McGill University
Knox / GEOG 321 / April 26, 2024
Climatic Environments

Answer Key

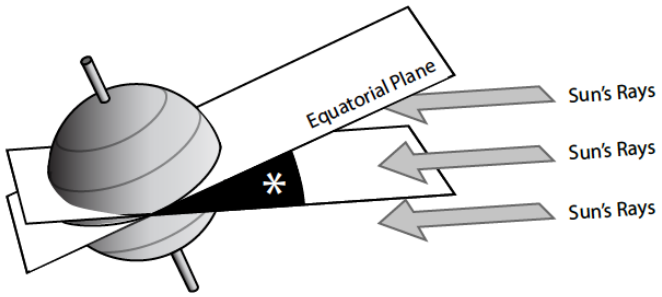
Part A: Multiple choice questions

1. What does the term z_d in the logarithmic wind law below represent [2]

$$\overline{u} = \frac{u_*}{k} \ln(\frac{z - z_d}{z_0})$$

◯ Roughness length
◯ Friction velocity
⊗ Zero-plane displacement
◯ Measurement height

2. What is the name of the angle (*) in the following figure? [2]



◯ Solar azimuth ◯ Declination ◯ Latitude ◯ Hour angle

3. Which term is <u>not</u> part of net ecosystem productivity (NEP)? [2]

◯ Gross Primary Productivity
◯ Heterotrophic respiration
⊗ Heat of assimilation of carbon
◯ Ecosystem respiration

4. Which term is <u>not</u> part of the water balance of a land-surface? [2]

◯ Evapotranspiration
⊗ Run-off ratio
◯ Change in storage
◯ Precipitation

5. Which term describes the friction velocity u_*? [2]

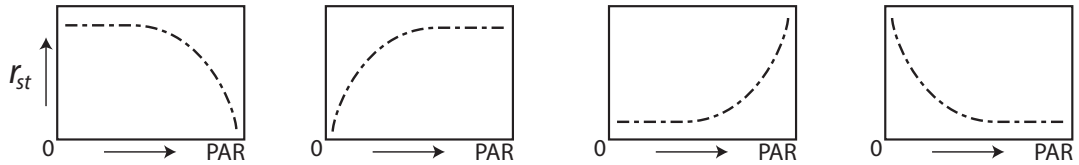
◯ τ^2 ◯ $K_M\, \partial u/\partial z$ ⊗ $\sqrt{-\overline{u'w'}}$ ◯ $K_M\%, \overline{u'w'}$

6. Which expression describes the latent heat flux density (Q_E) in $\mathrm{W\,m^{-2}}$? [2]

◯ $\rho_v\, L_v\, E$ ◯ $\rho_a\, c_p\, \partial\theta/\partial z$ ⊗ $L_v\, \overline{w'\rho'_v}$ ◯ $\rho_a\, c_p\, \overline{w'T'}$

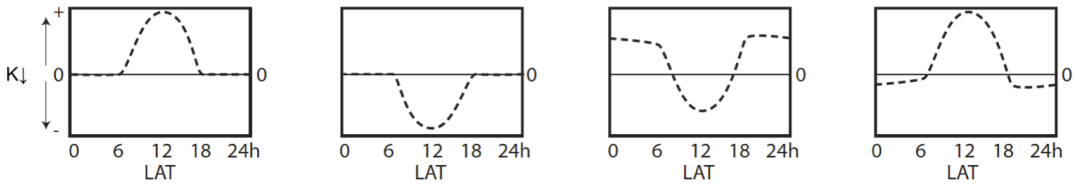
7. Which statement on turbulence in the atmospheric surface layer (SL) is correct? [2]
   ◯ All turbulence in the SL is produced by buoyancy.
   ◯ The typical size of eddies decreases with height above ground.
   ⊗ Mechanical production of turbulence dominates in the SL.
   ◯ The turbulent kinetic energy in the SL increases with stability.

8. How does stomatal resistance of a leaf (r_{st}) change with PAR? [2]



   ◯ ◯ ◯ ⊗

9. How do you expect incoming shortwave radiation ($K\downarrow$) to change with time over a 24h period? Assume summer, clear skies and a grass surface on UBC Totem Field. [2]

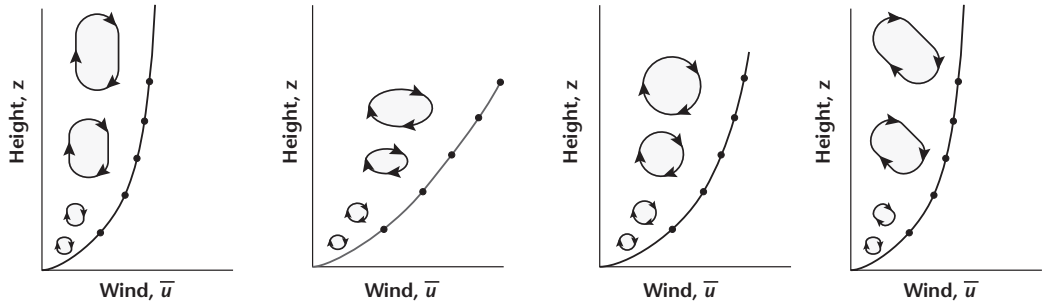


   ⊗ ◯ ◯ ◯

10. UBC researchers have installed the following instrumentation above a forest clear-cut. What variable can be measured using this instrumentation? [2]

   ⊗ Evapotranspiration (E).
   ◯ Net all-wave radiative flux density (Q^*).
   ◯ Soil heat flux density (Q_G).
   ◯ Interception (P_I).

11. Which sketch shows the eddy shape and the wind profile under stable conditions? [2]



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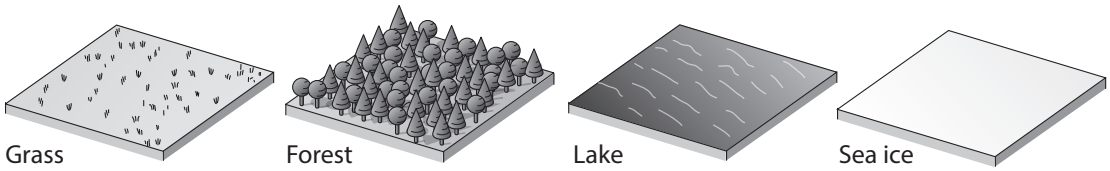
12. Which of the following surfaces has the largest aerodynamic roughness length z_0? [2]



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Part B: Terminology questions

Students must answer <u>all</u> of the following short answer questions. Total: 16 marks (16% of the exam).

1. *Name a term of your choice that is part of the surface energy balance equation. [2]*

   Can list any of: net [all-wave] radiation (or Q^*), sensible heat flux [density] (or Q_H), latent heat flux [density] (or Q_E), soil heat flux [density] (or Q_G). Can list name and/or symbol to get [2].

2. *Which wavelengths of the electromagnetic radiation spectrum fall within the shortwave band?*

   0.15 [1] – 3 μm [1] (or 150 – 3000 nm)

3. *What is the most effective transfer mechanism for sensible heat in the atmospheric boundary layer?*

   <u>Convection</u> [2] (or 'turbulence')

4. *What is the name of the term $\sqrt{\overline{T'^2}}$ if T is air temperature? [2]*

   <u>Standard deviation</u> [1] of (air) temperature [1]

5. *List a method of your choice that can be used to measure evapotranspiration of a crop. [2]*

   Any of the following: Eddy covariance, Lysimetry, Penman-Monteith (or combination model), Aerodynamic approach, Bowen ratio-energy balance approach, Monin-Obukhov similarity. DO not count: Porometry, Sap flow, Pan evaporation.

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

   $a = \overline{a} + a'$, where a can be any symbol (T, v, w, ρ, etc.) [2]

7. *How do you call an event in a turbulent flow that transports excess momentum from a high velocity region to a low velocity region?*

   <u>Sweep</u> [2]

8. *Name a process that can produce turbulence in the atmosphere. [2]*

   <u>Forced</u> (or mechanical) production

   Or

   <u>Free</u> (or thermal) production

Part C: Define and Compare Terms

Answer only three of the following five questions. For each of the three questions you choose to answer, briefly define each term and explain the differences between the two terms in italics. Only the first three questions with witting will be marked.. Total: 18 marks (18% of the exam).

1. Define *advection* and *entrainment* and briefly explain the difference between them. [6]

   Advection refers to a dominantly horizontal [1] (non-turbulent) transport [1] in the atmosphere by mean wind [1]. Entrainment is the downward transport [1] (or 'mixing') of warmer air [1] (or a 'sensible heat flux') from the free atmosphere into the ABL [1] by turbulence.

2. Define *throughfall* and *stemflow* and briefly explain the difference between these two terms. [6]

   Throughfall (P_T) is precipitation [1] directly falling through the canopy / crown space or deflected by the tree crowns reaching the ground [2]. Also accept for [1] that a special case of throughfall is canopy drip.

   Stem flow (P_S) is the process where water/precipitation [1] is drained along leaves, branches, and finally directed to the tree's stem [2].

3. Define *convective boundary layer (CBL)* and *stable boundary layer (SBL)* and briefly explain the difference between these two terms. [6]

   The convective boundary layer is a state in which the atmospheric boundary layer (ABL) is heated from below (i.e. surface) (can also say with a negative Q_H at the surface) [1], and exhibits strong turbulent mixing [1] by buoyancy [1] (can also say ABL is 'dynamically unstable' or 'statically neutral').

   The stable boundary layer is a state in which the ABL is cooled at the surface (e.g. night) (or can say 'with a negative Q_H at the surface') [1.5], and where buoyancy suppresses mixing [1.5] (can also say ABL is 'dynamically stable' or 'characterized by an inversion at the surface', 'contains waves').

4. Define *atmospheric boundary layer depth* and *damping depth* and briefly explain the difference between these two terms. [6]

   The atmospheric boundary layer depth is the height in the atmosphere [1] where there is no more a diurnal course of variables [2] (temperature, humidity, ect.) (Can also say where frictional influences of the surface vanish.). The damping depth in a soil is the depth at with the surface temperature [1] wave reaches 37% (Can also say to e^{-1} or $1/e$) [2] of the amplitude at the surface).

5. Define *respiration* and *transpiration* and briefly explain the difference between these two terms. [6]

   Respiration is the oxidation of carbohydrates [1] in living organisms [1] (can also say 'breathing') associated with the release of energy and carbon dioxide [1]. Transpiration is the process in which which liquid water is transformed into water vapour within leaves [1] which is physiologically controlled by the opening of the stomata [2].

Part D: Problem questions

Answer only three out of the following five questions. Again: the first three questions with any answer written into the space provided will be marked, hence solving more than three questions is not to your advantage. Total: 42 marks (42% of the exam).

1. *Stomatal resistance r_s is key control affecting land-atmosphere exchange. (a) Define in your words what r_s describes? (b) What are the units of r_s, and (c) list four environmental controls that affect r_s and describe with words or draw a diagram showing how an increase in each environmental control would impact r_s. [14]*

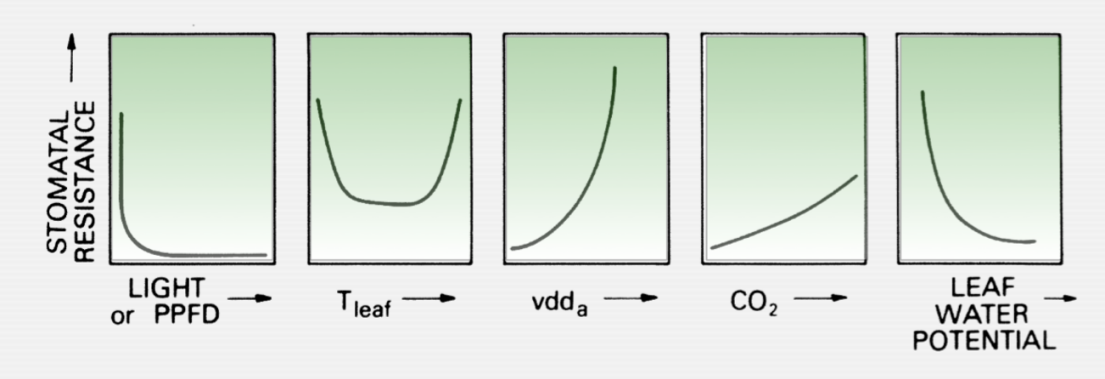
   (a) The resistance of a leaf to the exchange of water and carbon dioxide [1] between the leaf's interior and the atmosphere [1] (can also say: laminar boundary layer) physiologically controlled by the opening [1] (or: aperture) of the stomata (or: guard cells) [1]. [Max: 4]

   (b) s m^{-1} [2]

   (c) Allow any of those [1 for each, Max: 4]

   - Photosynthetically active radiation (or: PAR, or: Light, or: solar radiation)
   - Temperature (or: air temperature, leaf temperature)
   - Carbon-dioxide (CO_2) (or: CO_2 in stomatal cavity or CO_2 in atmosphere)
   - Vapour pressure deficit (or: humidity, relative humidity etc.)
   - Leaf water potential (or: water stress of plant, water availability, turgor)

   And the response to an increase in each variable is shown in the figure below: [1 for each, Max: 4]



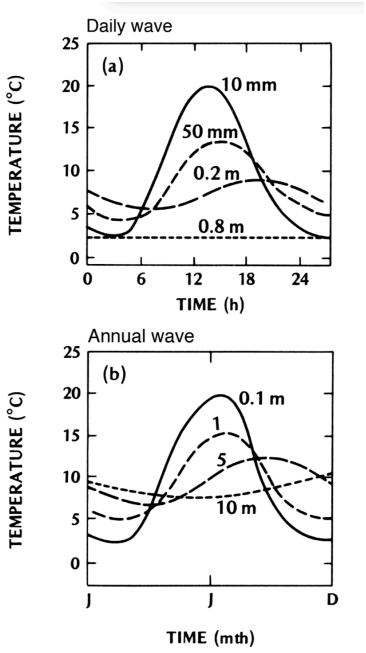
2. The questions below are related to the Fourier heat conduction equation in 1-D:

$$T(z,t) = \underbrace{\overline{T_o} + \Delta T_0 \times \exp\left[-z\left(\frac{\omega}{2\kappa}\right)^{1/2}\right]}_{\text{TermA}} \times \underbrace{\sin\left[\omega t - \left(\frac{\omega}{2\kappa}\right)^{1/2} z\right]}_{\text{TermB}}$$

Note that you do not need this equation to answer the questions below, but you might find it helpful when answering some of the questions.

(a) Describe or draw how the amplitude of the temperature wave varies with depth. [2]

The amplitude decreases exponentially with depth (Term A). Something similar to the figure below is also acceptable (same for (c)).



(b) At a depth of 10cm in the soil, is the amplitude of the diurnal wave larger or smaller in a soil with a large thermal diffusivity (κ_s)? [3]

The amplitude will be larger in a soil with a large κ_s (see Term A or the web applet)

(c) Describe or draw how the phase shift (time lag) varies with depth. [3]

The phase shift (time lag) increases linearly (Term B).

(d) Is the phase shift at a depth of 30 cm larger or smaller for soils with a large κ_s? [2]

The phase shift at that depth is less in soils with large κ_s

(e) Approximately how far down does the surface temperate wave move down into the soil in response to radiative forcing at the daily and annual time period. [4]

Annual to 14 m (or something between 10-20 m) [2] Daily to 0.75 m (or something between 0.5 and 1.5 m) [2]

→ Lecture 12 and corresponding reading package.

3. *A typical eddy covariance set-up to measure terms of the surface energy balance - such as the one you saw on Totem Field - is capable of measuring the following turbulent fluctuations:* u', v', w', T' *and* ρ_v', *where* u, v *and* w *are the components of the three-dimensional wind vector (in* $\mathrm{m\,s^{-1}}$*),* T *is temperature (in K) and* ρ_v *is the absolute humidity (in* $\mathrm{g\,m^{-3}}$*). (a) How many unique covariances can you form between the variables measured? Write all unique covariance terms down. (b) Circle two covariances of your choice that relate directly to terms of the surface energy balance and provide the equation how they relate to the terms mentioned.*

(a) There are a total of 10 unique covariances possible [1], give [5] marks for table below (Note: Students can write variables reversed $\overline{T'w'} = \overline{w'T'}$. Same in reversed form cannot be listed twice. Also do not allow variances.).

	v	w	T	ρ_v
u	$\overline{v'u'}$	$\overline{w'u'}$	$\overline{T'u'}$	$\overline{\rho_v'u'}$
v		$\overline{w'v'}$	$\overline{T'v'}$	$\overline{\rho_v'v'}$
w			$\overline{T'w'}$	$\overline{\rho_v'w'}$
T				$\overline{\rho_v'T'}$

The two of relevance are:

$$Q_H = \rho_a c_p \overline{w'T'} [= C_a \overline{w'T'}]$$

[2] for identifying (encircling $\overline{w'T'}$), [2] for correct equation.

$$Q_E = L_v \overline{w'\rho_v'}$$

[2] for identifying (encircling $\overline{w'\rho_v'}$), [2] for correct equation.

No need to define variables or units.

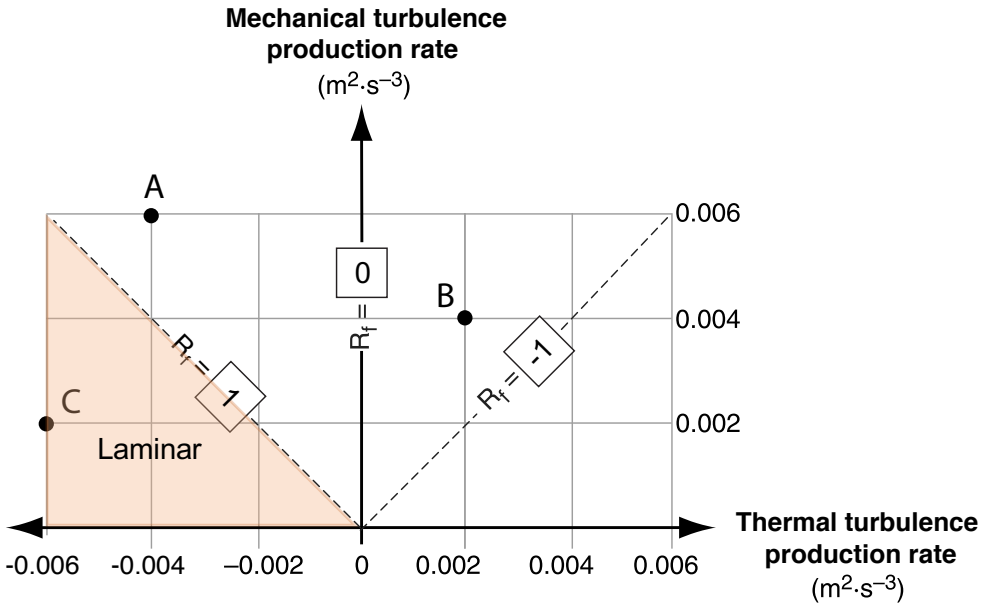
4. *The following graph illustrates the concept of the flux Richardson number (Rf).*

(a) What does Rf describe? [5]
The dynamic stability [5] (and/or the ratio of thermal production of turbulence to minus the mechanical production of turbulence).

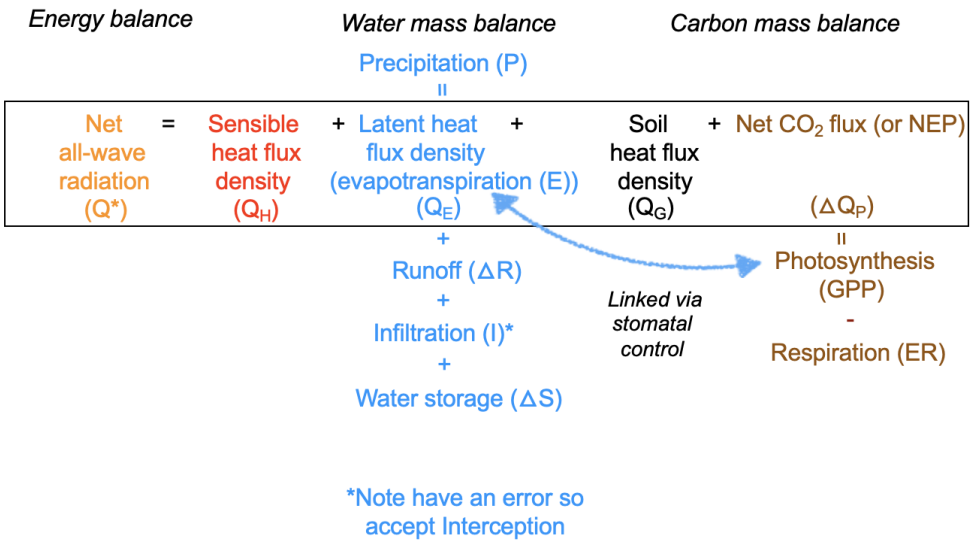
(b) Indicate in the graph, where you expect a laminar flow, and where you expect a turbulent flow? [2]
In region C in the figure below (i.e., below the line where $Rf = 1$) [2]

(c) Which point, A, B, or C, experiences highest turbulent kinetic energy (TKE)? [3].
B

(d) Insert into the three boxes the proper Rf values [6]



5. Demonstrate how the energy balance, water balance and carbon balance are linked. Make sure to include all terms in the energy, water and carbon balance. You can explain how they are linked using words or equations, but make sure to *define all symbols*. [14]



- Each term (e.g., Q*) of the energy, water, and carbon balances [1, Max: 11]. Make sure that each term is defined/described. Incorrect terms result in 1 mark being lost per incorrect term.
- Q_E links the energy and water balance [1].
- ΔQ_p (NEP is also acceptable) links the energy and carbon balance [1].
- Q_E and Photosynthesis (GEP) are linked via stomatal control [1].