Atmospheric Boundary Layer

What has happened thus far and next

- Dynamics

We have seen what causes vertical and horizontal motions in the atmosphere and how to describe these motions quantitatively. A set of equations which are called the “primitive equations” are the basis for weather forecasting. To reduce complexity, we formulated approximations to wind systems such as the geostrophic wind or the Ekman spiral.

- Boundary Layer Dynamics

Now we look at the layers of the atmosphere close to the Earth’s surface and at the surface energy balance in more detail. Going back the equations of motion, we basically try to understand the friction term. The friction term is governed by turbulence. The boundary layer is the most important part of the atmosphere for us humans as we live in it. It governs the dynamics of air pollutants, our wind energy, summer heat and winter cold and determines how fast the snow melts. These are things we will learn in class.

Outline:

- **Basic Characteristics of the ABL**
- Atmospheric Turbulence and Transport Properties in the ABL
- Blackboard: Reynolds Averaging, Turbulent Kinetic Energy (TKE), Correlations and Fluxes
- Blackboard: Logarithmic Wind Profile, Sensible and Latent Heat Fluxes, Stability Corrections
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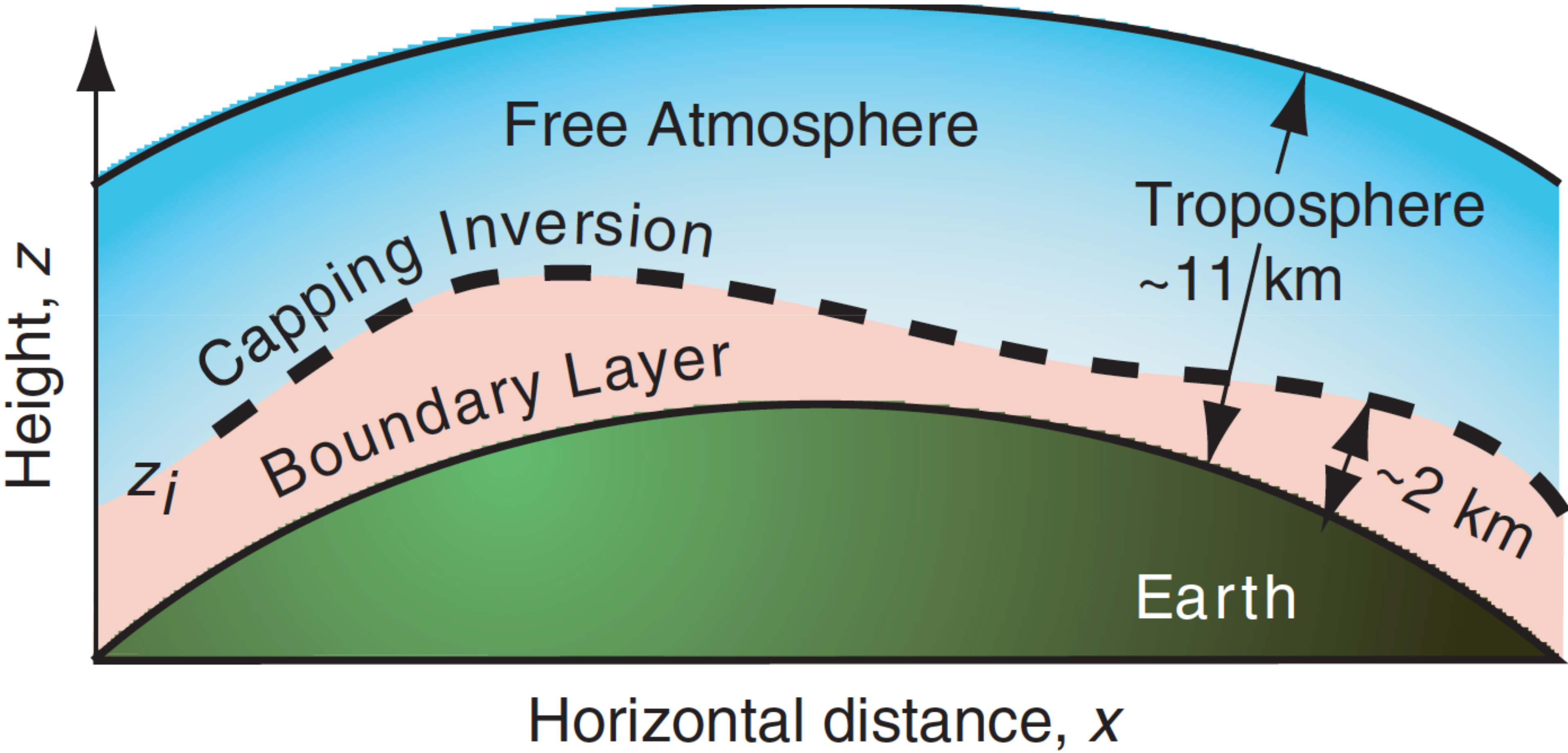
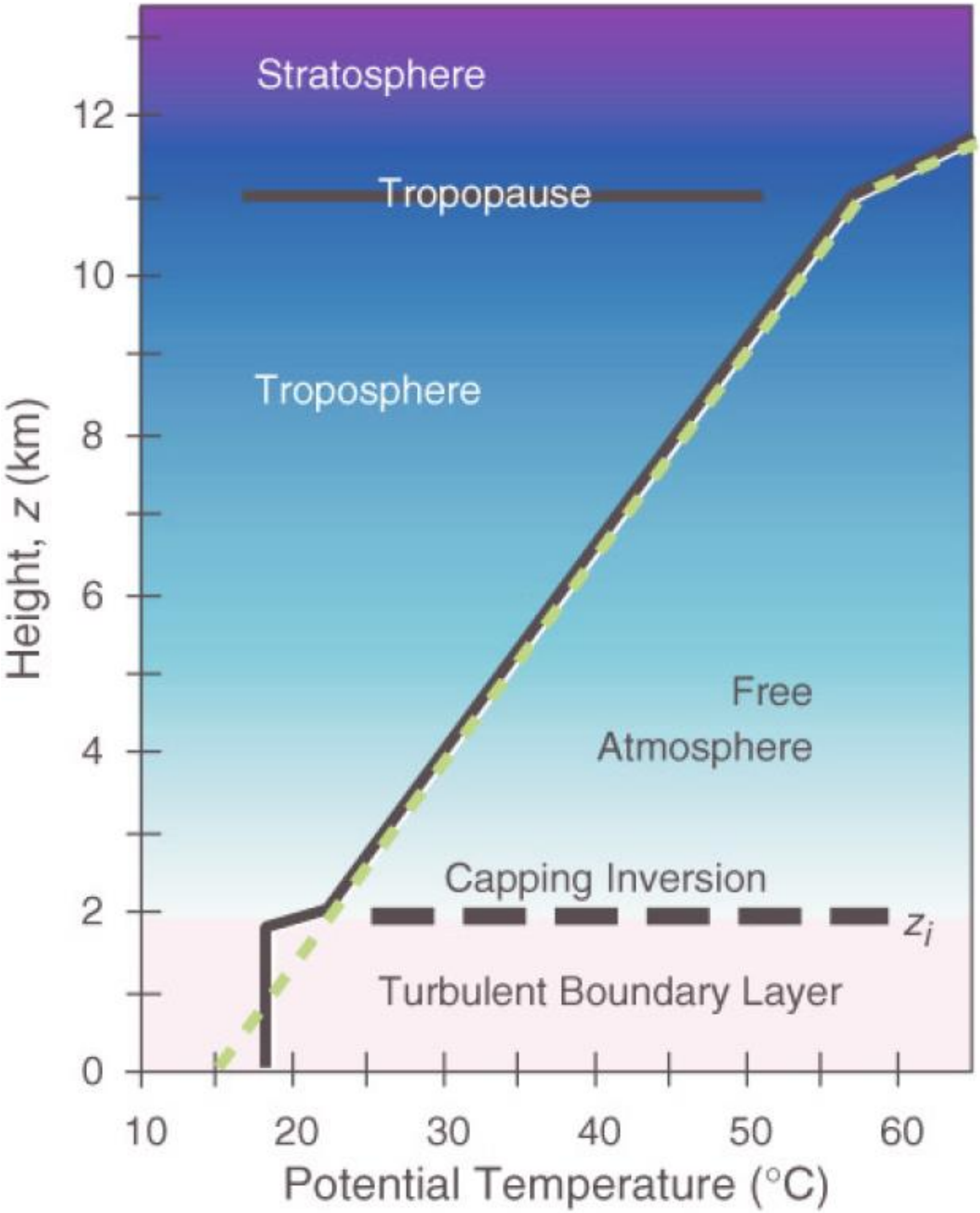
- Local and Special Effects

Boundary Layer Concept



The boundary layer is the tropospheric layer close to the earth's surface, which responds to changes in the surface forcings (e.g. radiation) on short time scales (hour).

Boundary Layer Concept



The daytime turbulent boundary layer (BL) is characterized by surface heating, which leads to instability and mixing and as a result to a constant potential temperature over some vertical distance. The upper limit of the BL is typically given by a region of stronger "inversion" i.e. increasing temperature with height. This capping inversion (CI) is a direct result of the surface heating and mixing, which leads to growth of the layer into a background troposphere (FA: free atmosphere), which has a weak but positive stability (- 6.5 ° C / 1000 m on average).

On the blackboard, we have shown how mixing leads to a CI. Which effects can weaken this inversion?

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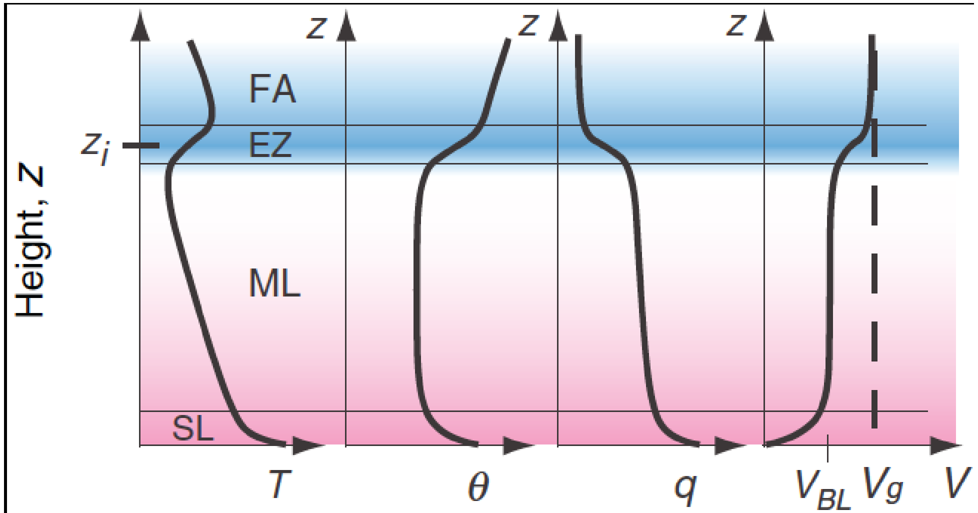
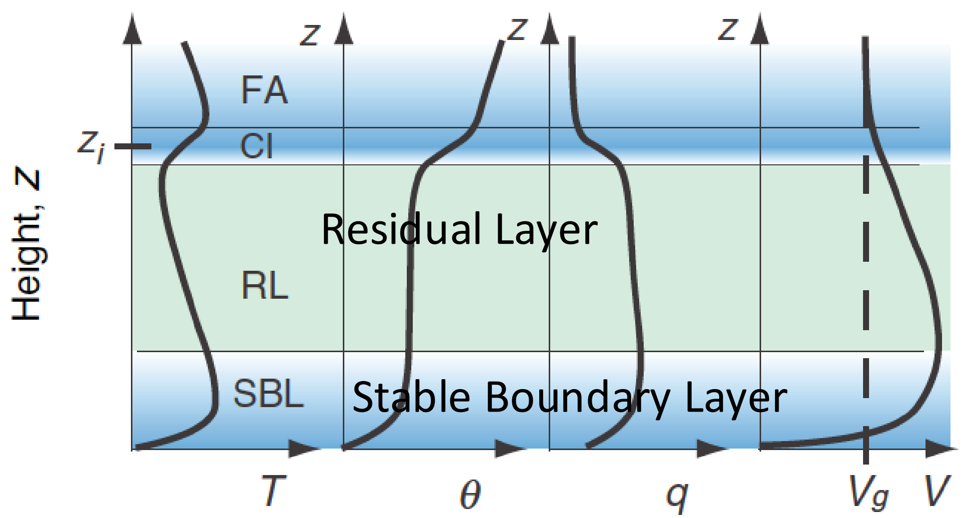
A. Heating of the BL through a hotter surface (sensible heat)
B. Advection of warm air aloft in the FA
C. BL cloud formation and latent heat release at the CI
D. Heating of the stratosphere by photodissociation

Profiles of important ABL quantities



(a) DAY

The surface layer (SL) is the lowest part of the ABL, where fluxes are constant with height



(b) NIGHT

Idealized profiles for day- and night-time BLs. During the growth of the mixed layer (ML) the capping inversion (CI) is also called entrainment zone (EZ) because the turbulent mixing from below erodes the air of the FA in this process and therefore “entrains” air into the BL. Also shown are typical profiles for potential temperature (θ), moisture (q) and the wind speed (V_{BL}), which is smaller than the geostrophic wind (V_g) because of friction in the day time but can become larger than V_g at night if additional forcing (e.g. sloping terrain) is present. The wind maximum is called a katabatic jet.

Question: Try to think why gradients of T and q change sign from day to night.

Why is the Boundary Layer distinct from the Free Troposphere / Rest of the Atmosphere?

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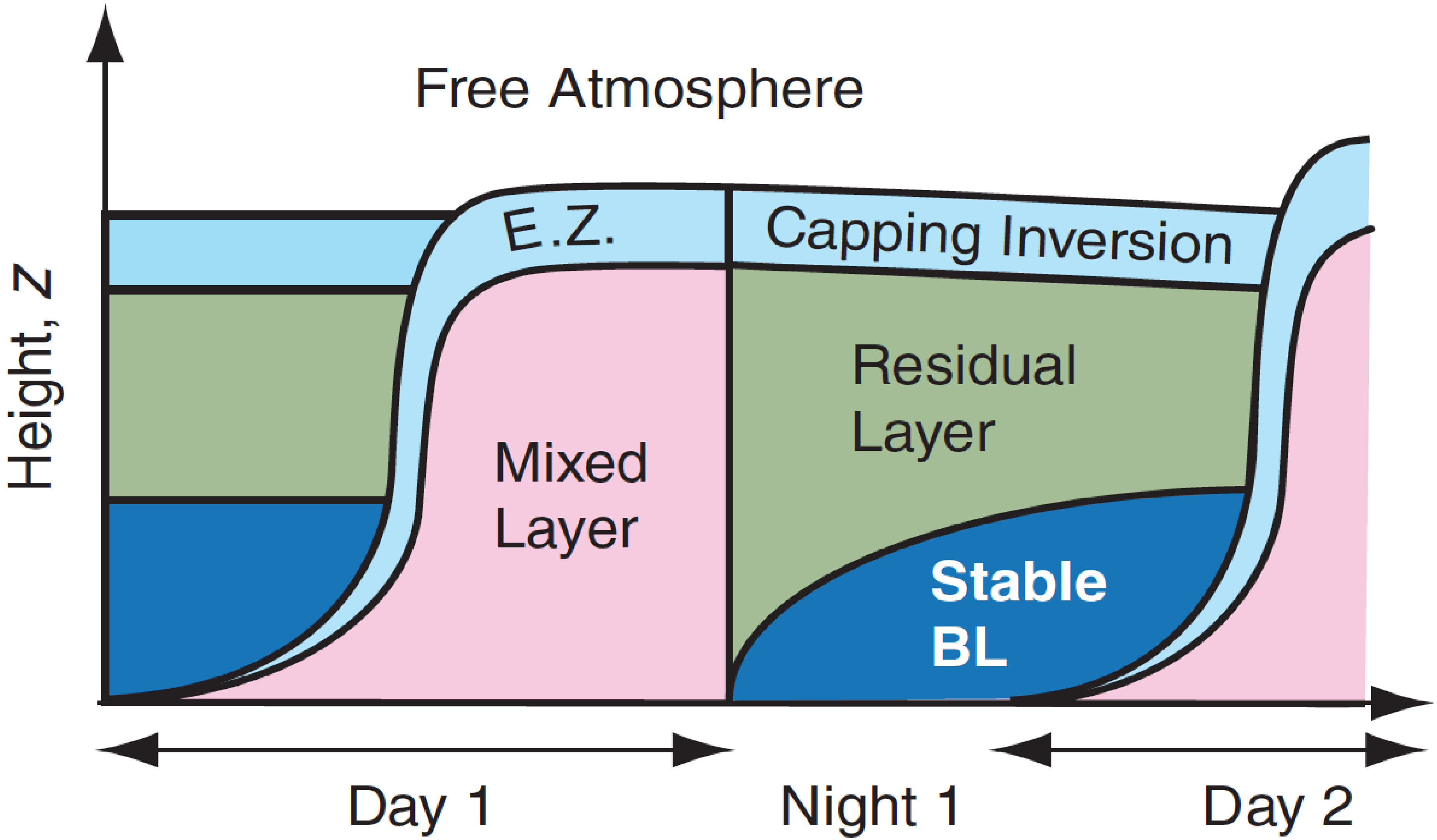
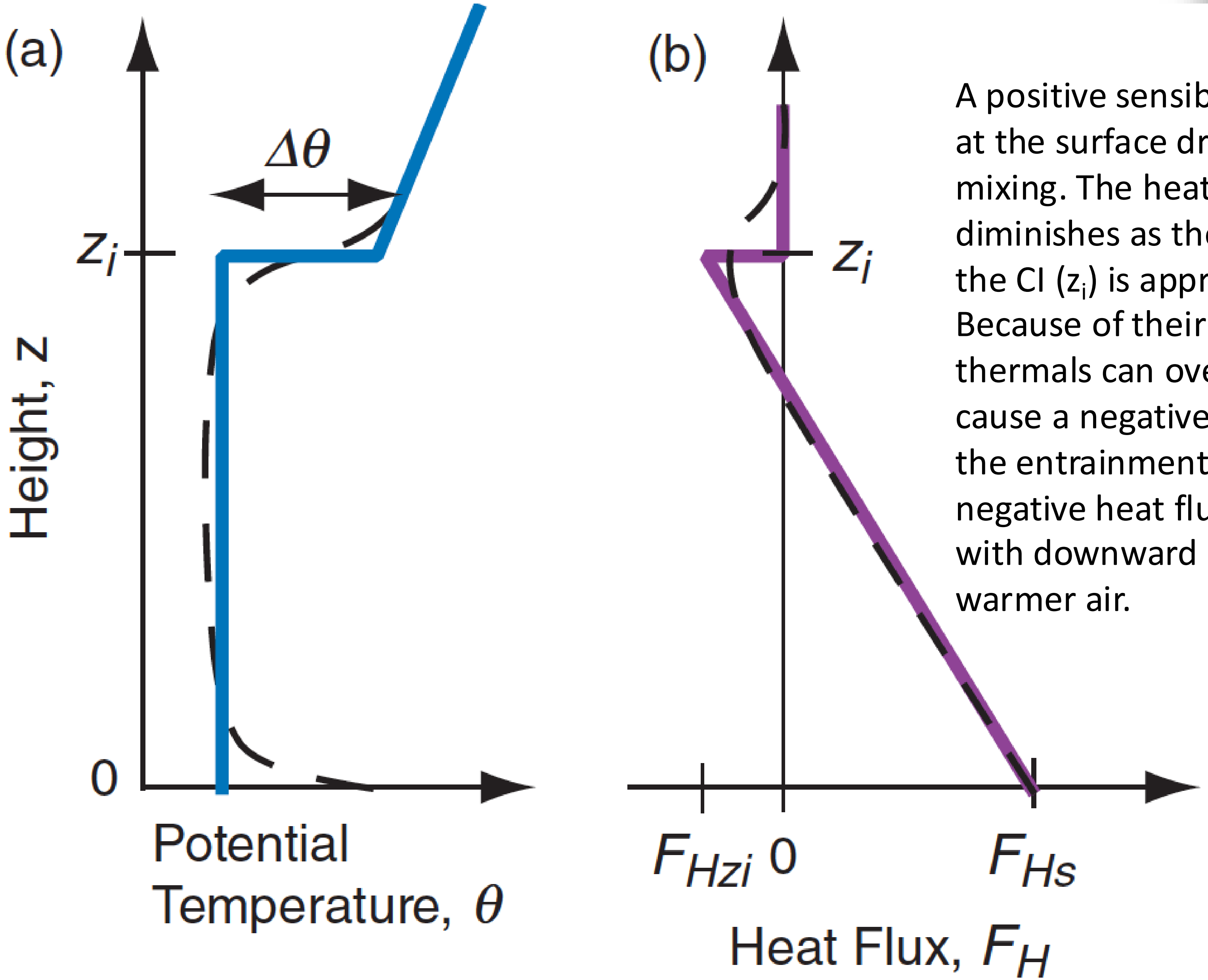
A. Surface heating leads to a stable stratification
B. The free atmosphere is in thermal equilibrium
C. Heat exchange processes are confined to the boundary layer
D. The capping inversion prevents significant exchange

Schematic Evolution

The daytime mixed layer becomes a residual layer (RL) at night as the surface decouples via the formation of a stable boundary layer (SBL), which is caused by surface cooling.



Boundary Layer Growth



A positive sensible heat flux at the surface drives the mixing. The heat flux steadily diminishes as the height of the CI (z_i) is approached. Because of their inertia, thermals can overshoot and cause a negative heat flux at the entrainment zone. The negative heat flux goes along with downward mixing of warmer air.

How can warmer air from aloft be mixed into the boundary layer against the stability of the capping inversion?

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A. Change of energy fluxes after sunset
B. Downdrafts after airflow crossing a mountain
C. Conversion of kinetic energy into potential energy
D. Erosion of the Mixed Layer by the Residual Layer

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Atmospheric Turbulence

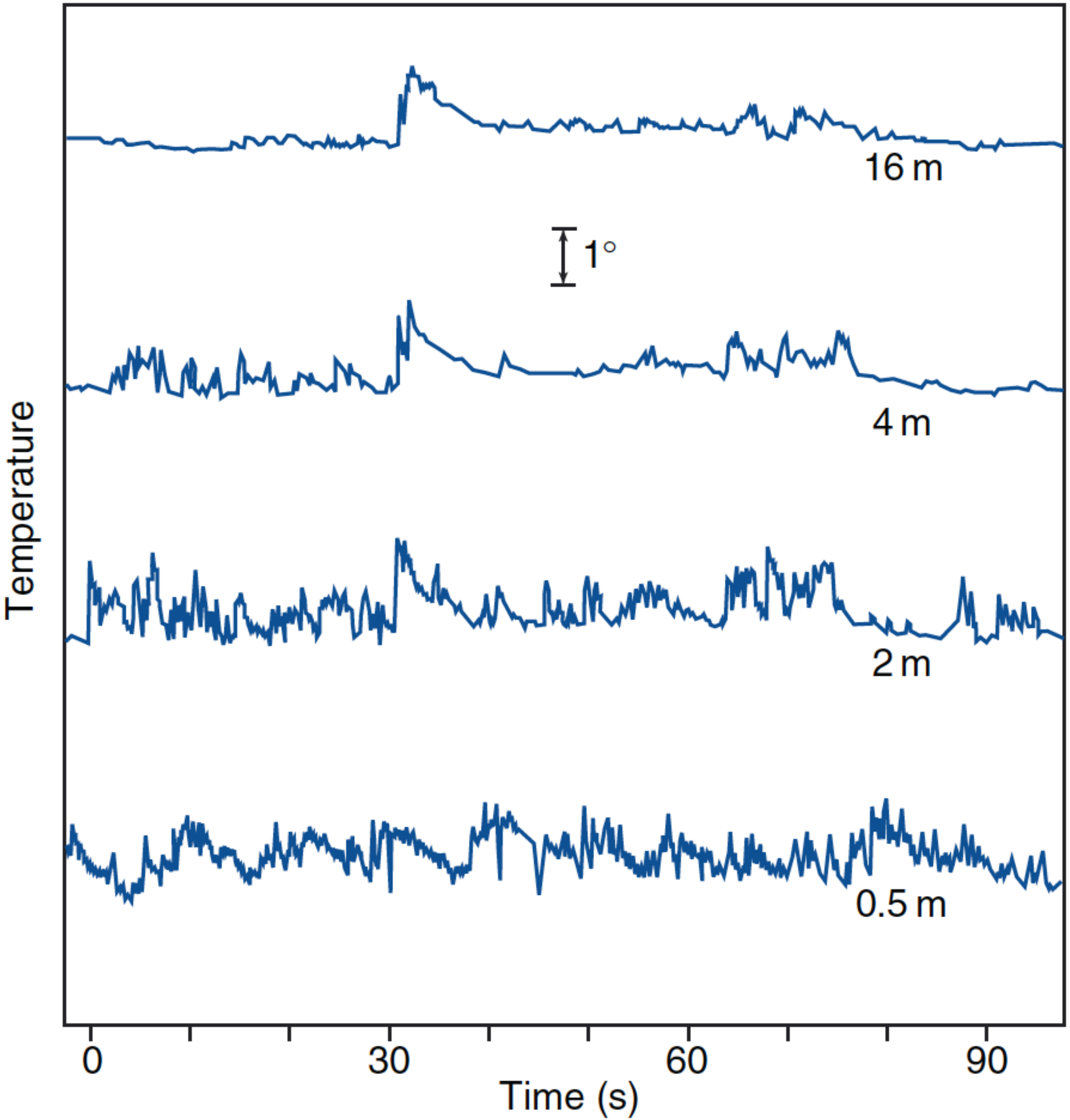
The motions in the boundary layer are highly turbulent, while in the FA less turbulent motion is possible. Turbulence is much more effective in transporting properties than laminar flow, which is restricted to molecular transport

Photograph shows the transition of laminar flow to turbulence via organized vortex structures

Eddy signals (wind) in the ABL in St. Sulpice

Video shows eddies (almost look like waves) moving in different directions. Local wind maxima cause low pressure (Bernoulli) and lift the cloth. Helps to visualize near-surface turbulence.

Eddy signals (T) in the ABL



The high shear close to the surface causes the larger eddies that are moving from higher elevations towards the surface (sweeps) to break up into smaller eddies. Smaller eddies (e.g. thermals) that move upwards (ejections) may combine into larger eddies. This is why temperature has a higher (high frequency) variability close to the surface.

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Why is the turbulent flux of a scalar represented by the correlation of a velocity fluctuation with the scalar?

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A. Velocity fluctuations are good estimators of scalar gradients
B. Because the correlation describes the movement of eddies which transport the scalar
C. Because mixing length scales are defined by the correlation
D. Because moisture and temperature are transported by the same eddies

Roughness Lengths and Drag Coefficients

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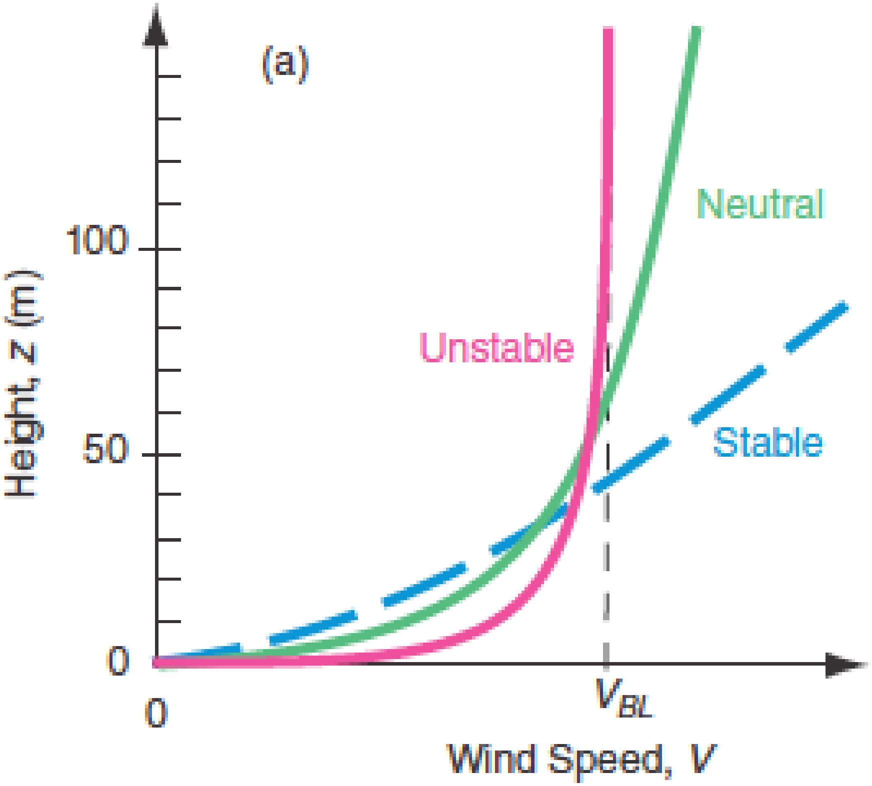
Table 9.2 The Davenport classification, where z_o is aerodynamic roughness length and C_{DN} is the corresponding drag coefficient for neutral static stability[a]

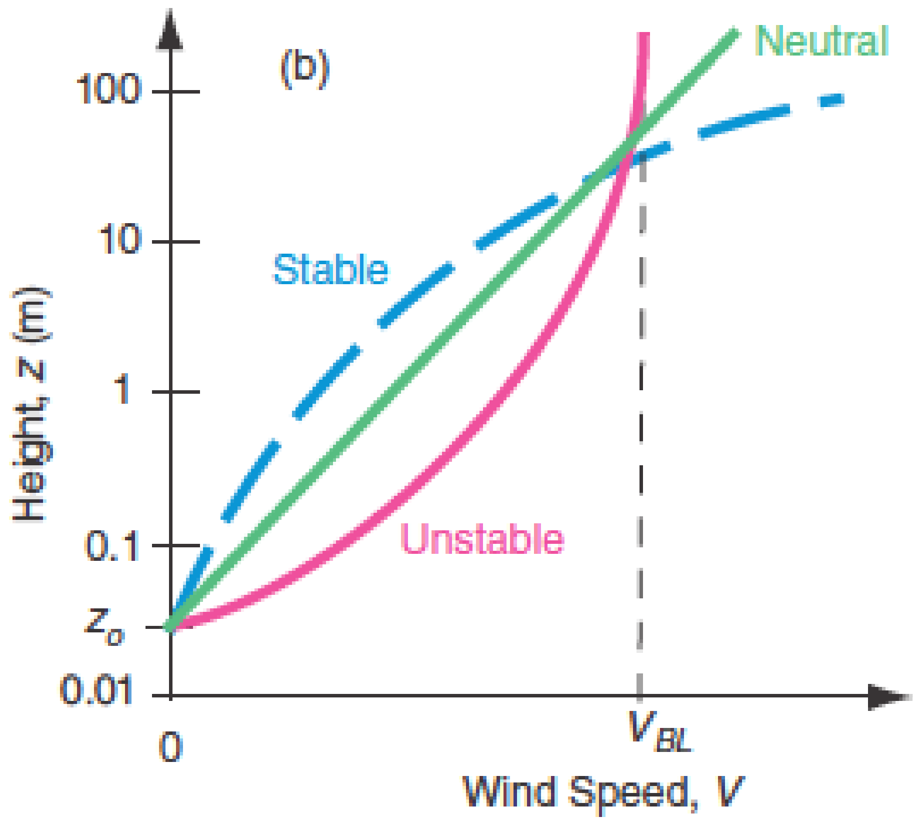
z_0 (m)	Classification	Landscape	C_{DN}
0.0002	Sea	Calm sea, paved areas, snow-covered flat plain, tide flat, smooth desert.	0.0014
0.005	Smooth	Beaches, pack ice, morass, snow-covered fields.	0.0028
0.03	Open	Grass prairie or farm fields, tundra, airports, heather.	0.0047
0.1	Roughly open	Cultivated area with low crops and occasional obstacles (single bushes).	0.0075
0.25	Rough	High crops, crops of varied height, scattered obstacles such as trees or hedgerows, vineyards.	0.012
0.5	Very rough	Mixed farm fields and forest clumps, orchards, scattered buildings.	0.018
1.0	Closed	Regular coverage with large size obstacles with open spaces roughly equal to obstacle heights, suburban houses, villages, mature forests.	0.030
≥2	Chaotic	Centers of large towns and cities, irregular forests with scattered clearings.	0.062

What is an Eddy?

Wind Profiles and Stability



The logarithmic wind profile is modified under the influence of stability. Under unstable conditions, the shear becomes concentrated close to the surface. Under stable conditions the shear is reduced but may extend to greater heights to reach the same average BL wind speed



Using a logarithmic y-axis, the influence of stability is seen through the deviation from the linear neutral profile: The unstable profile is characterized by a concave curve and the stable profile has a deviation towards a convex curve.

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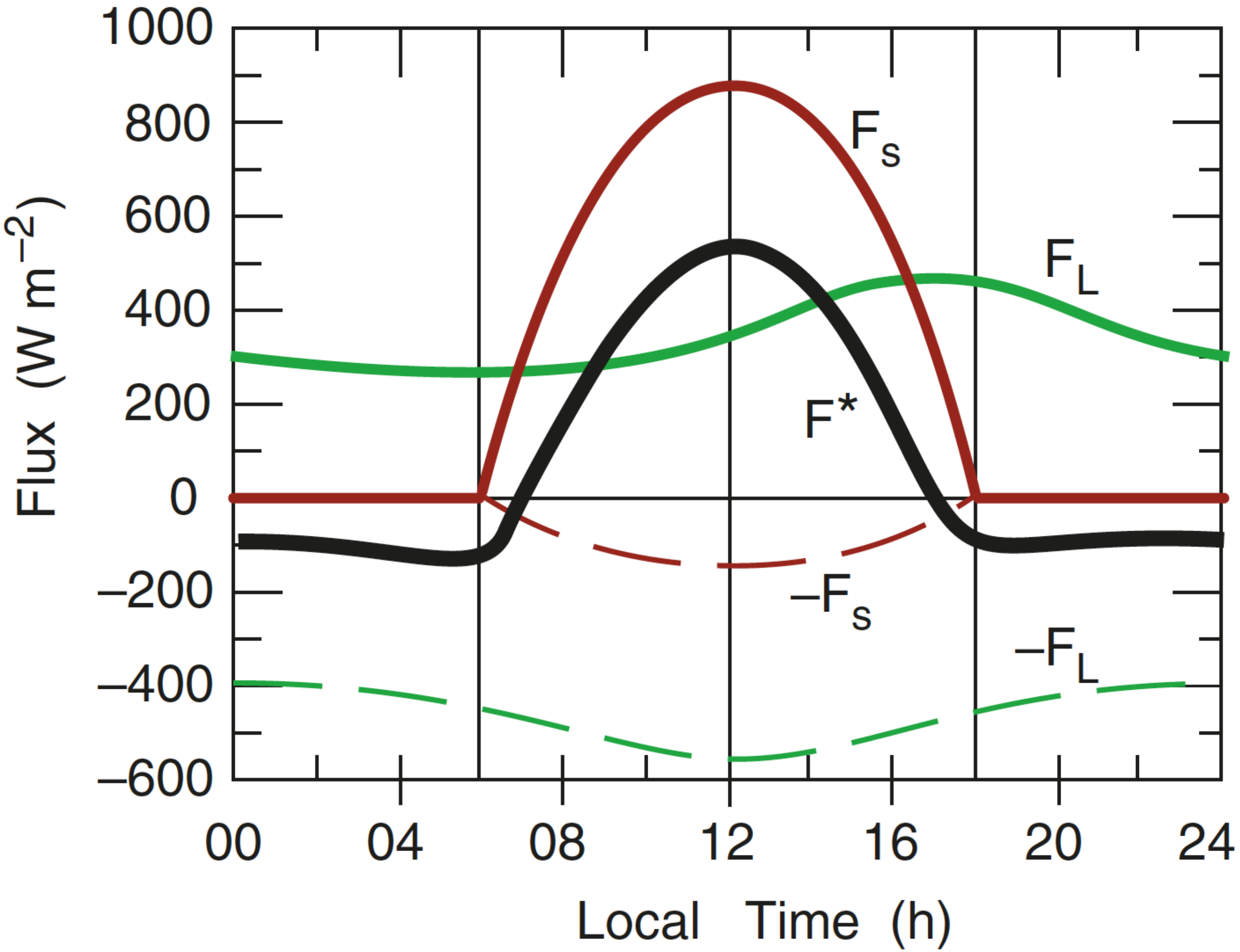
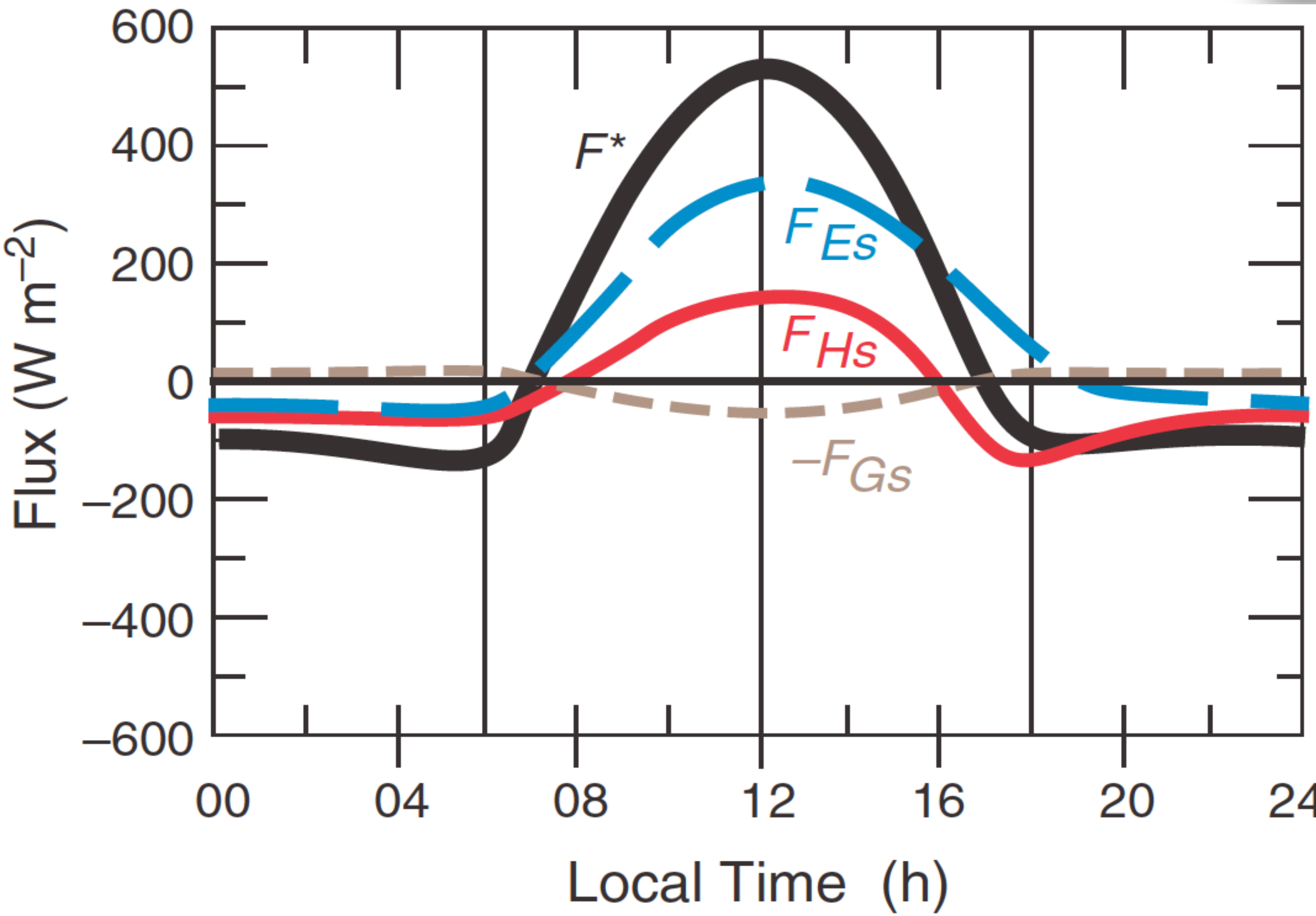
Surface Radiation Balance - Fair Weather



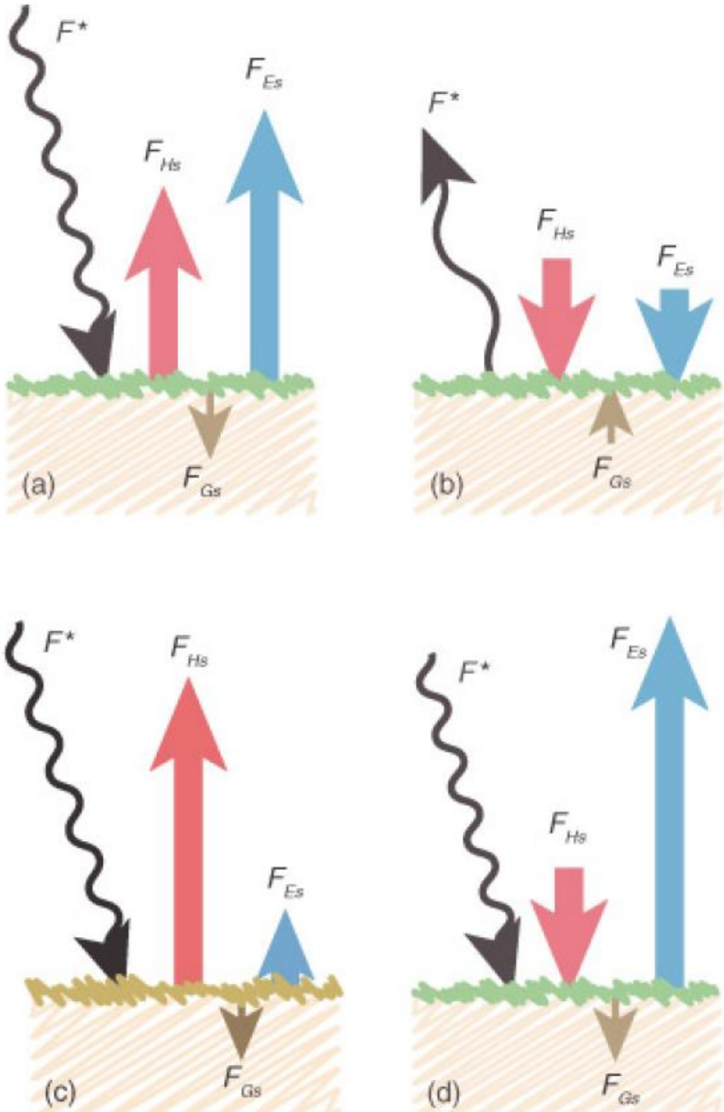
Typical diurnal cycle of net radiation (F^*), shortwave (F_S) and longwave (F_L) radiative fluxes. Negative (dashed) lines denote fluxes that leave (cool) the surface.

Surface Energy Balance - Fair Weather



Typical diurnal cycle of net radiation (F^*) as a source for sensible (F_{Hs}) and latent (F_{Es}) heat fluxes. The heat flux into the ground (F_{Gs}) closes the energy balance. The relative magnitude of the fluxes is valid for a moist and probably vegetated surface.

Typical Situations



Relative magnitude of the same fluxes as on the previous slide for different environments: (a) Daytime over a moist surface with vegetation – see previous slide; (b) At nighttime over the same surface, the radiative cooling causes the other fluxes to change sign; (c) Over a dry surface (rock or desert), the sensible heat flux becomes the dominant term to balance heating through radiation; (d) If a hot and dry wind finds moisture on a surface (oasis) the latent heat becomes dominant again.

Pick the right order of energy term contributions to a melting snow cover on a sunny day in late spring

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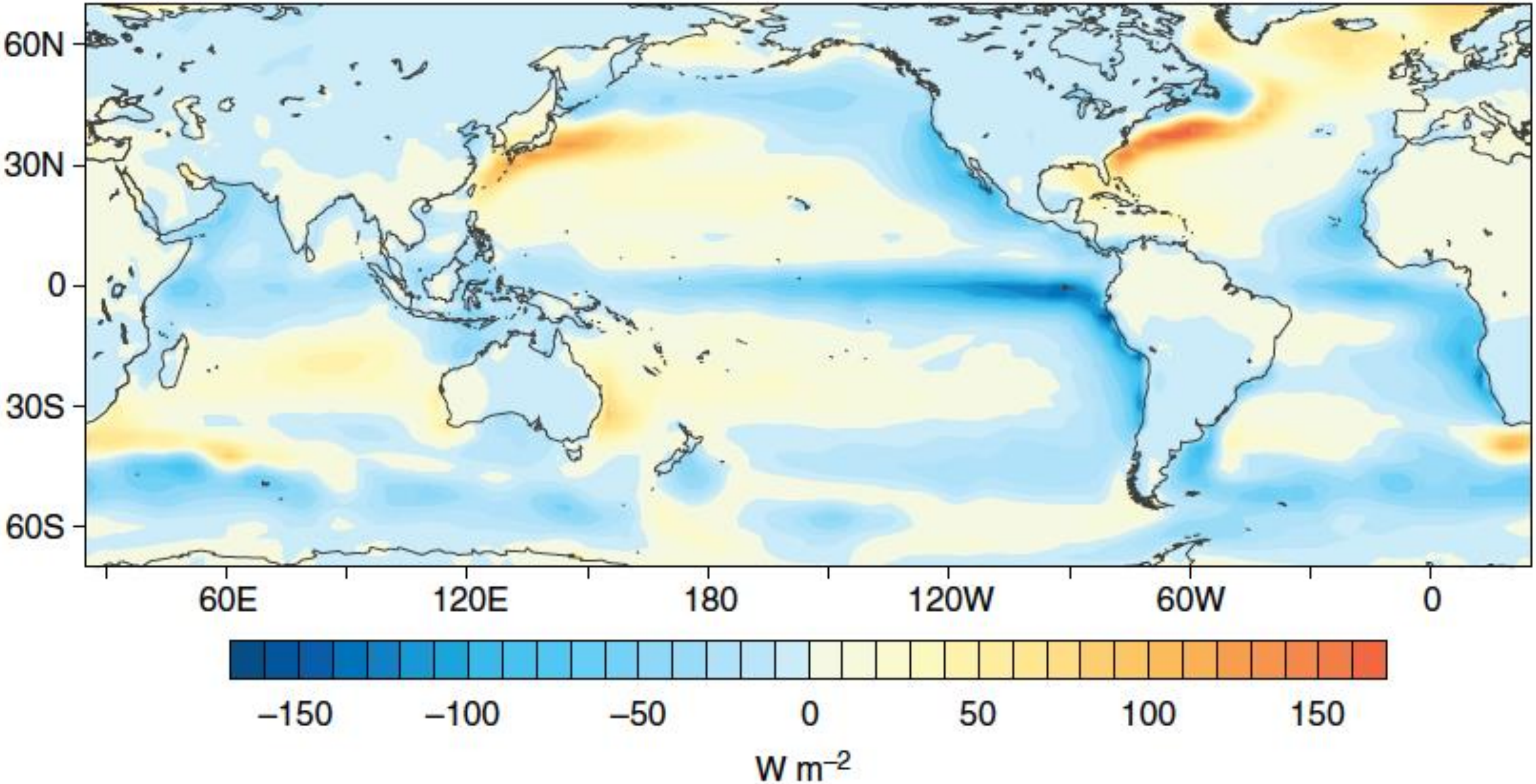
A. Sensible heat > latent heat > shortwave radiation
B. Shortwave radiation > longwave radiation > sensible heat
C. Shortwave radiation > sensible heat
D. Shortwave radiation > latent heat > sensible heat

Pick the right order of energy term contributions to a melting snow cover on a warm "rain on snow" day

P

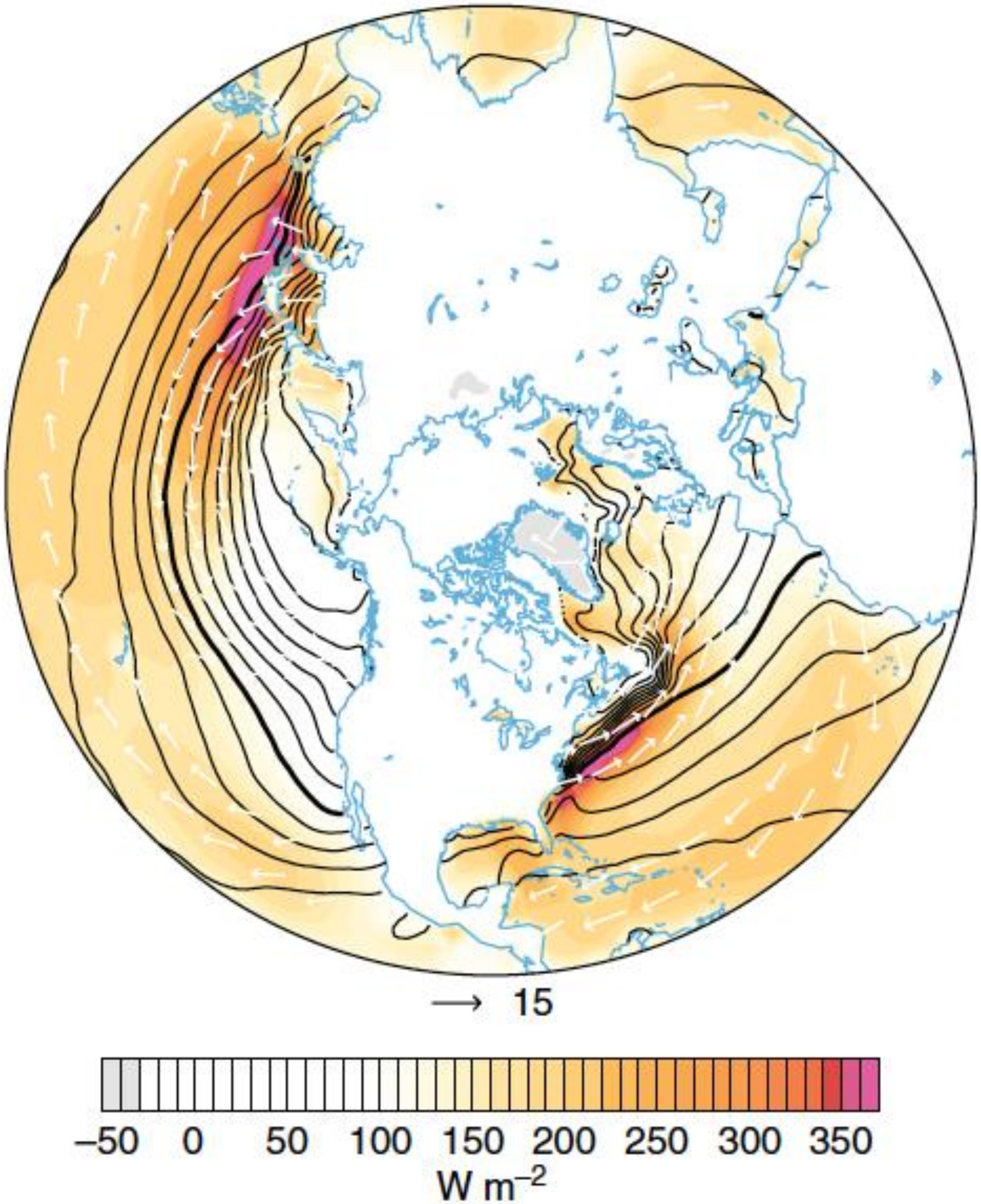
A. Sensible heat > latent heat > shortwave radiation
B. Shortwave radiation > longwave radiation > sensible heat
C. Longwave radiation > sensible heat
D. Longwave radiation > latent heat > sensible heat
E. Latent heat > sensible heat > rain advection

Mean (annual) upward surface energy flux



Upward total energy flux at the earth's surface. Local minima and maxima are associated with low respectively high surface temperatures with respect to the advected air temperature.
Question: Which is the direction (with respect to the coast) of the surface wind causing the minimum in the flux approximately at the Galapagos islands?

January Turbulent Flux to Atmosphere



Mean January turbulent (sensible and latent) upward heat flux together wind wind vectors explaining some of the regional features of the previous slide. Maximum fluxes are obtained when cold continental air flows over warm water currents such as the Gulf Stream or the Kurishio Current.

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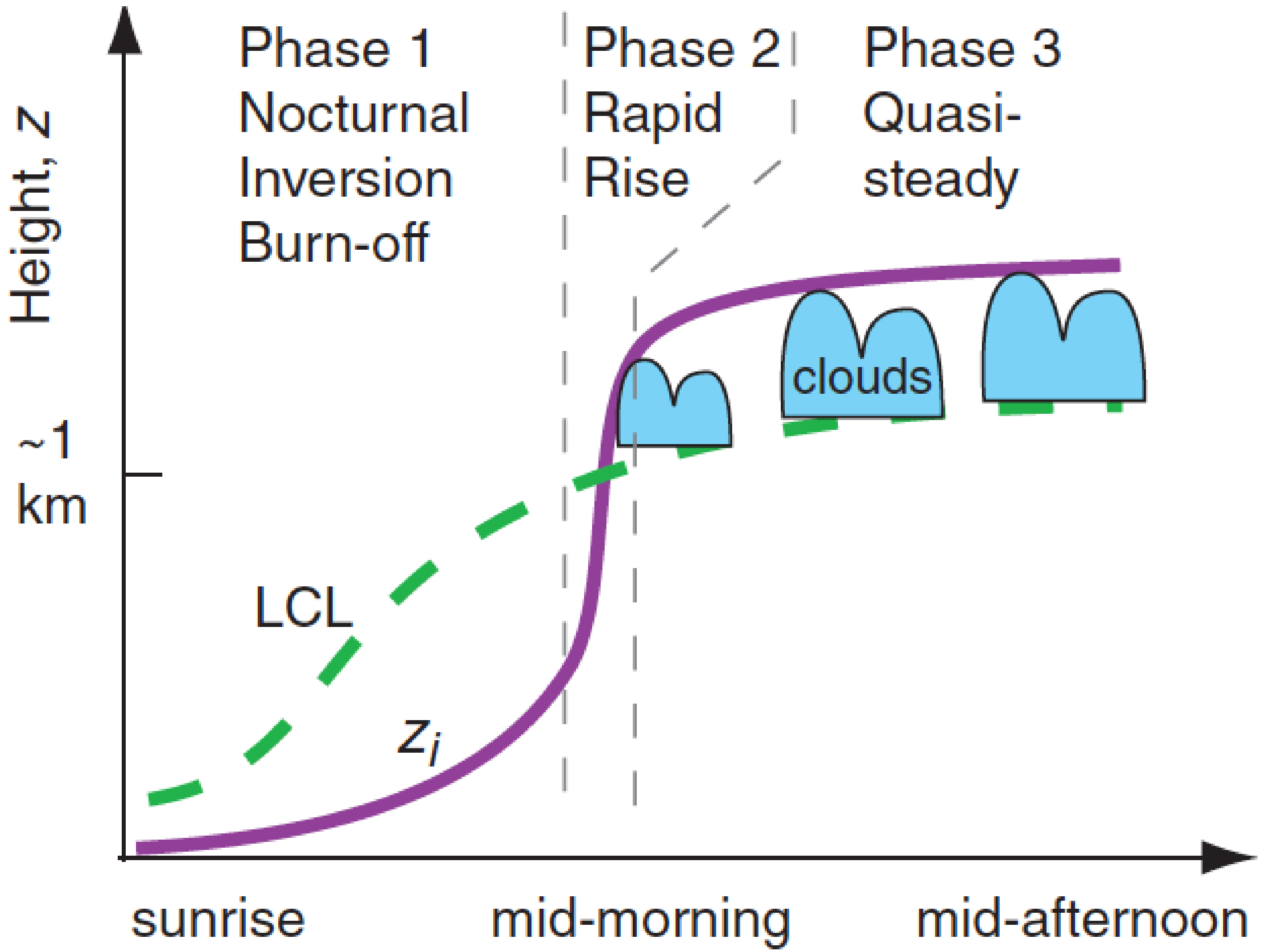
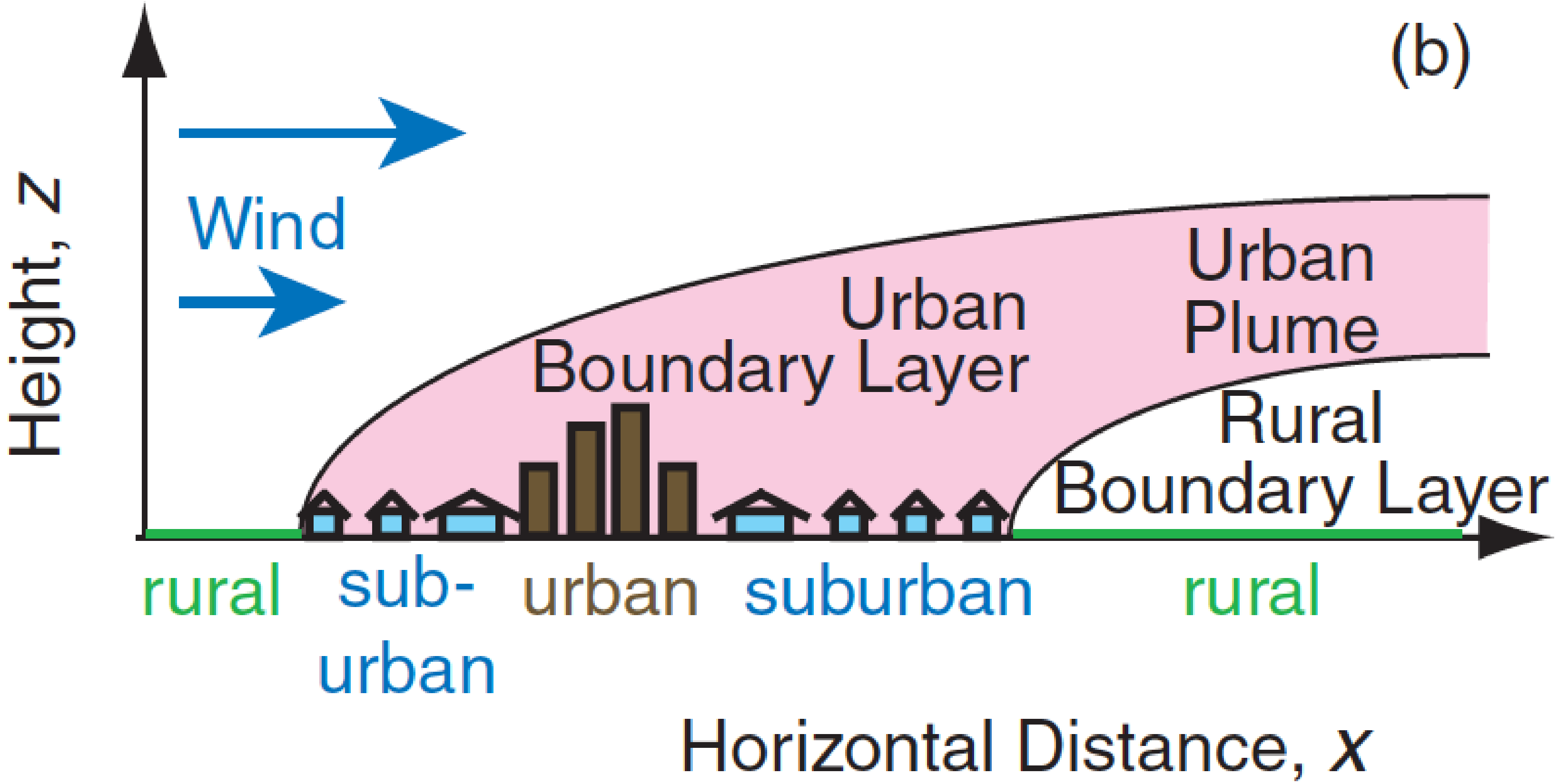
Local and small scale features



Remember the lifting condensation level (LCL)? In a rather moist atmosphere, the BL top (EZ) can cross the LCL and fair weather cumulus clouds will develop. These are different from a situation of deep convection, which you have already seen in the introduction lecture.

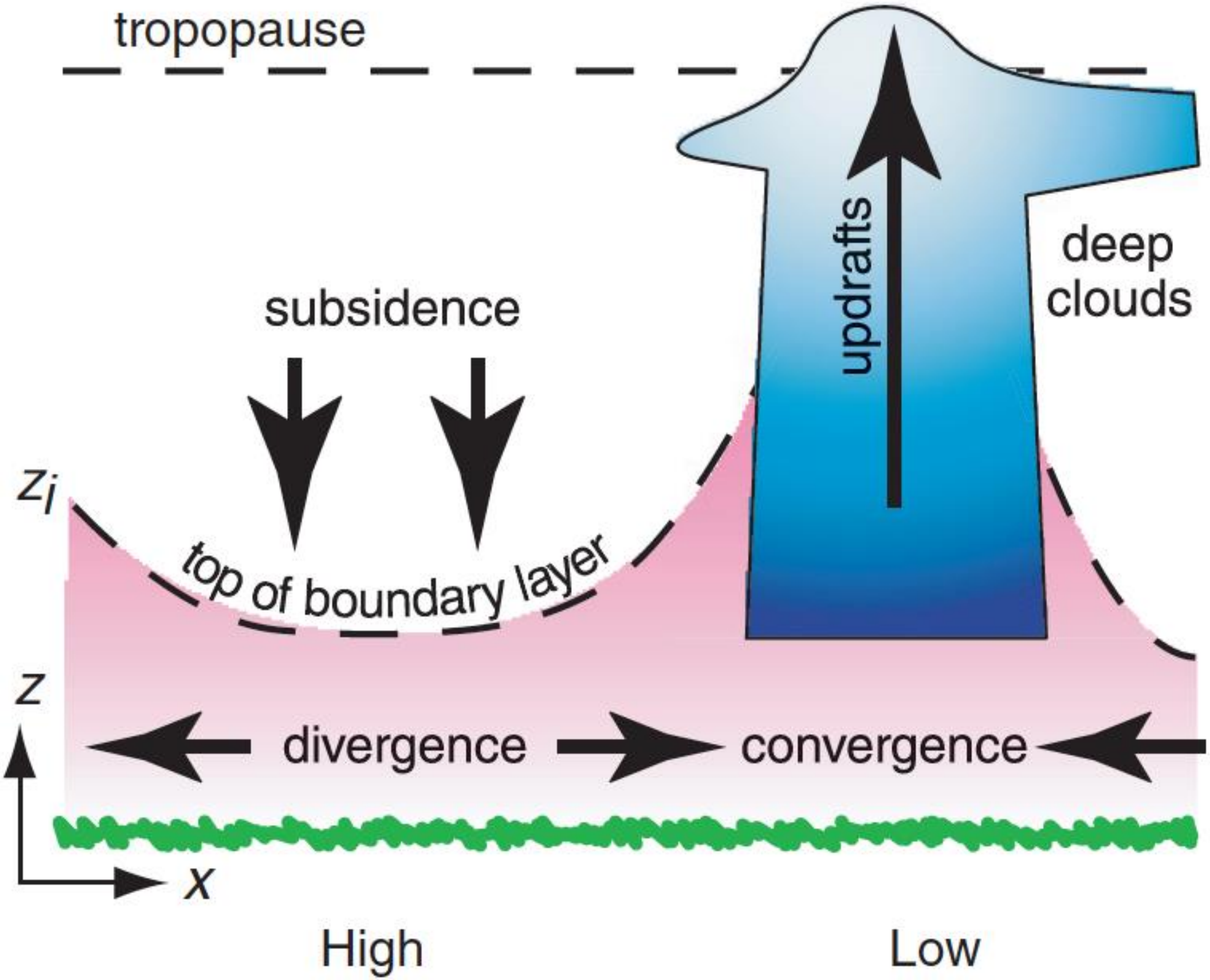
Urban Heat Island



Over horizontally inhomogeneous terrain such as urban versus rural landscapes, different boundary layers develop with typical characteristics, which then may be advected quite some distance in the downwind direction. A urban environment creates a heat island in summer.

Q: Think about two main reasons why urban environments are hotter under the summer sun.

Effects on the ABL



Subsidence in high pressure systems can lower the height of the BL (z_i) and convection can completely wipe out the upper BL boundary.

Take Home Messages

- The ABL is the layer which reacts on the time scale of hours to changes in the surface (energy balance).
- Different types of ABLs are: Constant flux layer = surface layer, stable boundary layer (nighttime), convective boundary layer (fair weather). The convective boundary layer is well-mixed (small gradients in wind, moisture and temperature), the stable boundary layer may produce a low-level jet.
- The boundary layer is typically highly turbulent (exception: very stable situations), which leads to an efficient vertical transport of heat and moisture.
- The correlation of turbulent quantities (velocity, temperature, moisture), which are defined as deviations from their (ergodic, **temporal** or spatial) mean, are a measure of turbulent (momentum, sensible heat, latent heat) fluxes.

Take Home Messages

- Scaling considerations (Monin – Obukhov) or mixing length assumptions (Prandtl) lead to the famous logarithmic wind profile and allow to calculate momentum fluxes based on a wind speed measurement and the knowledge of surface roughness. Knowing additionally the temperature or moisture difference between surface and air, we can also calculate sensible and latent heat fluxes respectively.

- The surface radiation balance is approximately balanced by the sum of latent and sensible heat fluxes. Ground heat flux is typically small. The partitioning between sensible and latent heat fluxes depends on both, surface and atmospheric conditions.

- The idealized BL is modified by clouds, canopies, urban areas, convection and fronts, topography, land – water boundaries, snow distribution…..