16 Production of atmospheric turbulence.

Learning objectives

- Describe how, when and where is turbulence produced in the atmospheric boundary layer.
- Explain where the energy for turbulent motions comes from.
- Explain whether the characteristics of a turbulent flow depend on the processes causing them.

Visualization of entropy in a box of turbulence (http://www.lcse.umn.edu/)

Reynold’s number (*Re*)

Osborne Reynolds showed there is a critical point in fluid flow when well-behaved laminar flow breaks down into turbulent ‘chaos’.

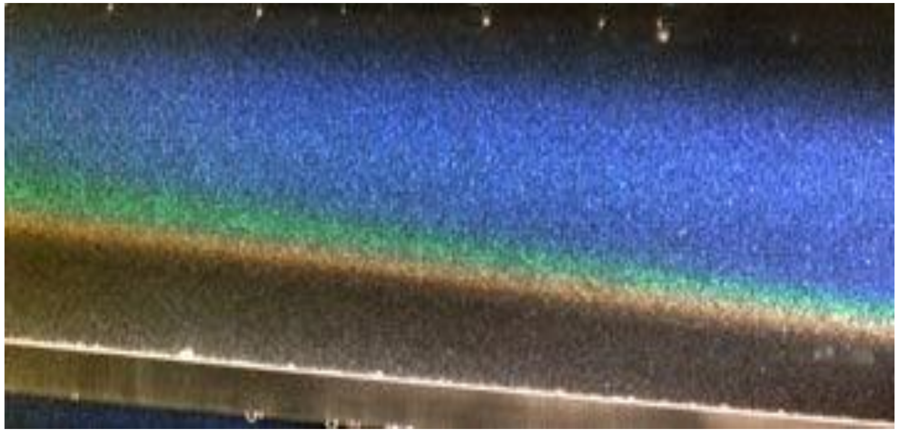
He showed this depended on ratio of inertial forces (associated with horizontal motion in fluids) to the viscosity of the fluid:

$$Re = \frac{u\,d}{\nu}$$ ★

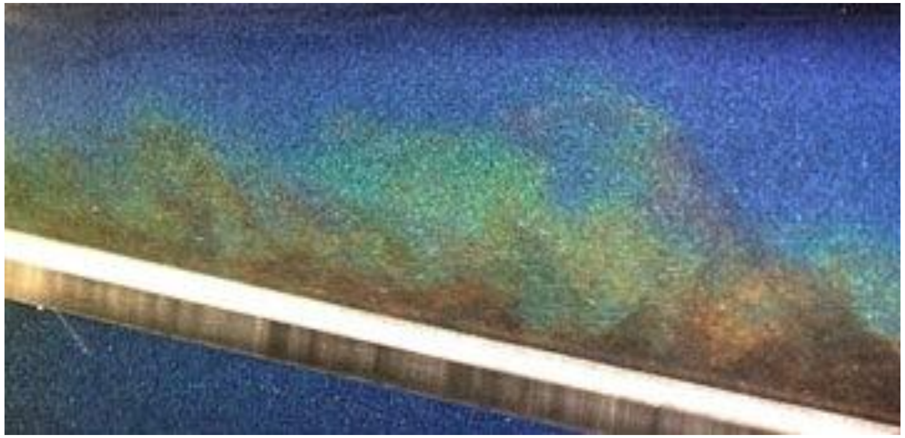
u - characteristic velocity of the fluid

d - characteristic length scale

ν - kinematic viscosity (includes density)



Laminar boundary layer.



Turbulent boundary layer (Los Alamos Natl. Laboratory).

Reynold's number - Examples

Daytime atmospheric boundary layer (ABL):

$$Re = \frac{u\,d}{\nu} = \frac{10\,\mathrm{m\,s^{-1}} \times 1000\,\mathrm{m}}{1.51 \times 10^{-5}\,\mathrm{m^2\,s^{-1}}} = 6.6 \times 10^8$$

kinematic viscosity of air

Model in a wind tunnel

$$Re = \frac{u\,d}{\nu} = \frac{1.5\,\mathrm{m\,s^{-1}} \times 0.3\,\mathrm{m}}{1.51 \times 10^{-5}\,\mathrm{m^2\,s^{-1}}} = 3.0 \times 10^4$$

$Re_{crit} \cong 10^6$ in real atmospheric flows, $Re_{crit} \cong 2 \times 10^4$ in engineering flows.

But Re is of **limited value in real atmospheric flows** because of role of buoyancy (that increases or decreases the amount of turbulence).

How is turbulence produced?

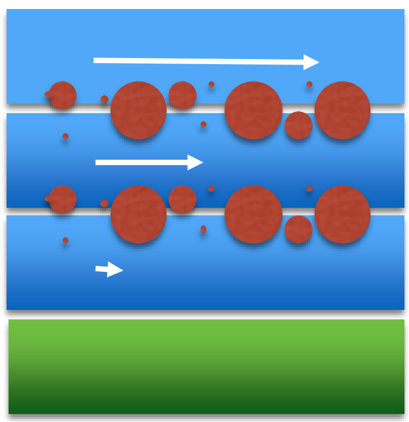
Production of turbulence

- Turbulence in the ABL is a ‘mixture’ of **mechanical (forced)** and **thermal (free)** convection.

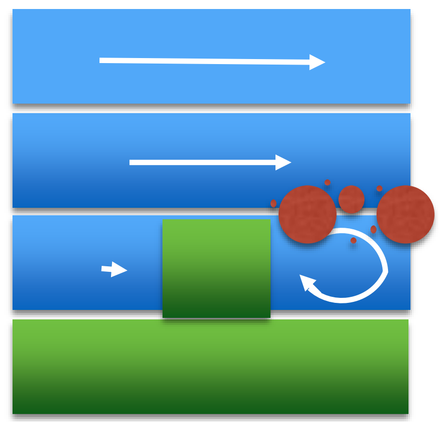
- **Mechanical turbulence** in the ABL is caused by instabilities arising from strong **mean velocity gradients**, which in turn are caused by surface skin or form drag (obstacles) or shear flow.

Mechanical (forced) convection

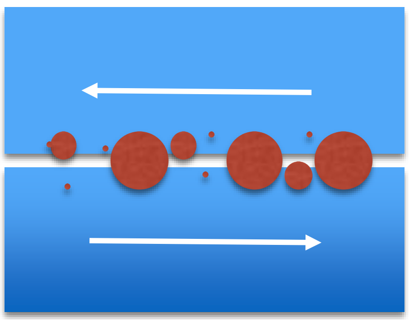
We can have three different scenarios that create turbulence mechanically:



Air layers are slowed by **skin friction** at surface, hence layers above have different speed (Skin drag)



Obstacles block flow and pressure differences cause overturning and flow separation (**Form drag**)



Two air layers with different **speeds and/ or direction**

Skin drag

In micrometeorology and climatology we encounter fully adjusted wall-bounded flows with the surface as the lower boundary condition.

A strong velocity gradient is caused due to the no-slip condition at solid boundaries - **skin drag**. This velocity gradient becomes unstable when reaching higher *Re.*

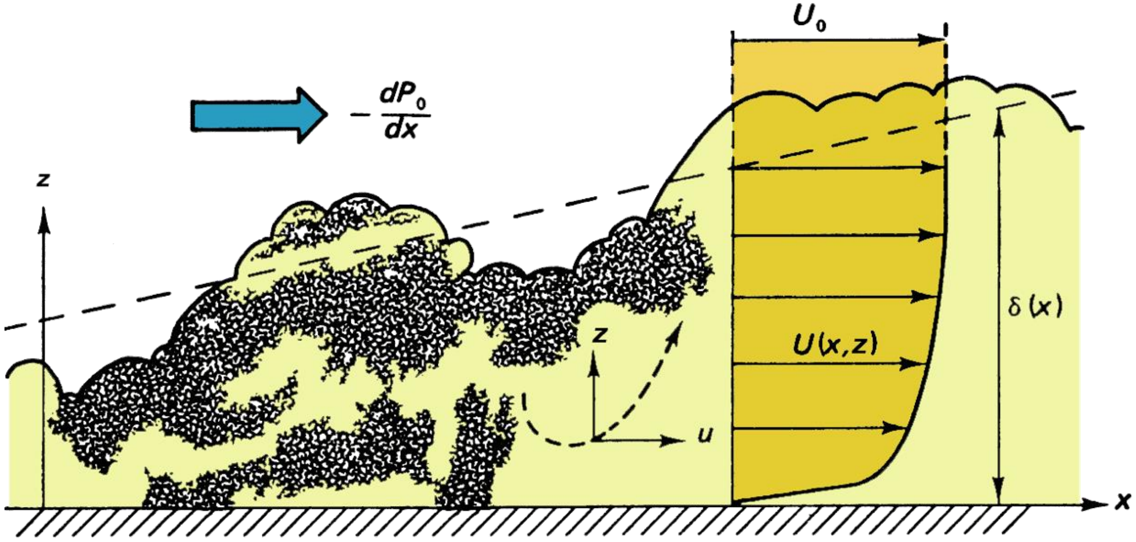
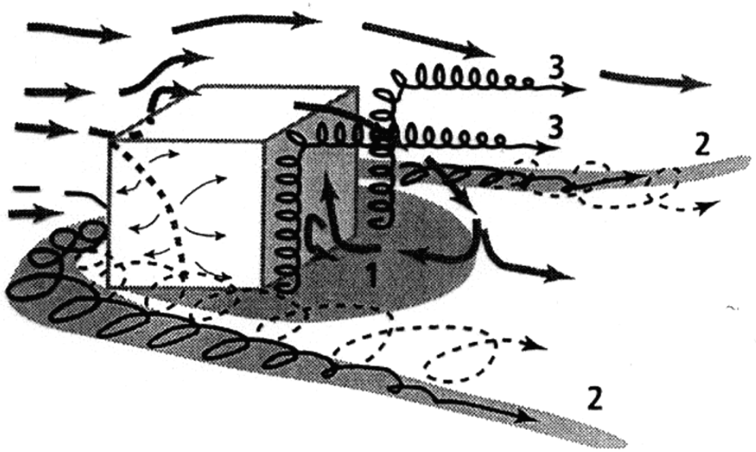


Figure 5.16. Definition sketch of plane boundary-layer flow.

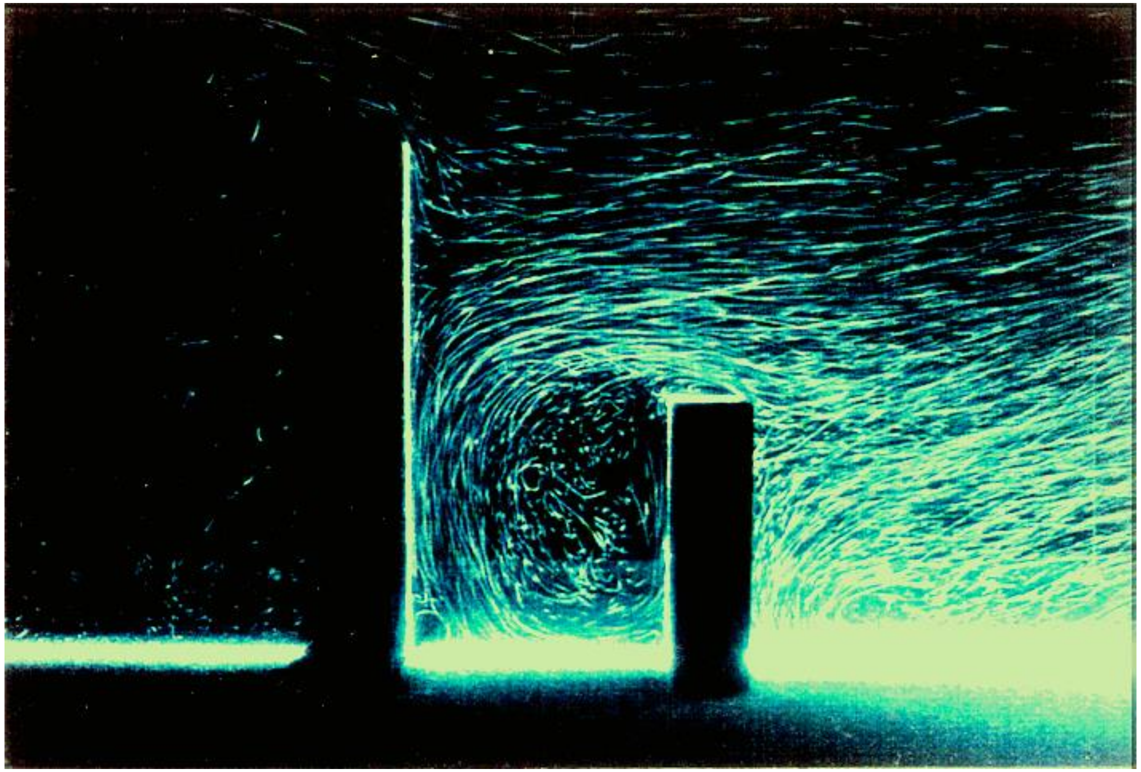
H. Tennekes and J. L. Lumley (1972): A first course in turbulence. Massachusetts Institute of Technology.

Form drag

Obstacles in the flow (trees, houses, boulders, etc.) cause **separation** and pressure differences giving eddies in the wake - **form drag**.



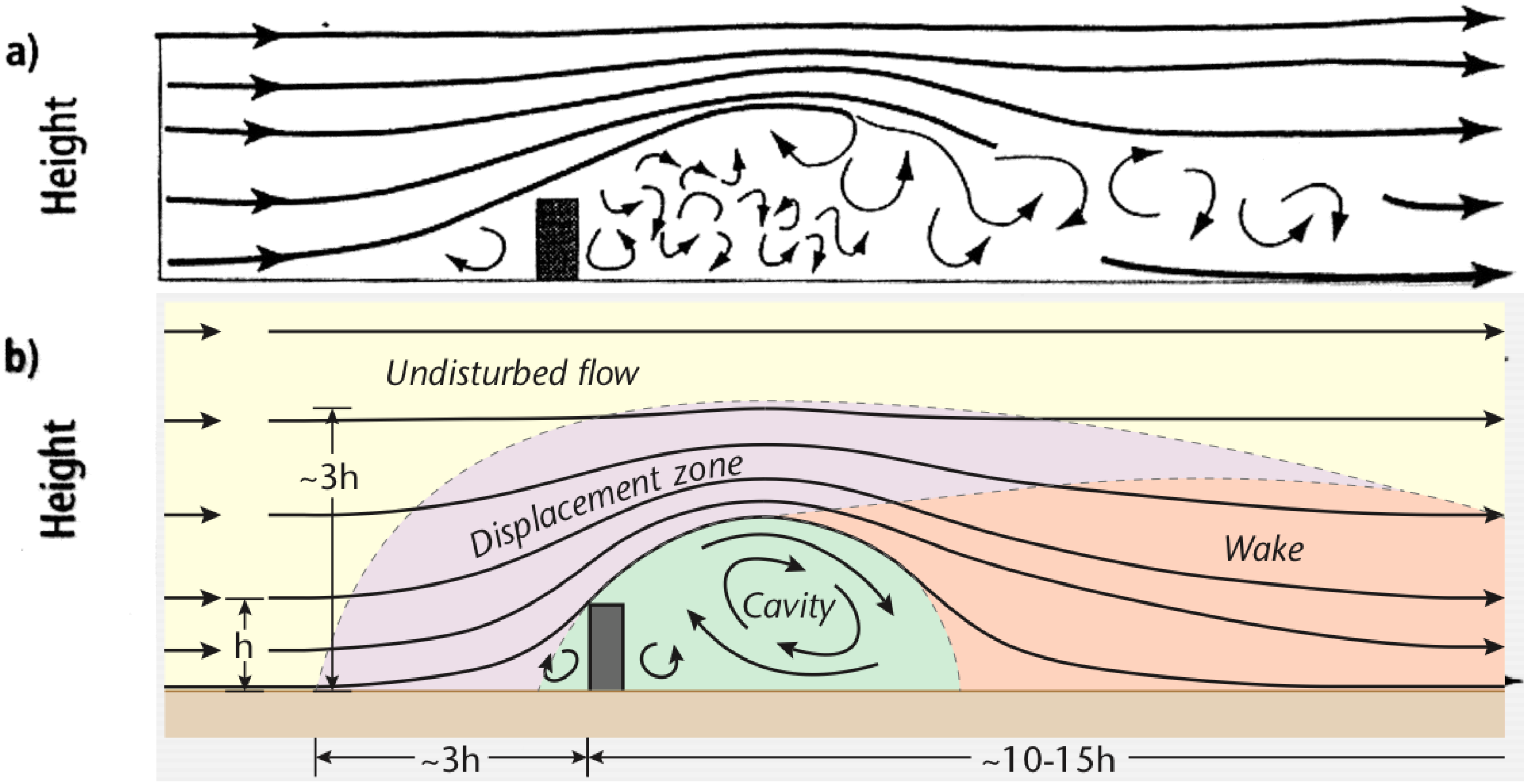
Flow and turbulence around a cube



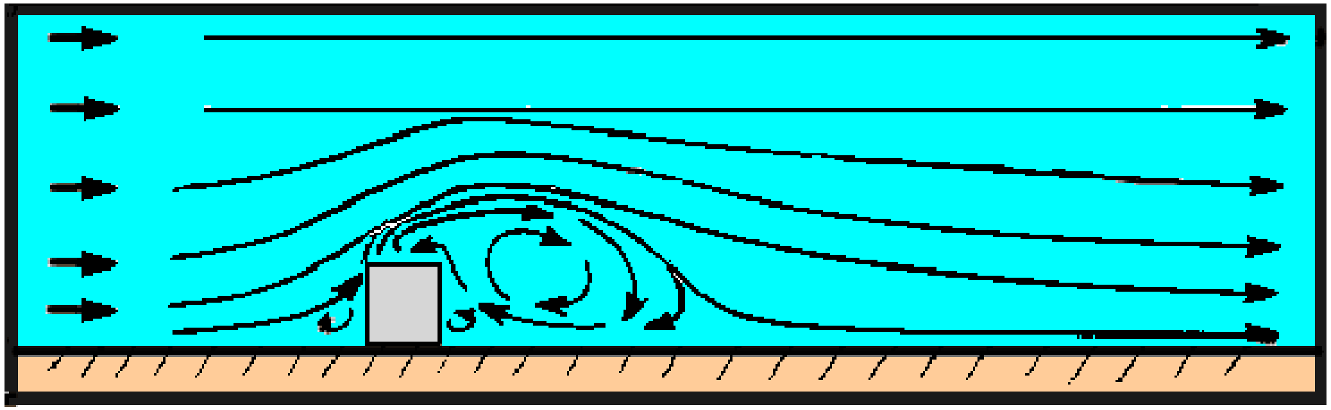
Flow around building models placed in wind tunnel visualized using Laser Light Sheet (Institute of Industrial Science, University of Tokyo)

Mechanical (forced) convection caused by an obstacle

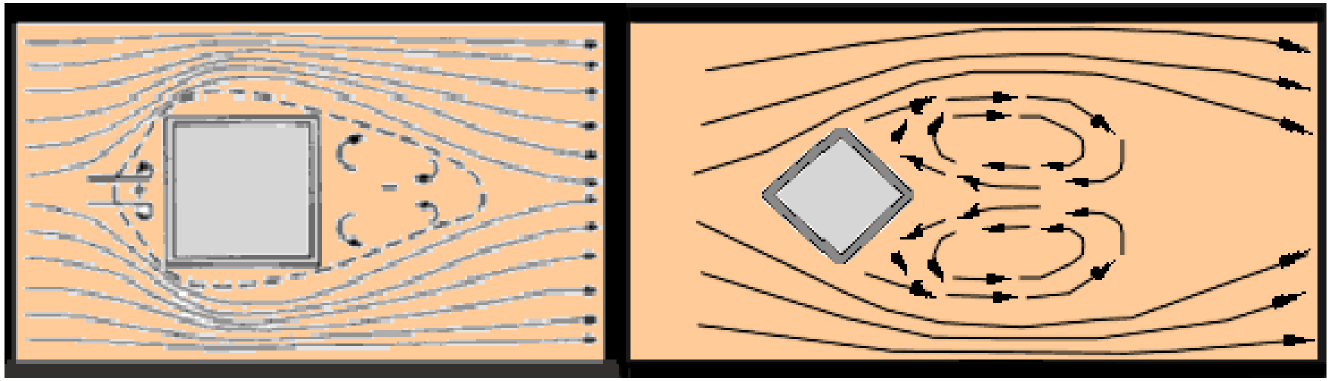
Size of eddies scales with size of obstacles.



Air flow around buildings



Flow Pattern: Side View Wind Against Face

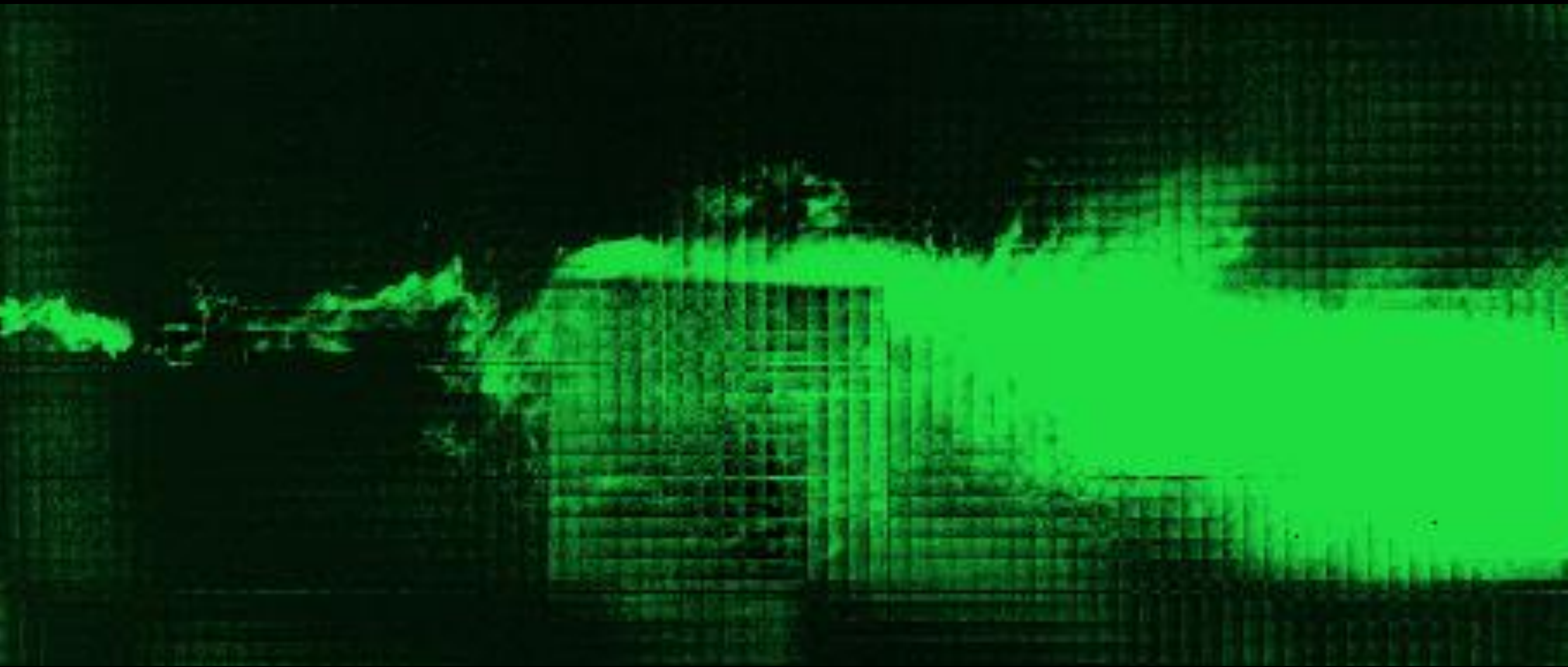


Flow Pattern: Top View Wind Against Face

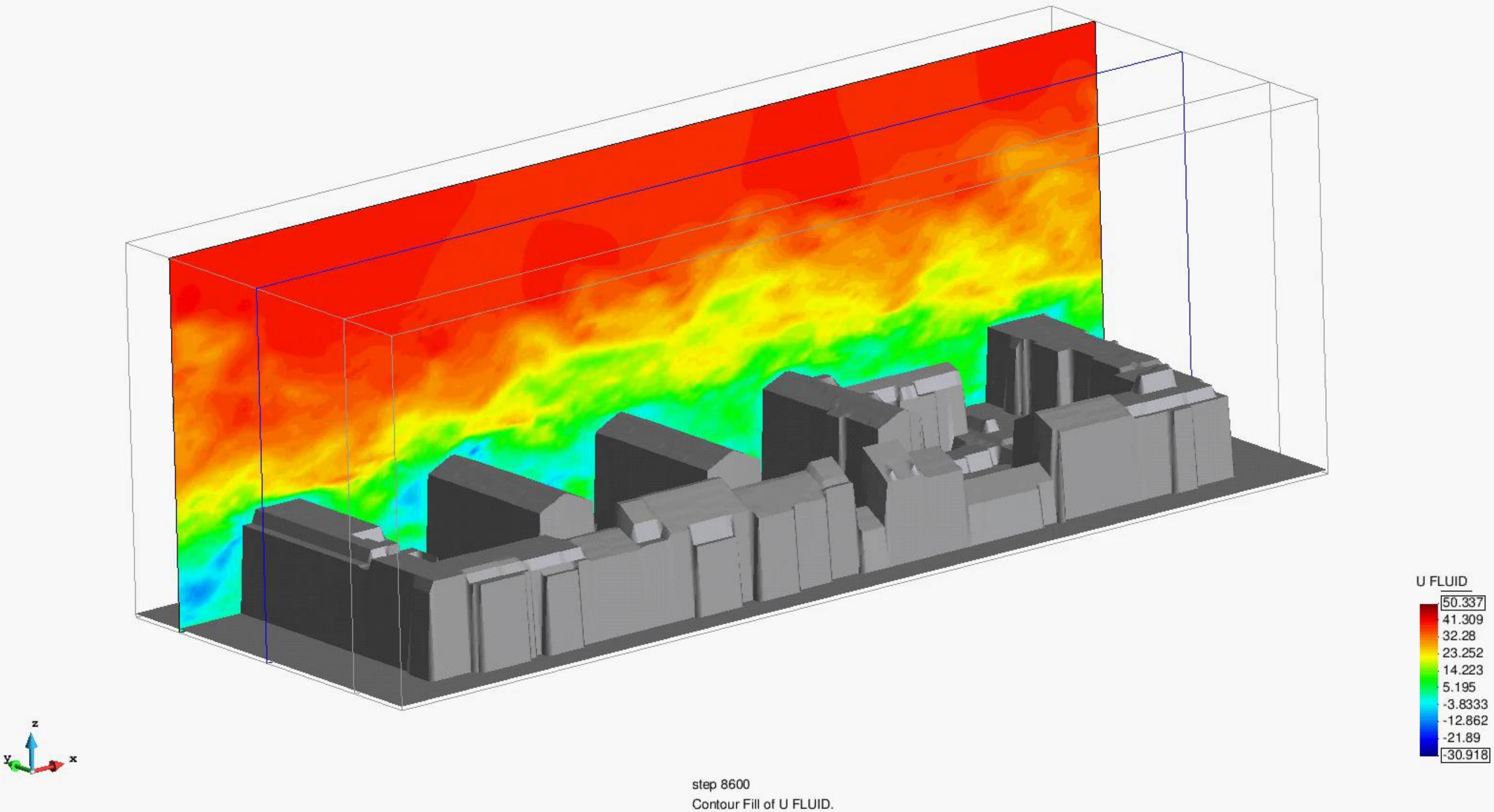
Flow Pattern: Top View Wind Against Edge

T.R. Oke (1987): 'Boundary Layer Climates' 2nd Edition.

Clouds over high-rise buildings in Panama City Beach, Florida, USA. Wind is from the right (ocean). (Photo courtesy of J. R. Hott, Panhandle Helicopters).



Simulation of turbulence above a city block using a numerical model
(Courtesy of M. Parlange / M. Giometto, UBC)

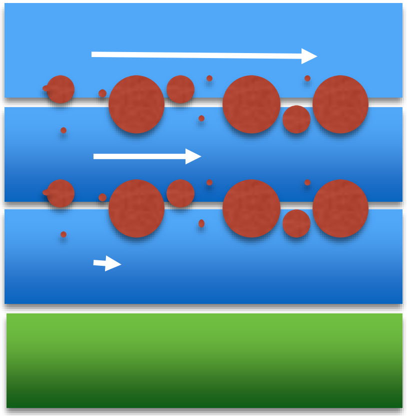


Mechanical (forced) convection due to shear

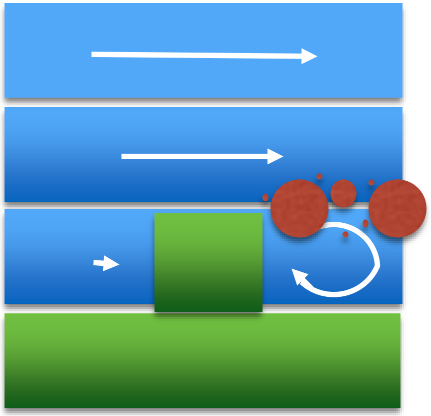
Direct numerical simulation of turbulence in a Kelvin Helmholtz instability
Colorado Research Associates

Mechanical (forced) convection

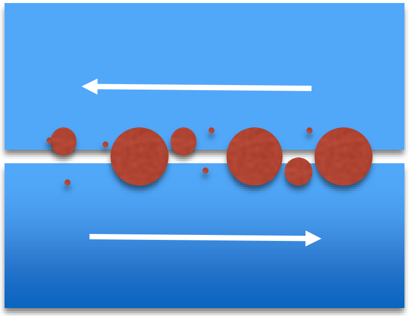
We can have three different scenarios that create turbulence mechanically:



Air layers are slowed by **skin friction** at surface, hence layers above have different speed (Skin drag)



Obstacles block flow and pressure differences cause overturning and flow separation (**Form drag**)

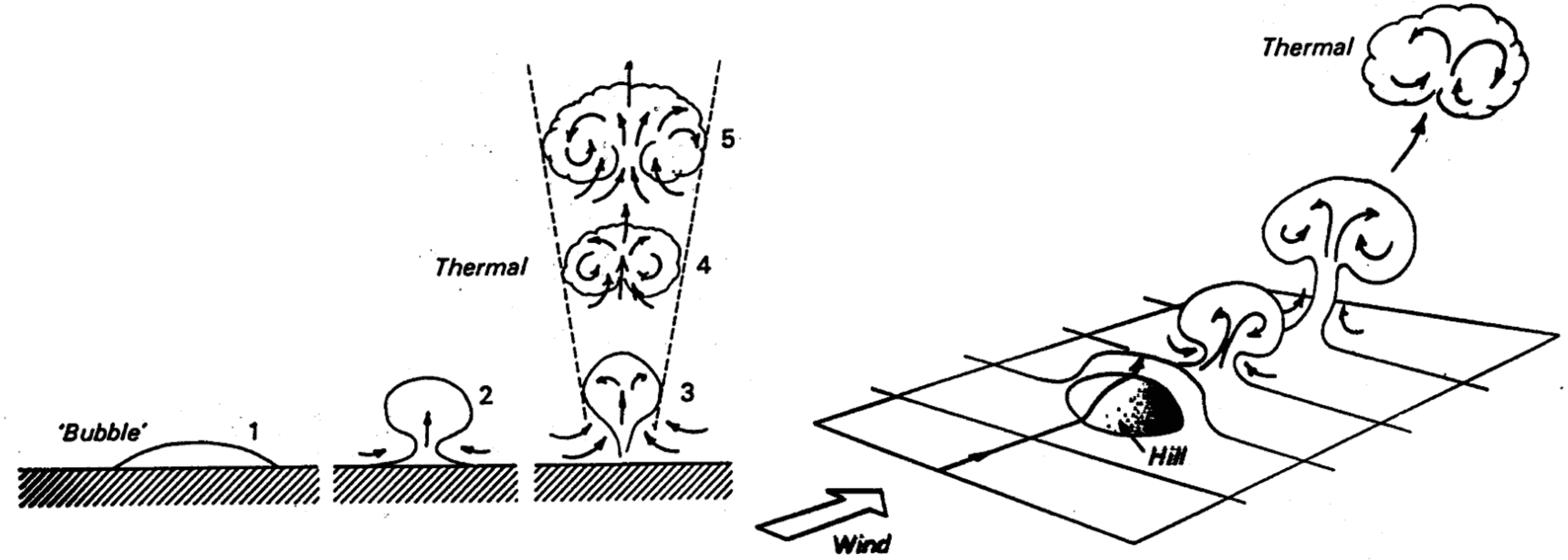


Two air layers with different **speeds and/ or direction**

Thermal (free) convection

Surface heating → density differences in air → convective exchange due to **buoyancy**.

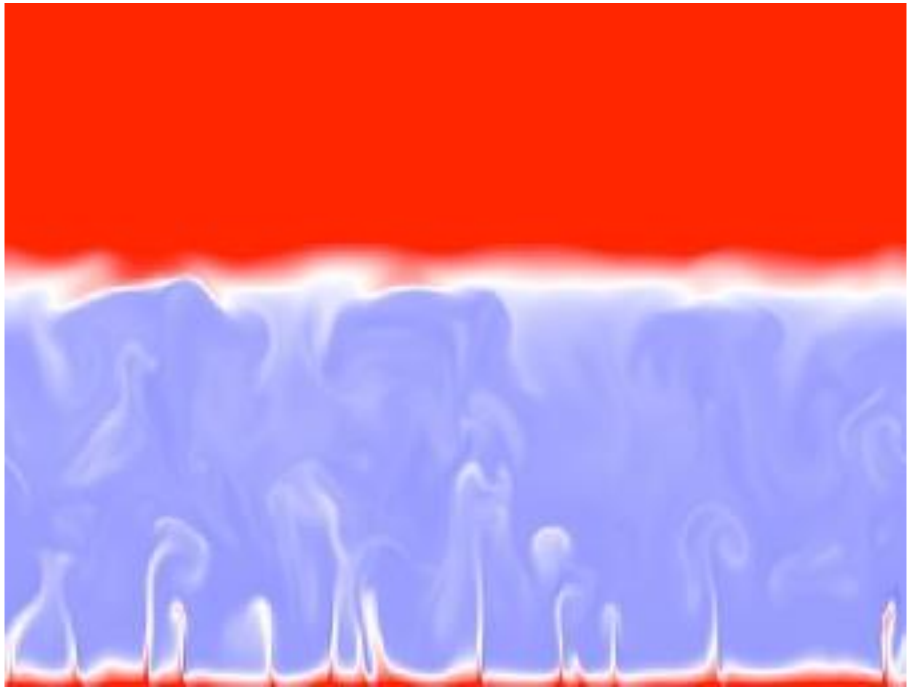
Thermal turbulence production requires continual **input of heat** which is converted to turbulent kinetic energy.



T.R. Oke (1987): 'Boundary Layer Climates' 2nd Edition.


Movie: A. Christen

Thermally produced turbulence - free convection



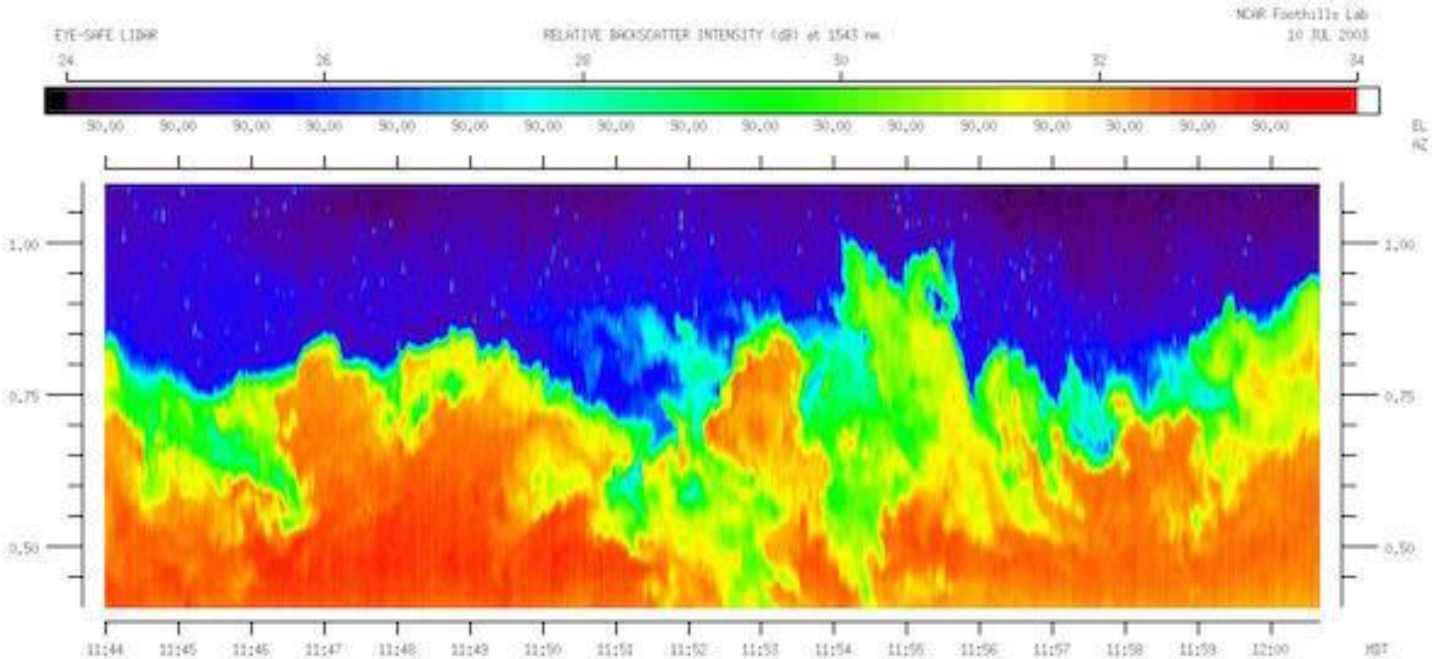
Snapshot of the temperature field in a direct numerical simulation of convection in the ABL [Figure by Peter Sullivan (NCAR/MMM) and H. Jonker (Delft University, Netherlands)]

Size of eddies scales are restricted by the **height of the atmospheric boundary layer** (ABL)

The height of the ABL depends on the profile of potential temperature which in turn is controlled by turbulent mixing

Thermally produced turbulence - free convection

This lidar image is like a vertical slice through the atmospheric boundary layer, where polluted air (green, yellow, and red in this false color image) is being carried upward from the surface by thermals of warm rising air.



Source: https://www.eoas.ubc.ca/courses/atsc113/flying/met_concepts/03-met_concepts/03f-BL_obstacle_wake/index.html

Mechanical vs. thermal turbulence

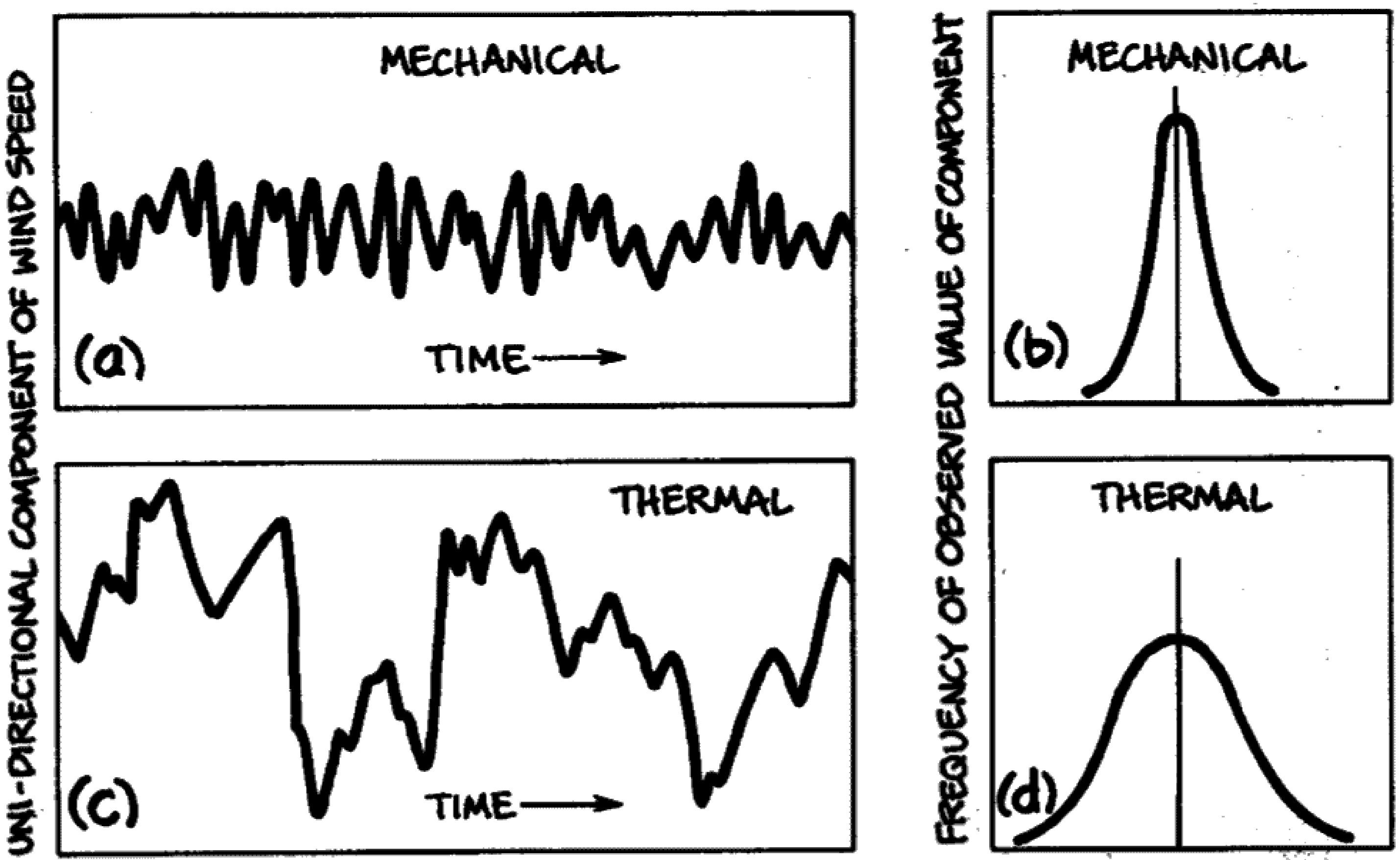
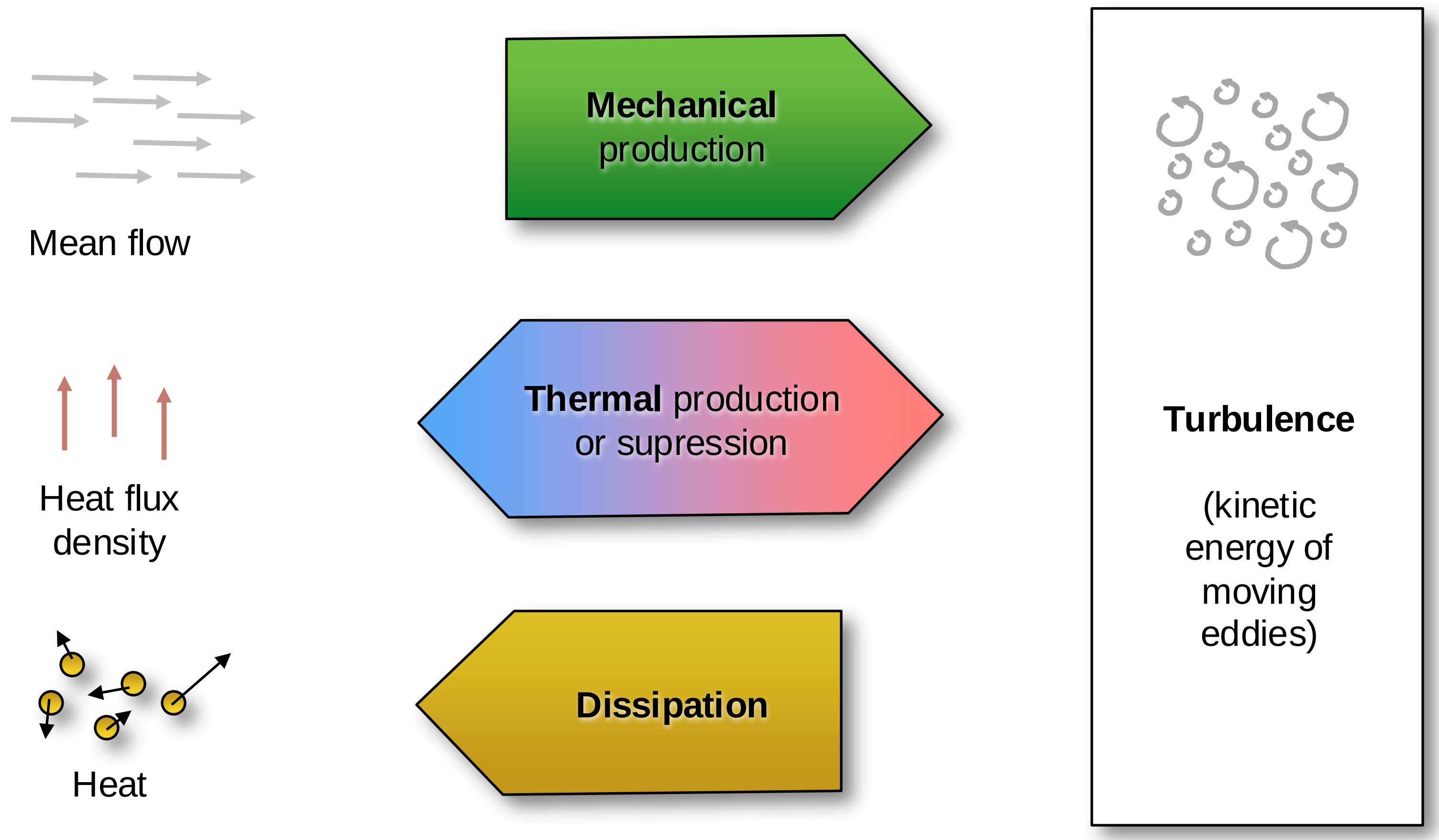


Fig. 7-2 Rapid-response records of wind speed in **(a)** mechanical and **(c)** thermal turbulence. From these records are derived statistical frequency distributions of the departures from the mean values of speed: **(b)** mechanical and **(d)** thermal.

W. P. Lowry, P. P. Lowry (1989)

Conservation of energy - The Turbulent Kinetic Energy (TKE) budget



Take home points

- Turbulence in the ABL is a ‘mixture’ of **mechanical (forced)** and **thermal (free)** convection.

- Mechanical turbulence in the ABL is caused by instabilities arising from strong **mean velocity gradients**, which in turn are caused by surface skin or form drag (obstacles) or shear flow.

- Thermal turbulence is the generation of turbulent motion in a fluid due to temperature differences, which create buoyancy-driven instabilitiesis (i.e., warm air **plumes** rising up in the ABL which in turn are caused by **differential surface heating**).

- Mechanical turbulence production requires **continual supply of kinetic energy** (mean wind) while thermal turbulence requires continual supply of a **sensible heat flux** (surface heating).