Part A: Multiple choice questions

Solve all multiple choice questions. Check only one box per question. If you check none or multiple boxes, your answer will be invalid. Total: 24 marks (24% of exam).

1. What is the dominant heat transfer mechanism in the planetary boundary layer? [2]

   ◯ Conduction ☒ Convection ◯ Diffusion ◯ Dissipation

2. Name the layer of the atmosphere from the surface to the level where the frictional influence of the surface is absent. [2]

   ☒ Planetary boundary layer ◯ Residual layer ◯ Troposphere ◯ Laminar boundary layer

3. What is the name of the characteristic vertical mixing distance which occurs in a turbulent flow? [2]

   ◯ Roughness length ◯ Free molecular path length ◯ Obukhov length ☒ Mixing length

4. The pathway of water vapour from the stomatal cavity of a leaf to the surface layer can be described by a series of resistances – the stomatal resistance r_s, the laminar boundary layer resistance r_b, and the aerodynamic resistance r_a. What is the total resistance r_t of the entire system? [2]

   ☒ $r_t = r_s + r_b + r_a$ ◯ $r_t = \frac{1}{r_s + r_b + r_a}$ ◯ $r_t = \frac{r_s + r_b + r_a}{3}$ ◯ $r_t = r_s \times r_b \times r_a$

5. How is net long-wave radiation L^* defined? [2]

   ◯ $L^* = L\downarrow / L\uparrow$ ◯ $L^* = L\uparrow / L\downarrow$ ◯ $L^* = K\downarrow + L\downarrow$ ☒ $L^* = L\downarrow - L\uparrow$

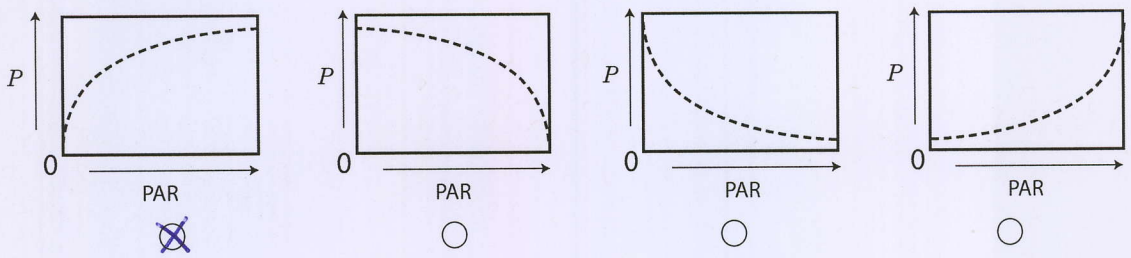
6. Which condition is typical for an oasis effect? [2]

   ◯ $Q^* < Q_H$ ◯ $Q^* > Q_E$ ☒ $\beta < 0$ ◯ $Q^* < 0$

7. What is the unit of the variance of the vertical wind velocity w? [2]

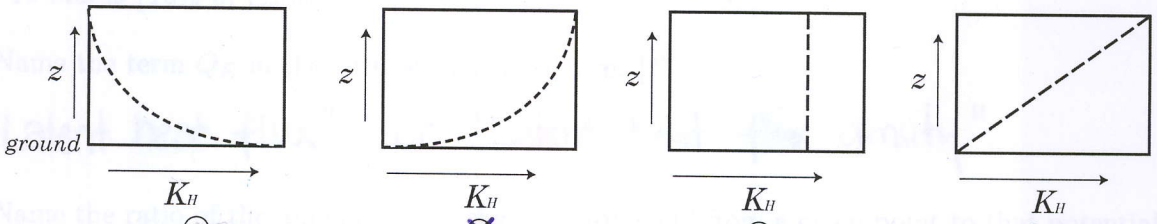
   ◯ $\mathrm{m\,s^{-1}}$ ◯ $\mathrm{m\,s^{-2}}$ ☒ $\mathrm{m^2\,s^{-2}}$ ◯ $\mathrm{m^2\,s^{-1}}$

8. How does the rate of photosynthesis P (in $\mathrm{g\ C\ m^{-2}\ s^{-1}}$) respond to incident photosynthetically active radiation PAR? [2]



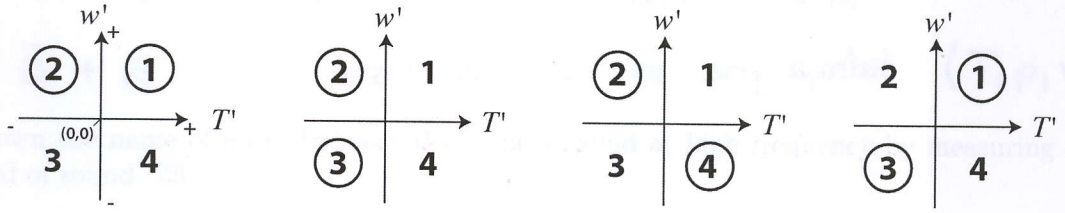
☒ ◯ ◯ ◯

9. How does the eddy diffusivity for sensible heat K_H change with height above ground z in the surface layer? [2]



○ ⊗ ○ ○

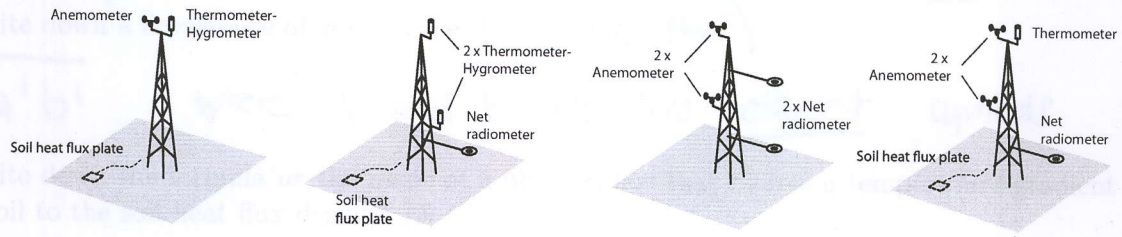
10. In the surface layer, which two quadrants (combinations) of the joint probability distribution between vertical wind w' and air temperature fluctuation T' are the two most likely ones to occur in the late evening (after sunset)? [2]



○ ○ ⊗ ○

11. Which statement about the laminar boundary layer (LBL) thickness is incorrect? [2]
- ⊗ The LBL thickness shrinks with increasing object size.
- ○ The LBL thickness shrinks with increasing wind speed.
- ○ The LBL thickness shrinks with increasing buoyancy.
- ○ The LBL thickness shrinks with increasing roughness of the surface.

12. Which experimental set-up allows a quantitative determination of all terms of the surface energy balance above an extensive, flat land-surface under all atmospheric conditions? [2]



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Part B: One-word questions

Answer all of the following short answer questions in one or a few words, or provide a formula. Total: 16 marks (16% of exam).

1. Name the term Q_E in the surface energy balance. [2]

   "Latent heat flux" or "Latent heat flux density"

2. Name the ratio of the amount of the sky actually 'seen' from a given point to that potentially available (i.e. the entire upper hemisphere)? [2]

   "Sky view factor" or Ψ_{sky}

3. Write down the Reynolds decomposition for any variable of your choice. [2]

   $a = \bar{a} + a'$ where a can be any symbol (T, p, v, w etc.)

4. Write down the name of an instrument that reports wind at high frequency by measuring of the speed of sound. [2]

   "Sonic anemometer" or "Ultrasonic anemometer" (not Eddy covariance!)

5. Name a number or parameter that describes the dynamic stability of the atmosphere. [2]

   Richardson flux number (Rf), Richardson (gradient) number (Ri) or z/L (give 1 mark for "Obukhov length L")

6. List an approach you can use to measure evapotranspiration from an ecosystem. [2]

   Eddy covariance, Bowen-ratio energy balance, aerodynamic approach, lysimetry, Penman-Monteith approach, Combination model (not Perometry and not sap flow)

7. Write down a covariance of your choice. [2]

   $\overline{a'b'}$ where a and b are two different symbols

8. Write down the formula *or* the name of a physical law that relates a temperature gradient in a soil to the soil heat flux density. [2]

   "Fourier's law" or $Q_G = -k \frac{\partial T}{\partial z}$

   ↑ can be also Δ

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Answer Key for Part C

C1 [5 total]

Evaporation is the process of vaporization of water[1] [1] to the atmosphere (from surfaces, soils, surface of leaves etc.) without the involvement the plants[2].

Transpiration is the process of vaporization of water [1] to the atmosphere within (and on) plant tissues[3] [1] which is physiologically controlled[4] by the plant [1]

[1] Can also say 'the process by which liquid water is transformed into water vapour'
[2] Can say 'not controlled by plant physiology', or 'a process purely controlled by thermodynamics / physics'
[3] Can also say 'within leaves' or through the 'stomata of leaves'
[4] Can also say 'controlled by stomatal resistance' or through the 'controlled by stomatal aperture'

C2 [5 total]

A *'cold' snowpack* is considerably below 0ºC, so that it only contains ice [1]. The only relevant energy exchanges are net-radiation (Q^*), the sensible heat flux density to the atmosphere (Q_H) and heat storage change (ΔQ_S) [1].

In contrast, a *'wet' snowpack* contains simultaneously ice and water [1] and in addition also a substantial exchange of latent heat Q_E [1] and the energy required to melt the snow (ΔQ_M) [1]

[1] You can also mention the input of energy by rain Q_R, but this is not truly an difference (can happen with cold sno packs as well, so no additional marks for Q_R.

C3 [5 total]

Photosynthesis is the formation of carbohydrates[1] in the chlorophyll-containing tissues of plants [1] from water and atmospheric CO_2 [1] under the input of photosynthetically active radiation [1].

Respiration is the reverse process, oxidation[3] of carbohydrates [1] with the release of CO_2 (to the atmosphere), water and energy [1] in order to provide energy for plants, microbes and animals.

[1] Instead of carbohydrates can say 'complex organic molecules' or 'plant material'
[2] Can also say "carbon-dioxide" but must mention uptake of CO_2 from atmosphere.
[3] Can also say 'decomposition of carbohydrates'

C4 [5 total]

Anabatic wind is a flow[1] in complex topography[2] [1] that flows upwards [1] (up-hill or up-valley, from lower orography to higher orography) due to pressure differences along a slope[3] [1]

A katabatic wind is a flow blowing down [1] an incline due its colder temperatures (higher density) compared to the surrounding air [1].

[1] 'Wind' or 'breeze' are both OK.
[2] Instead of complex topography, can say in mountainous terrain or similar. Need reference to orography / topography / elevation in some form.
[2] If they say because it is warmer than the surrounding air only 0.5 marks.

C5 [5 total]

Both are instruments [1] used in meteorology. A lysimeter measures evapotranspiration [1] from a soil-plant monolith by tracking the weight of the monolith [1] over time.

A pyranometer is an instrument to measure the short-wave irradiance $K\downarrow$ (or short-wave reflectance $K\uparrow$ if installed upside down) [1] by measuring the warming of a black absorber disk [1] relative to the instrument body.

C6 [5 total]

(Those two are essentially not related other than the name of the scientist)

Reynolds number (Re) - A (dimensionless) number [1] that can be used to describe the state of a flow (turbulent or laminar). [1] The Reynolds number is the ratio of inertial forces ($\rho\ u$) to viscous forces (μ/L)[1]. [1]

Reynolds analogy - is an assumption [1] that eddy diffusivities for different entities (heat flux densities, mass flux densities, momentum flux density) are equal. [1]

[1] Instead can provide formula, i.e. Re = $\rho\ u\ L\ /\ \mu$ or Re = $u\ L\ /\ \nu$

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Answer Key for Part D

D1 [10 total]

(a) is from the clear-sky summer day [2]
(b) is from the windy, overcast day [2]

Justification:

In (a) we have both thermal [1] and mechanical convection. / turbulence The dominating thermal convection creates large eddies [1] (i.e. long wavelength, low frequency) that scale with the height of the entire PBL [1]

In (b) we have only mechanical [1]convection / turbulence. The mechanical convection creates smaller eddies [1] (i.e. shorter wavelength, higher frequency) that scale with the size of roughness elements in the landscape. [1]

D2 [10 total]

a) The dynamic stability is neutral [3] (justification: the graph is a straight line).
b) The roughness length is z_0 = 0.1 m [4]
   a. 1 mark for mentioning it is where u =0, or sketch of extending down to u = 0.
   b. 1 marks for value.
   c. 1 mark for unit metres.
c) The expected graph is shown below [3]
   - 1 mark if the graph has same *y*-intersect (same z_0) .
   - 1 marks if the graph is straight (not curved).
   - 1 mark if the graph is below (less slope) than the one shown.

D3 [10 total]

a)

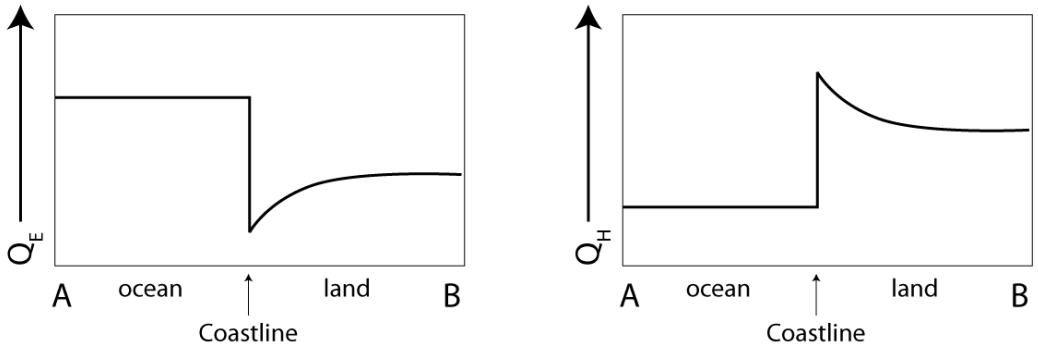
Comparison between ℓ and D	Atmospheric / weather situations
1) ℓ < D [1]	"Mechanical turbulence only" *or* "windy, overcast" *or* "In the surface layer close to the ground" [1]
2) ℓ = D [1]	"Mechanical and thermal turbulence" *or* "windy + sunny" *or* "In the surface layer somewhat above ground" [1]
3) ℓ > D [1]	"Thermal turbulence only" *or* "calm + sunny (in summer)" *or* "in the mixed layer well above ground" [1]

Can also attribute stable to 1), neutral to 2) and unstable to 3) [full marks]. Although not completely correct.

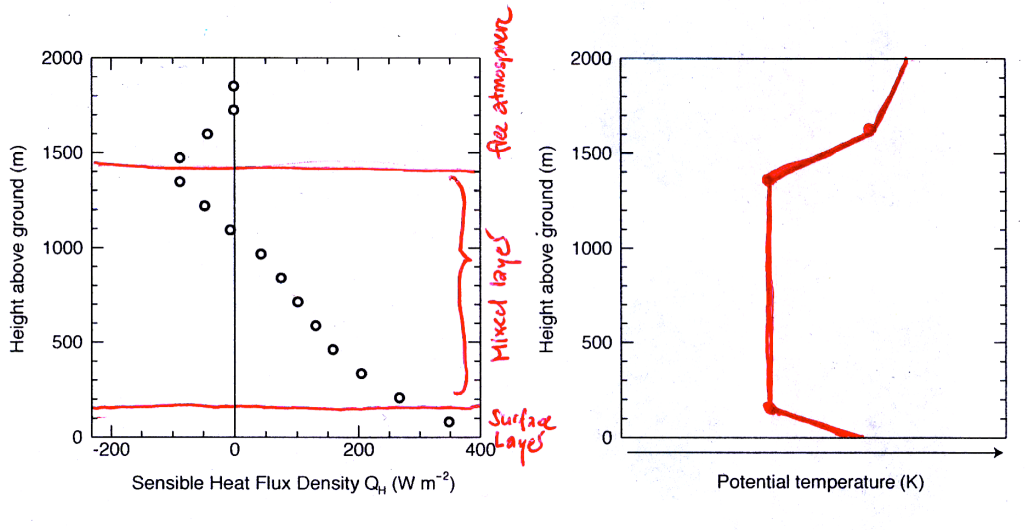
b) a=3, b=2, c=1 [2 marks is one correct attribution and two mixed up, 4 marks if all correct]

D4 [10 total]

a) The left map is 00:00 and the right map is 16:00 [2]
b) The left map shows a land breeze and the right map shows a sea breeze [2]
c) Sketch of Q_E and Q_H from A to B [3 each], give partial marks for change of flux from ocean to land, and shape. Over ocean flux does not change (must be horizontal line):



D5 [10 total]



a) [3 marks] for correct attribution of layers. Surface layer must be about 10% of Mixed layer / free atmosphere boundary.
b) The negative Q_H is due to a downward flux of Q_H in the entrainment zone [2]. Acceleration due to buoyancy causes thermals in the mixed layer to penetrate some distance up into stable layer [1], where they mix and bring down warmer air from the free atmosphere into the mixed layer [1].

c) [3 marks for correct profile]. Potential temperature must be constant with height within mixed layer, and unstable at bottom, stable at top. Inversion strength should decrease above entrainment zone.

D6 [10 total]

a) This is an infrared thermometer [3]
b) It measures long-wave emittance [2] (specifically in the atmospheric window) of an object and uses the Stefan-Boltzman law[2] [2] to solve for temperature.
c) This button allows to adjust the emissivity [2] of the object, as most objects are grey bodies ($\varepsilon < 1$) rather than black bodies ($\varepsilon = 1$) [1]

[1] Alternatively: 'IRT' or 'bolometer'
[2] Alternatively: $E = \sigma T^4$ or $E = \varepsilon\sigma T^4$