

An introduction to the Atmospheric Boundary Layer

Modelling wind and dispersion in urban environments

Text book references: And Introduction to Boundary Meteorology, R.B. Stull, chapter 1

Learning Objectives:

After this class, you will be able to:

- Explain what is the Atmospheric Boundary Layer (ABL)
- Identify applications that rely on the ABL
- Distinguish the different Atmospheric Boundary Layer structures during the day.

Activities during the class:

During this class, you will perform the following activities:

1. Think-pair-share
2. Quiz multiple choice
3. Picture prompt in groups
4. One-minute notes (the muddiest point)

**NO summative
assignments**

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Outline of the class:

1. What is the Atmospheric Boundary Layer
2. Winds in the ABL: Turbulence
3. Applications
4. Taylor's Hypothesis
5. Buoyancy and virtual temperature concepts
6. ABL structure
7. Micrometeorology
8. Wrap-up
9. One-minute notes (the muddiest point)

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Think, pair, share

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Think, pair, share



Quiz

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Quiz

Picture Prompt

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What is the ABL?



What is the ABL?



What is the ABL?

Atmospheric/Planetary boundary layer



What is the ABL?



divephotoguide.com

The ocean and the ABL are similar in a sense....

What is the ABL?



divephotoguide.com

The ocean and the ABL are similar in a sense....



What is the ABL?



divephotoguide.com

The ocean is to the aquatic life what the ABL is to the terrestrial life



The ocean and the ABL are similar in a sense....

What is the ABL?

- What is a boundary layer in fluid dynamics?

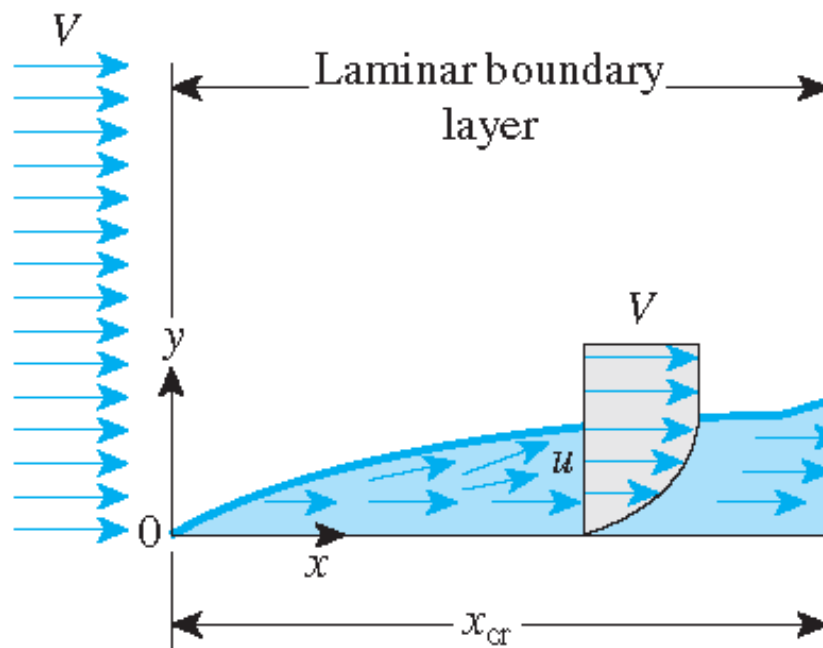


FIGURE 6–14

The development of the boundary layer for flow over a flat plate, and the different flow regimes.

Courtesy of University of Delaware.

What is the ABL?

- What is a boundary layer in fluid dynamics?

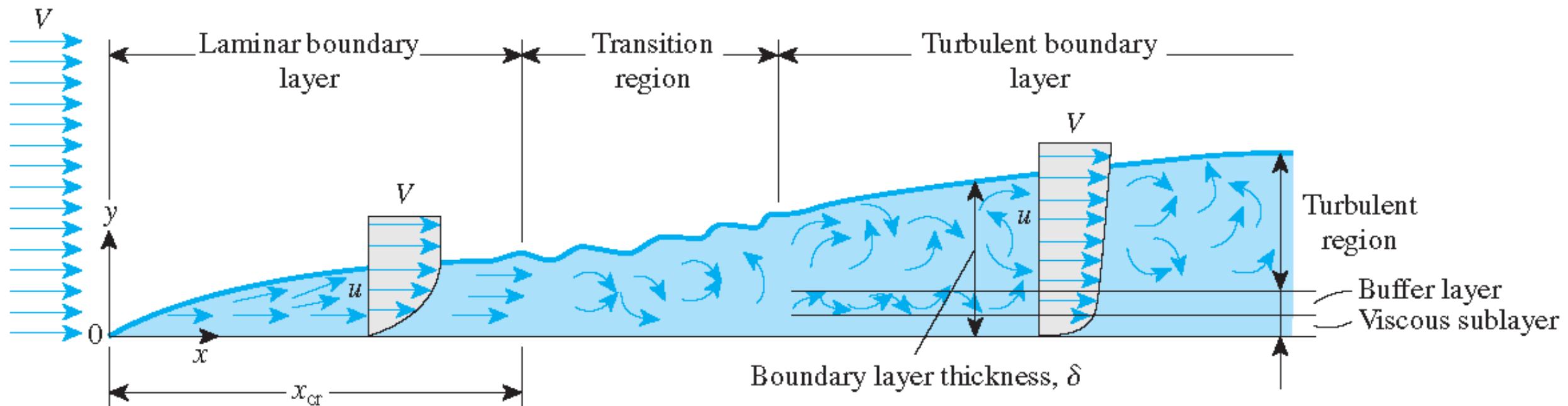


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What is the ABL?

- What is a **boundary layer** in fluid dynamics?

Entry #: V84181

Spatially developing turbulent boundary layer on a flat plate

J.H. Lee, Y.S. Kwon, N. Hutchins and J.P. Monty

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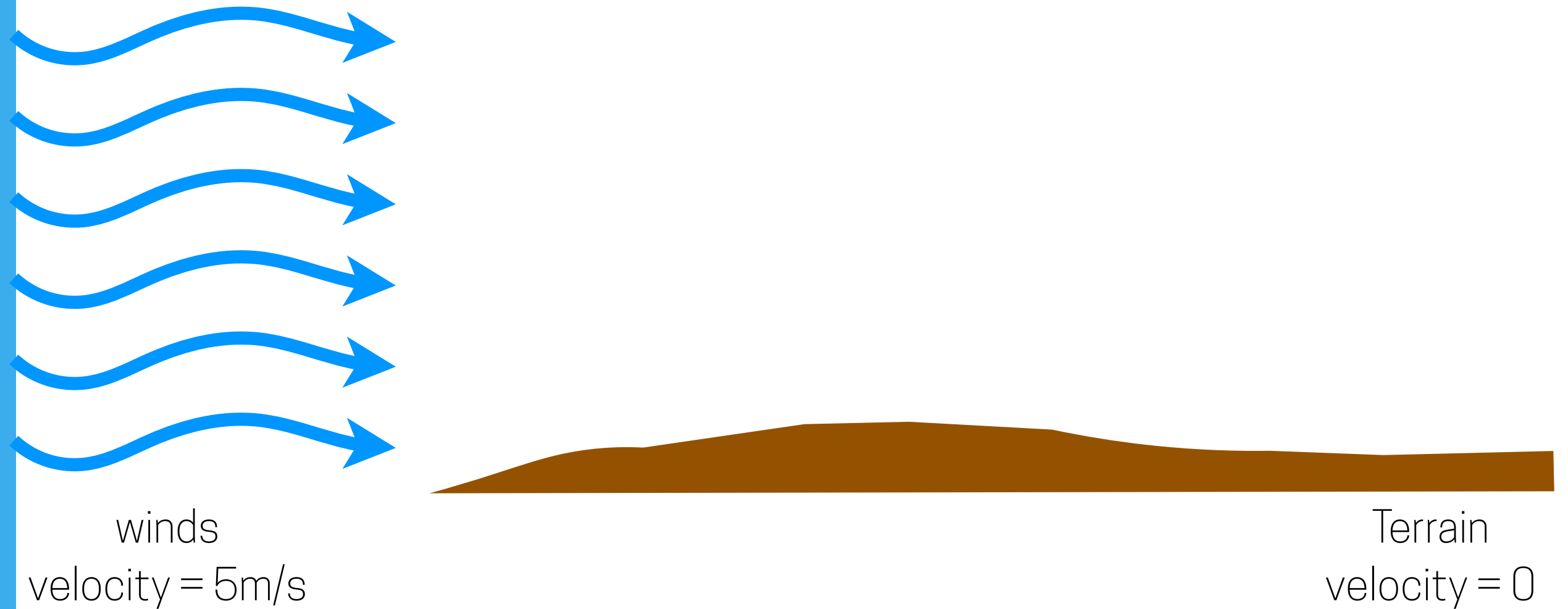
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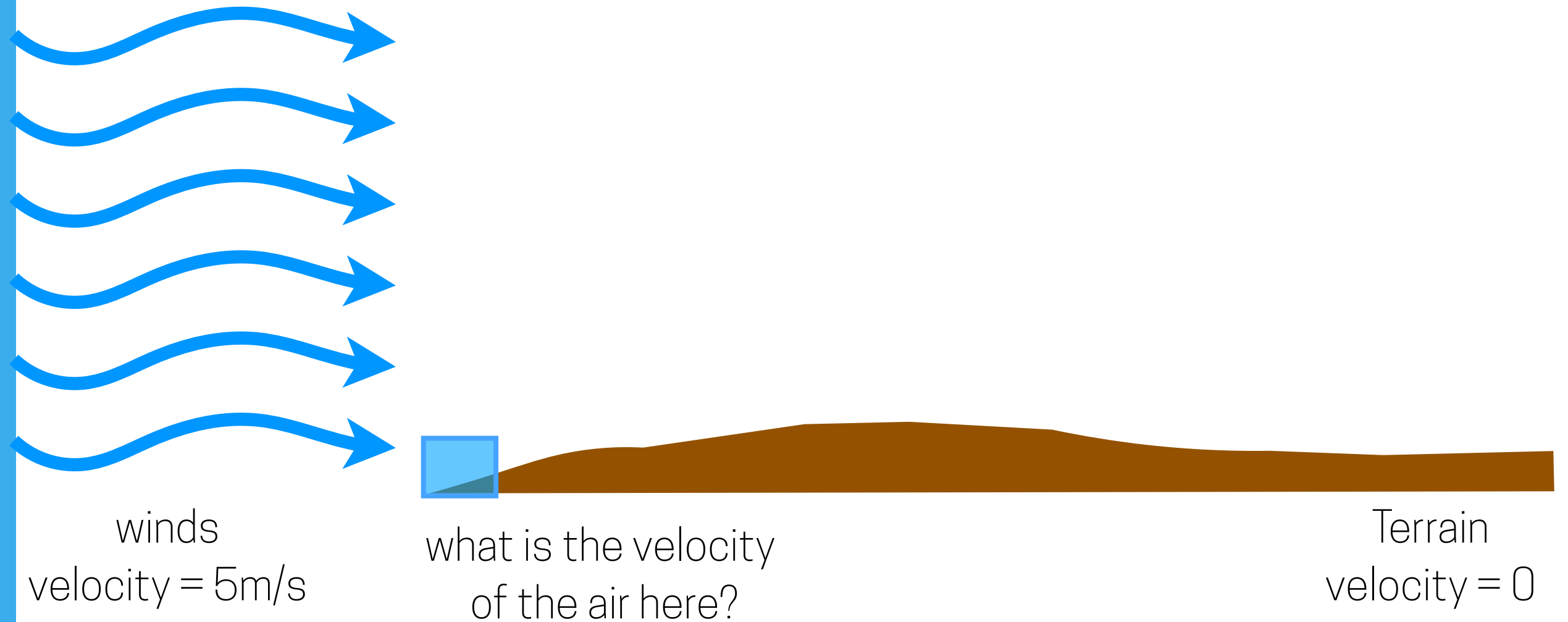
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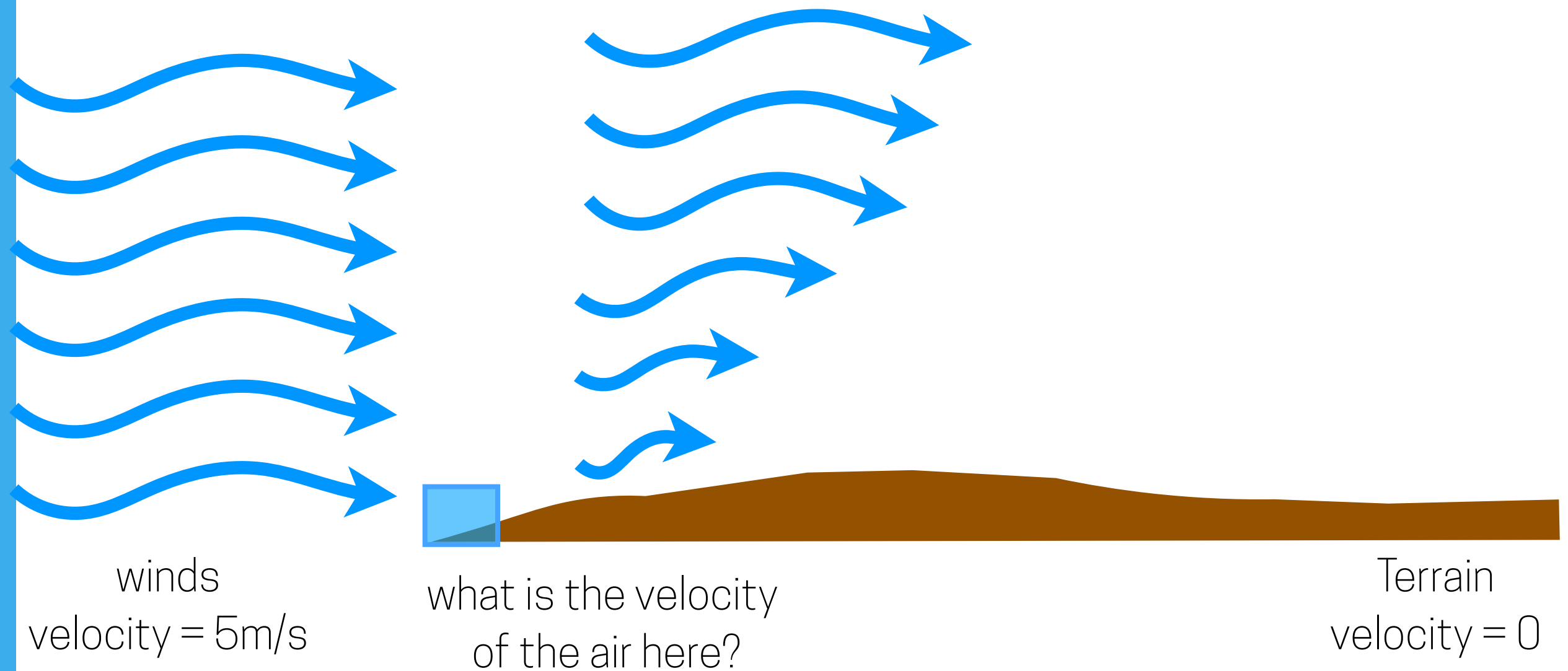
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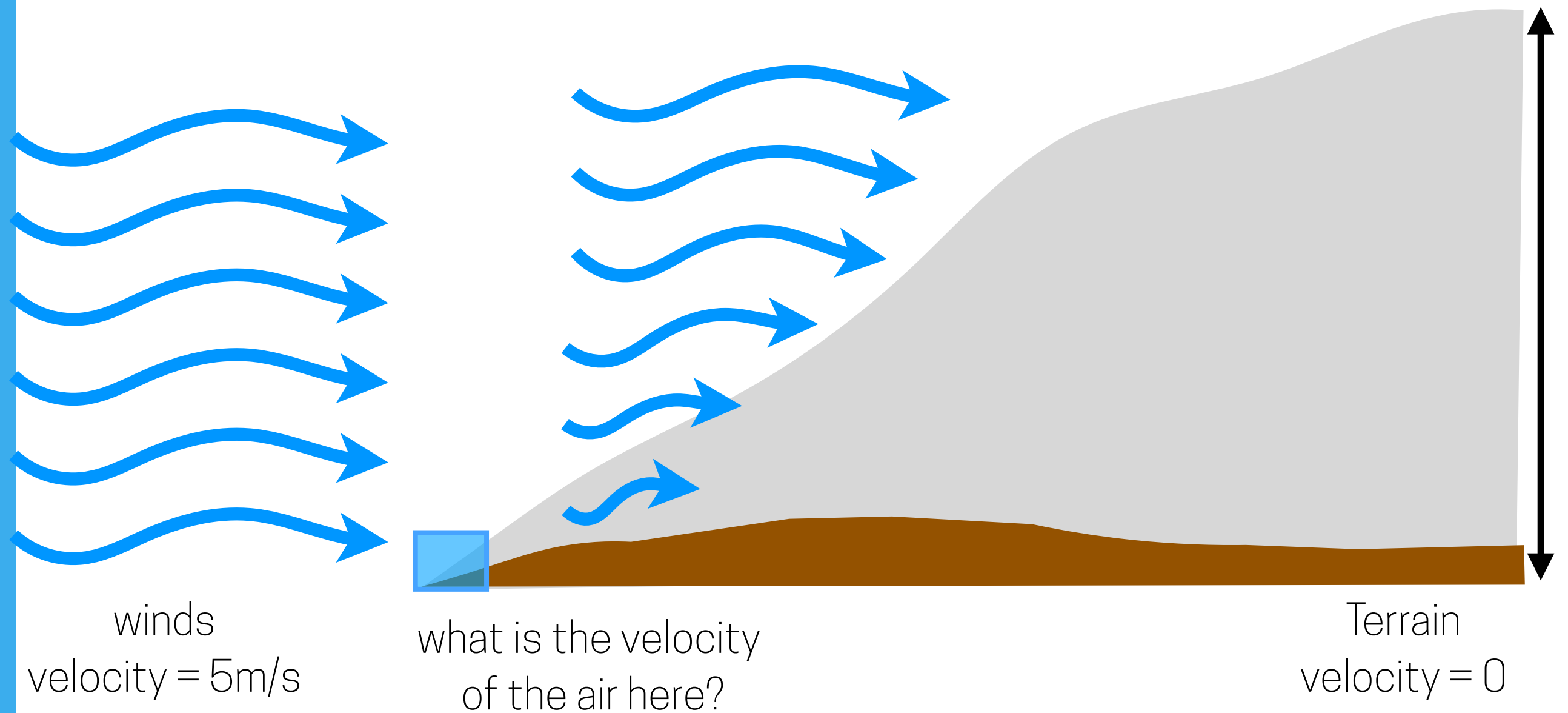
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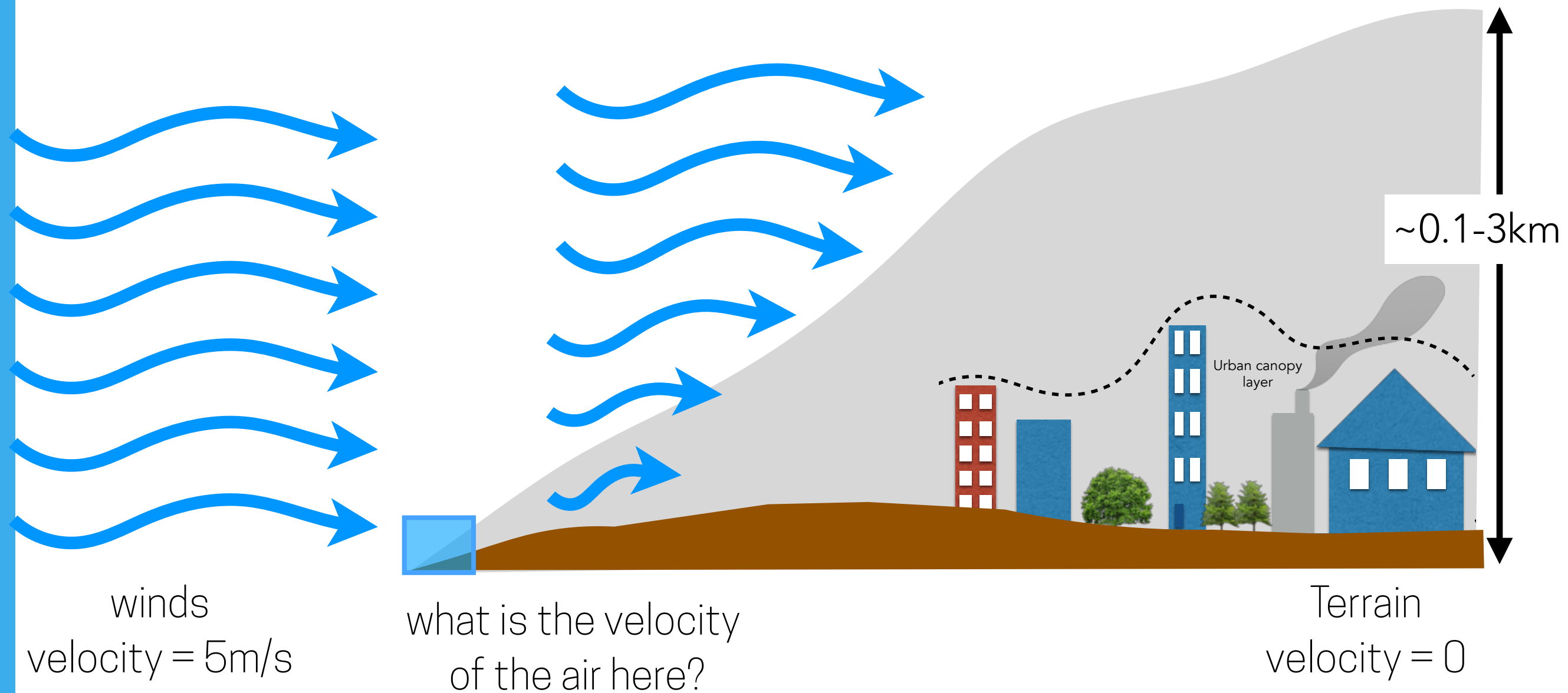
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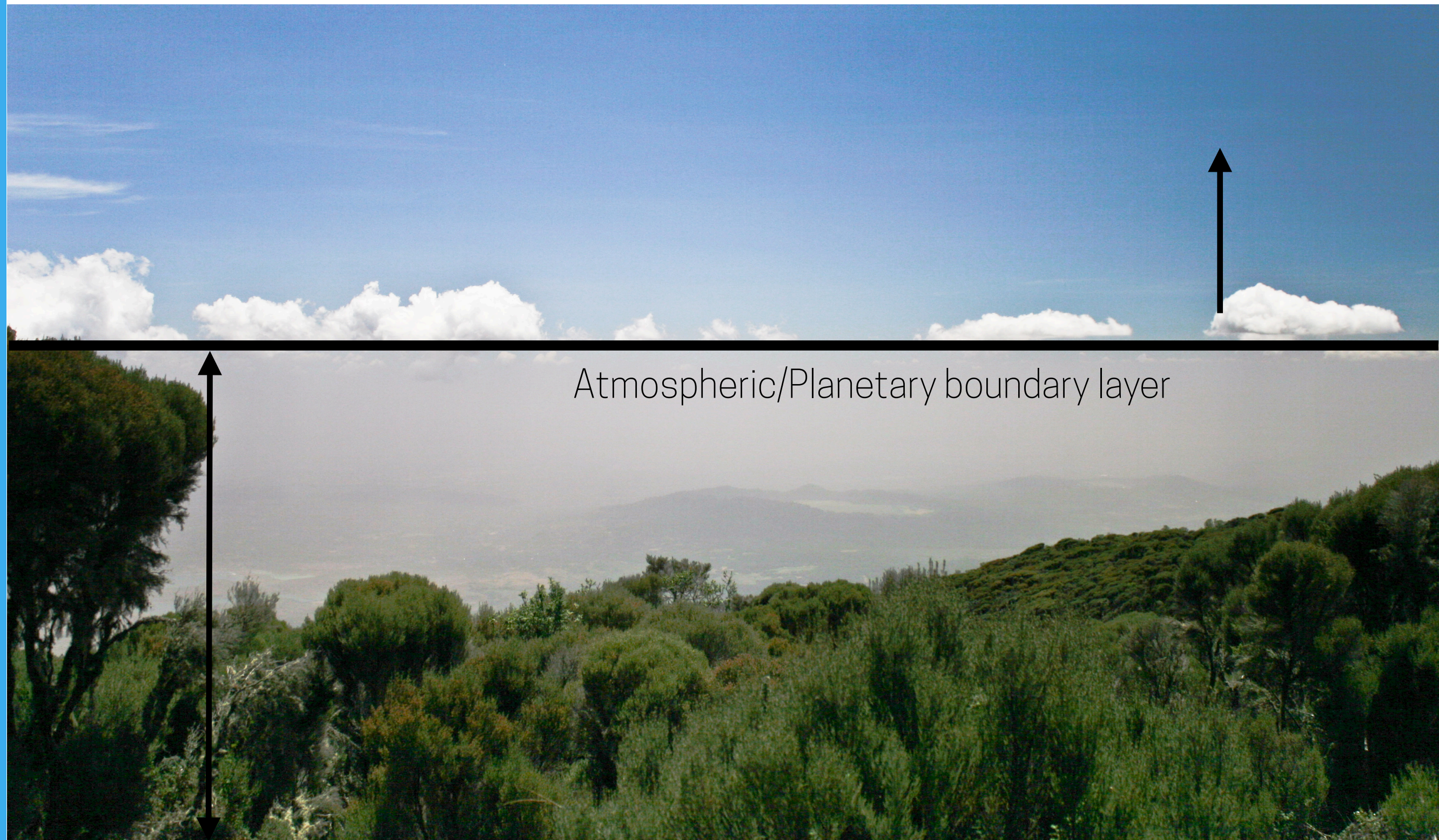
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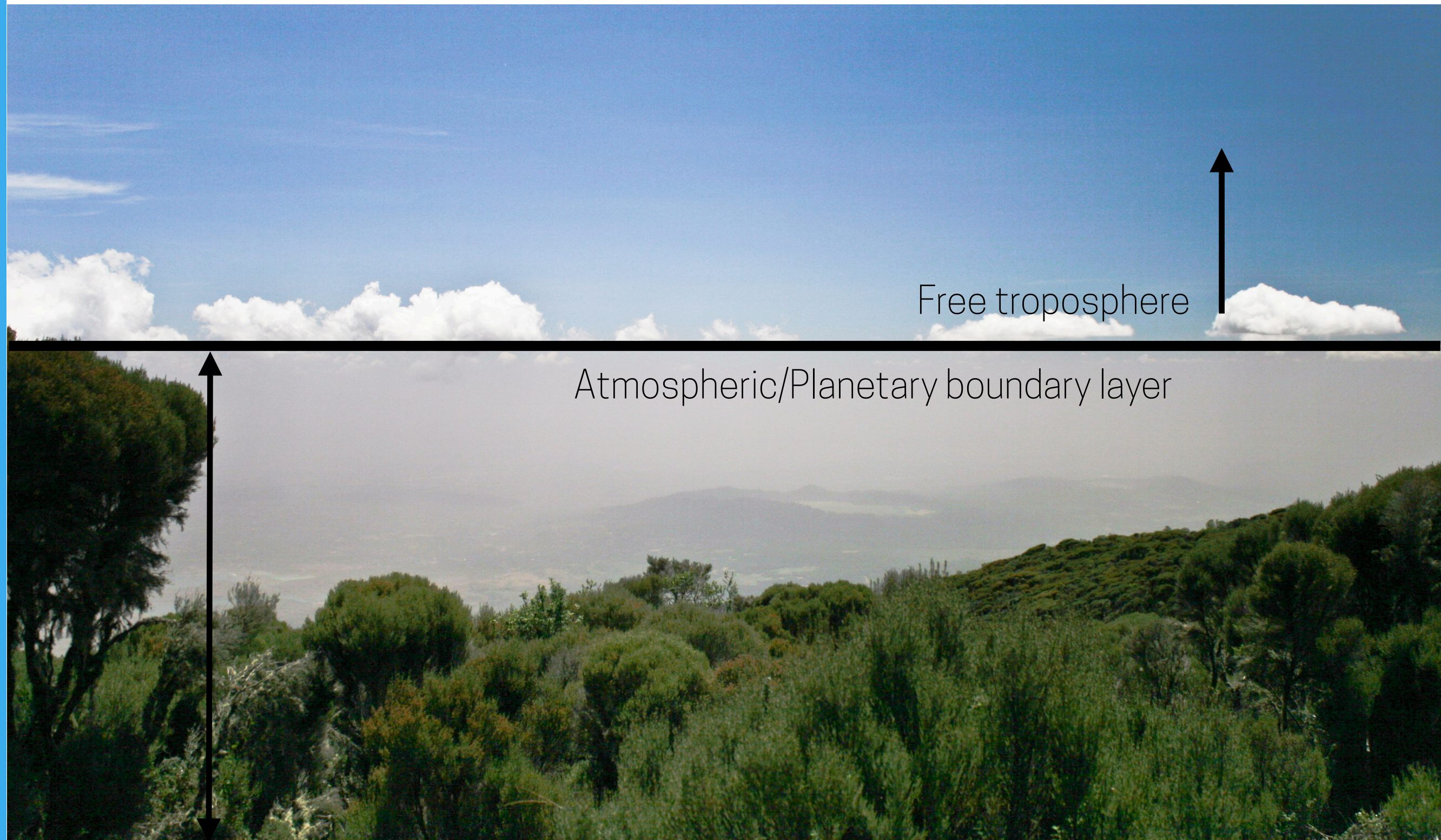
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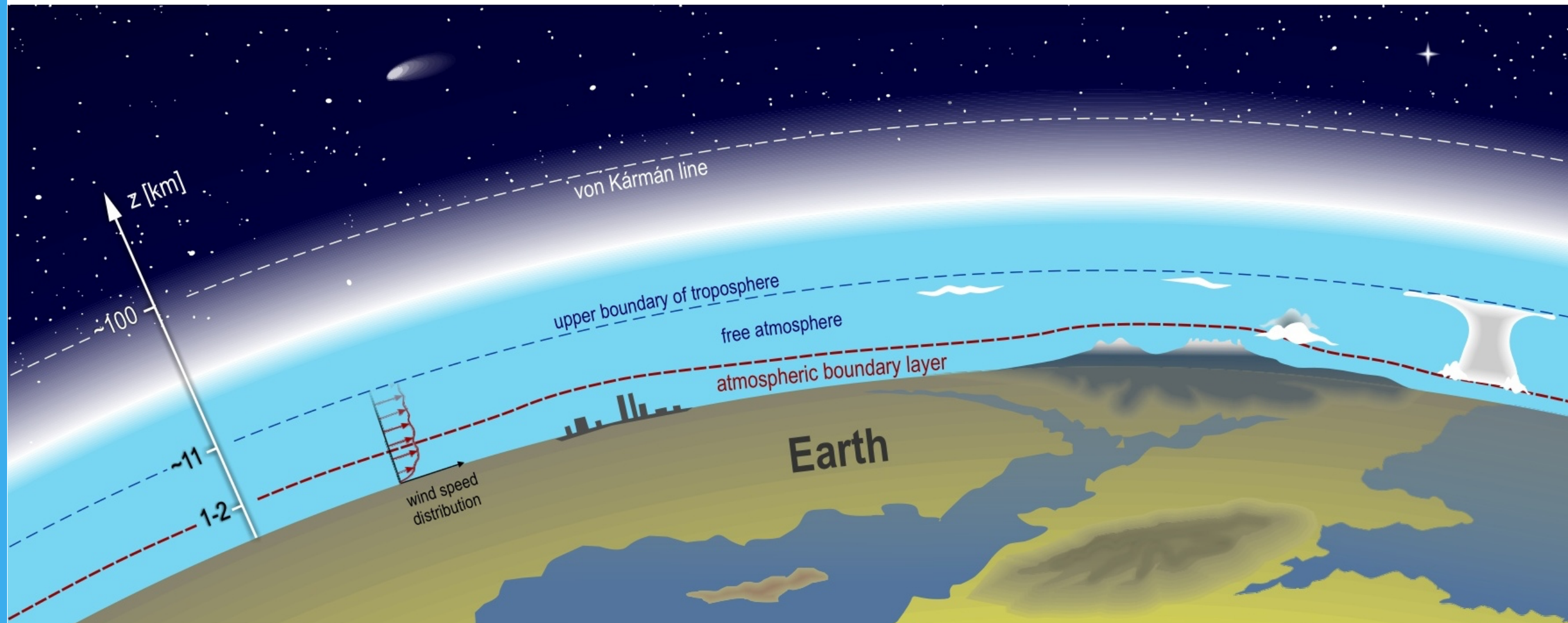


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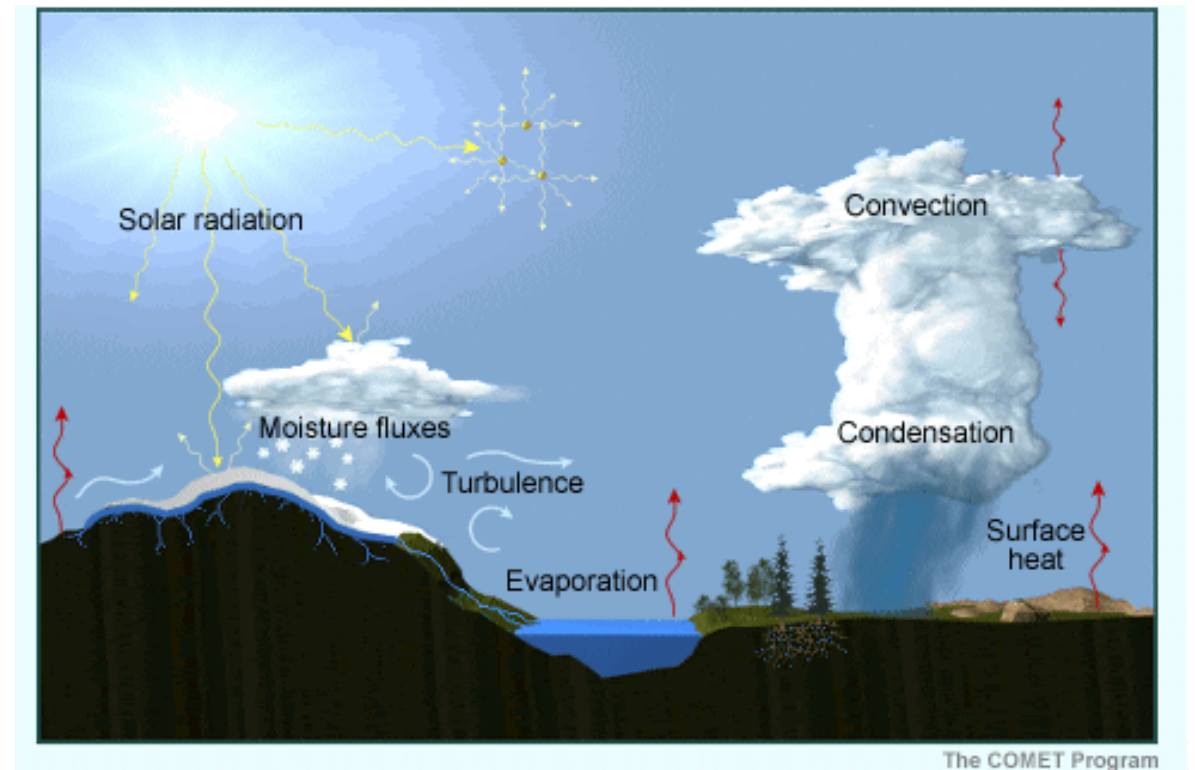
What is the ABL?

- We, humans, spend our lives in the boundary layer
- It is the part of the troposphere that is directly influenced by the Earth



What is the ABL?

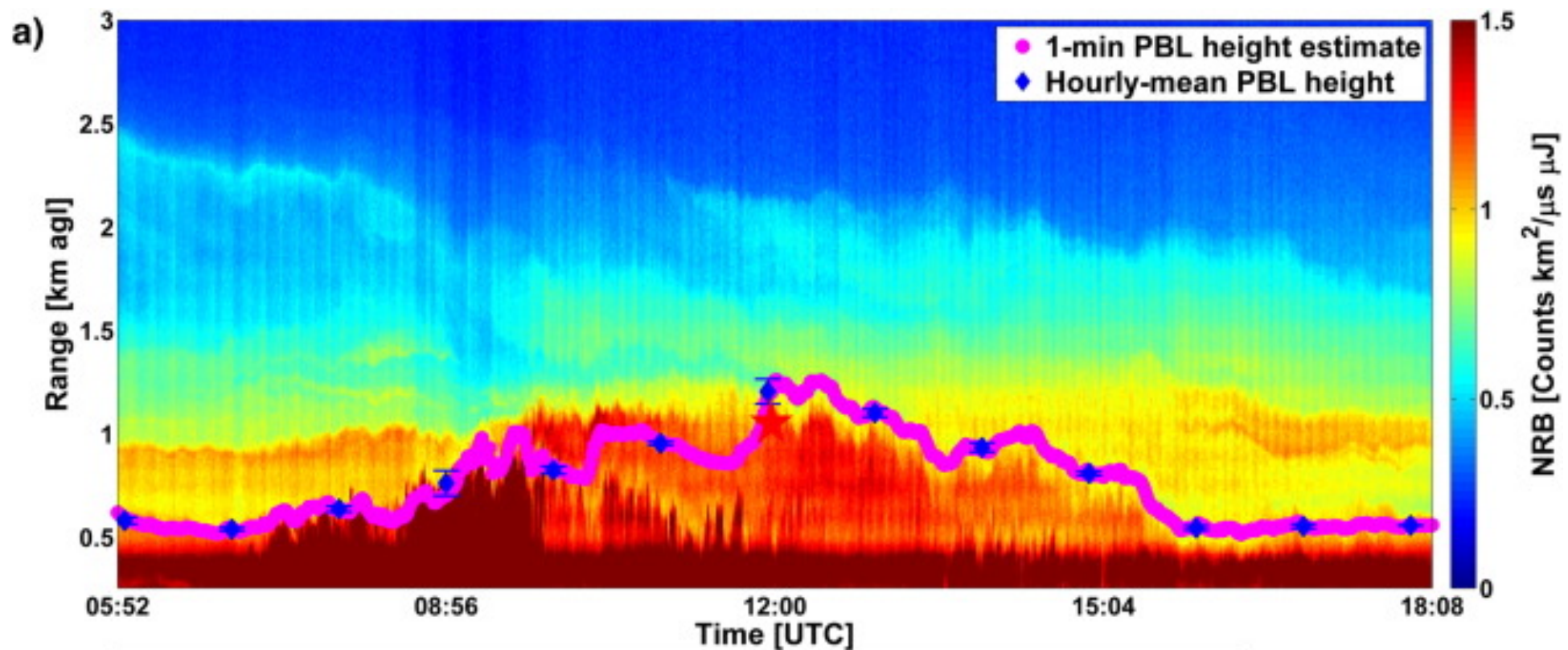
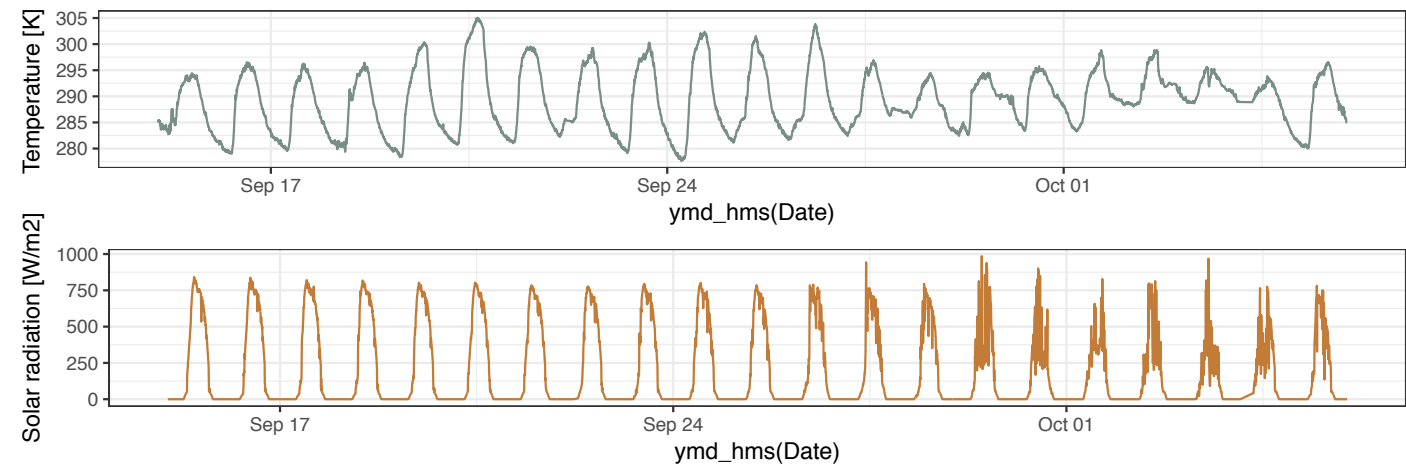
- The ABL responds to surface forcing with time scales within 1 hour or less
- Some of the forcing are:
 1. Frictional drag (buildings)
 2. Evaporation and transpiration
 3. Heat transfer to/from the surface
 4. Pollutant emissions



- The ABL depth is variable with time, between few hundreds of meters up to 3km

What is the ABL?

- During the day/night the ground warms/ cools in response to solar radiation which forces changes in the ABL through fluxes and transport processes



[Impact of WRF model PBL schemes on air quality simulations over Catalonia, Spain, Banks and Baldasano, Sci. Of. Total Env. 2016]

What is the ABL?

ABL

Almost turbulent constantly

Strong drag (earth's surface), large energy dissipation

Rapid turbulent mixing in 3D

Near logarithmic wind speed profile in the SFL; subgeostrophic, cross-isobaric flow is common

Thickness varies between 100m-3km

Free Atmosphere

Mostly laminar; turbulence in convective clouds, and sporadic Clear Air Turbulence in thin layers of large horizontal extent

Small viscous dissipation

Mean wind and cumulus scale dominate

Winds nearly geostrophic

Less variable (8????-18km); slow time variations

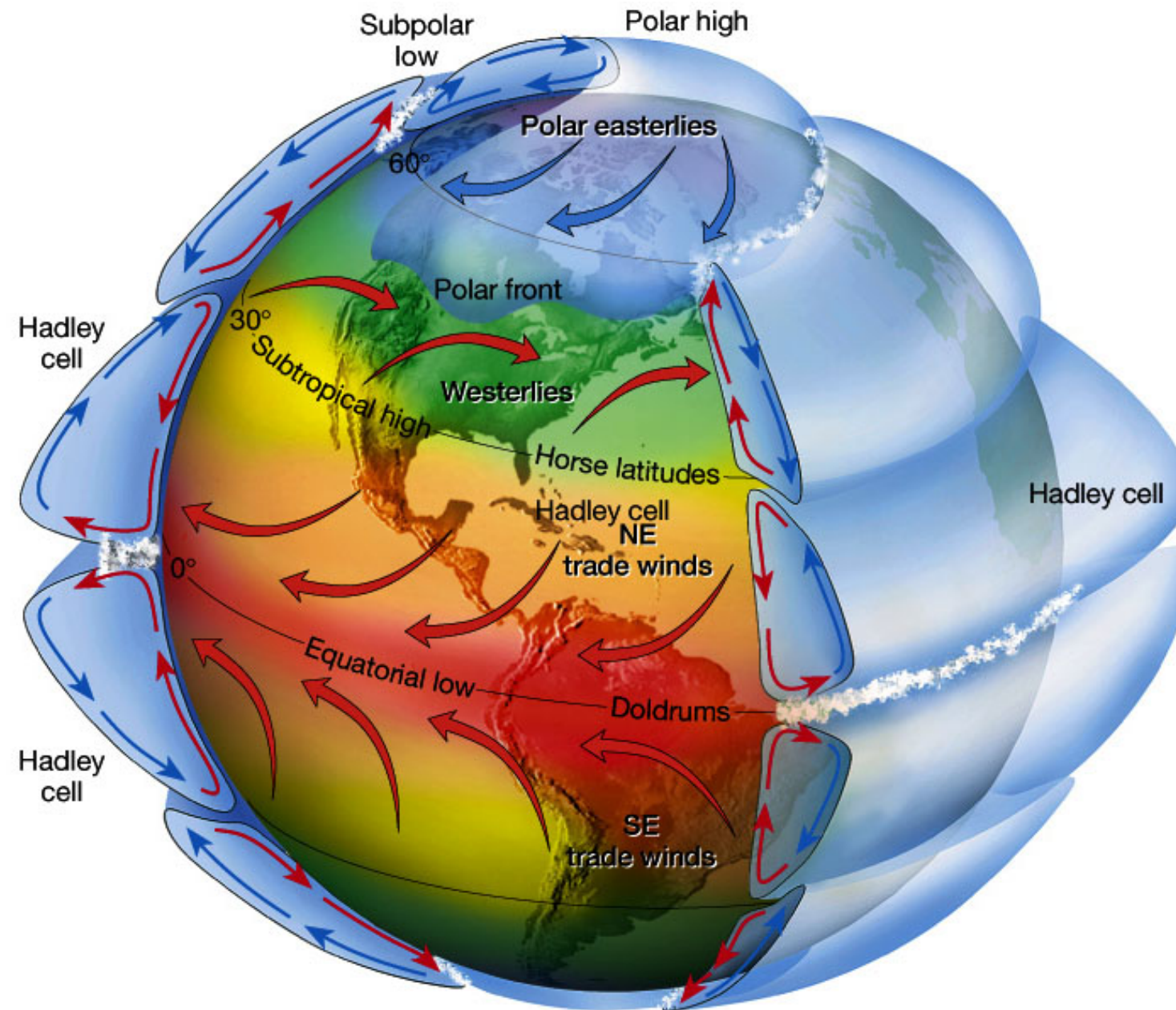
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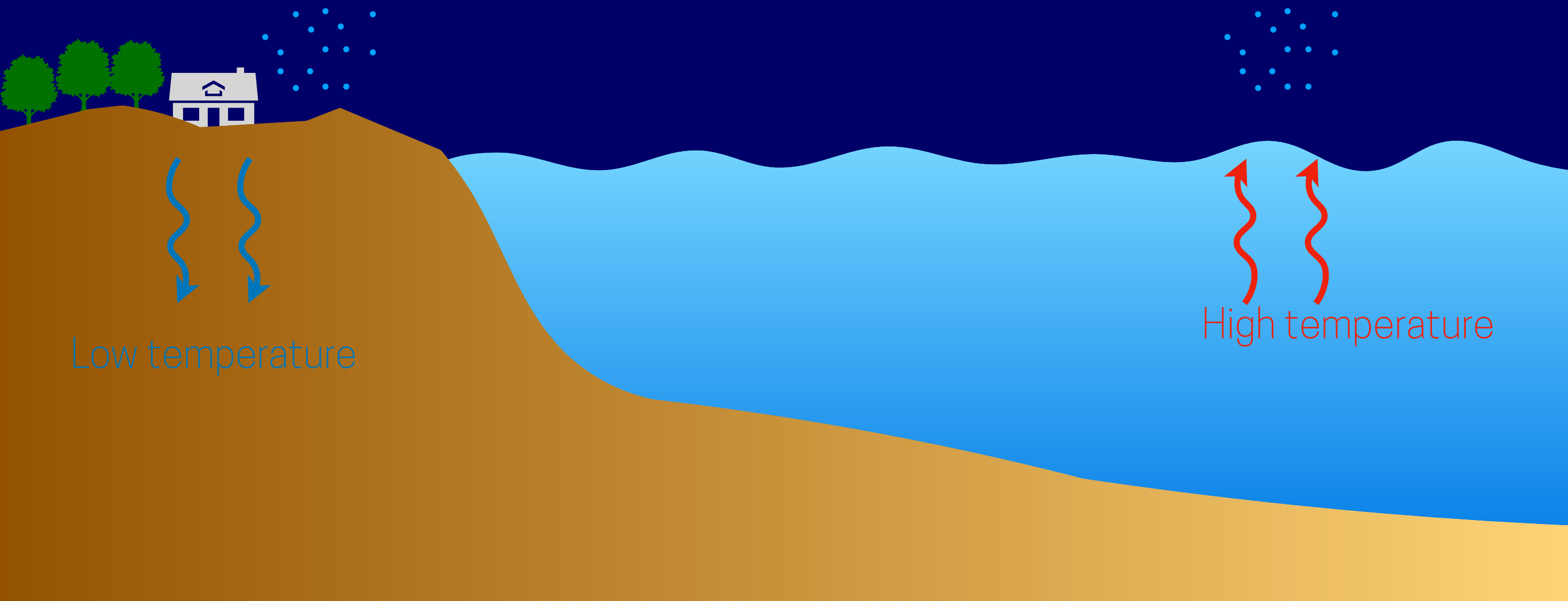
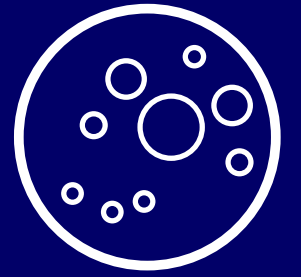
Winds in the ABL: turbulence

- Where do winds come from?



<https://www.youtube.com/watch?v=PDEcAxfSYal>

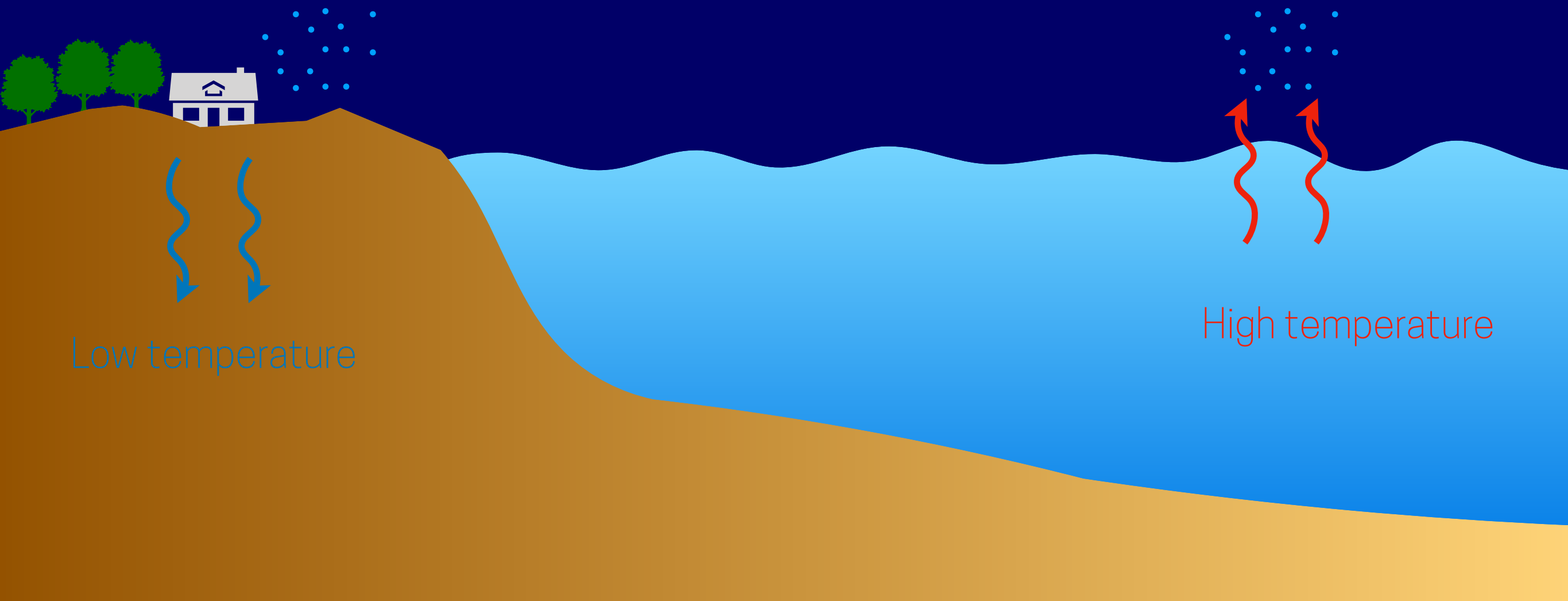
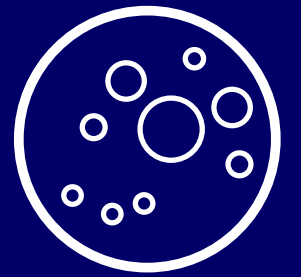
Wind flows



Low temperature

High temperature

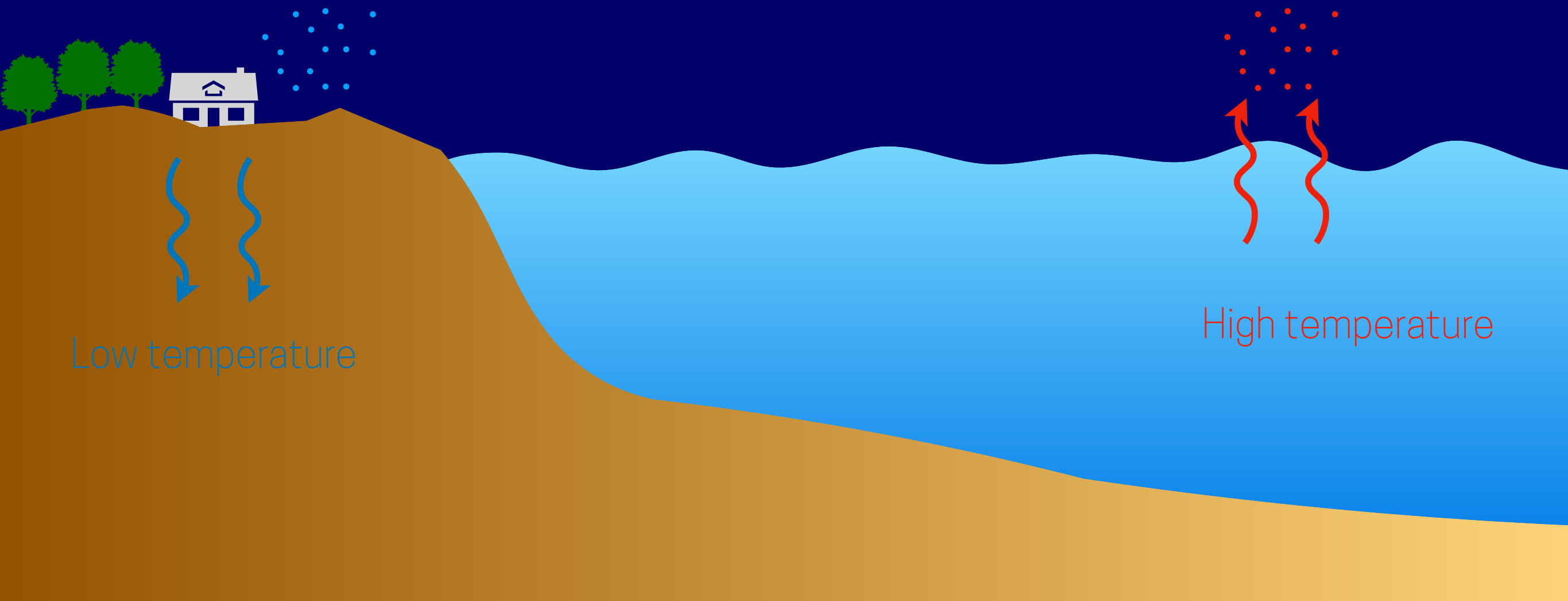
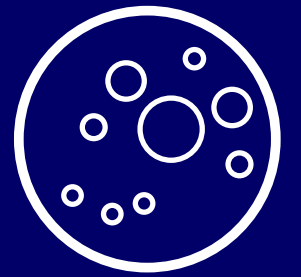
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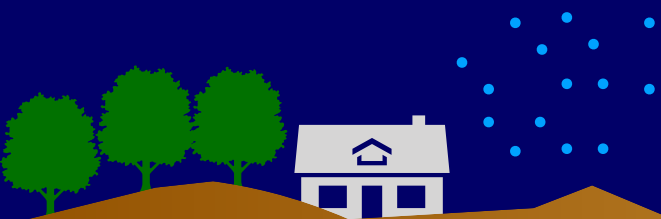
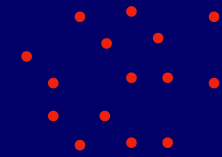
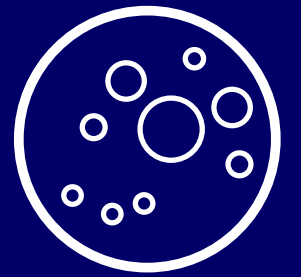
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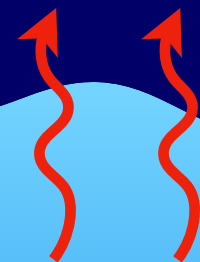
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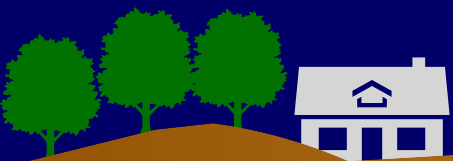
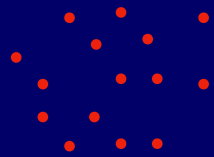
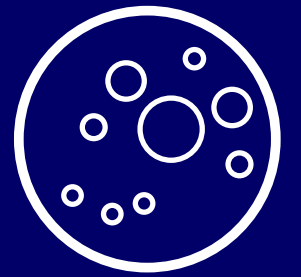


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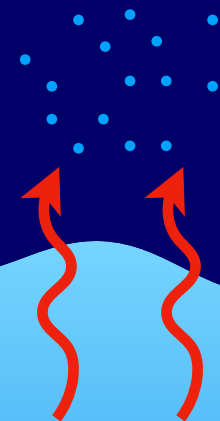


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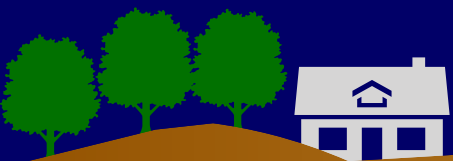
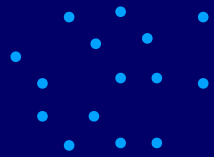
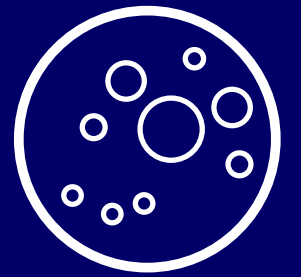


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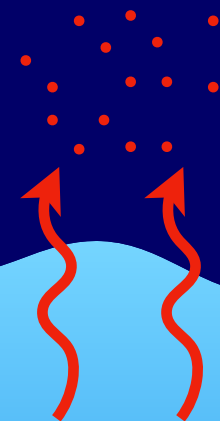


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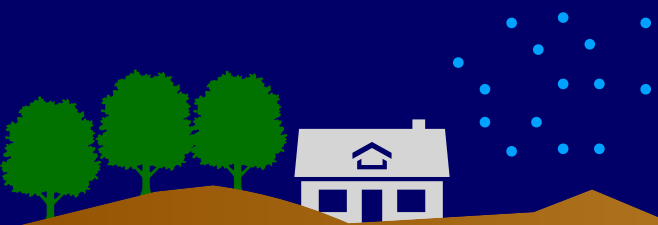
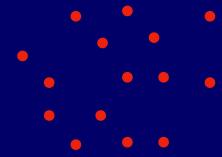
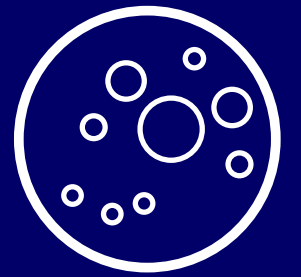


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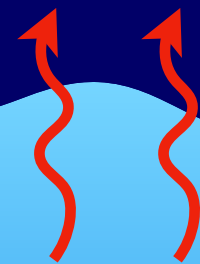


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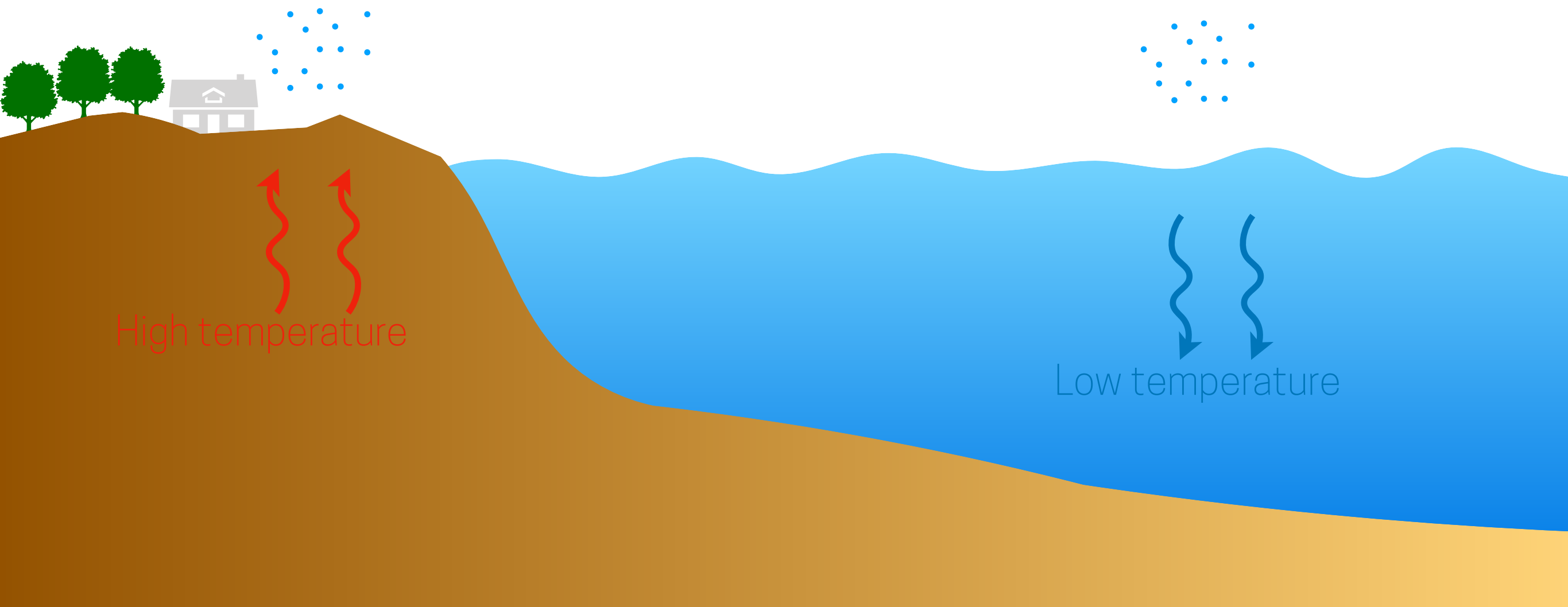


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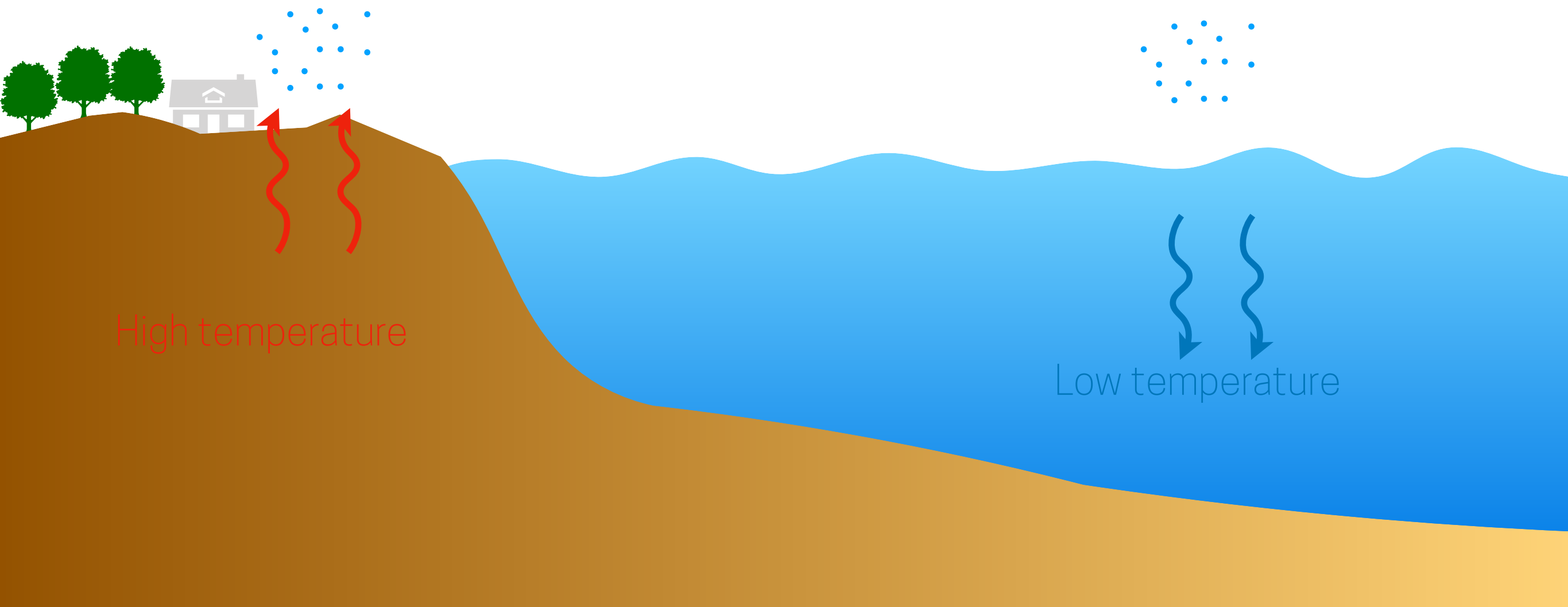


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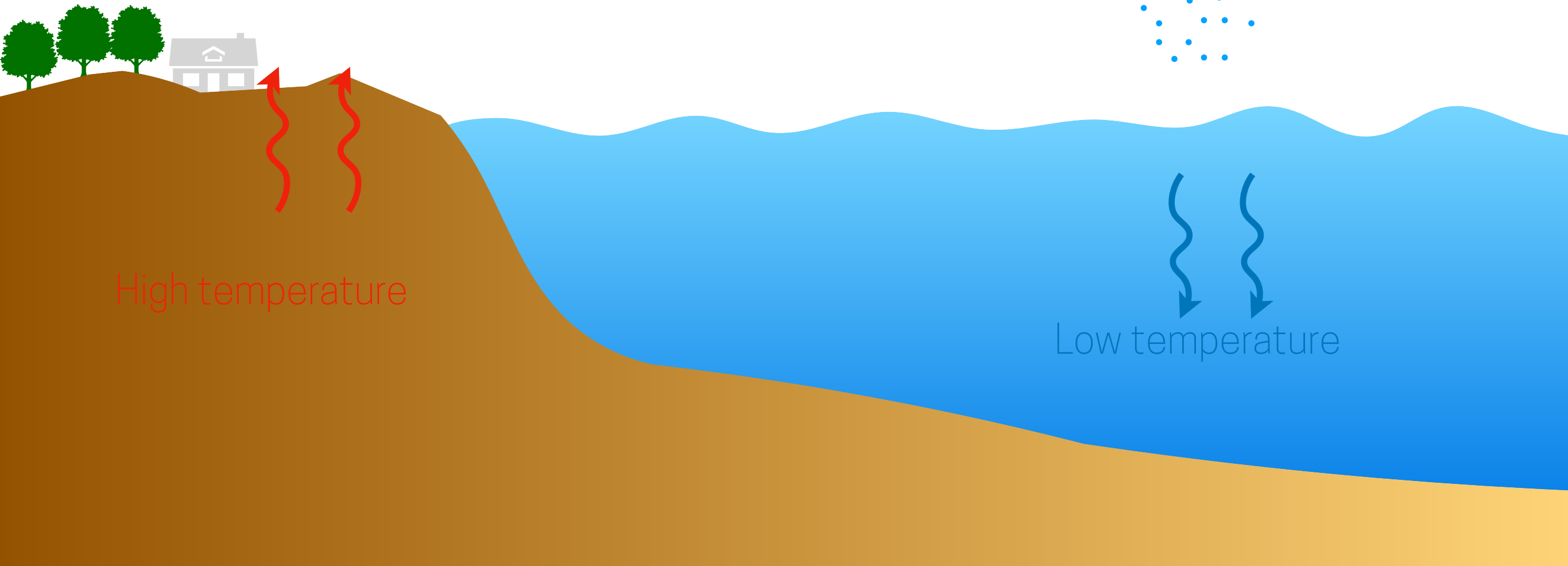
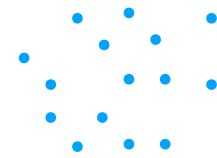
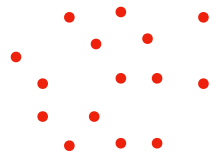
Wind flows



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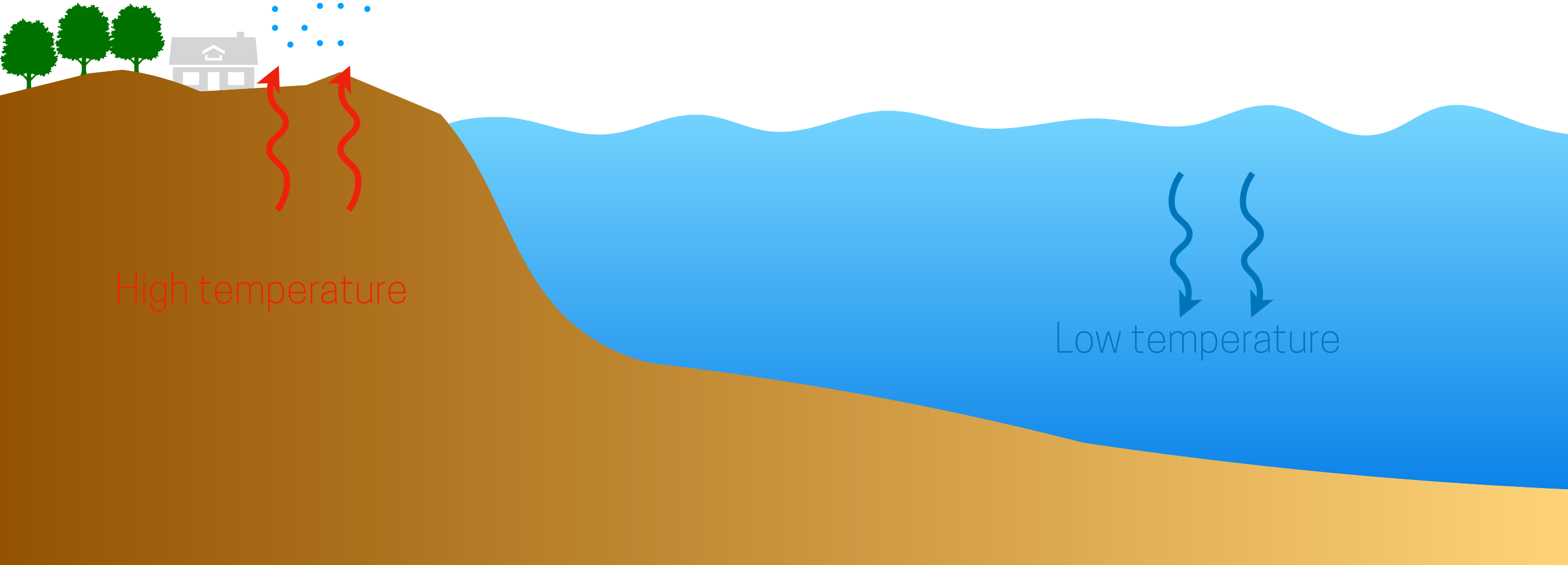
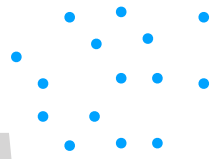
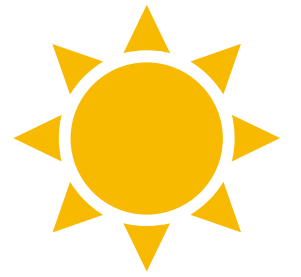
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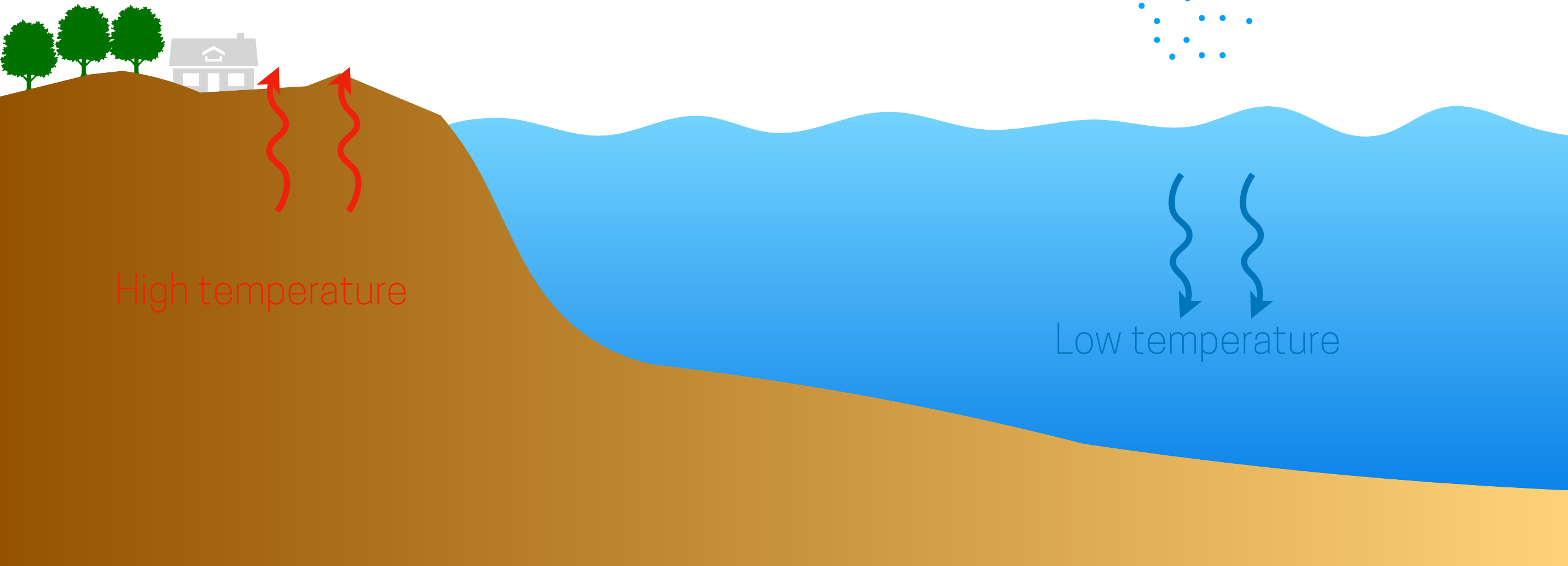
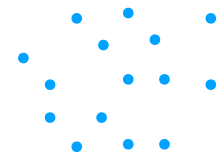
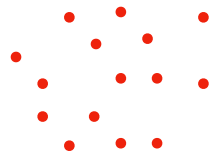
Wind flows



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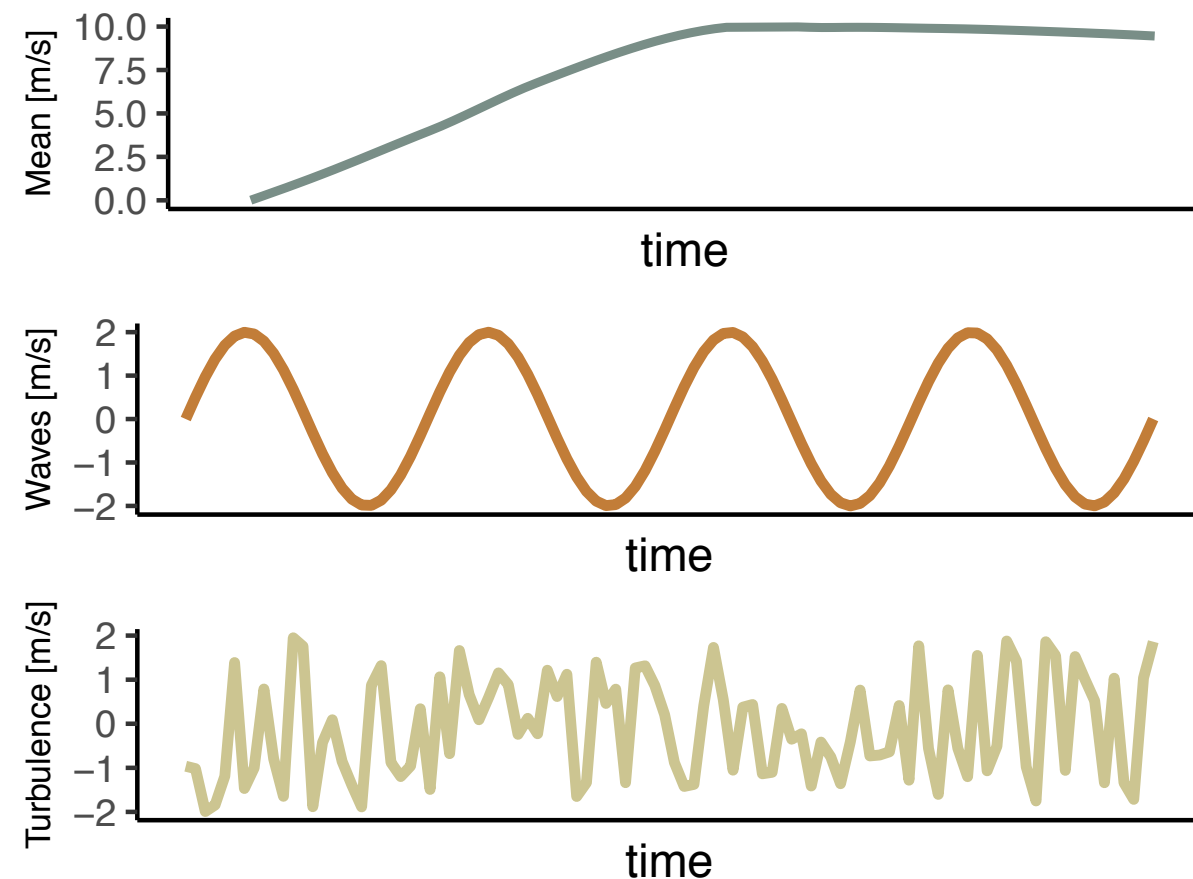
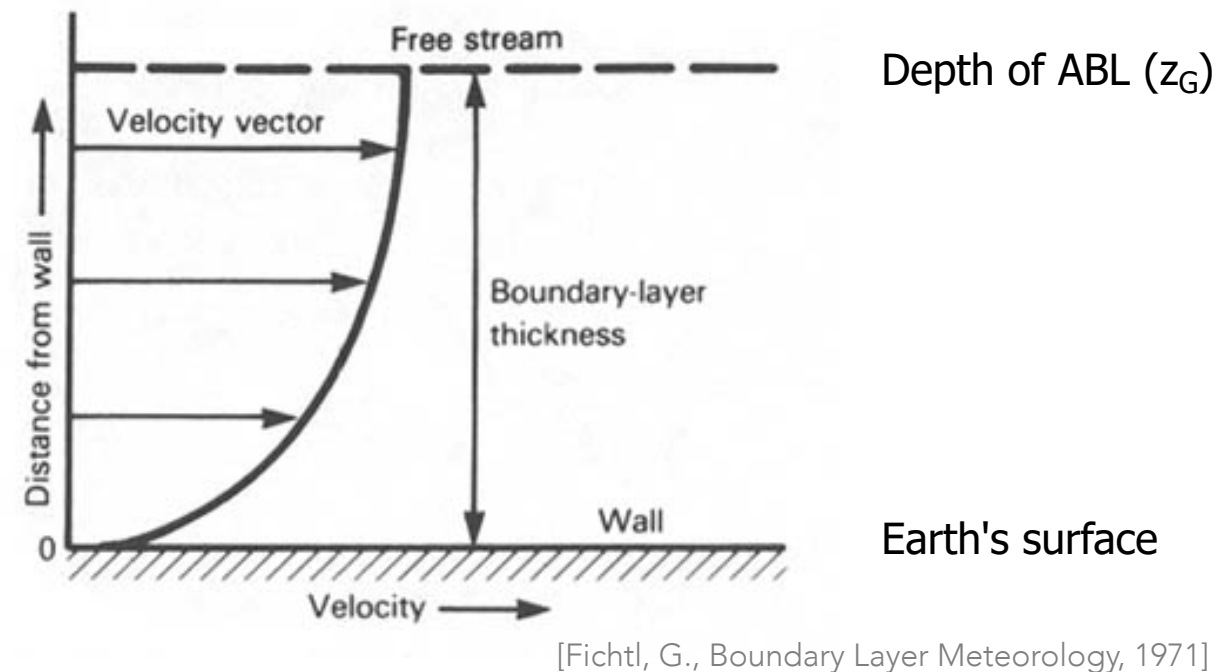


High temperature

Low temperature

Winds in the ABL: turbulence

- Mean wind:
 - Very important for horizontal transport (advection) of quantities (pollutants, heat, moisture, rain)
 - Friction decreases the wind at the surface, where is 0m/s to increase with height following a logarithmic profile
- Waves:
 - Occur mainly at night time
 - Little transport of quantities as pollutants, heat and moisture
 - Efficient transport of energy and momentum
- Turbulence:
 - Dominates vertical transport and mixing of quantities such as pollutants, heat, moisture



Winds in the ABL: turbulence

Turbulence: is one of the biggest unresolved problems in classical physics

- Chaotic system, highly sensitive to initial conditions
- Governing equations (Navier-Stokes) are known, but they do NOT have analytical solution in turbulent flows

Characteristics

- 3D
- Unsteady
- Increases mixing and transport
- Stochastic, random, not coherent structures
- Continuous spectrum from eddy-sizes

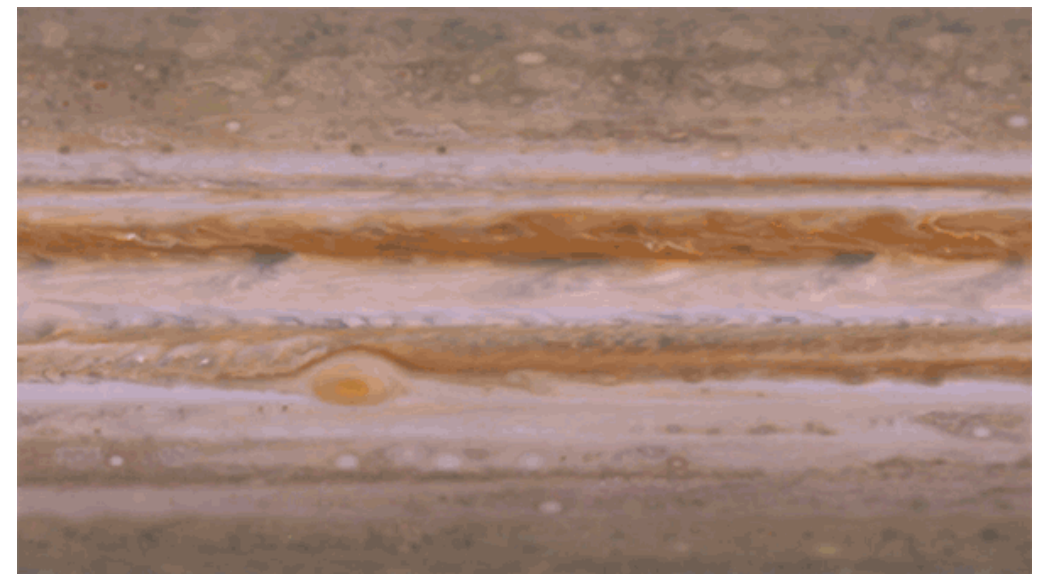
Turbulence tip vortex



Jets



Cloud bands on Jupiter



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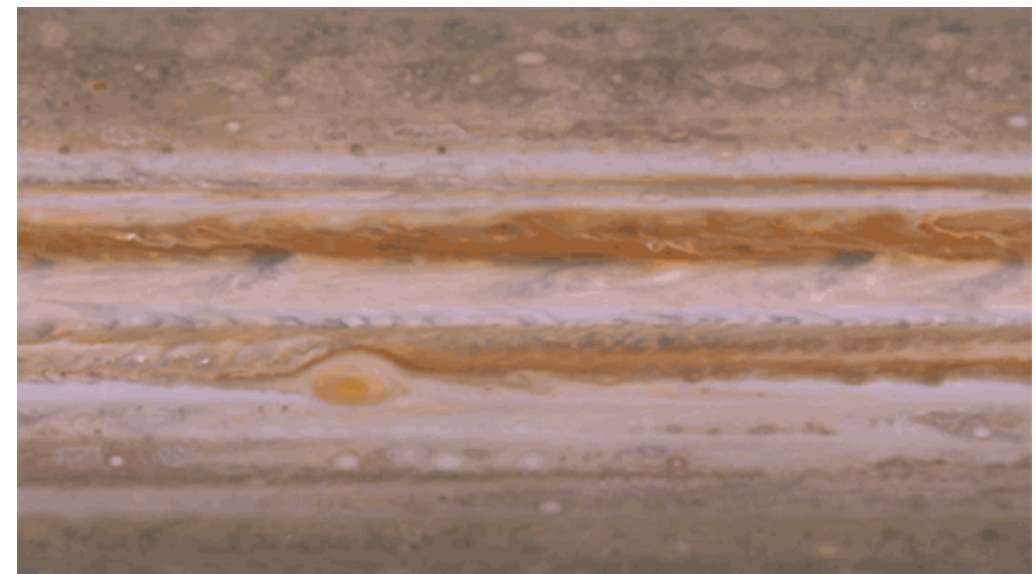
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Winds in the ABL: turbulence

- Reynolds number (1883):
 - Analysed experimentally in which circumstances the motion of water in parallel channels shall be direct or sinuous and the law of resistance in parallel channels

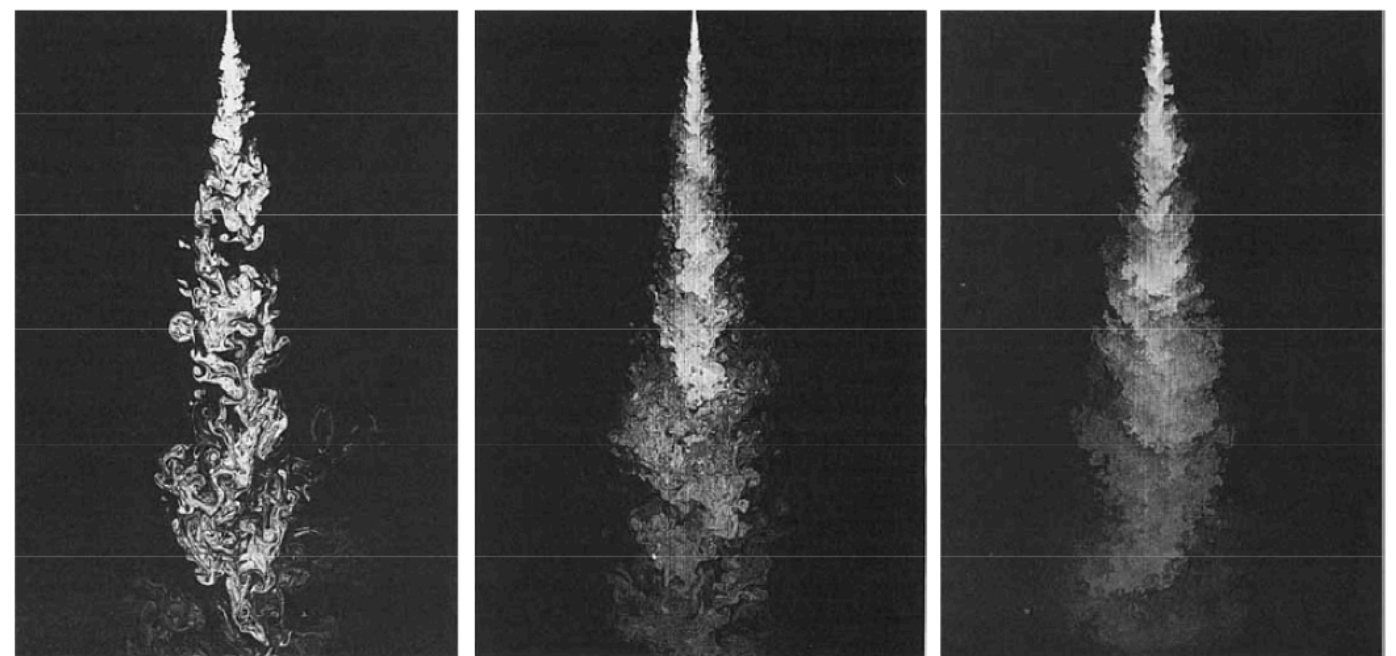
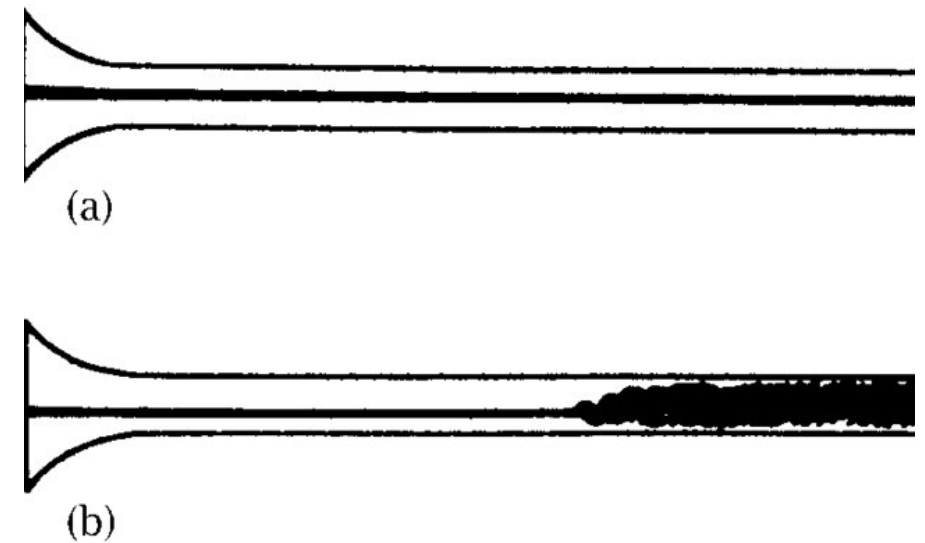
Diagram illustrating the components of the Reynolds number (Re):

Velocity, Length, Density, and Viscosity are factors influencing Re .

$$Re = \frac{\rho UL}{\mu} = \frac{UL}{\nu} = \frac{\text{inertial forces}}{\text{viscosity forces}}$$



chemistscorner.com



Re ~ 1500

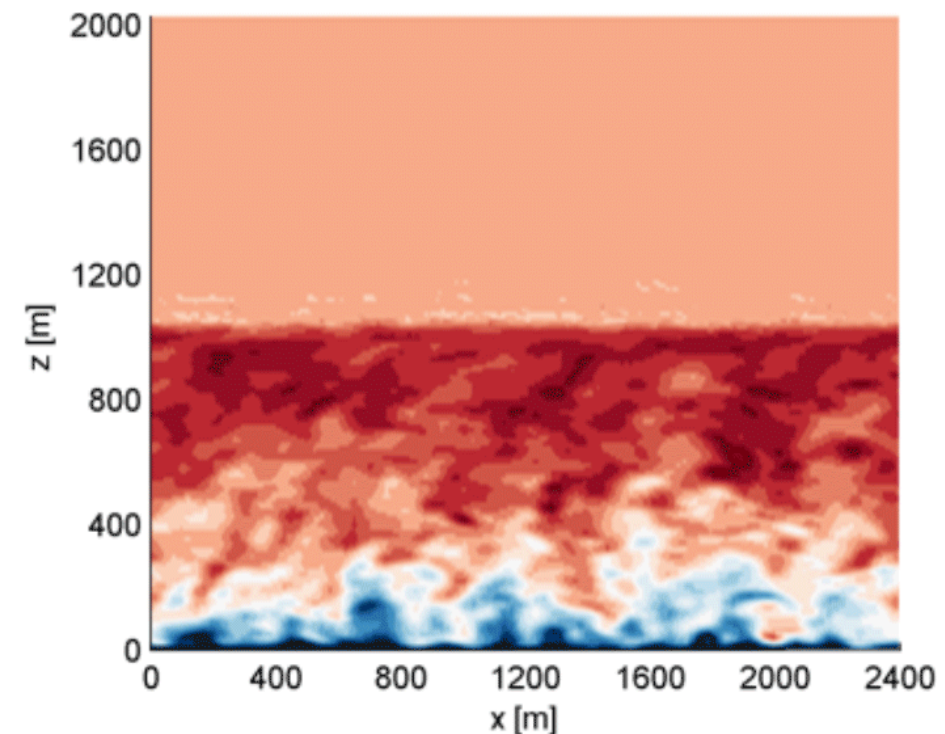
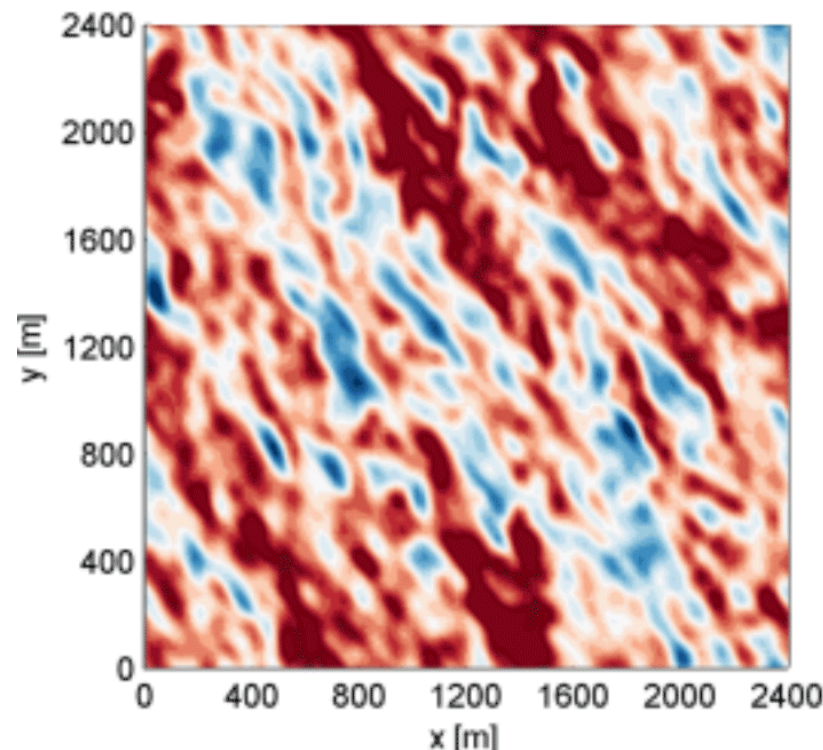
Re ~ 5000

Re ~ 20 000

Winds in the ABL: turbulence

- Why care about turbulence:

$Re \sim 10^6 - 10^8$ in the atmospheric boundary layer
—> ABL IS TURBULENT MOST TIMES!



- Why is there turbulence? —> Forcings

Ground heating and free atmosphere cooling, that create thermals

Buildings and terrain obstacles, create wind shear that become turbulent

What is an eddy?

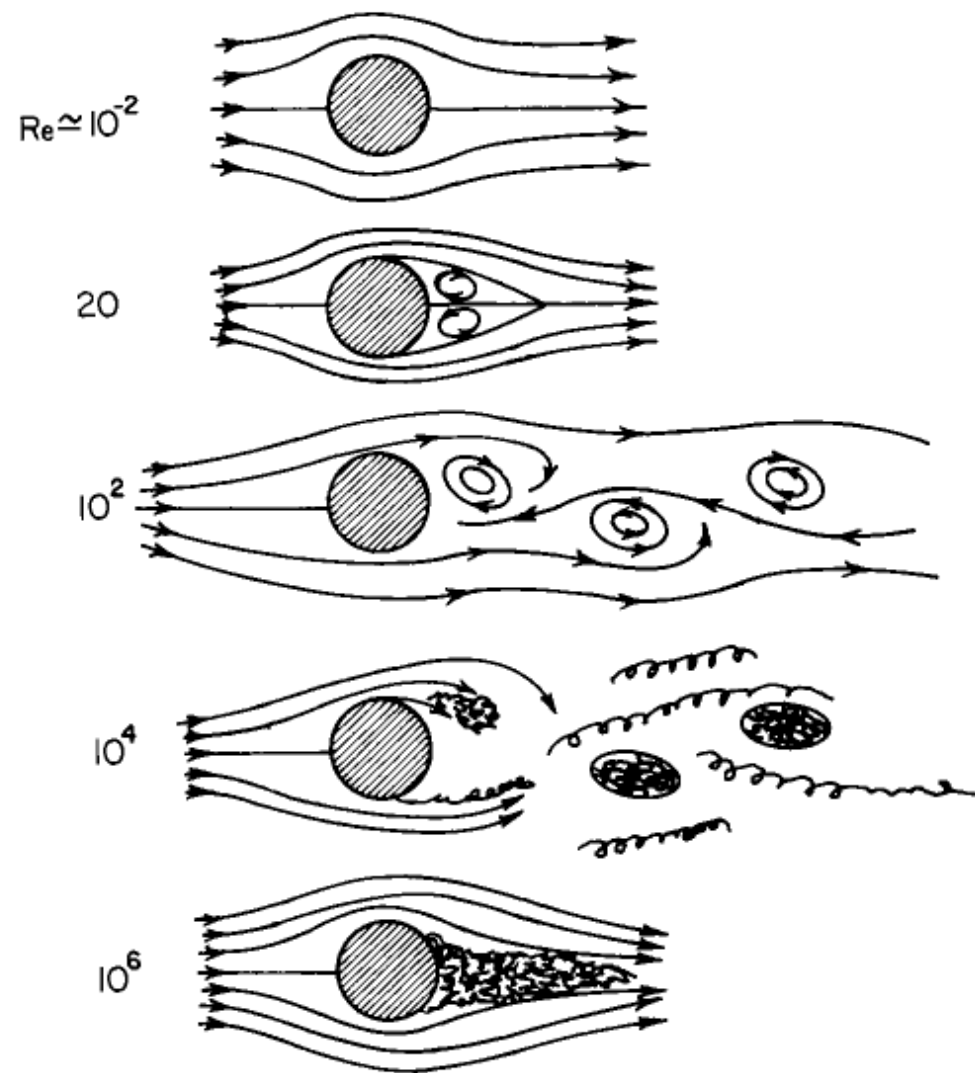
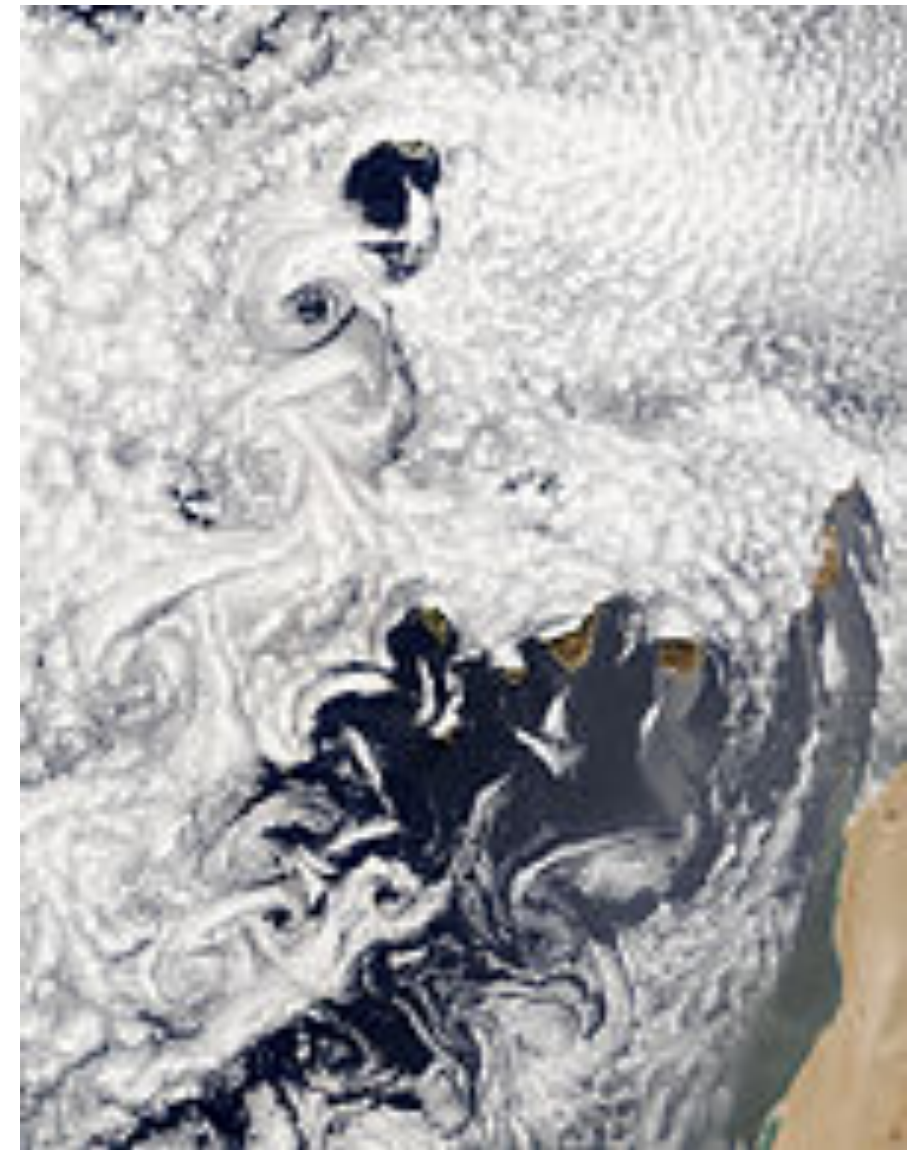


Figure 1.1 Schematic picture of a fluid around a cylinder at different Reynolds numbers.

<https://www.azimuthproject.org/azimuth/show/Blog+-+eddy+who%3F>



Downwind of obstacles, in this case, the [Madeira](#) and the [Canary Islands](#) off the west African coast, eddies create turbulent patterns called vortex streets.

wikipedia

Questions so far?

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Think, pair, share

Applications

Instructions: go to menti.com

Then reply to the question: can you name applications that could benefit from predictions of the ABL?

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Applications

- Air pollution



Air pollution could kill 6.6 million
people/year by 2050

J. Lelieveld et al., Nature 2015

Fast action to tackle air pollution
can't come soon enough

M. Neira, UN WHO 2016

Applications

- Wind loads and extreme winds



A changing climate leads to changes in the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events

Applications

- Fires



A changing climate leads to changes in the frequency, intensity, spatial extent, duration and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events

Applications

- Pedestrian wind comfort



Applications

- Pedestrian wind comfort



Applications

- Pedestrian wind comfort



Applications

- Wind energy



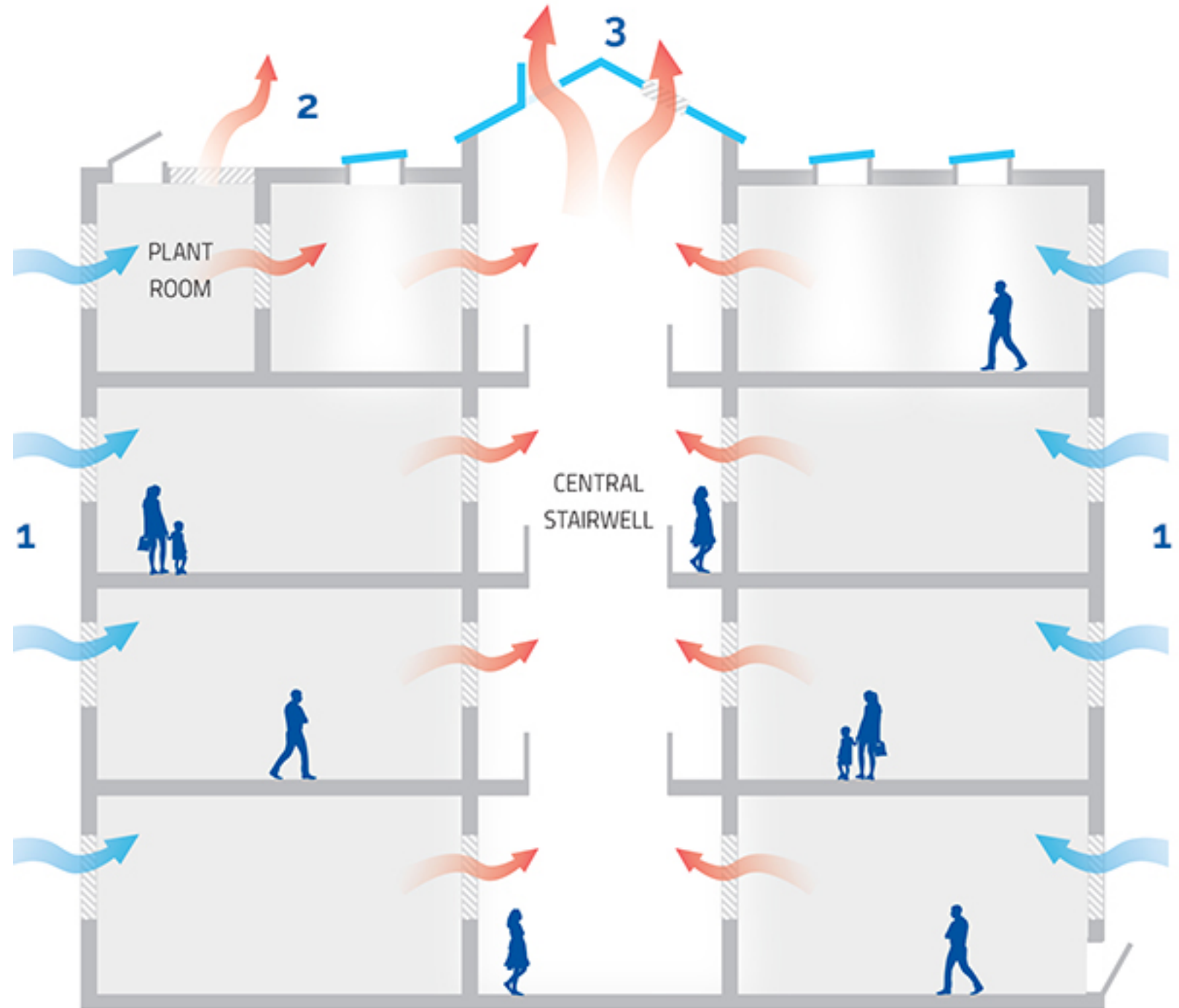
power-technology.com



www.enelgreenpower.com

Applications

- Natural ventilation and thermal comfort



lareineengineering.com

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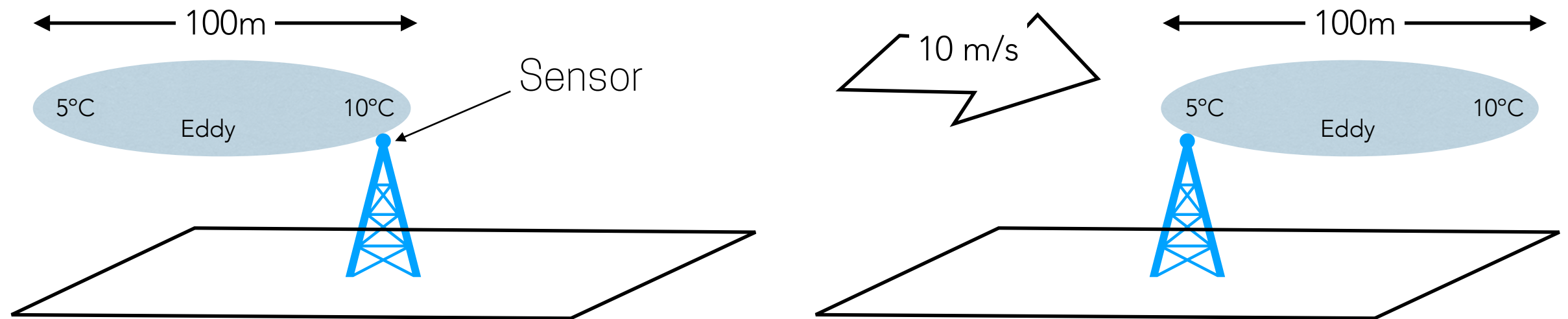
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9. One-minute notes (the muddiest point)

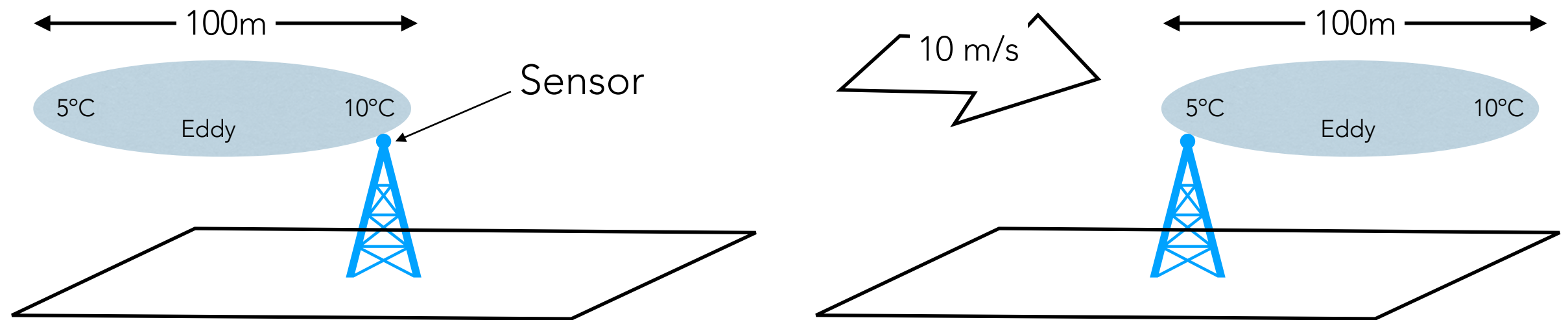
Taylor's frozen hypothesis (1983)

In meteorology, measurements in one point during long time is the most common approach. However, that doesn't allow us to see entire eddies.

Taylor suggested that for some special cases, turbulence might be frozen as it passes over a sensor:



Taylor's frozen hypothesis (1983)



Then the mean wind speed can be used to translate measurements in time, to measurements in space:

$$t = \frac{D}{U} = \frac{100m}{10m/s} = 10s$$

$$\frac{\partial T}{\partial t} = -U \frac{\partial T}{\partial x} \longrightarrow \frac{\partial T}{\partial t} = -U \frac{\partial T}{\partial x} = -10 \cdot \frac{5}{100} = -0.5K/s$$

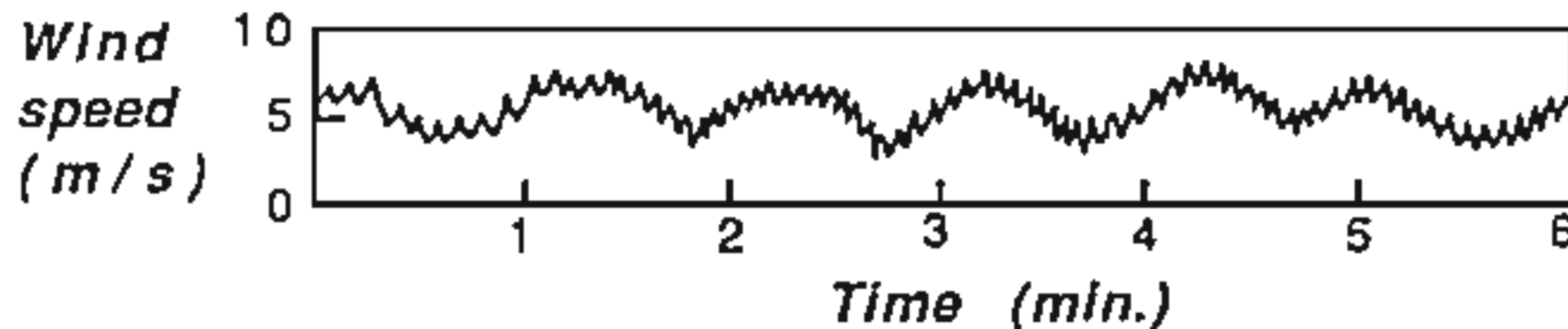
Can we apply this theory always?

NO, only for eddies that evolve at a timescale longer than the time it takes the eddy to be advected pass a sensor

$$\frac{\sigma_U}{\overline{U}} < 0.5$$

Taylor's frozen hypothesis exercise

5) If you observed the following measurement of wind speed on a strip chart, then what diameter (in meters) are the major eddies? (Hint: First find the typical time duration of an eddy, and then employ Taylor's Hypothesis.)



Can we apply this theory?

Diameter of the major eddy?

$$t = \frac{D}{U} = \frac{100m}{10m/s} = 10s$$

Questions so far?

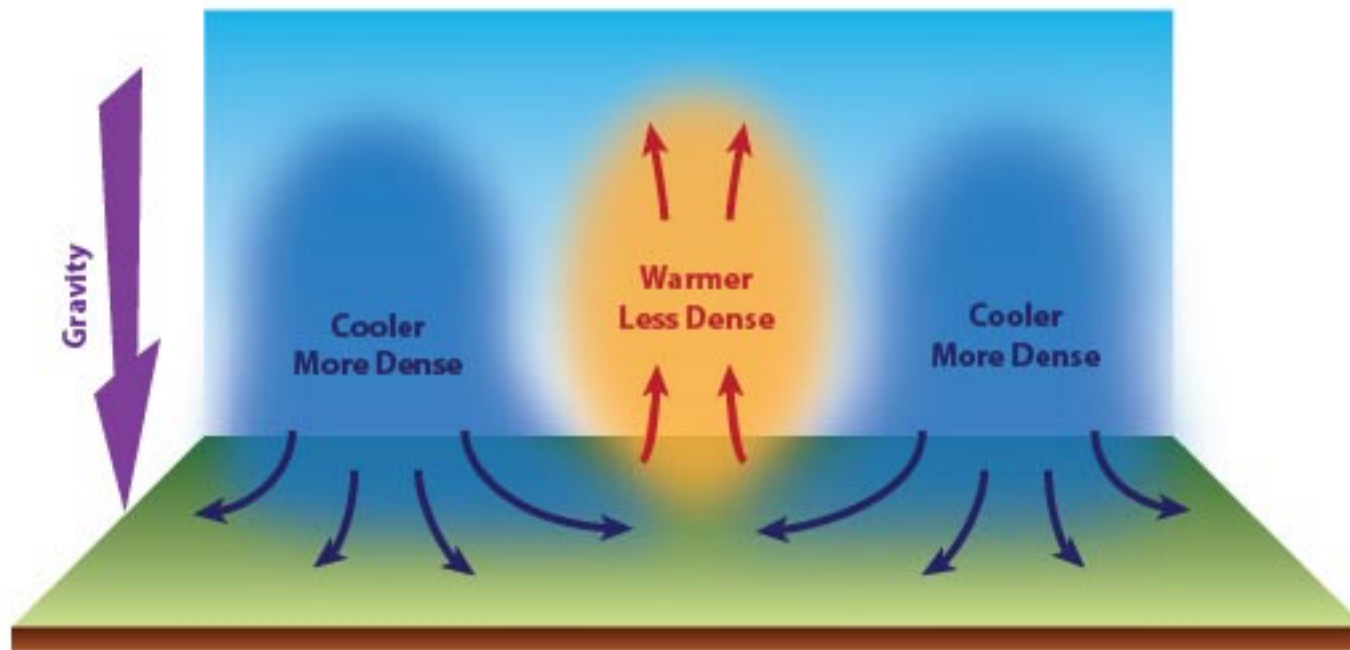
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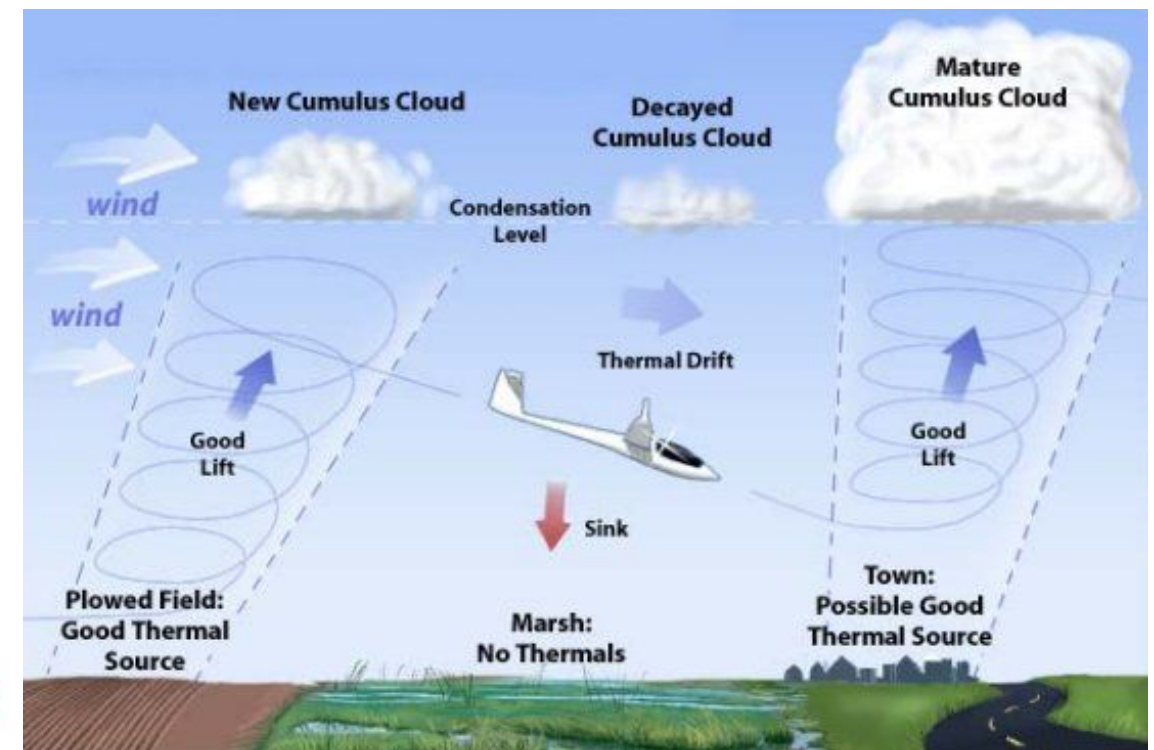
Buoyancy & virtual potential temperature concepts

- Buoyancy

Warm air is less dense and rises, while cool air is more dense and moves downwards



<https://www.boydcorp.com/>



[<http://www.cugc.org.uk>]

Buoyancy & virtual potential temperature concepts

Warm air density < Cool air density

Moist air density < Dry air density

- Virtual Temperature

It is the temperature to which we need to heat dry air to equal the density of moist air at the same pressure.

Variations of virtual temperature can be studied in place of variations in density

$$T_v = T (1 + 0.61r)$$

$$r = \text{mixing ratio} \frac{\text{kg water vapor}}{\text{kg dry air}}$$

Liquid water density > Dry air density

————→ Cloudy air density > Cloud-free air density

Buoyancy & virtual potential temperature concepts

Removes the temperature variation caused by changes in pressure altitude of the air parcel

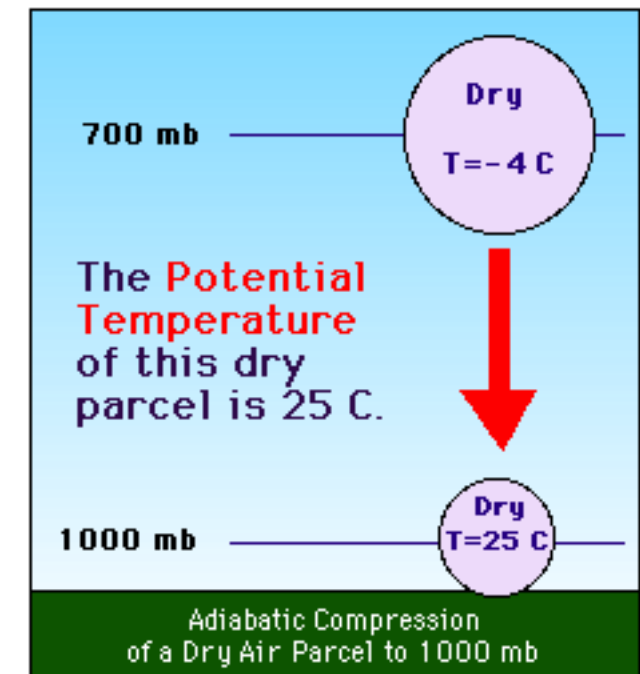
■ Potential Temperature

It is the temperature an air parcel would have if it were expanded or compressed adiabatically (no heat exchange) to a pressure of 100kPa (1000mb).

$$\theta = T \left(\frac{P_0}{P} \right)^{0.286}$$

P: pressure

P₀: reference pressure (100kPa)



$$\theta \equiv T + \left(\frac{g}{C_p} \right) z$$

g: gravity, 9.8 m/s²

C_p: specific heat at constant pressure for air 1000 J/kgK

z: height above 100kPa (surface)

g/C_p: 0.0098K/m is the negative of the dry adiabatic lapse rate

Buoyancy & virtual potential temperature concepts

Removes the virtual temperature variation caused by changes in pressure altitude of the air parcel

- Virtual Potential Temperature

For unsaturated air: $\theta_v = \theta (1 + 0.61r)$

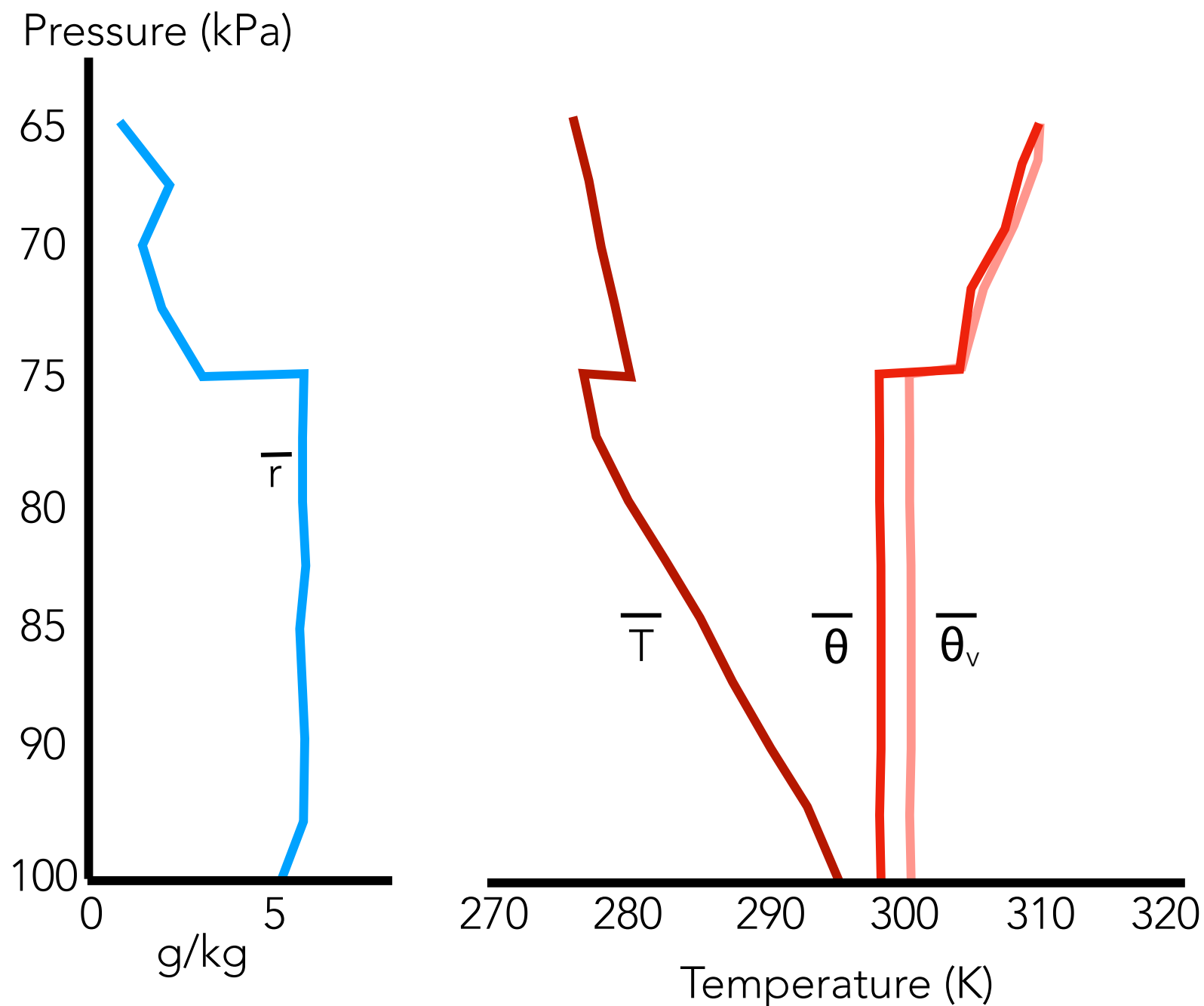
For saturated (cloudy) air: $\theta_v = \theta (1 + 0.61r_{sat} - r_L)$

Since turbulence implies vertical motion of the air, have the virtual potential temperature is very useful

Why did meteorologist define virtual temperature?

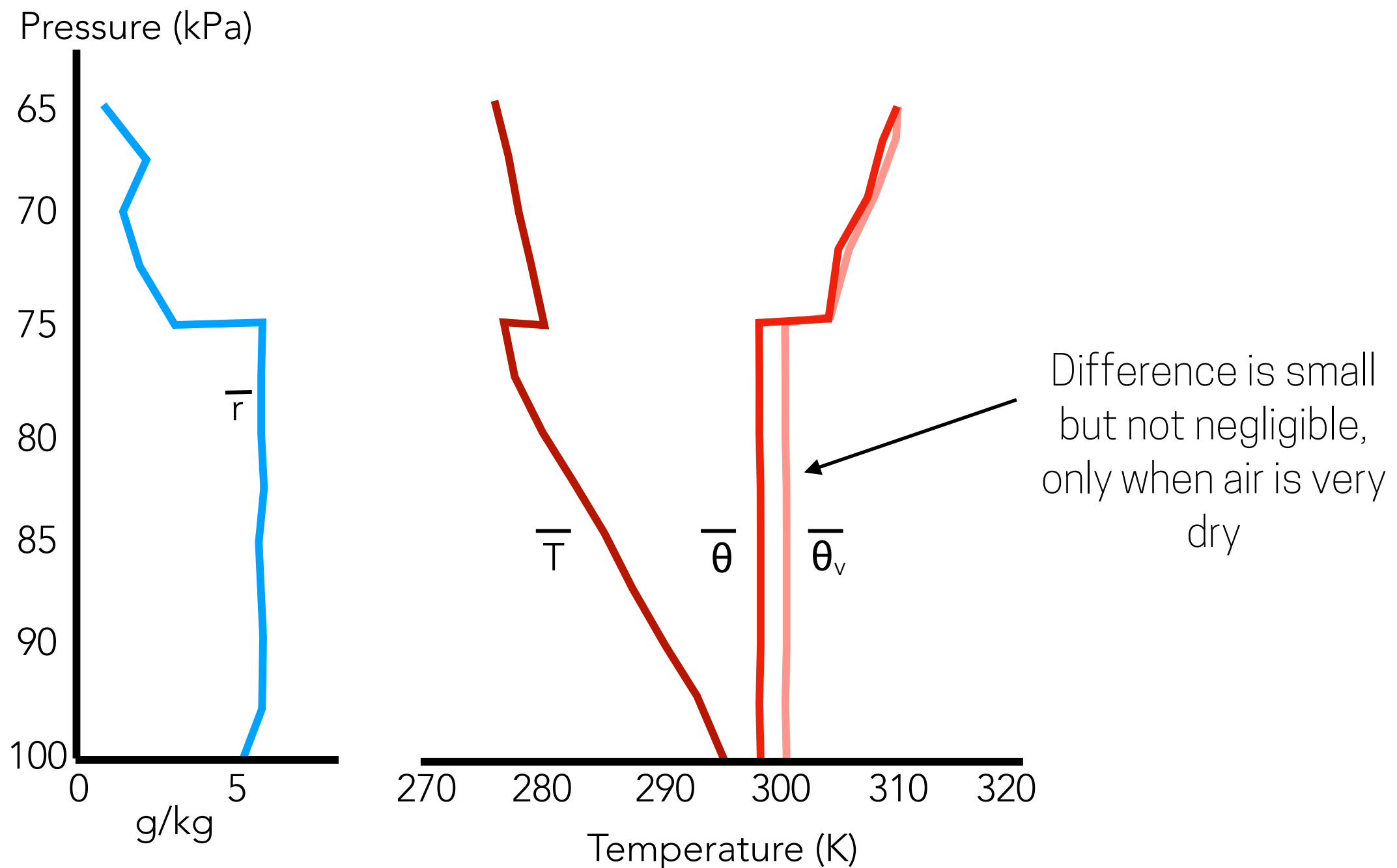
Why did meteorologist define potential temperature?

Buoyancy & virtual potential temperature concepts



Example of the difference between mean potential temperature and mean virtual potential temperature given observations of mixing ratio and absolute temperature

Buoyancy & virtual potential temperature concepts



Example of the difference between mean potential temperature and mean virtual potential temperature given observations of mixing ratio and absolute temperature

Questions so far?

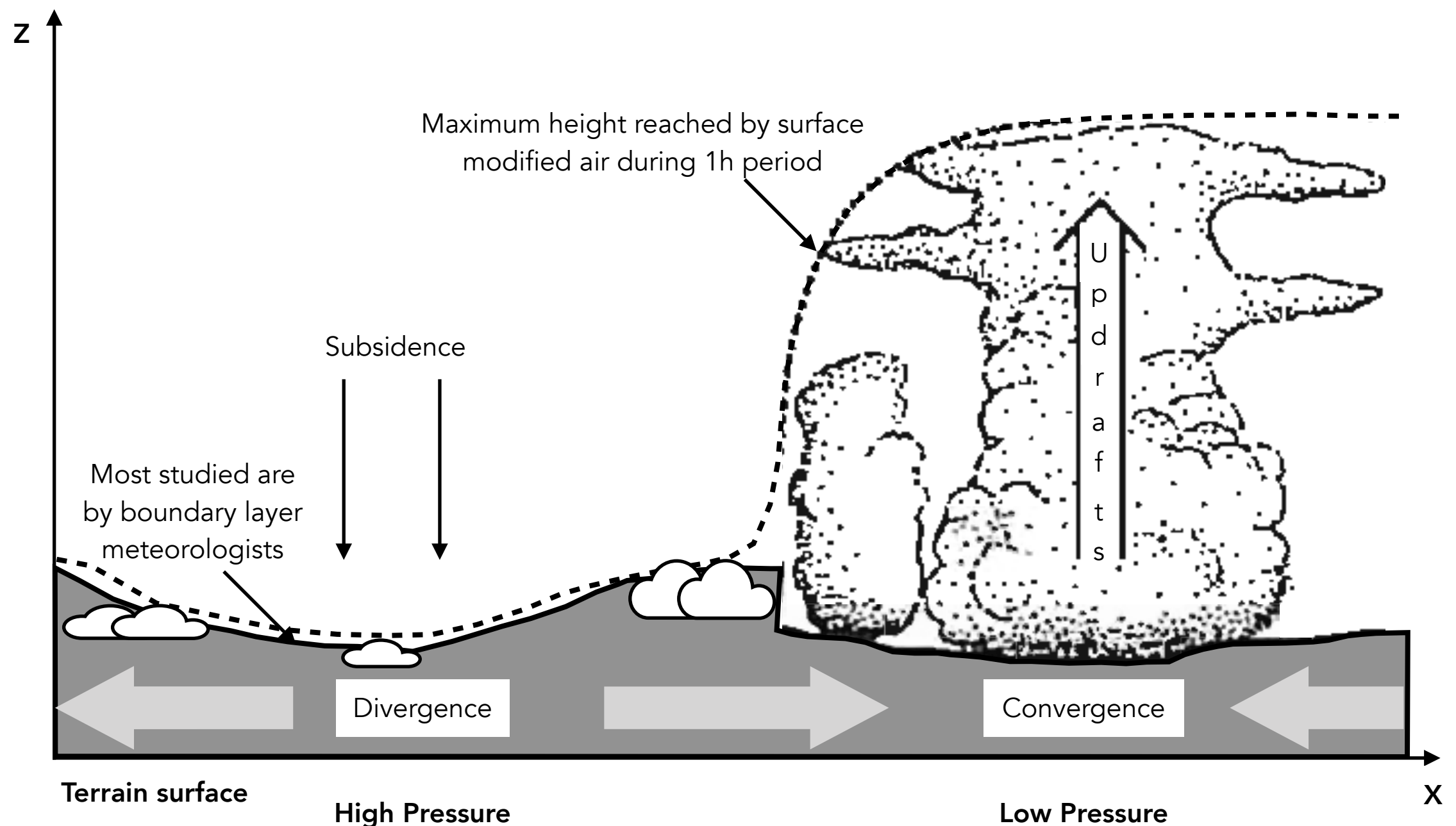
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ABL structure

- Characteristics of the ABL:

Thinner in high pressure zones, and deeper in low pressure zones due to air motion



ABL structure

- Acronyms:

BL: Boundary Layer

CL: Cloud Layer

FA: Free Atmosphere

IBL: Internal Boundary Layer

ML: Mixed Layer (CBL)

RL: Residual Layer

SBL: Stable Boundary Layer (NBL)

SCL: Sub Cloud Layer

SL: Surface Layer

ABL structure

- Characteristics of the ABL:

Over sea

varies much slower in space and time (variations ~10% over 1000km horizontal)

limited sea surface temperature changes due to mixing of the ocean

water large heat capacity (can absorb large amounts of heat with relatively small temperature change)

Most changes in BL over oceans are caused by synoptic or mesoscale processes of vertical motion and advection of air masses

Over land

In high pressure regions the BL has a well defined structure with 2 components: mixed layer, residual layer and stable BL

Surface layer is the region at the bottom of the BL where turbulence fluxes and stress vary <10% their magnitude

Microlayer lowest few cm where molecular transport dominates over turbulent transport

ABL structure

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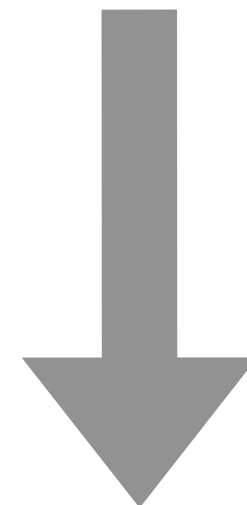
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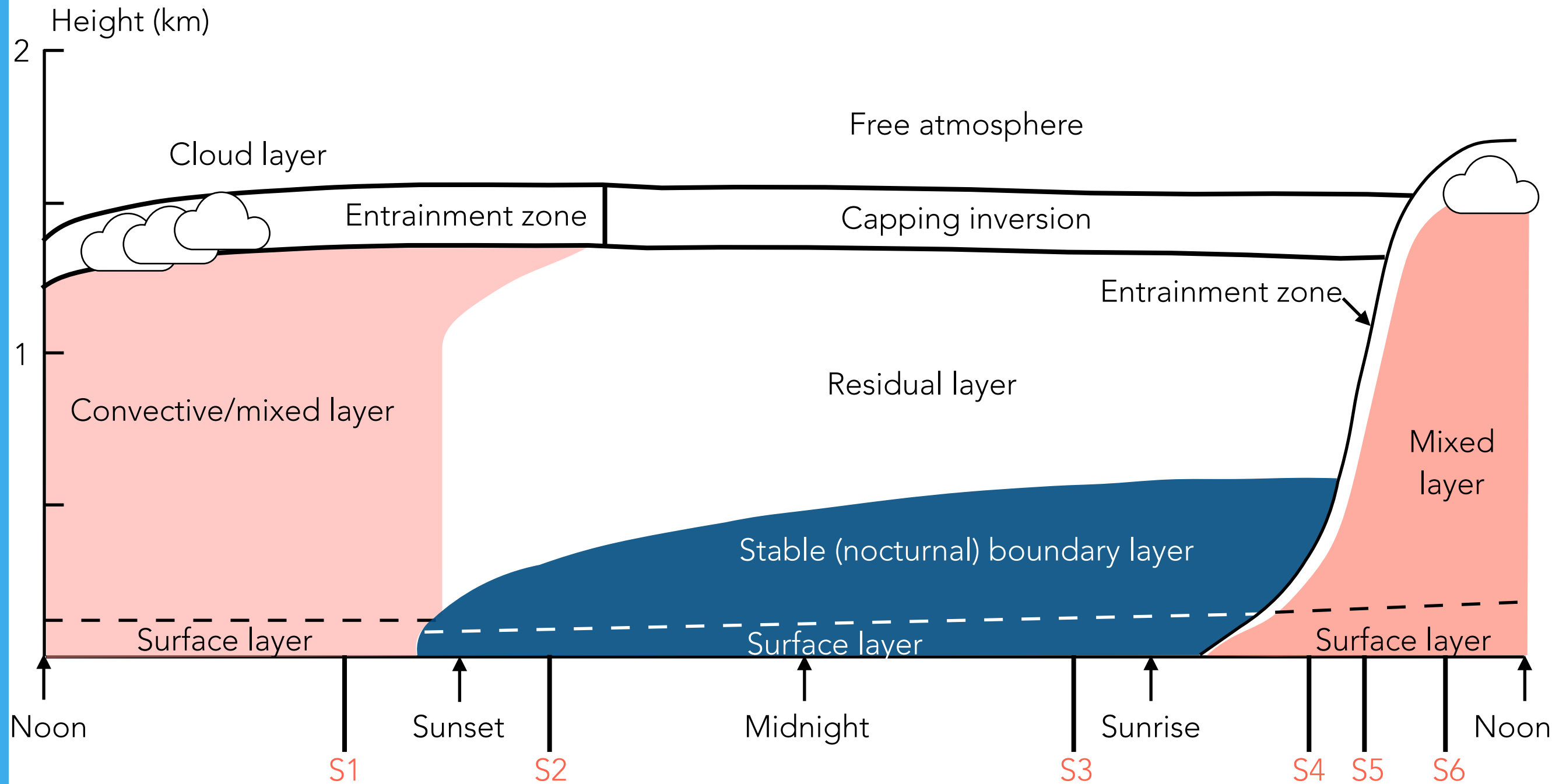
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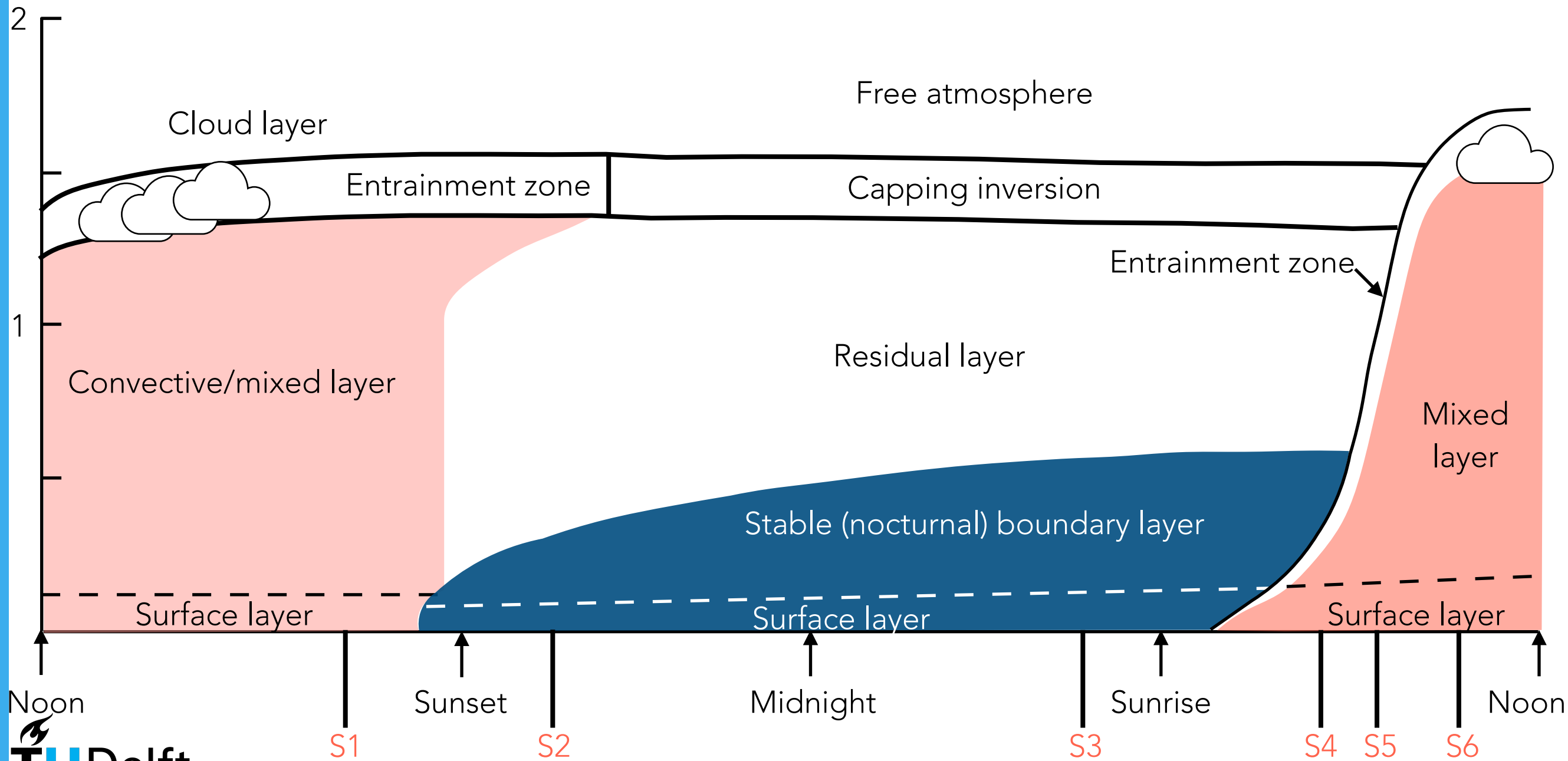
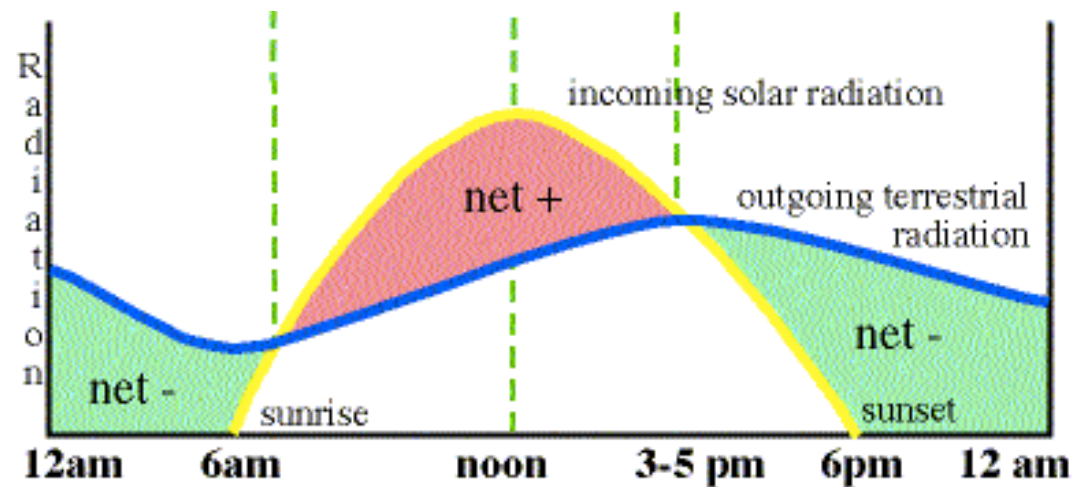
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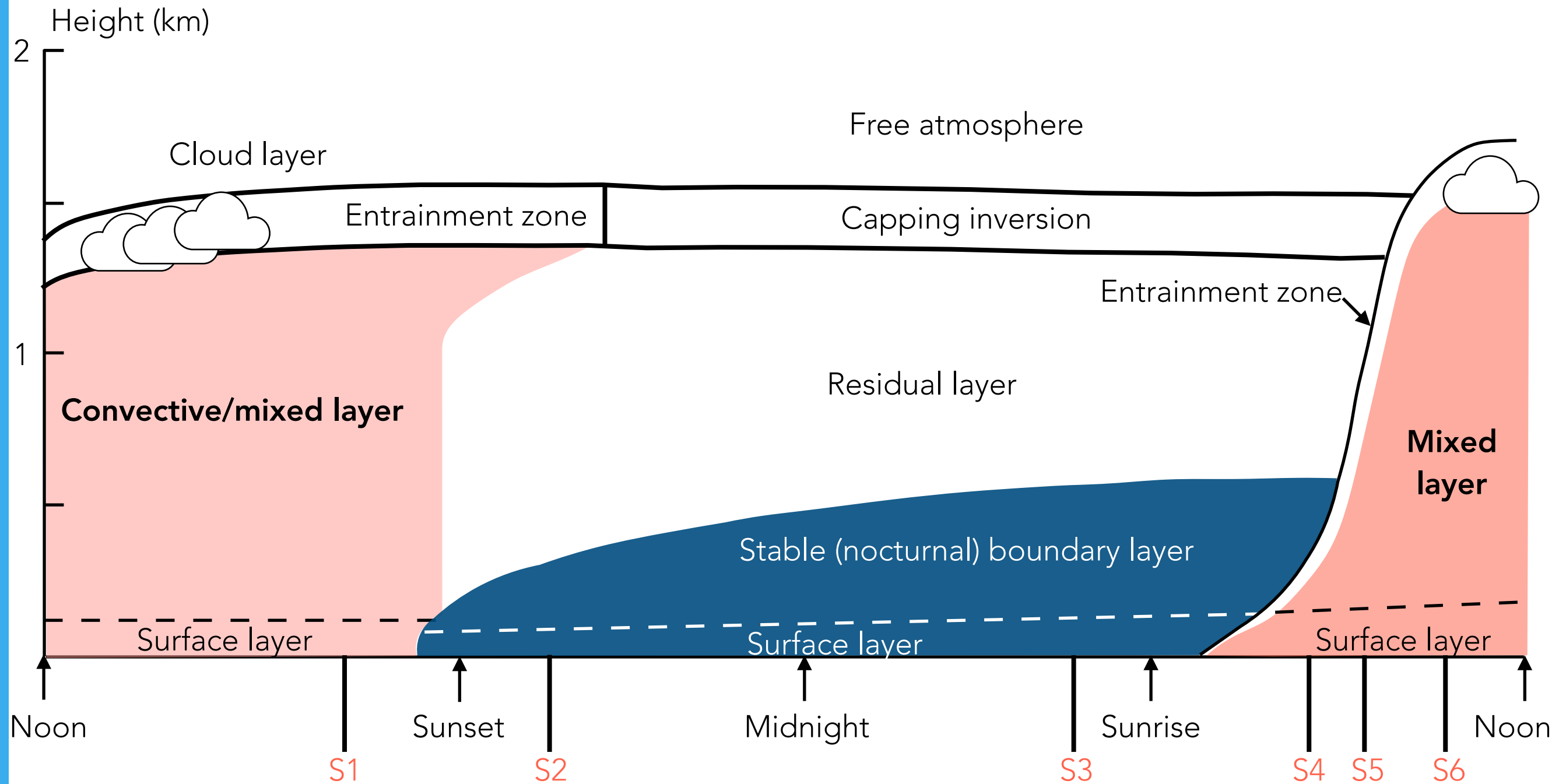
ABL structure



ABL structure



ABL structure



ABL structure

Convective, mixed Layer or unstable boundary layer



Occurs +/-30min after sunrise, a turbulent ML starts growing in depth, characterised by intense mixing, with thermals of warm air rising. Grows by entraining or mixing down from the less turbulent air above. The maximum depth occurs in the afternoon.

ABL structure

Convective, mixed Layer or unstable boundary layer



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Turbulence is convectively driven!!

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Radiative cooling from the top of the cloud layer creates thermal of cool air sinking from the cloud top

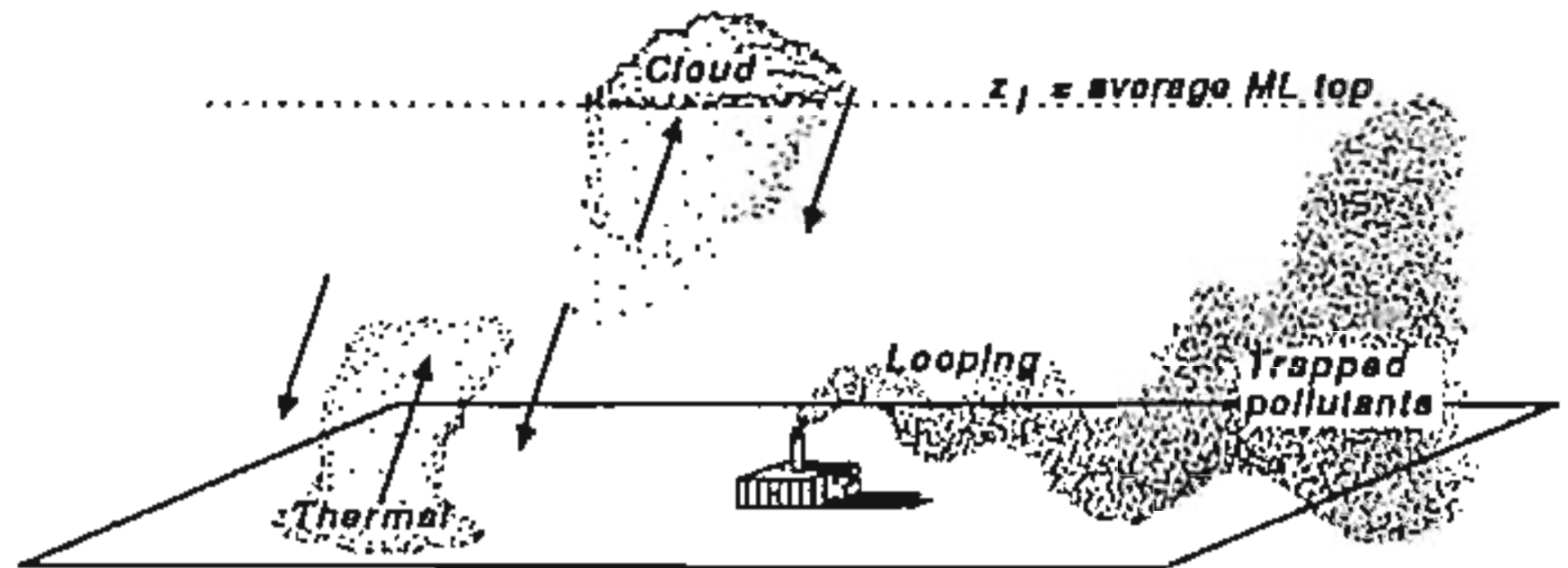
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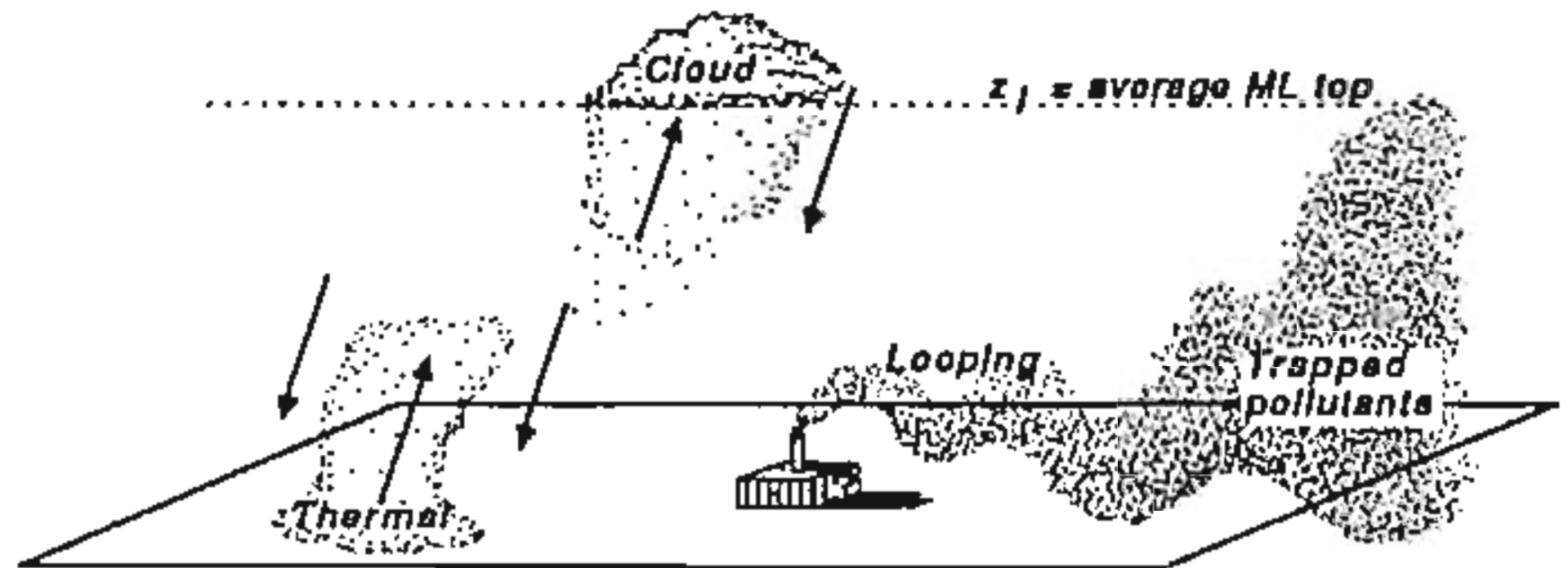
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Wind shear across the top contributes to turbulence generation —> free shear situation (CAT)

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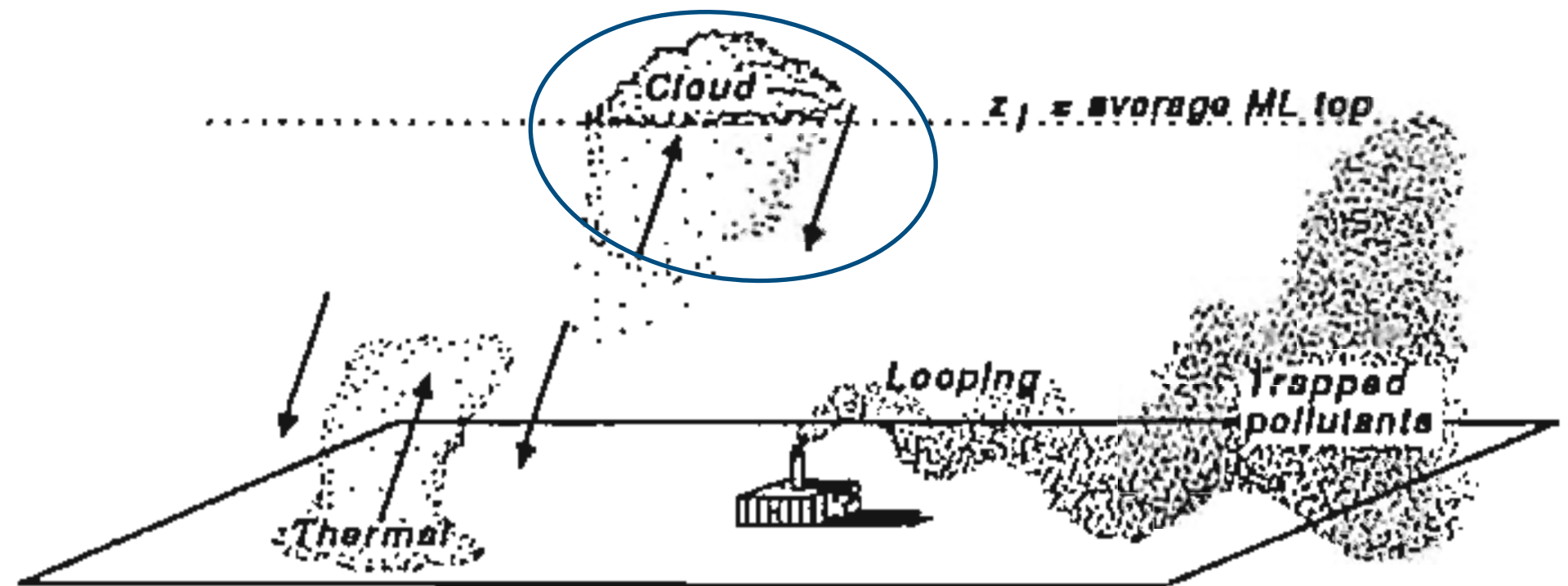
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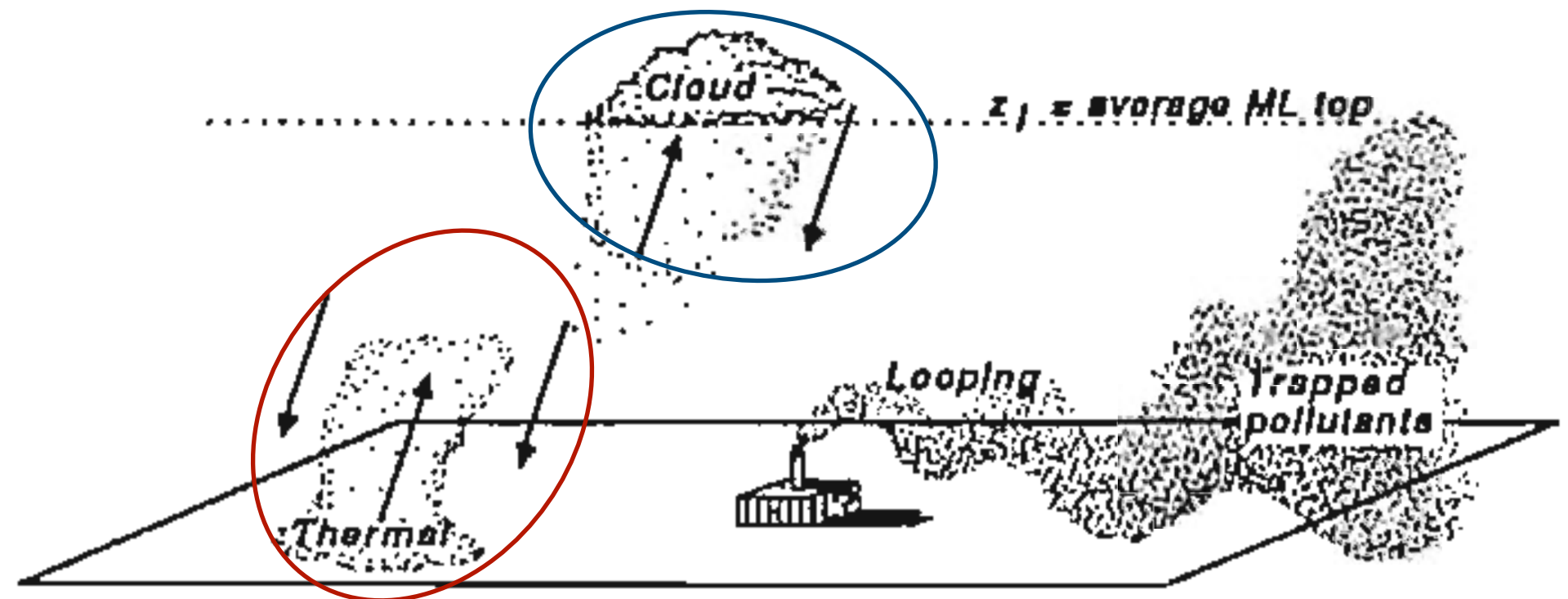
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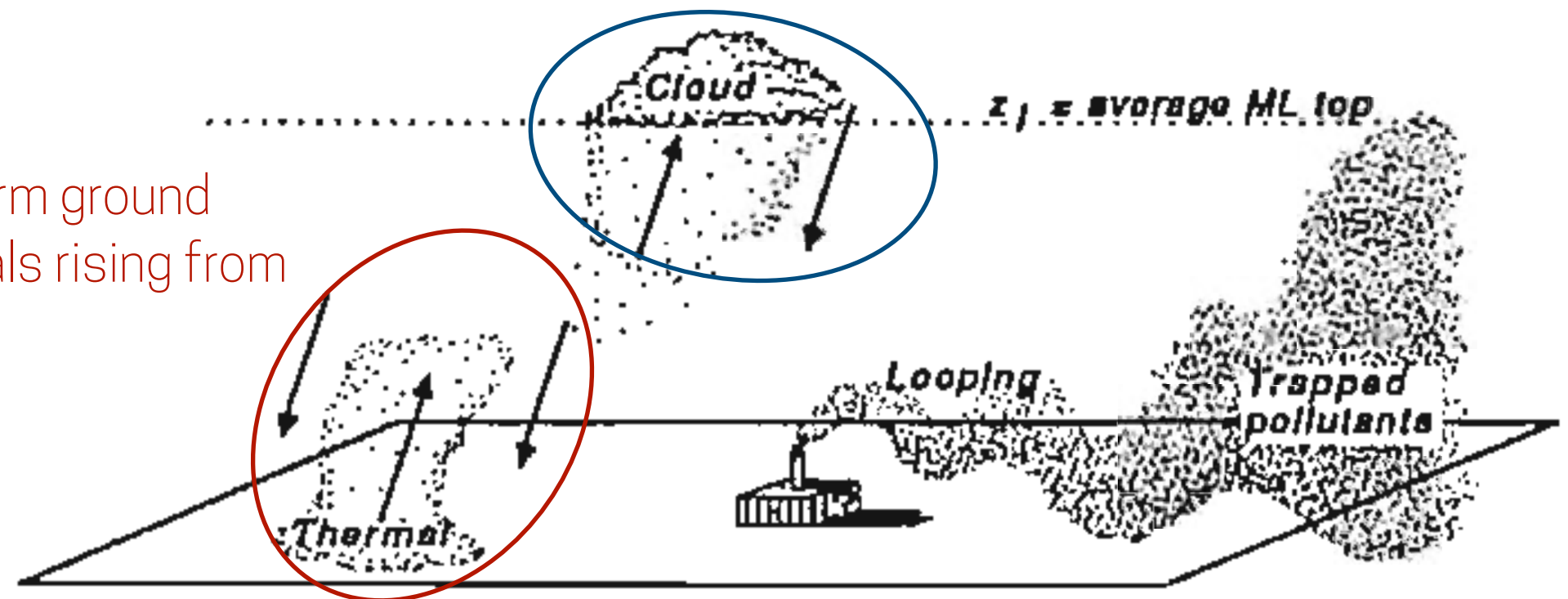
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Heat transfer from a warm ground surface, creates thermals rising from the ground



ABL structure

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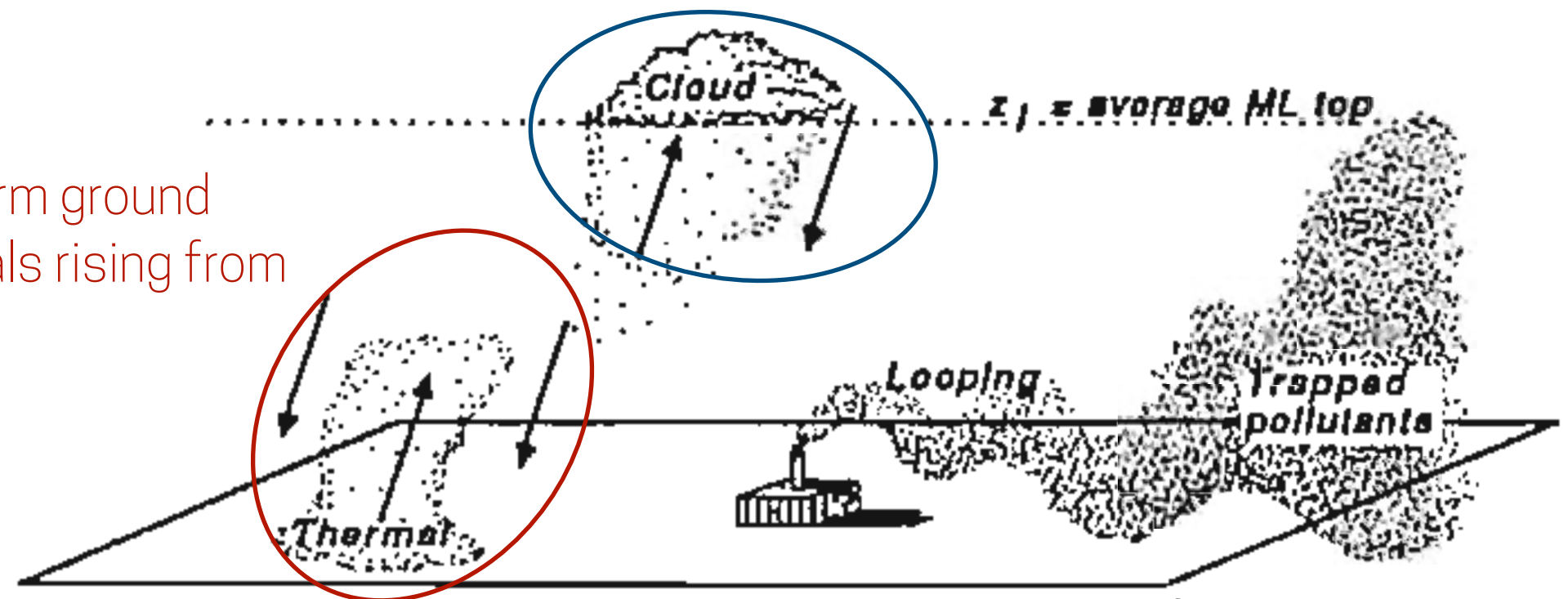
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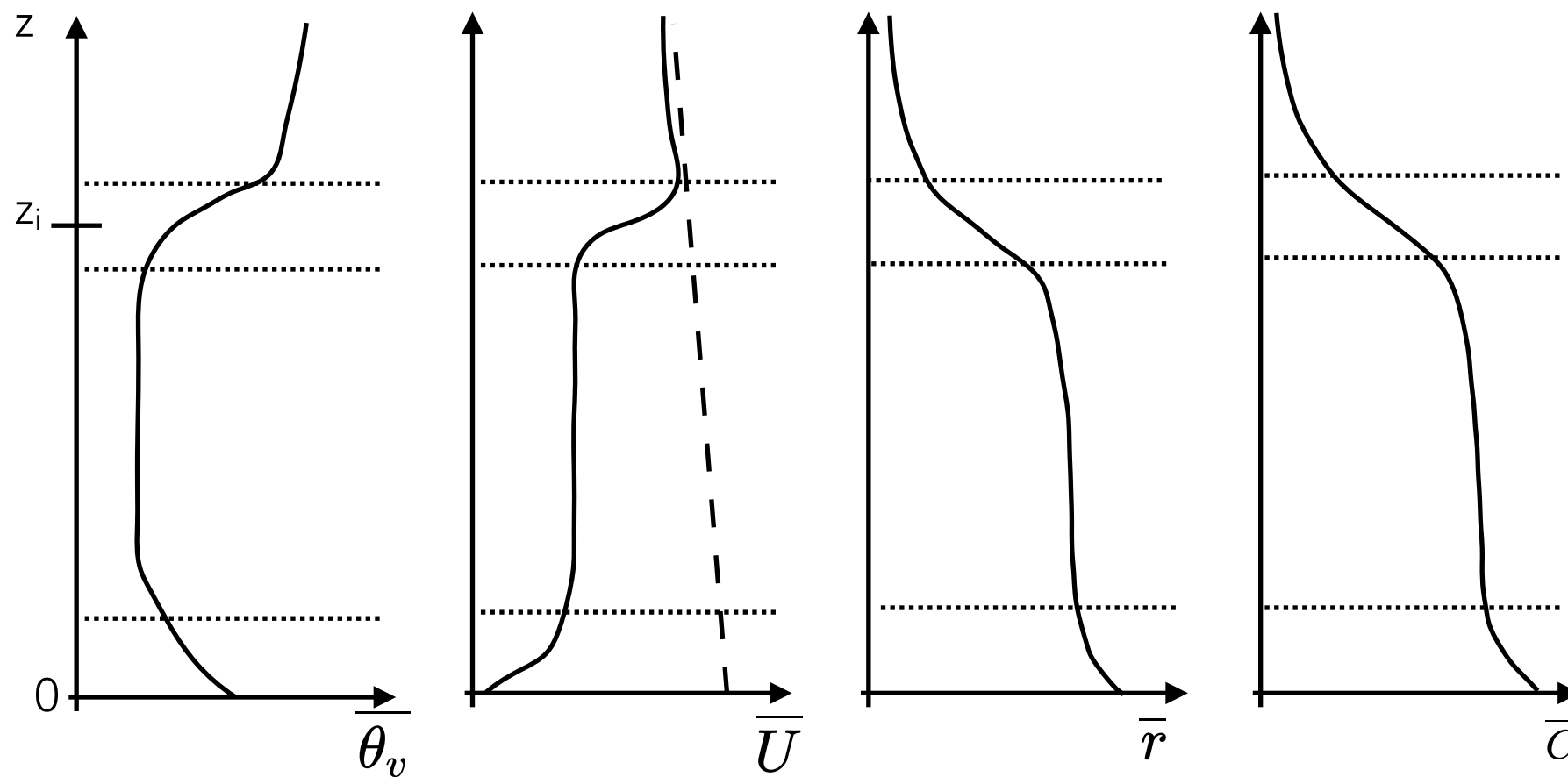
Heat transfer from a warm ground surface, creates thermals rising from the ground



Turbulence mixes heat, moisture and momentum uniformly in the vertical. Pollutants experience **looping** due to the thermals

ABL structure

Convective, mixed Layer or unstable boundary layer

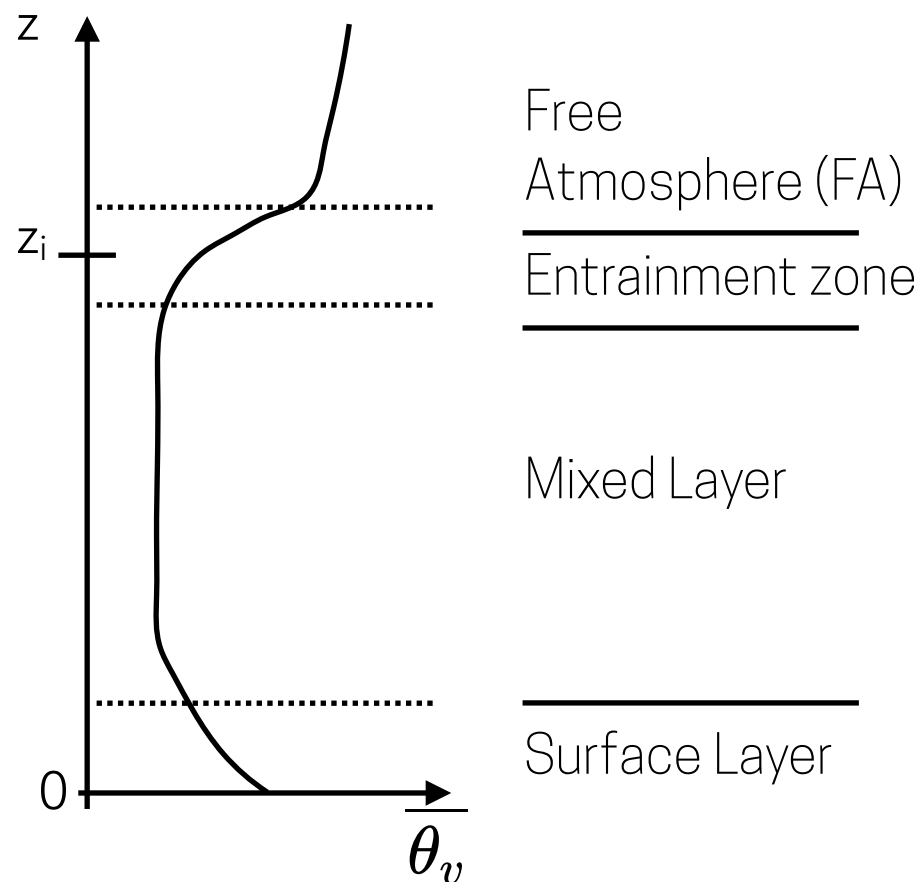


Free
Atmosphere
Entrainment zone
Mixed Layer
Surface Layer

Mean profiles for: virtual potential temperature, wind speed, water vapour mixing, pollutant concentration

ABL structure

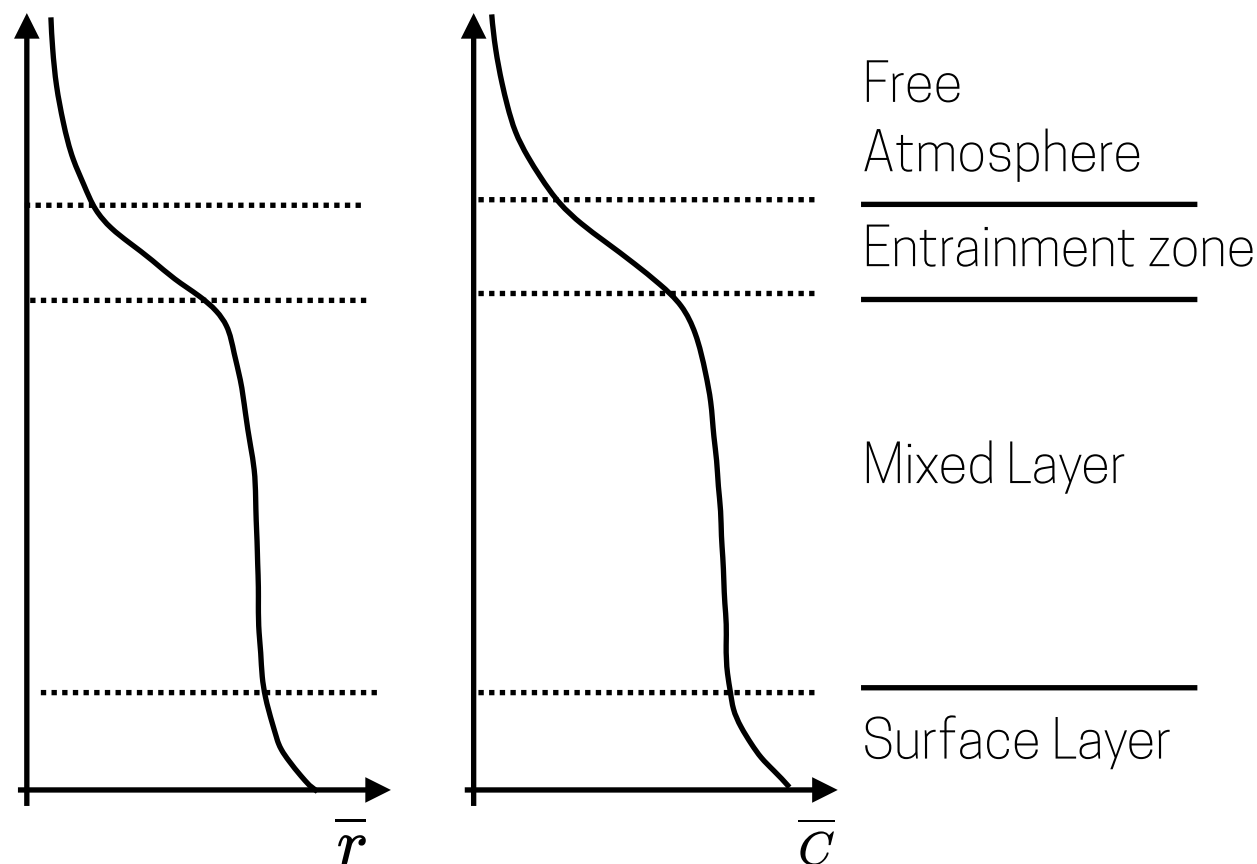
Convective, mixed Layer or unstable boundary layer



- From the profile, we can see that a stable layer acts like a lid to the rising thermals
- Entrain air into the ML
- When this stable layer is strong enough it can be classified as an inversion layer
- ML: nearly adiabatic (no temperature variation)
- SL: often superadiabatic

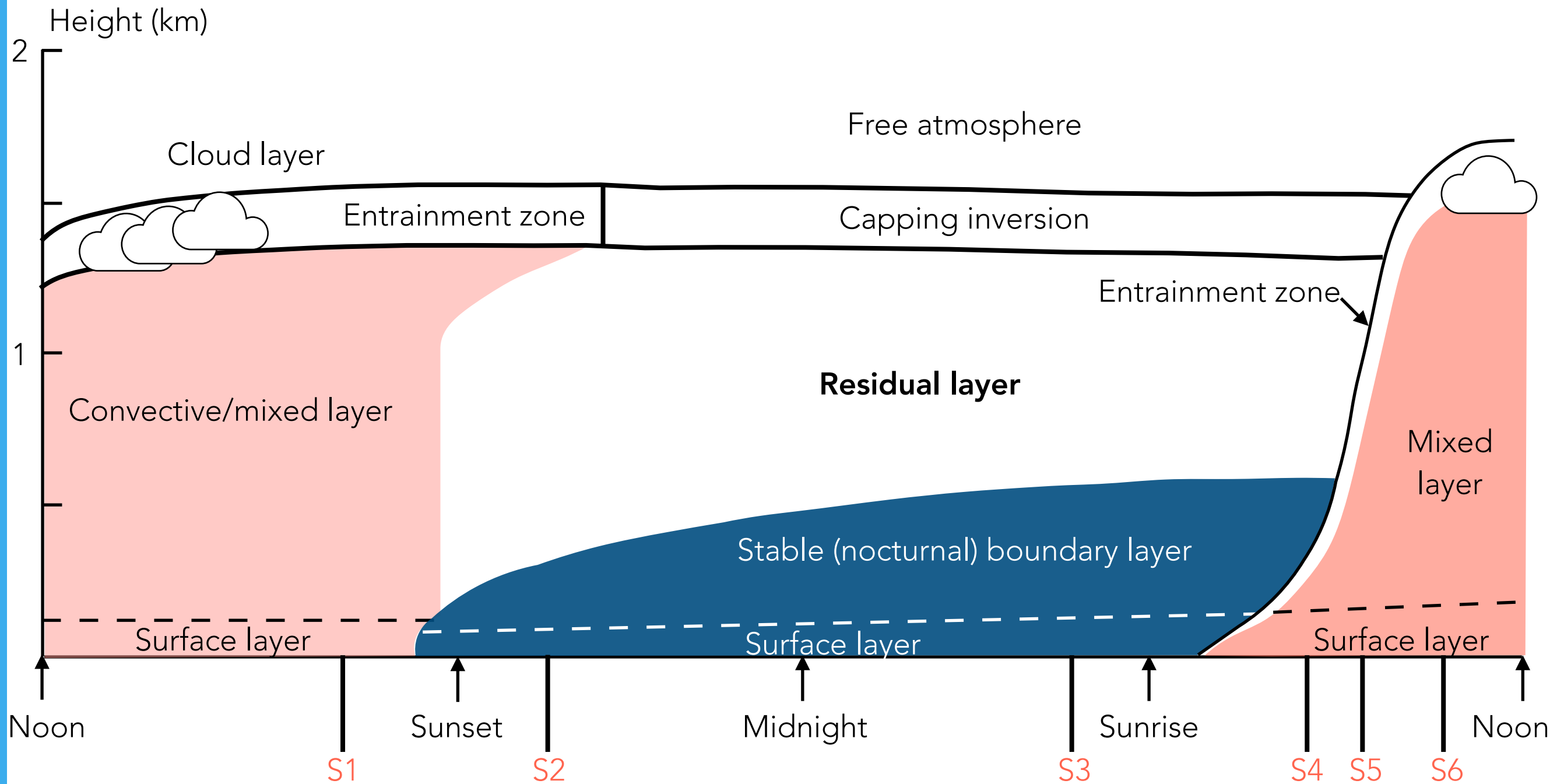
ABL structure

Convective, mixed Layer or unstable boundary layer



- Both decrease with height, even at the centre portion of the MK
- Entrainment zone very pronounced decrease, which can be used to identify the ML end. Acts as a lid for pollutants, since thermals cannot cross far into.
- r is related to the evaporation of soil and plant moisture from below and the entrainment of drier air from above
- C can build up in the ML and remain low in the FA. Transported by eddies, such as thermals. Trapping pollutants below the inversion layer is common in high pressure regions

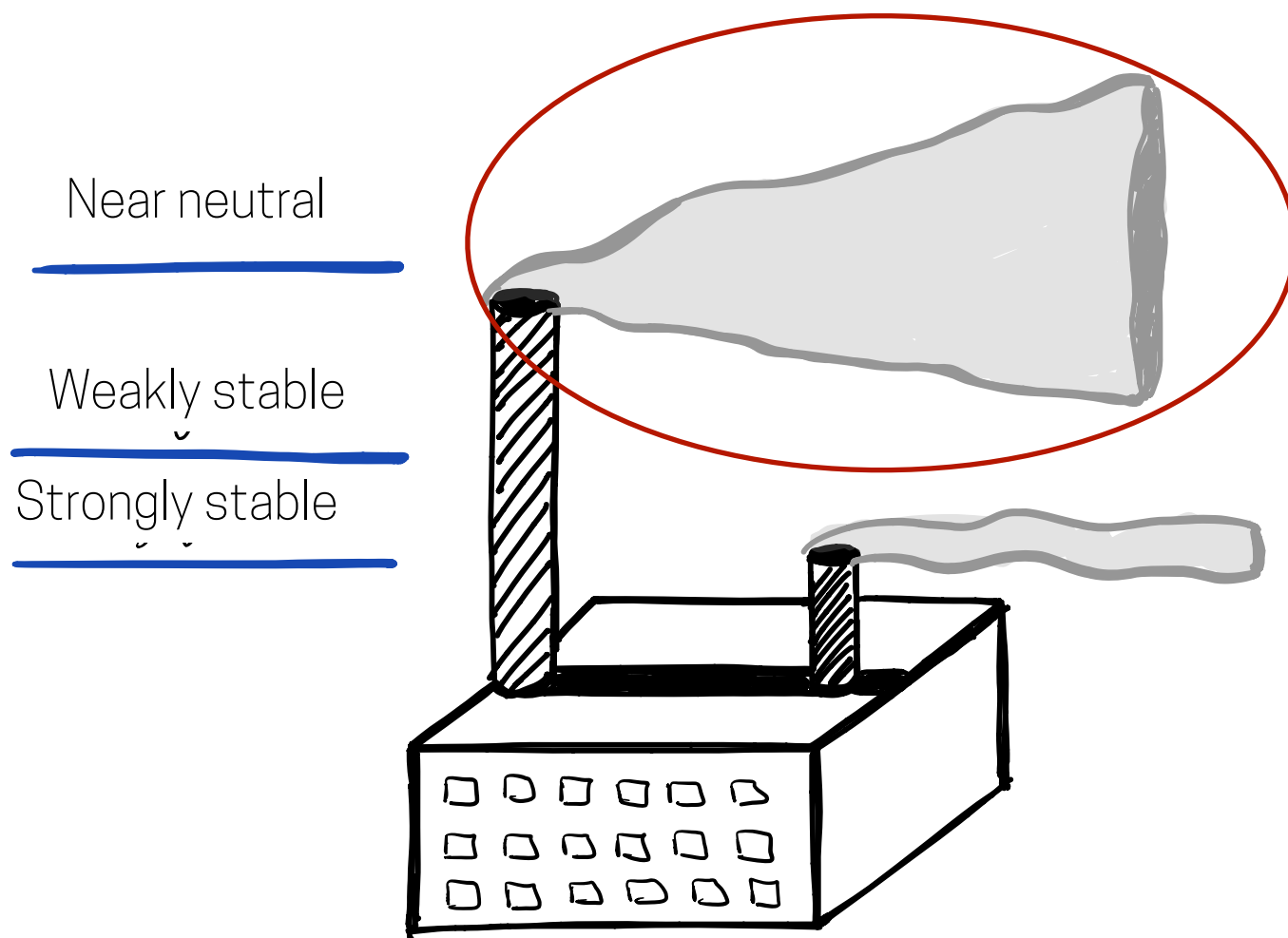
ABL structure



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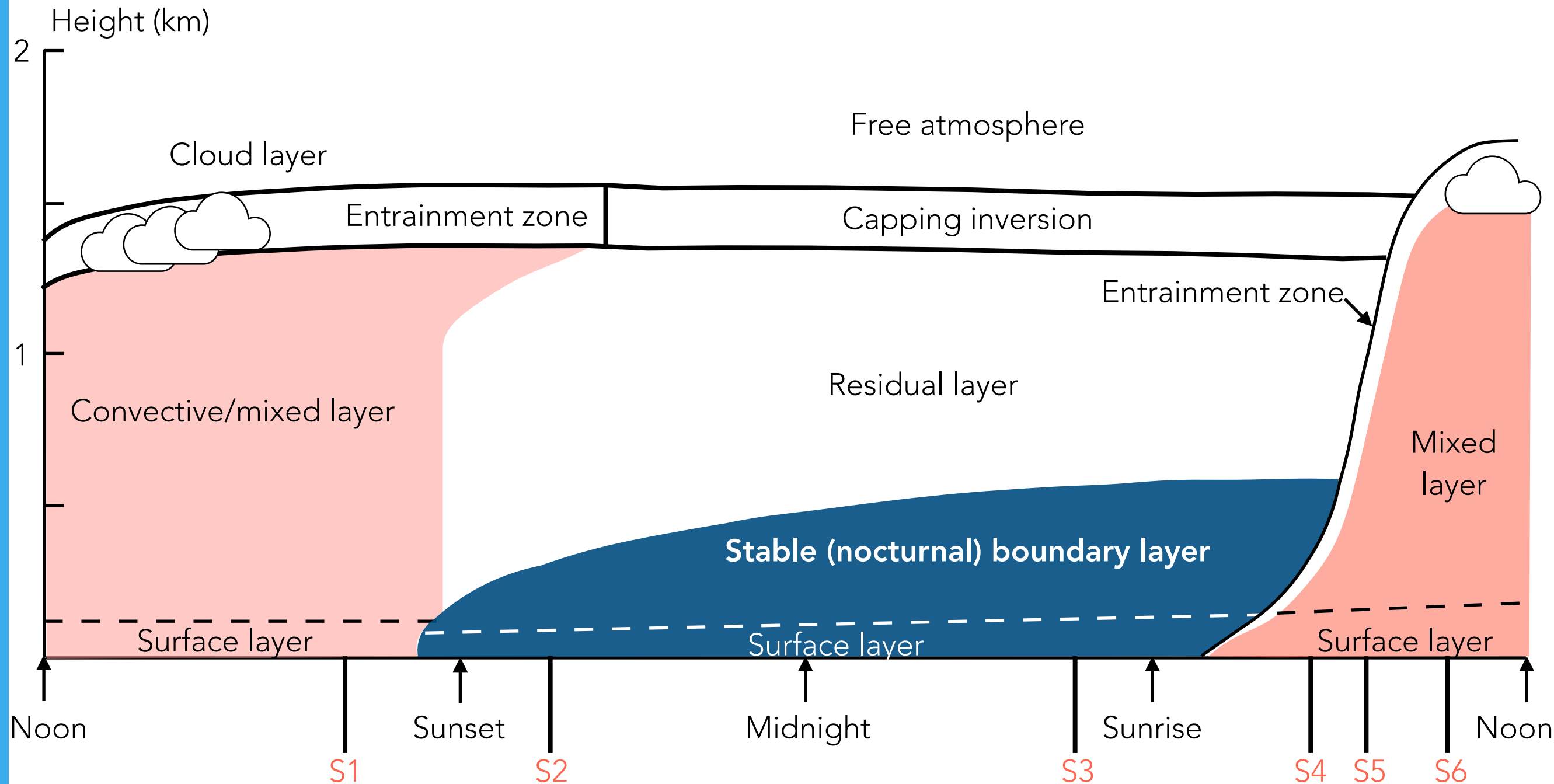
Residual layer

30min before sunset: thermals cease to form in absence of cold air advection & turbulence decays in the formerly well-mixed layer.



- The initial mean state variables and concentration variables are the same as those of the recently decayed mixed-layer.
- It is not a boundary layer per se.
- In the absence of advection: passive tracers dispersed into the daytime ML remain aloft the RL during the night
- RL is neutrally stratified, so turbulence is nearly equal intensity in all directions
- Smoke plumes tend to disperse at equal rates in the vertical and lateral directions, coning

ABL structure



ABL structure

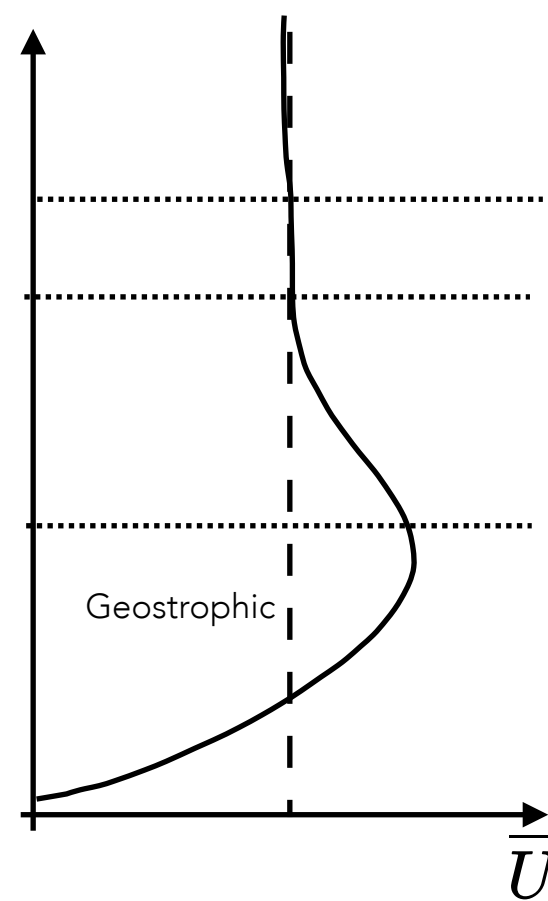
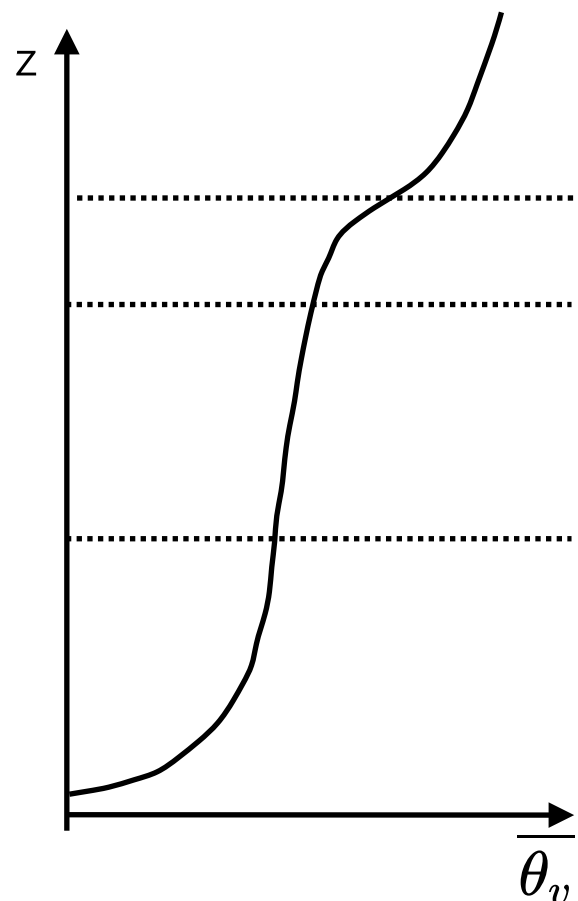
Stable or nocturnal boundary layer

Exists at the bottom of the RL ~0-200m, also can form during the day as well, when the underlying surface is colder than the air (common during warm-air advection over a colder surface: frontal passage, near shorelines). Poorly defined top that blends within the RL, the SBL top is defined as the height where Tl is a small fraction of its surface value.

Turbulence is weaker and more sporadic

Suppressed by statically stable

During non-turbulence periods, the flow becomes decoupled from the surface



Free
Atmosphere

Former entrainment zone

Residual Layer

Stable Boundary Layer

ABL structure

Stable or nocturnal boundary layer

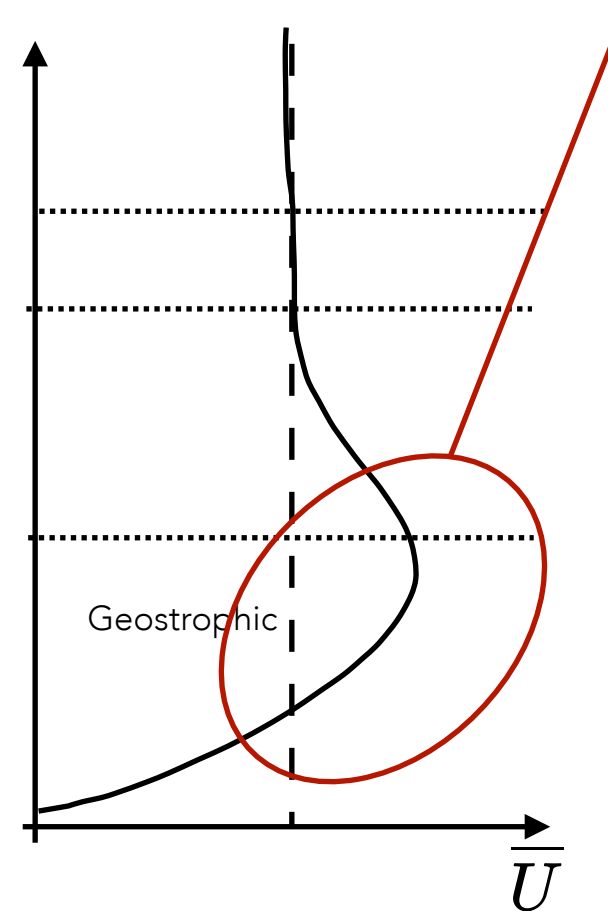
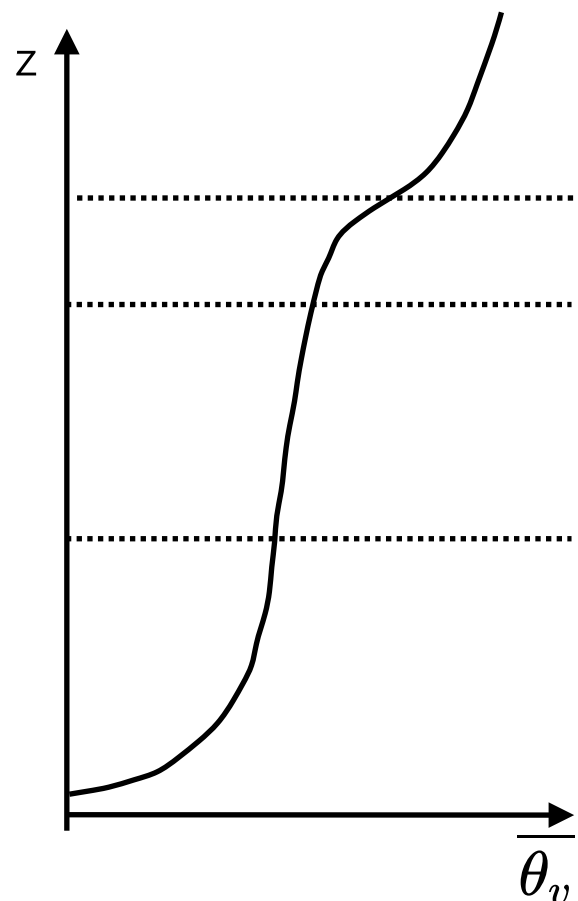
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Turbulence is weaker and more sporadic

Suppressed by statically stable

During non-turbulence periods, the flow becomes decoupled from the surface

Turbulence generated by enhanced wind shears from nocturnal jet. Short bursts, that cause mixing throughout the SBL, intermittency.



Free
Atmosphere

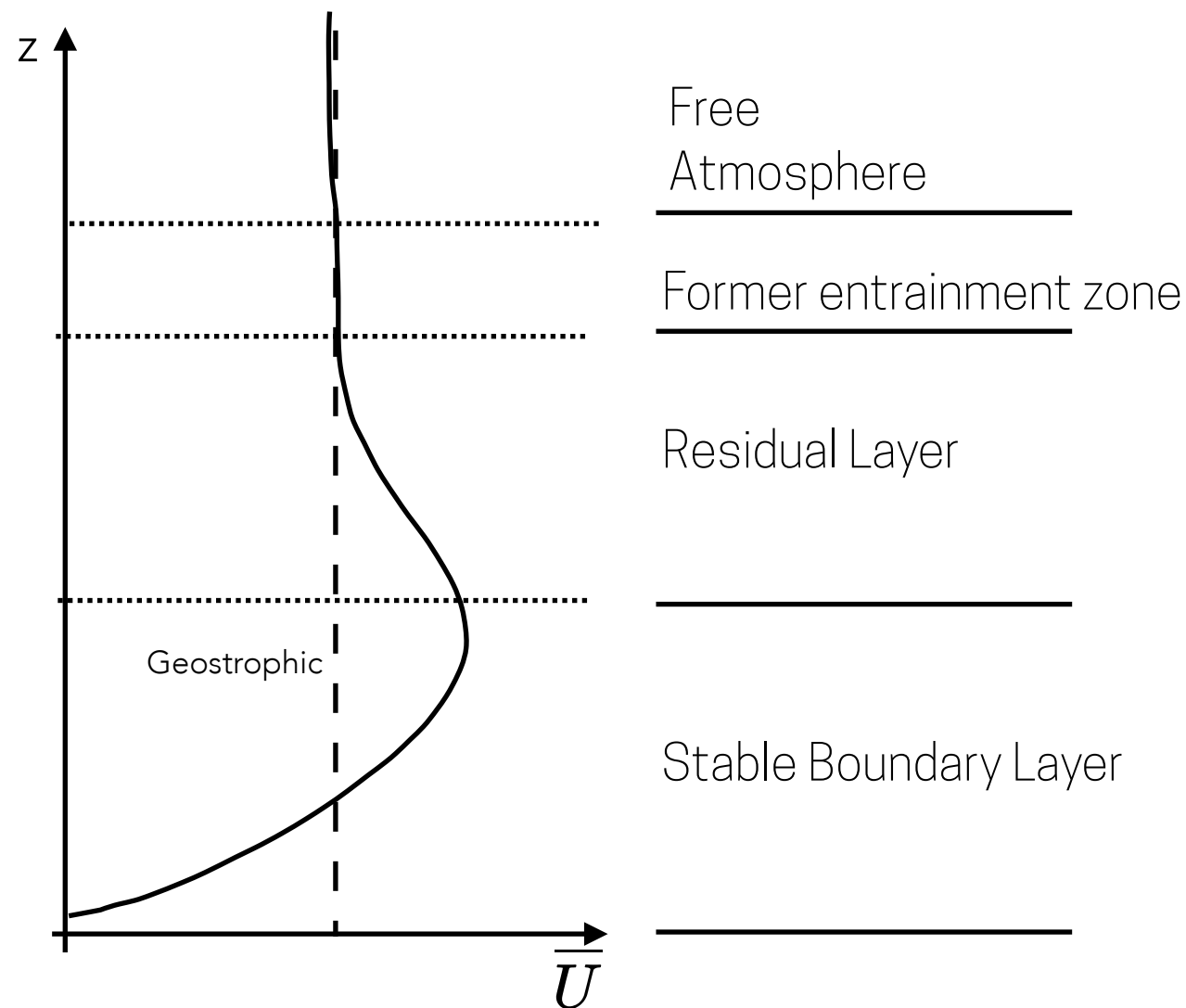
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Residual Layer

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ABL structure

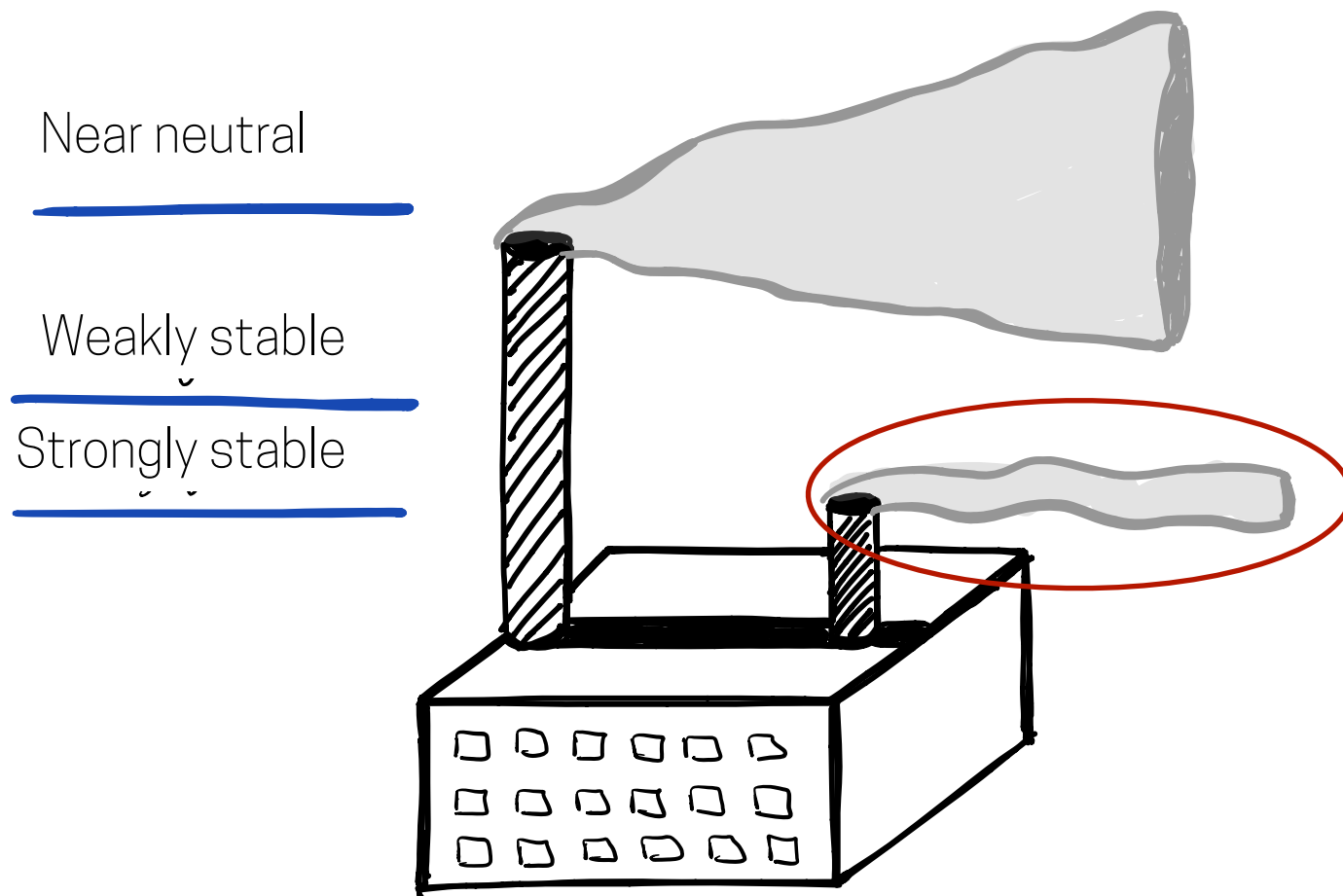
Stable or nocturnal boundary layer



- Complex behaviour due to the intermittency
- Just above ground level the state is calm
- Around 200m, wind speeds up to 10-30m/s, supergeostrophic in the nocturnal jet or low-level jet
- Few hundred meters higher: wind speed is smaller and closer to its geostrophic value

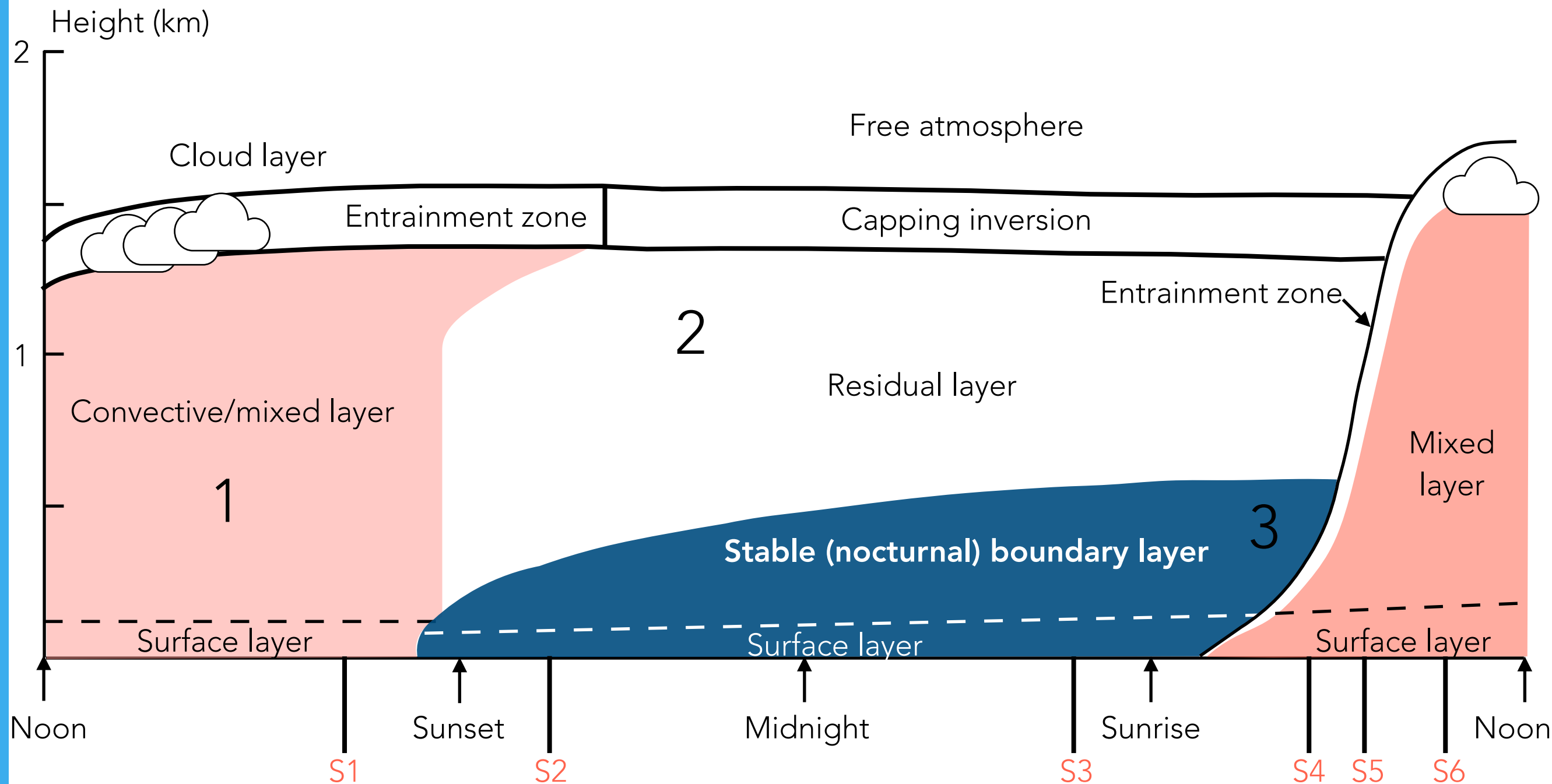
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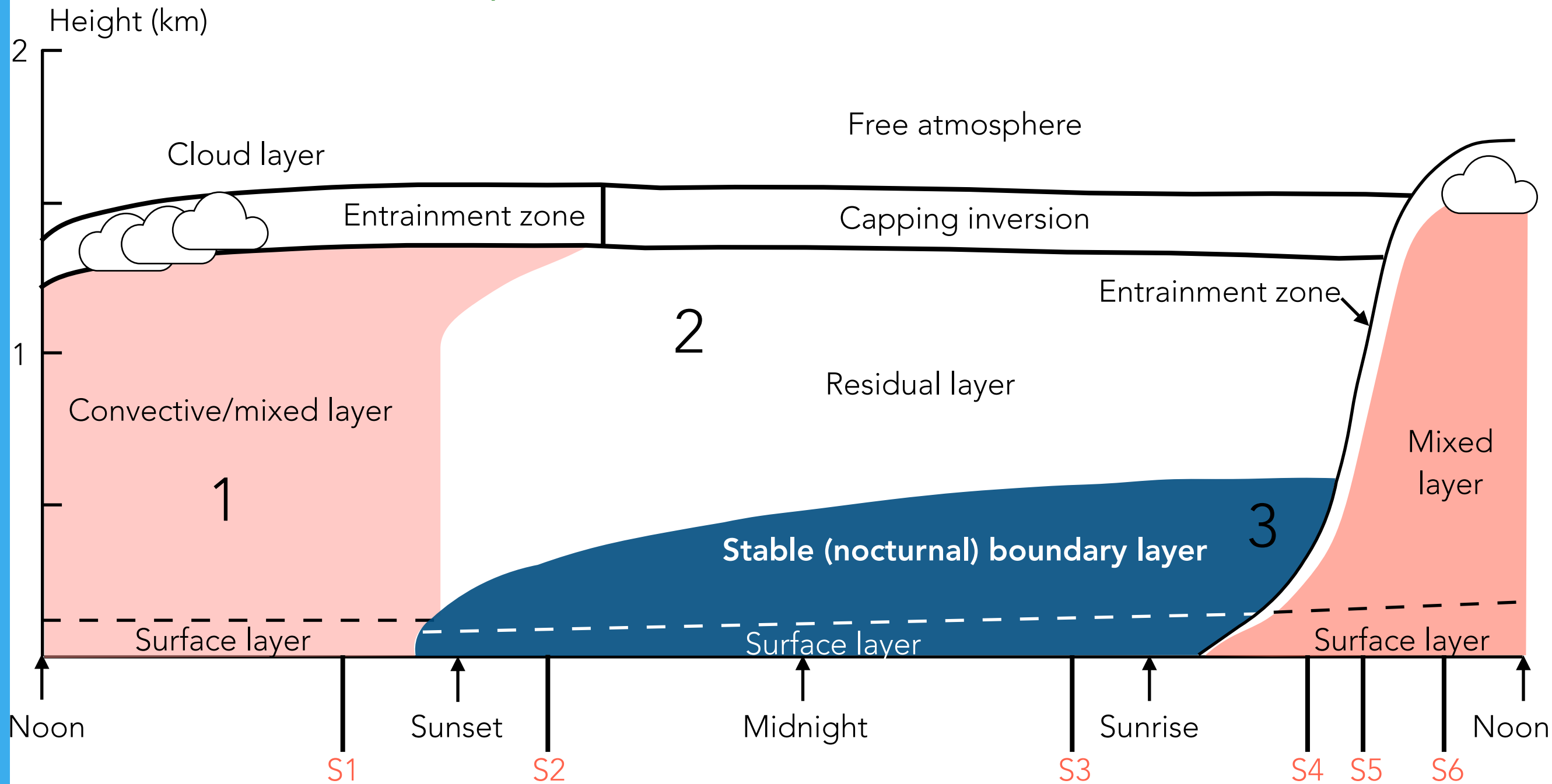


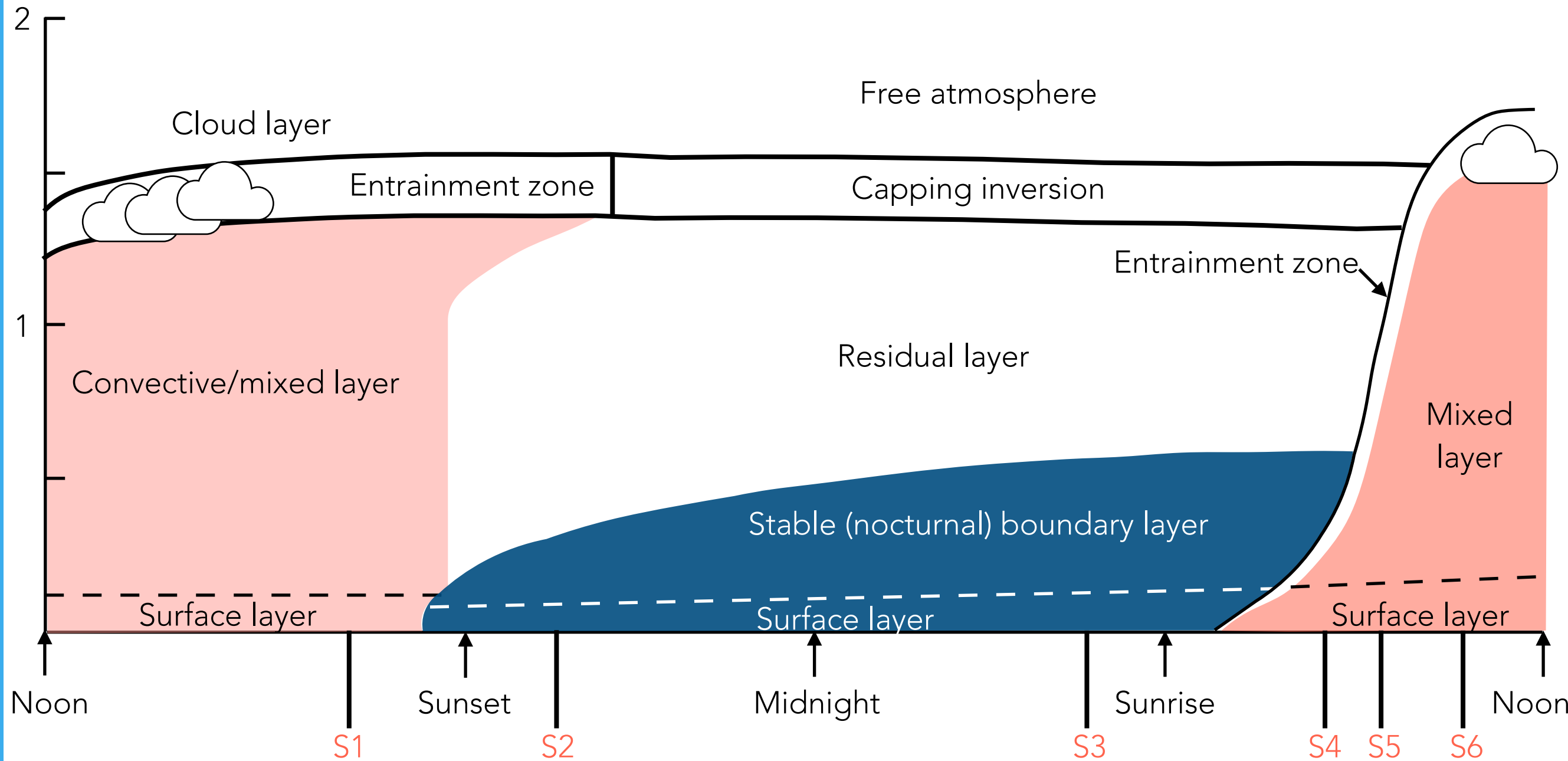
- Relatively little dispersion in the vertical direction
- More rapid dispersion in the horizontal direction: fanning
- When winds are lighter: meanders and drifts downwind

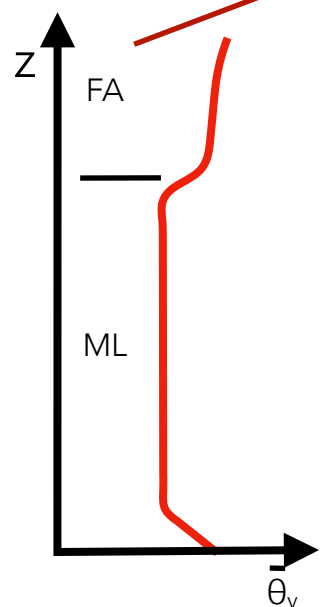
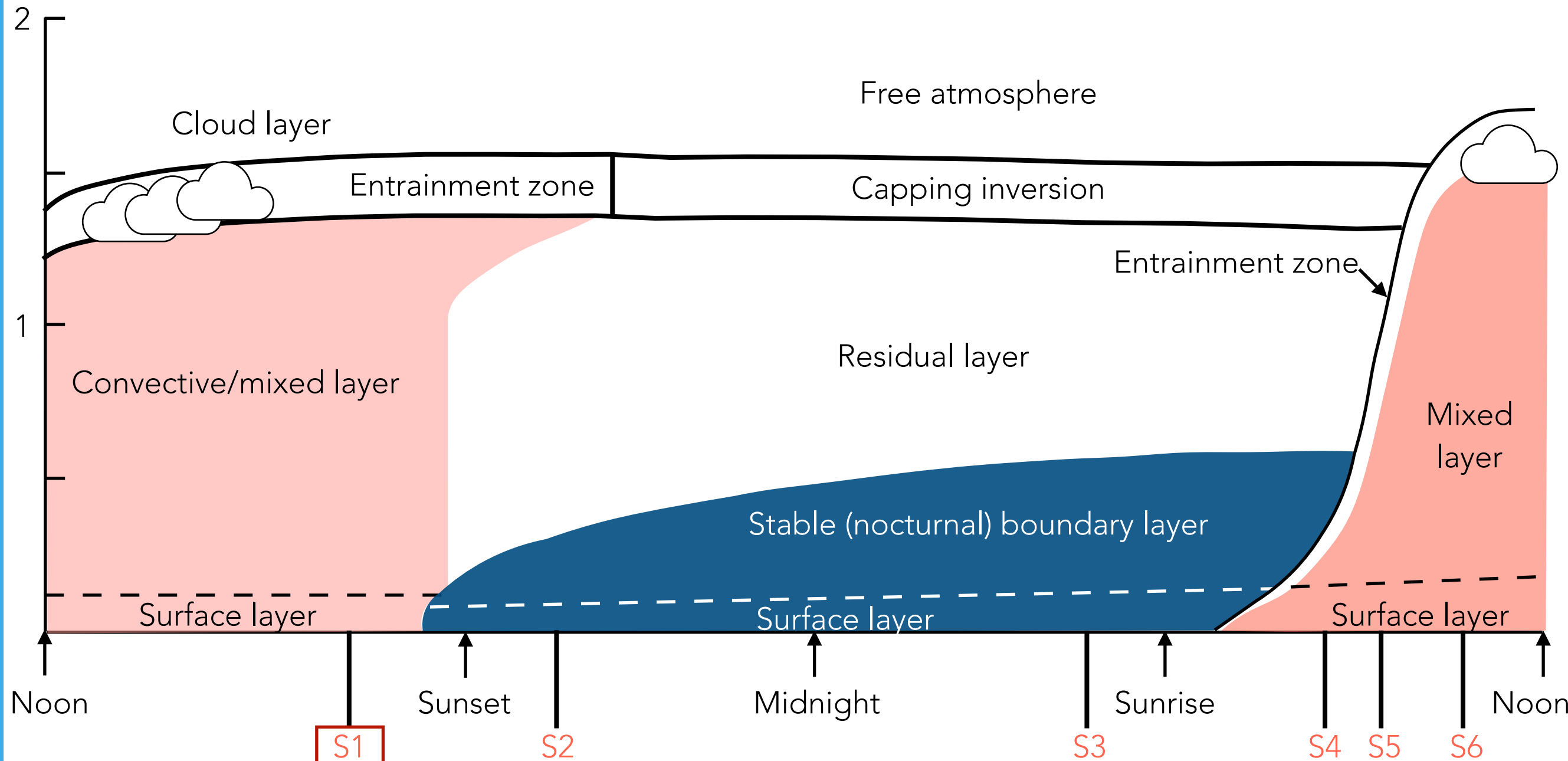
How does dispersion behave in 1, 2 and 3?

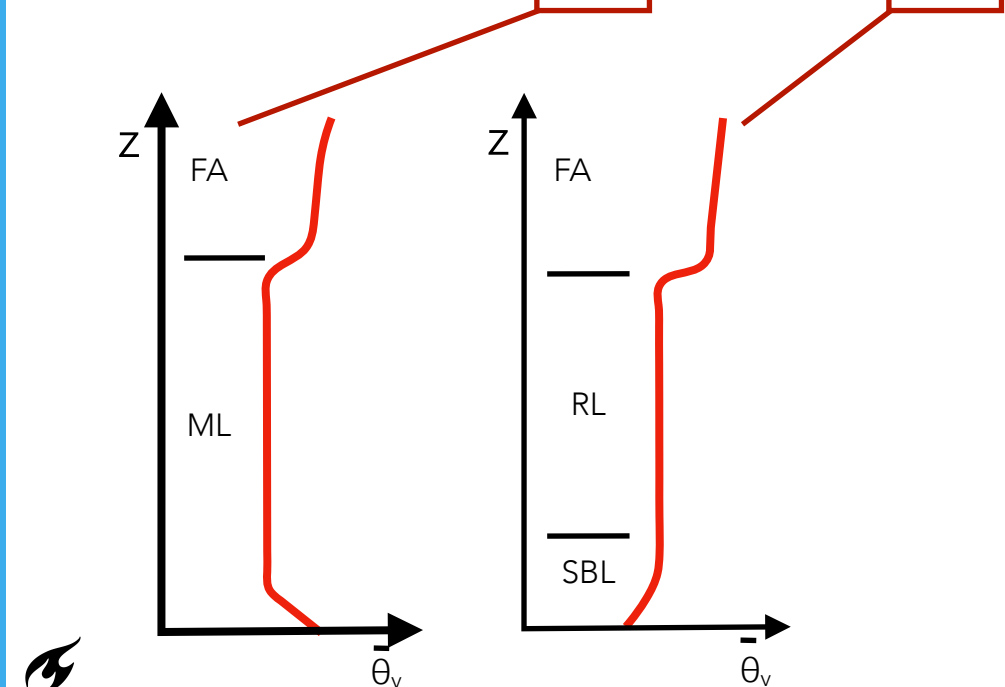
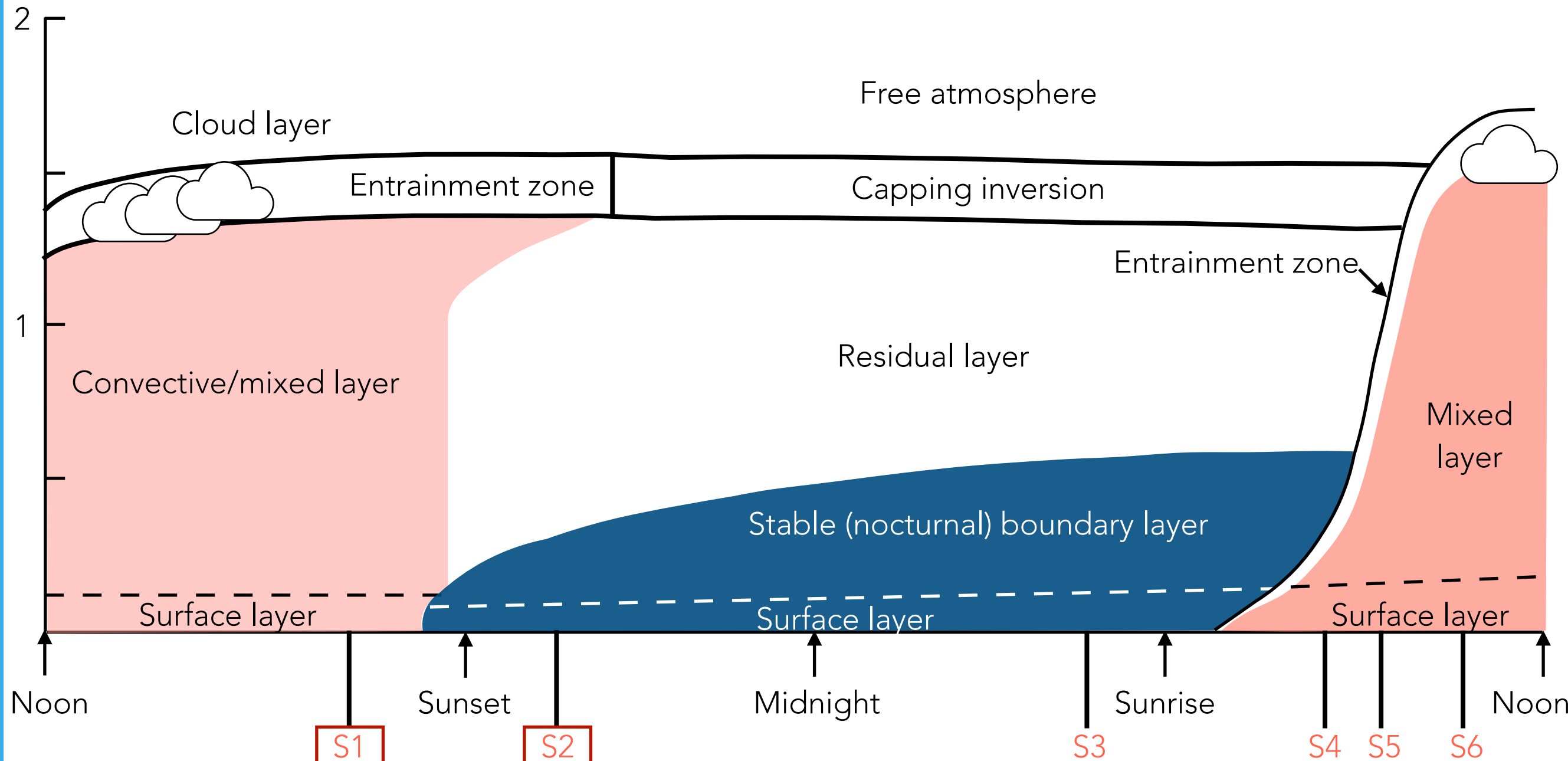


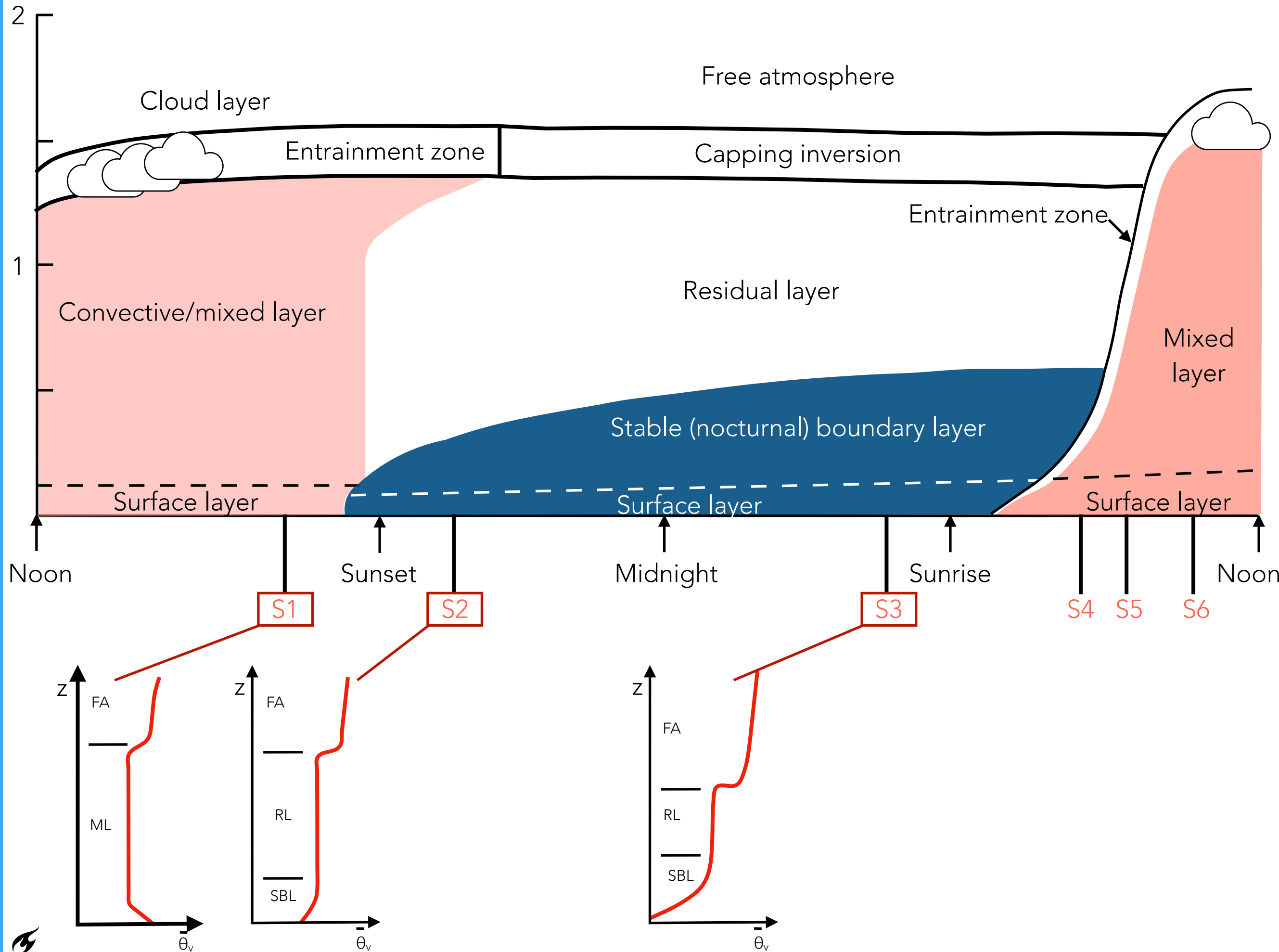
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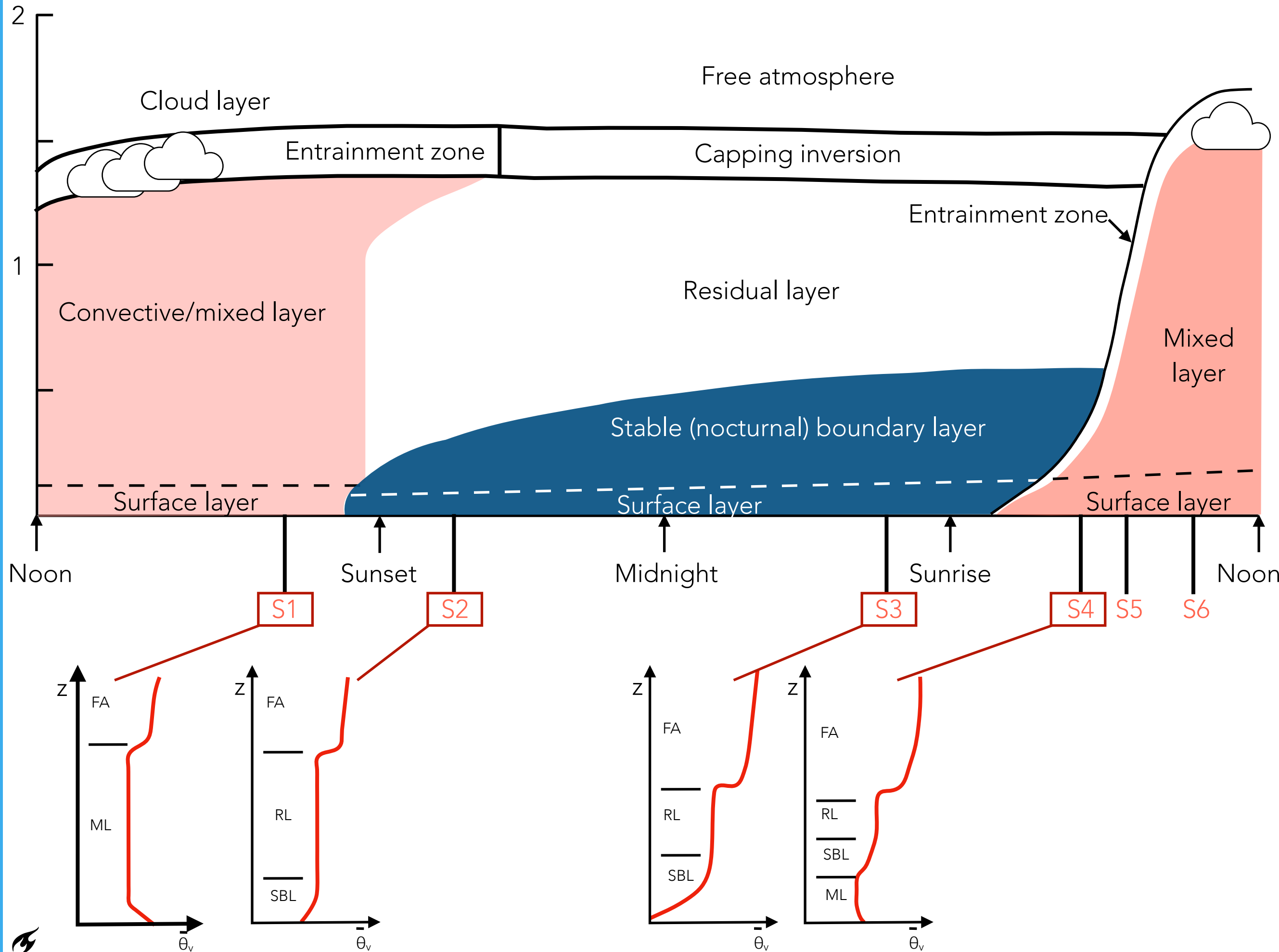


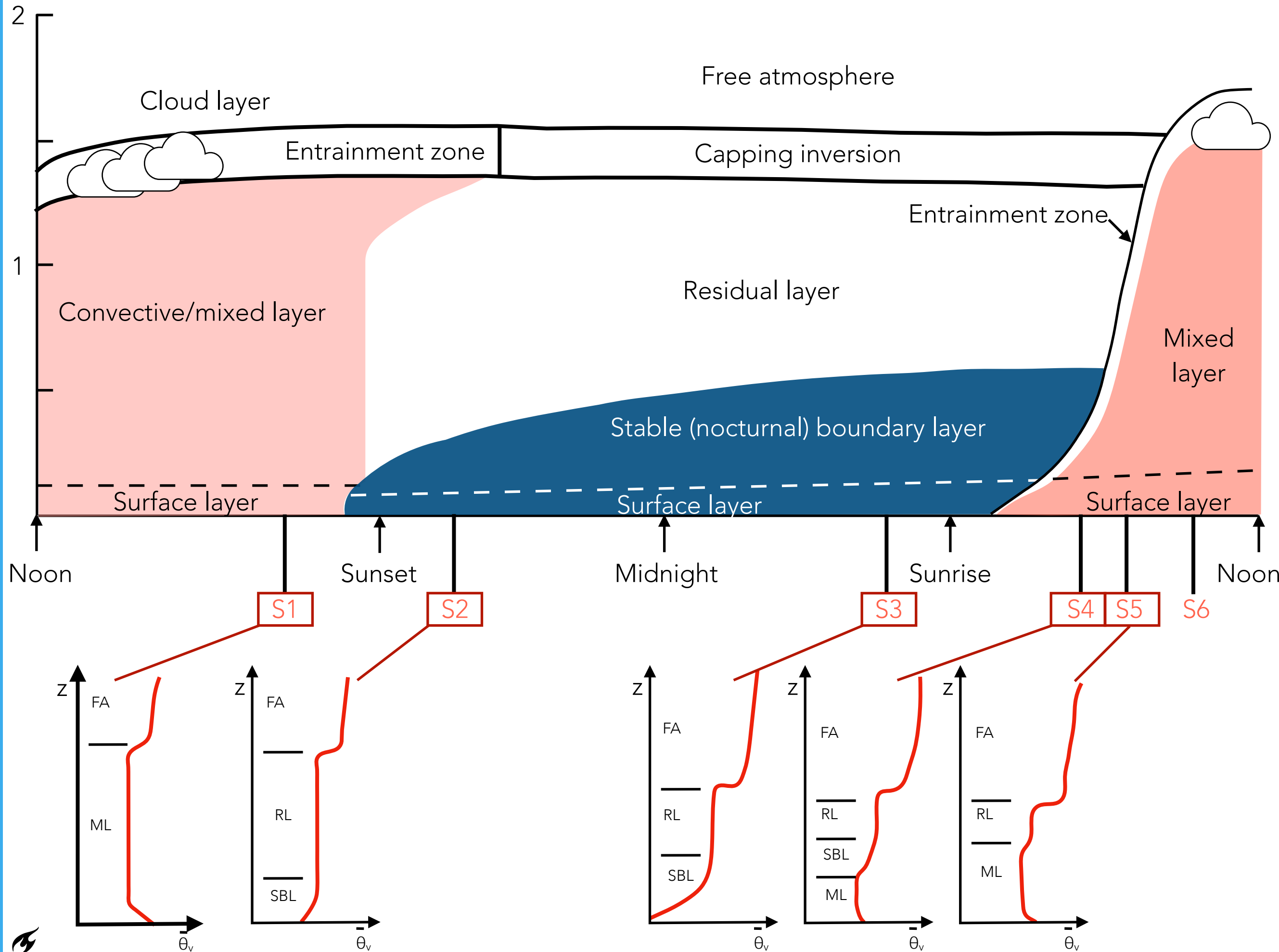


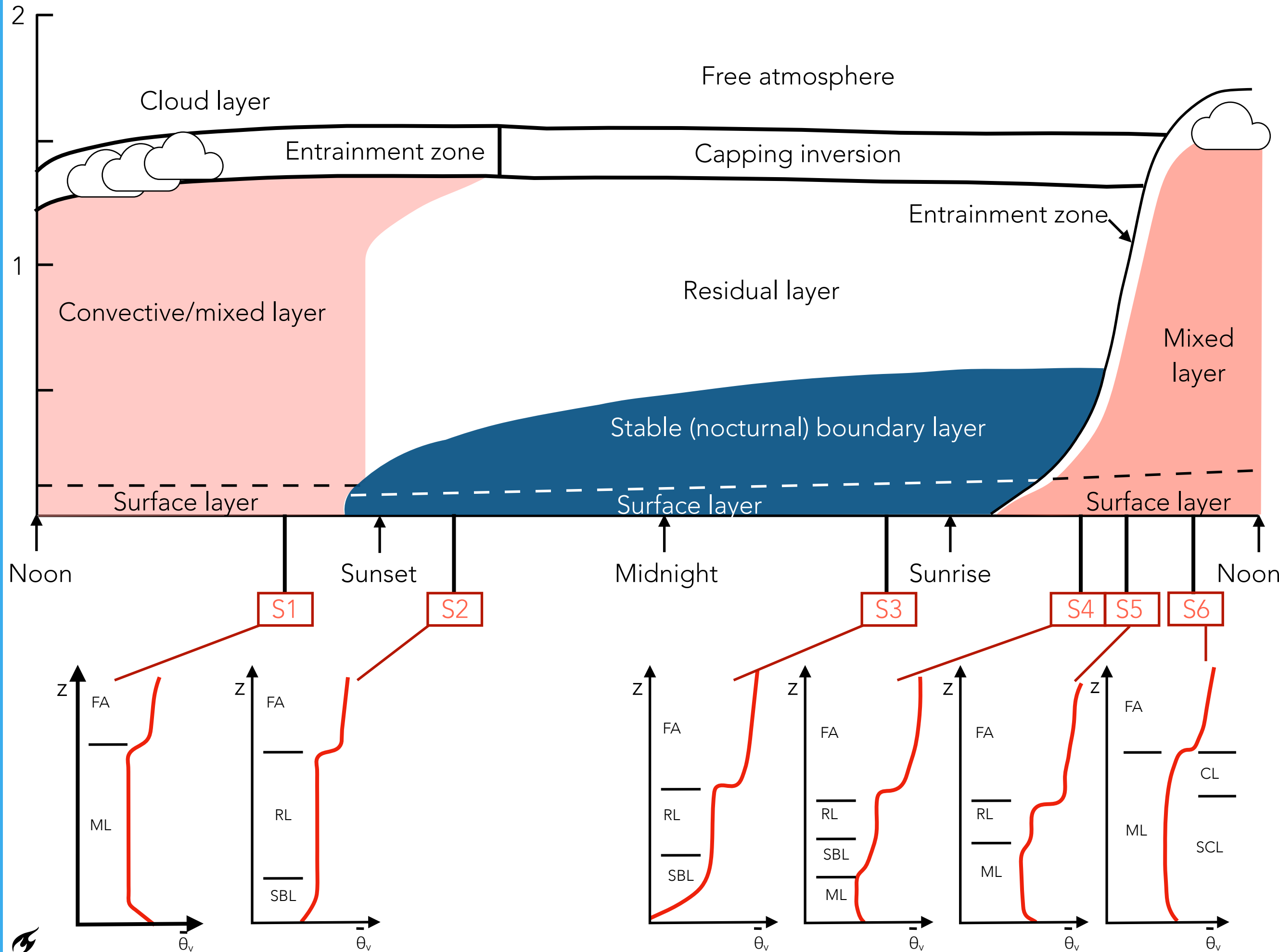












ABL structure

Definition of atmospheric stability

Stability	Lapse rate	
NEUTRAL	$\frac{\partial \theta_v}{\partial z} = 0$	Dry adiabatic, no convection
UNSTABLE	$\frac{\partial \theta_v}{\partial z} < 0$	Superadiabatic
STABLE	$\frac{\partial \theta_v}{\partial z} > 0$	Subadiabatic

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Quiz

Quiz

Instructions: go to [menti.com](https://www.menti.com) !

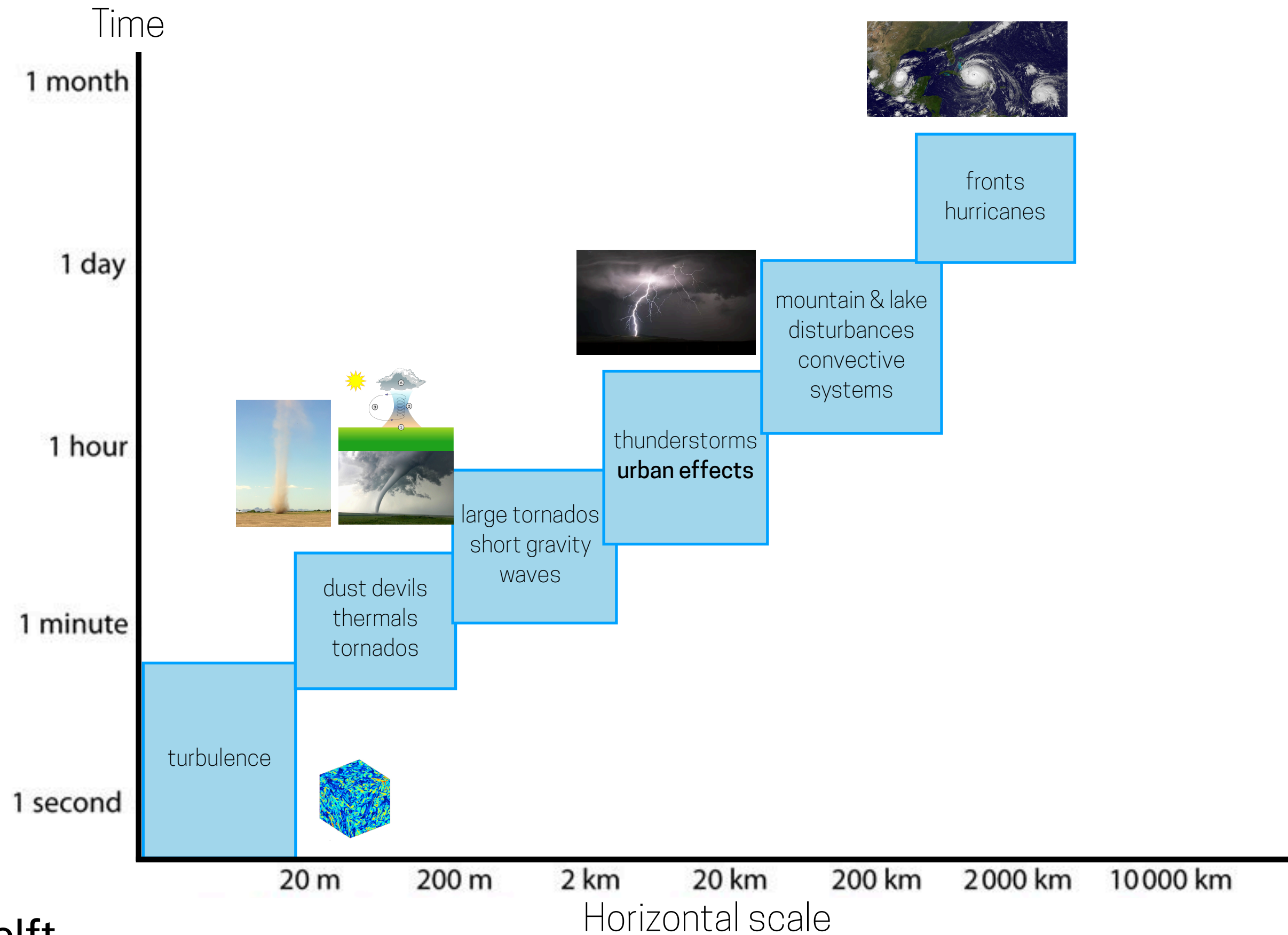
Then compete in the quiz!

Questions so far?

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Micrometeorology



Micrometeorology

Micrometeorology is the study of turbulence with space scales smaller than $\sim 3\text{km}$ and with time scales under 1h.

Since the phenomena is so transient in nature, deterministic description and forecasting of each individual eddy is virtually impossible. Therefore, micrometeorology relies on:

- Stochastic methods: deal with the average statistical effects of the eddies
- Similarity theory: involves the common behaviour exhibited by many empirically-observed phenomena, when properly scaled
- Phenomenological classifications: the largest size structures such as thermal are classified and sometimes approached in a partially deterministic manner.
- Field and Laboratory experiments
- Numerical Simulations

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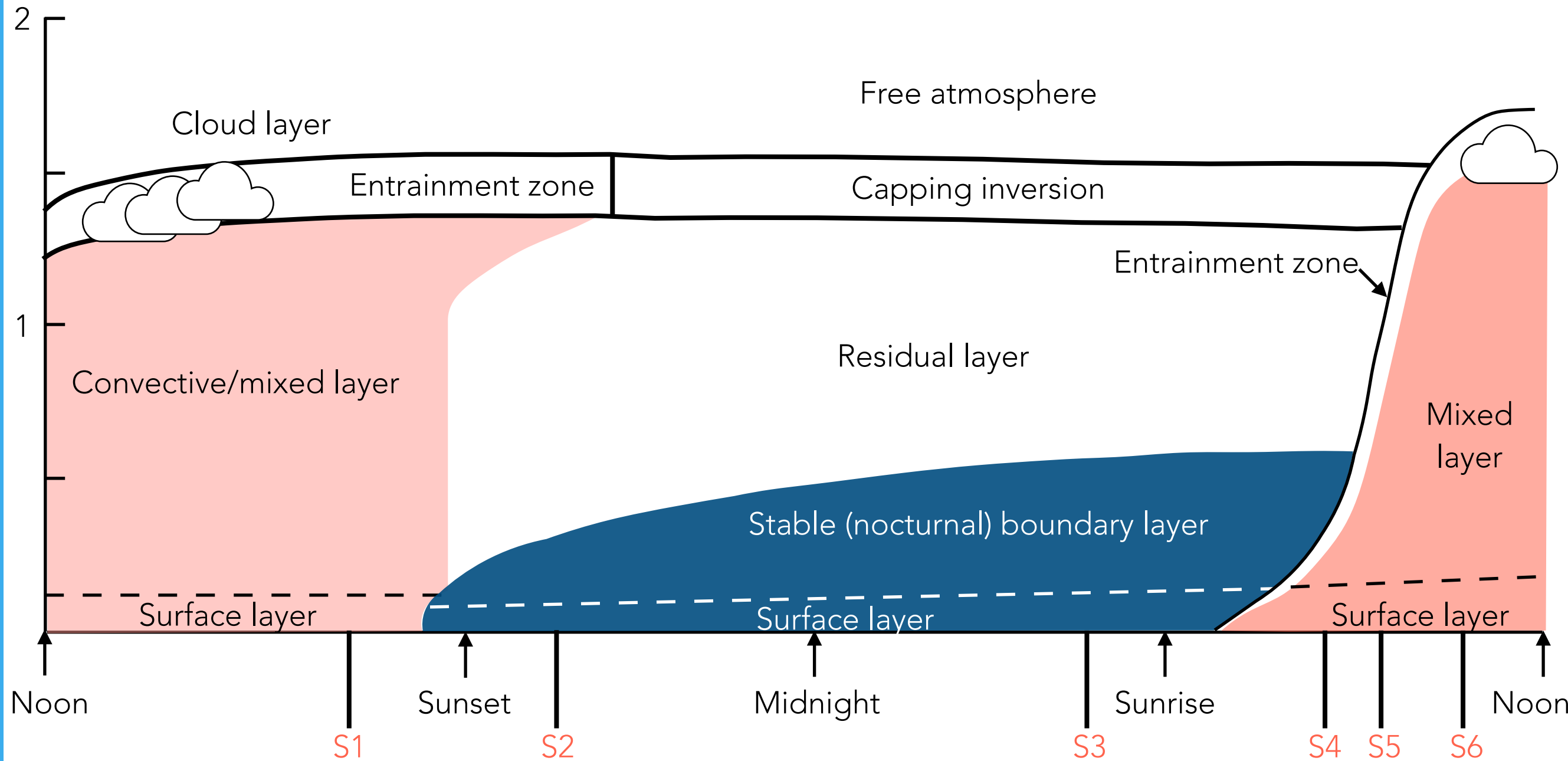
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Picture Prompt

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 CL: Cloud Layer
 FA: Free Atmosphere
 IBL: Internal Boundary Layer
 ML: Mixed Layer (CBL)
 RL: Residual Layer
 SBL: Stable Boundary Layer (NBL)
 SCL: Sub Cloud Layer
 SL: Surface Layer

Outline of the class:

1. What is the Atmospheric Boundary Layer
2. Winds in the ABL: Turbulence
3. Applications
4. Taylor's Hypothesis
5. Buoyancy and virtual temperature concepts
6. ABL structure
7. Micrometeorology
8. **Wrap-up**
9. One-minute notes (the muddiest point)

Wrap Up:

- 1.** The Atmospheric Boundary Layer is..... Some applications:.....can benefit on knowing the state of the ABL.
- 2.** Looking at the profile of temperature in this picture...we can say that the Atmospheric Boundary Layer structures corresponds to approximately daytime...

Next class:

Some mathematical and conceptual tools used in fluid dynamics

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Next class:

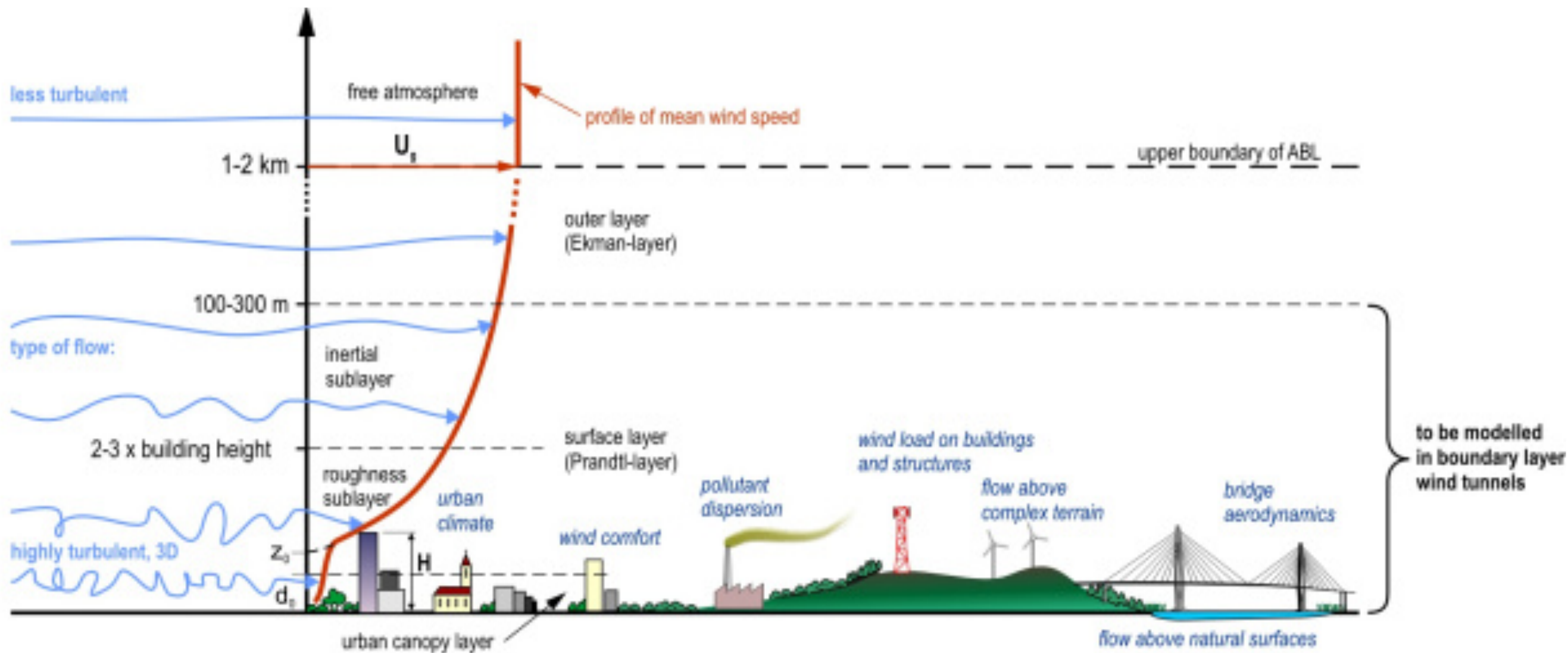
Some mathematical and conceptual tools used in fluid dynamics

Don't forget the one-min note for me!

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Backup



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Quizz questions

What is the height of the atmospheric boundary layer?

- From 1 to 2 km
- **From few hundred meters to 3 km**

Assuming the Taylor hypothesis, with mean flow in X direction of 5m/s, how long it will the wind to cover a distance of 250m

- 25 seconds
- **50 seconds**

What does the Reynolds number relate?

- Interstitial forces and viscous forces
- **Inertial forces and viscous forces**

When is the atmospheric boundary layer typically deeper?

- **During the day**
- At night

When are vertical wind flows stronger typically?

- **During the day**
- At night

Quizz questions

The Reynolds number of a fluid is 5000, can we assume the flow is turbulent?

- Yes
- No

What is the importance of vertical motions in the atmospheric boundary layer?

- **Important**
- Very low

What is the importance of vertical motions in the free troposphere?

- Important
- **Very low**

The change of the depth of the atmospheric boundary layer is equal over the sea than over land?

- Yes
- No

Turbulence nowadays is an unsolved problem because...

- **It is highly chaotic and we do not have analytical solution of the Navier-Stokes equations**

