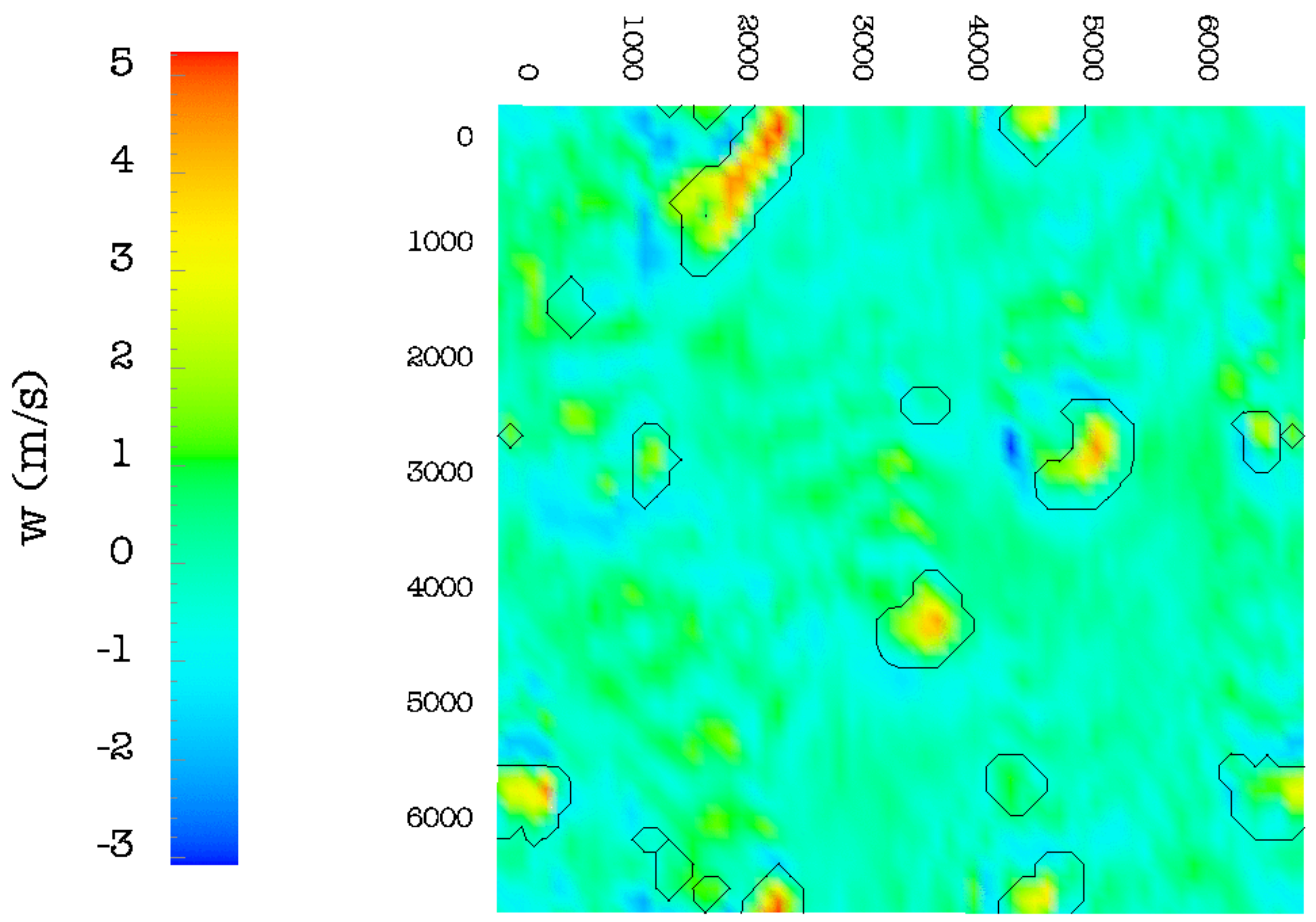
Isosurface of cloud water: 0.001 (g/kg)

PDFs of cumulus clouds



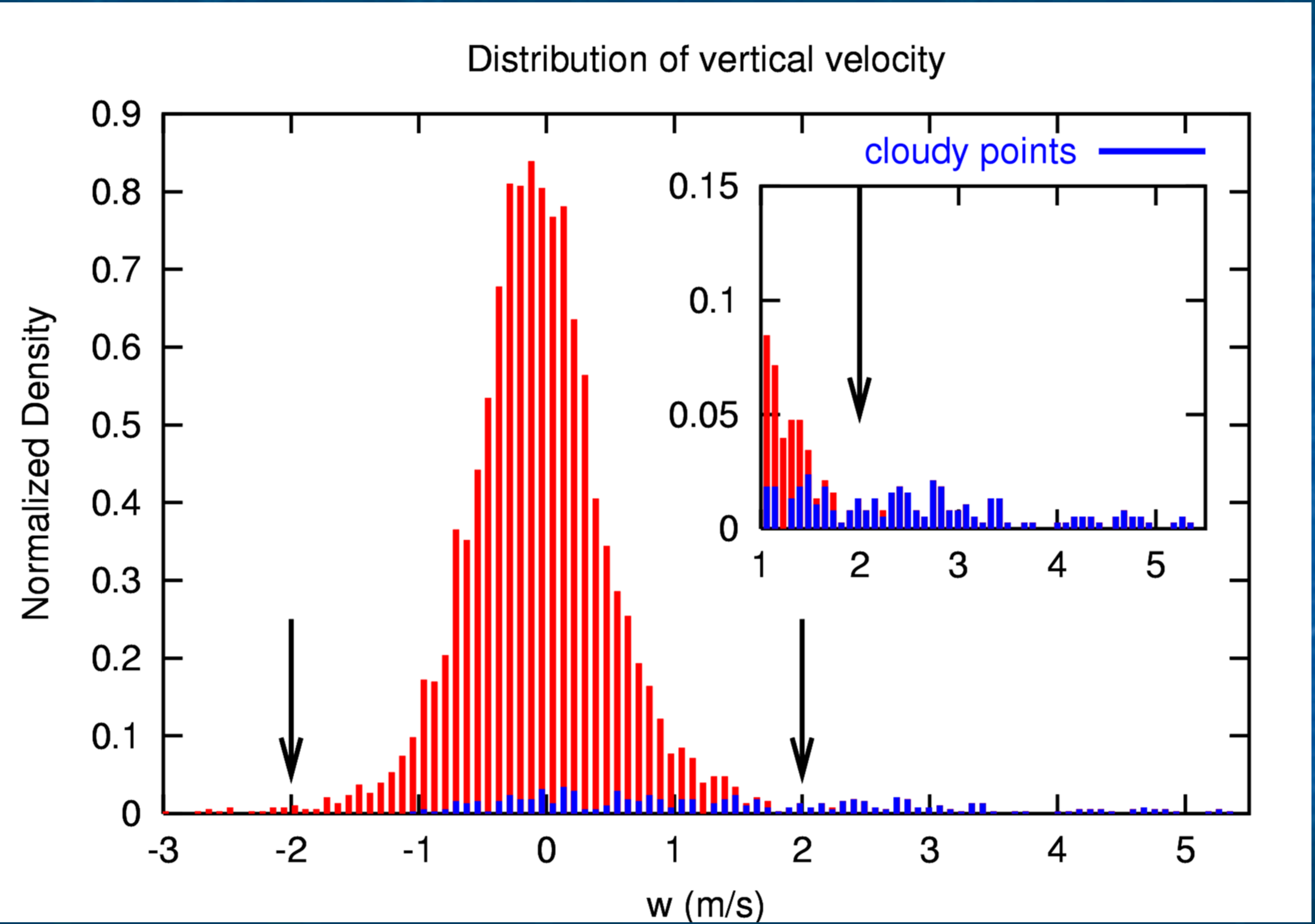
Isosurface of cloud water: 0.001 (g/kg); horizontal cross section a = 1680 (m)

PDFs of cumulus clouds



Horizontal cross section of vertical velocity; z=1680(m)

PDFs of cumulus clouds



Statistical Description of Turbulence

- Time series of measurements in turbulence show apparently random signals.
- But over a given time period such as 30 minutes, there is a well-defined *mean*, and a statistically robust *standard deviation* about the mean.

Statistical Description of Turbulence

Sample velocity u at regular intervals Δt to obtain a time series

$$u_i = u(i \cdot \Delta t)$$

for $i = 1$ to N. Then the mean velocity $\bar{u}$ is the average over time period $T = N \cdot \Delta t$:

$$\bar{u} = \frac{1}{N} \sum_{1}^{N} u_i .$$

The mean values typically change slowly with time on diurnal and synoptic time scales.

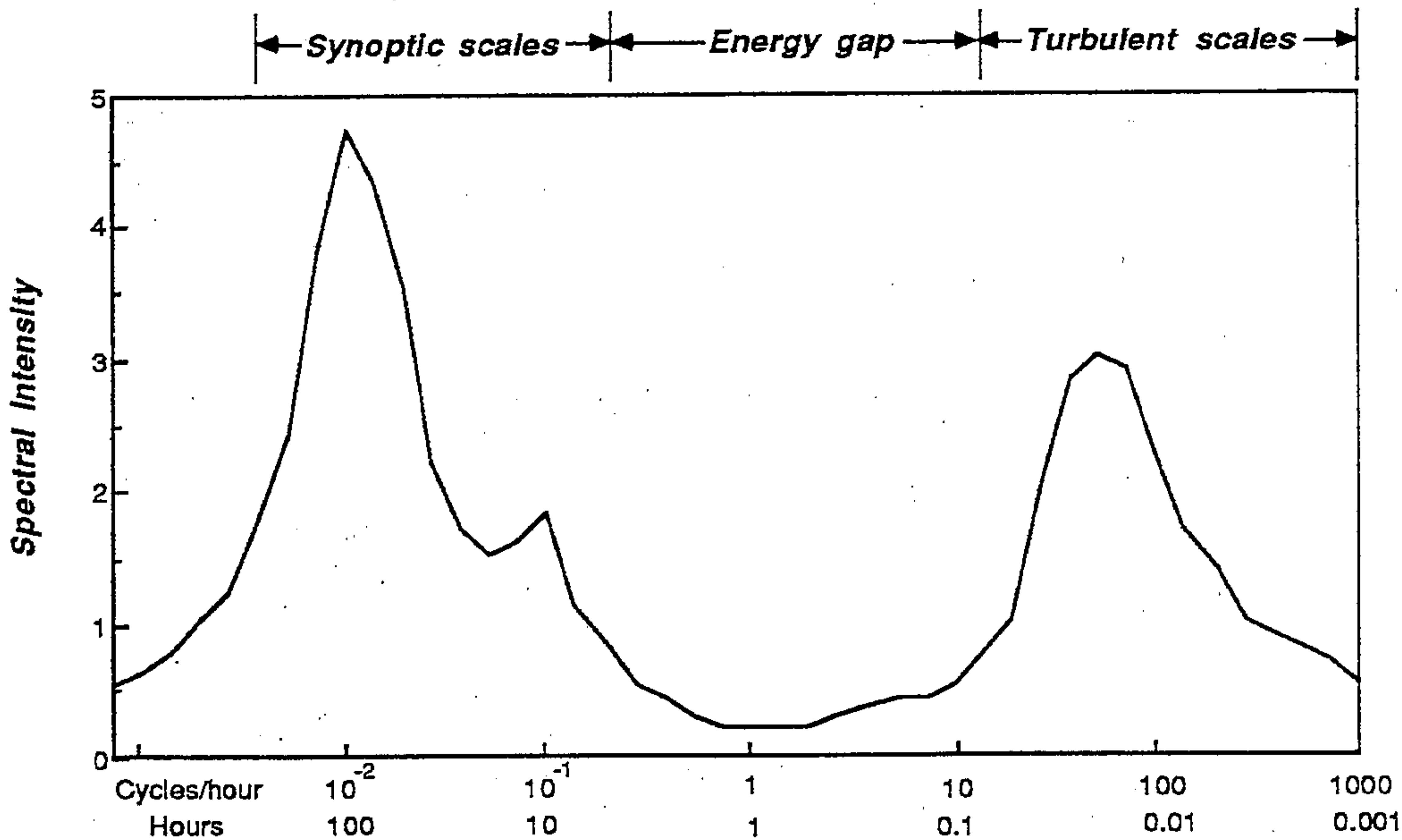


Fig. 2.2 Schematic spectrum of wind speed near the ground estimated from a study of Van der Hoven (1957).

Statistical Description of Turbulence

The *fluctuating (gust) portion* of the wind velocity is

$$u_i' = u_i - \bar{u}$$

which varies rapidly. The turbulence intensity of the u–component is

$$\sigma_u^2 = \frac{1}{N}\sum_1^N [u_i - \bar{u}]^2 = \frac{1}{N}\sum_1^N [u_i']^2 = \overline{[u']^2}.$$

Statistical Description of Turbulence

If σ_u^2 is relatively steady (constant in time), the turbulence is *stationary*.

If σ_u^2 is relatively uniform in space, the turbulence is *homogeneous*.

If $\sigma_u^2 = \sigma_v^2 = \sigma_w^2$, the turbulence is *isotropic* (same in all directions).

Statistical Description of Turbulence

Fluctuations often vary together. The covariance is a measure of this tendency:

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

If warm air parcels are rising and cold air parcels are sinking, then

$$\overline{w'\theta'} > 0$$

and turbulence kinetic energy is being produced.