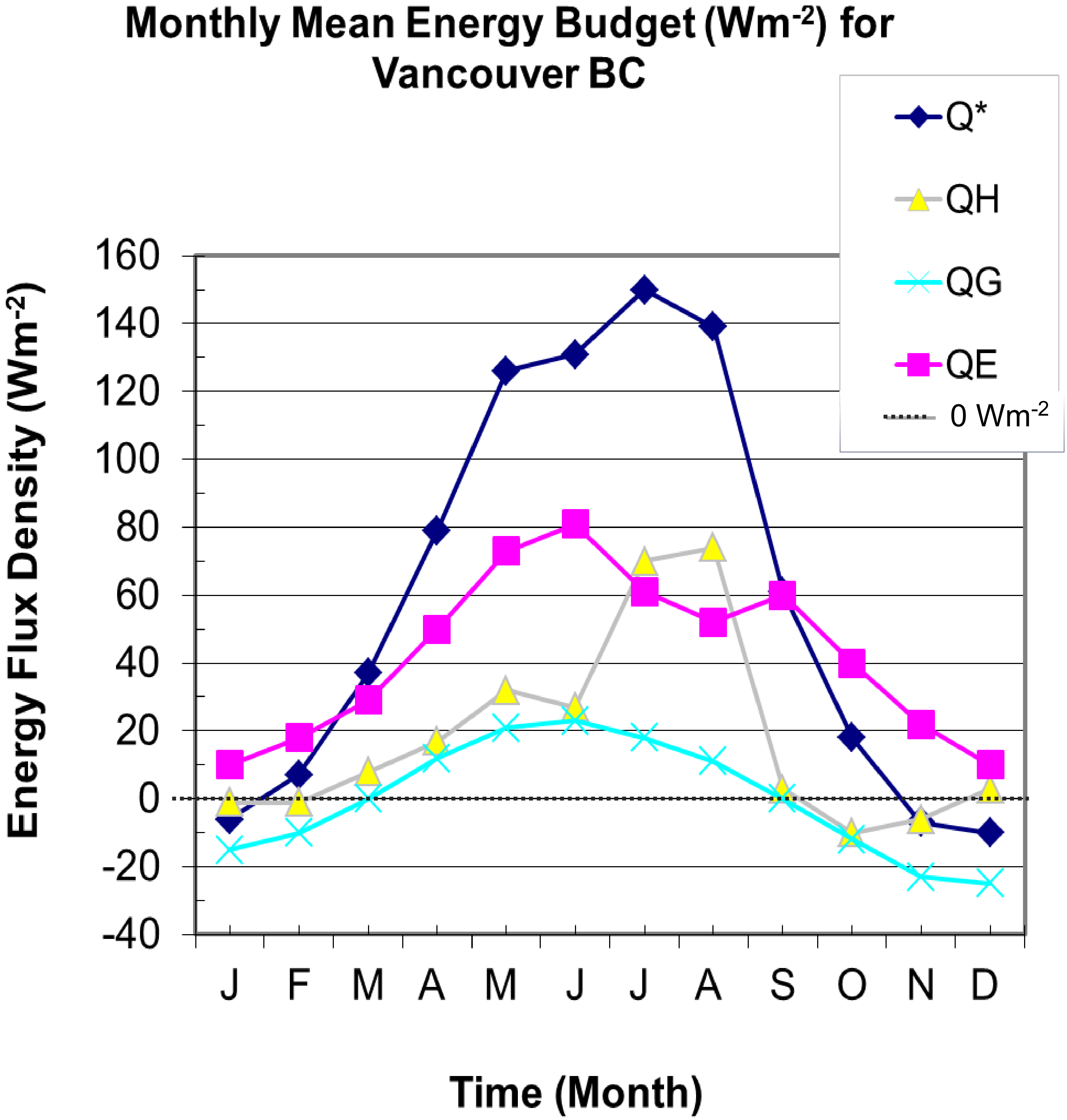
Lab 3 Answers

1) Below is Table 3.1 graphed with appropriate legend, axis labels, title, and required scales.



2) Energy flow directions for positive & negative energy budget components (Q^* Q_E Q_H Q_G). The concept of "the surface" as a massless plane indicates the boundary between the ground and the air is so thin that it can't store energy. Consequently, conservation of energy (i.e. energy is not created or destroyed, just moved around) requires that radiant energy gained or lost at the surface must be utilized as either Q_E Q_H or Q_G. Therefore, a:

- surplus of Q^* requires that energy must be removed from the surface by Q_E Q_H or Q_G
- deficit of Q^* requires that energy must be supplied by Q_E Q_H or Q_G.

The table below reports and organizes the interpretation of positive and negative energy budget components (Q^* Q_E Q_H Q_G) and helps you understand /use these conventions properly. Required answer components are highlighted in yellow.

		between the surface & the air		*between the surface & the ground*
→ → **Defines the process & form of Energy:** All are measured in Wm^{-2}	**Q^*** Net Radiation Q^* is the energy from the Radiation Balance: $Q^* = (K\downarrow - K\uparrow) + (L\downarrow - L\uparrow)$ *Q^* is the energy source for the system*	**Q_E** Latent heat flux *convective* Energy flow caused by phase changes. The atmosphere dominantly transfers liquid to gas & vice versa. *Specifies types and locations of moisture changes.*	**Q_H** Sensible heat flux *convective* Energy flow causing air temperature changes. *Specifies whether the air cools or warms.*	**Q_G** Ground heat flux *conductive* Energy flow by the conduction of sensible heat to or from deeper layers of the ground. *Specifies whether the ground cools or warms*
		← energy flows away from the surface →		
positive (+)	**Energy surplus** *The surface has a net gain of radiation*	**Evaporation & sublimation use surface energy to put vapour into the air:** *When surface water (liquid) **evaporates** into water vapour (gas), latent heat flows away from the surface towards the air.* *When ice (solid) **sublimates** into water vapour (gas), latent heat also flows away from the surface towards the air.*	**Air warms:** *Sensible heat flows away from the surface toward the air causing the air to warm.*	**Ground warms:** *Ground heat flows away from the surface into deeper layers of the ground increasing the temperature of the ground.*
		← energy flows towards the surface →		
negative (−)	**Energy deficit** *The surface has a net loss of radiation*	**Condensation & deposition use atmospheric energy to put water /ice on the surface:** *When atmospheric water vapour (gas) **condenses** into liquid surface water, latent heat flows towards the surface from the air.* *When atmospheric water vapour (gas) **deposits** as surface ice (solid), latent heat also flows towards the surface from the air.*	**Air cools:** *Sensible heat flows towards the surface from the air causing the air to cool.*	**Ground cools:** *Ground heat flows towards the surface from deeper layers in the ground decreasing the temperature of the ground.*

3) Summary and explanation of the annual variation in each term of the Energy Budget $Q^* = Q_E + Q_H + Q_G$ and relationships between terms.

For these answers you must understand that the graph shows the cycle of expected annual patterns based on long term averages.

Q^*	Q^* (net radiation) provides energy for the other fluxes (Q_E, Q_H, Q_G). Net radiation provides the energy that is distributed by the surface energy budget. It is dominated by the annual solar and cloud cover patterns in Vancouver. Q^* is positive in spring, summer, and fall and becomes negative in the winter months of Nov, Dec, and Jan. On an average annual basis Q^* has a positive value of 59 Wm^{-2}.
Q_E	Q_E (latent heat) is the energy used or gained by phase changes. It is driven by Q^*, the temperature of the surface, the availability of water at the surface and the air's humidity. Q_E is proportional to the net evapotranspiration (E_t) each month. You can convert Q_E (in Wm^{-2}) to E_t (in mm of water) for a specified time. In Vancouver the monthly average Q_E is always positive and generally follows the pattern of Q^* except for July and August when Q_E drops because water is now limited (not enough to keep evaporation as high), even though temperatures are great enough to cause even higher evaporation rates if more moisture were available.
Q_H	Q_H (sensible heat) is the energy used to change air temperatures. In Vancouver the monthly average Q_H is positive or almost positive except for the fall months of Oct and Nov when Q_H is negative. This indicates that the surface temperature is generally greater than the air temperature (using the previous positive /negative conventions). Q_H increases dramatically in July when Q^* is at its maximum and the surface heats up because water for evaporation has become limited (note how Q_E is reduced as Q_H rises and more energy is utilized to heat the air.)
Q_G	Q_G (ground heat) has a smooth profile similar to a reduced profile of Q^*. It is positive for half the year and negative for the other half. On an annual basis it is zero indicating that on average the subsurface in Vancouver is not heating / cooling on average annual basis.

4) Interpretation of Vancouver's situation from the Soil Water and Energy Budgets:

a) The Soil Water Budget indicates the following patterns for Vancouver:

- high annual precipitation (P) that occurs every month but decreases dramatically to a minimum during the summer, giving Vancouver a moist climate with a summer precipitation minimum
- measureable evapotranspiration (E_t) occurs all year because Vancouver's monthly average temperatures are always above zero; the seasonal pattern of evapotranspiration (E_t) follows the seasonal temperature pattern

- precipitation (P) is almost the same as E_t in April and Sept, but P is much greater than E_t in all months except May, June, July, and Aug when E_t is at its peak and P is at its minimum.
- water is taken from storage (ΔS) during the summer drier period when $P < E_t$ (shown by the negative ΔS values)
- recharge occurs quickly in the fall once heavier fall rainstorms increase precipitation (shown by the positive ΔS values) in Oct & Nov; runoff takes over in Nov
- runnoff (Δr) occurs when the soil is saturated in Nov, it carries on through the winter, and into the spring; (Δr occurs once precipitation has recharged water taken from the soil during the summer months).

b) In Vancouver, the interaction between the Energy Budget and Soil Moisture Budget occurs because Q* and negative Q_G (late in the year) provide and control the energy available for Q_E and E_t. Both budgets are dominated by the seasonal heating and precipitation cycles indicated in the previous answers. (Notice that Q_E and E_t appear to have the same graph pattern/profile, and it requires 680 Wm^{-2} of energy to vapourize 1 mm h^{-1} of water.)

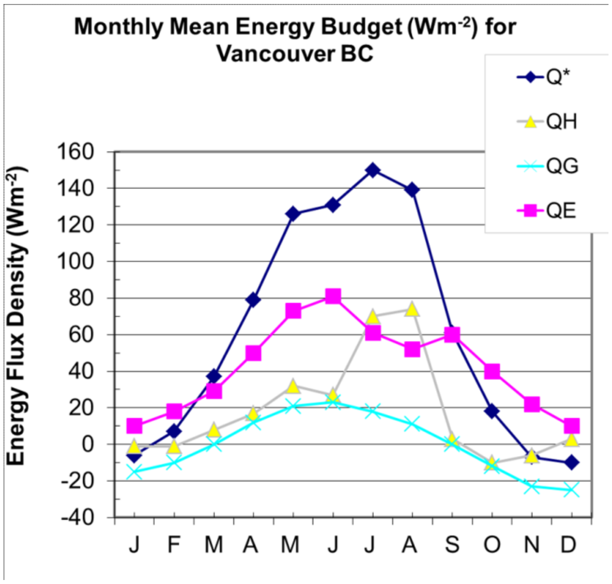
5) Explanation of the dip in Q_E in July and August: The dip in the Q_E curve is related to the rise in the Q_H curve during July and August because both are caused by the lack of summer precipitation when there is no longer enough soil moisture to meet the maximum potential for evaporation. Since Q* is at its peak when water availability is at its lowest, more energy goes into heating the air (Q_H) and less into evaporation (Q_E).

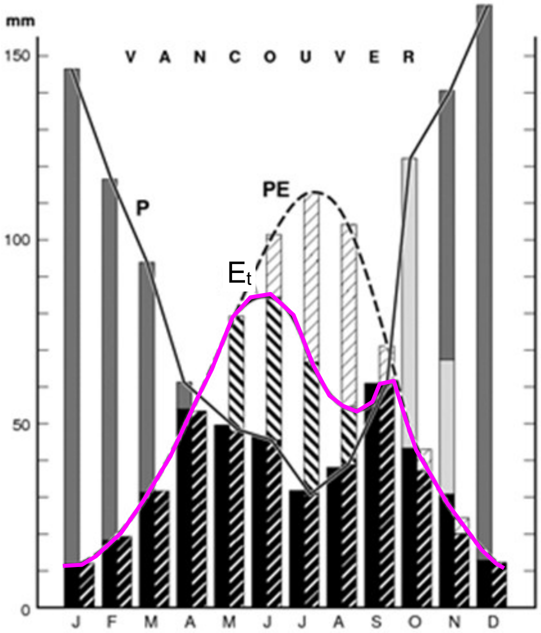
6) Explanation of how Q_E exceeds Q* in the Sept. to Feb. period: It is possible for the energy used for evapotranspiration (Q_E) to exceed the net radiation (Q*) during the September to February period (fall to winter) because energy is supplied by the upward flow of conductive ground heat (- Q_G) that was stored in deeper layers of the ground during the warmer spring and summer period. Energy also comes from the air as negative sensible heat (- Q_H) flows toward the surface. (In the case of Vancouver, the sensible heat input most likely comes from warm air which blows from the south during winter storms.)

7) Solutions showing that on an average annual basis the movement of water to the air (the soil moisture budget's E_t) is equivalent to the energy used to vaporize it (Q_E).

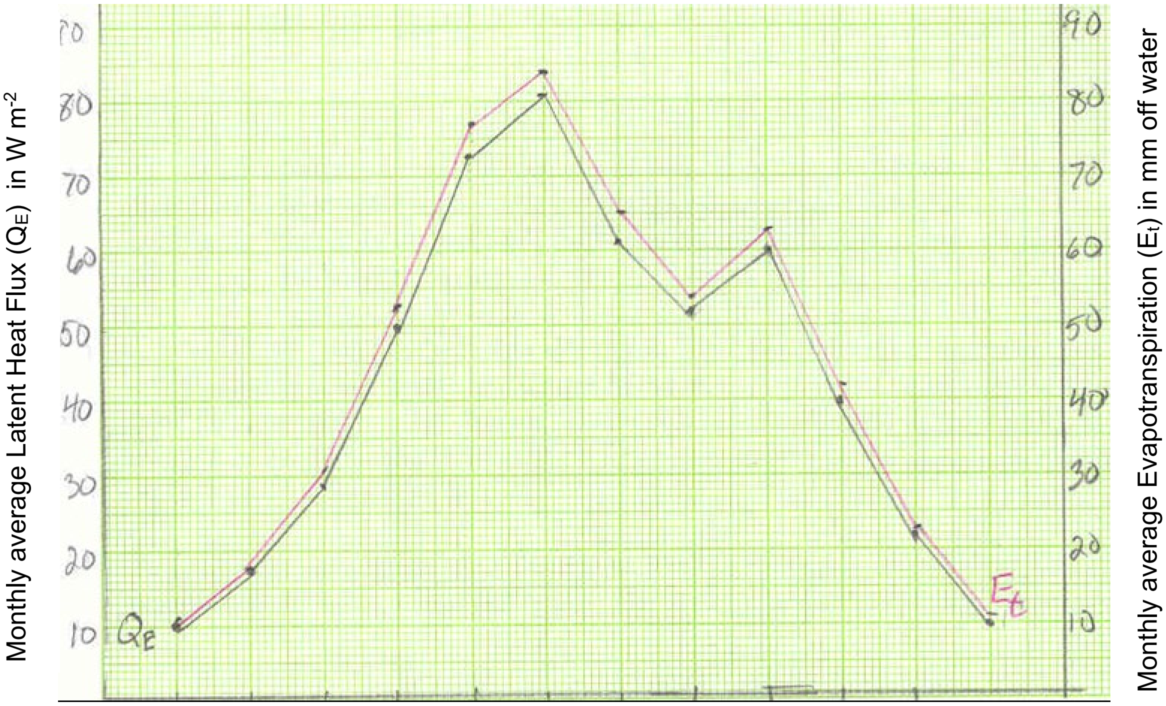
This answer requires you show that E_t is equivalent to Q_E. The hint indicates there are a 3 ways to answer this question, two are mathematical, and one is graphical. You are asked to show all three solutions.

a) The graphical solution: The line for Q_E is the same as the line for E_t (both have the same patterns /trends). See the same patterns in the pink lines below.





This is shown more explicitly by graphing both Q_E and E_t on proportional scales.



Comparison of Annual Latent Heat (Q_E) & Evapotranspiration (E_t) for Vancouver

b) One mathematical way to show E_t is equal to Q_E , is to use the relationship given in the lab as a conversion factor: "An evapotranspiration rate (E_t) of 1 mm hr^{-1} requires 680 Wm^{-2} of energy (Q_E)" becomes: a Q_E of 680 Wm^{-2} = 1 mm hr^{-1} of E_t

From the Table data, we know on an annual basis 533 mm of water evaporates in one year (533 mm yr^{-1}). We can convert this to millimeters of evaporation per hour:

$$\left(\frac{533\ mm}{yr}\right)\left(\frac{1\ yr}{365.25\ days}\right)\left(\frac{1\ day}{24\ hr}\right) = 0.060803\ \frac{mm}{hr}$$

Using the relationship that 1 mm hr^{-1} requires 680 Wm^{-2} of energy (notice that this is really a conversion factor); we get:

$$\left(\frac{0.060803\ \frac{mm}{hr}}{1}\right)\left(\frac{680\ \frac{W}{m^2}}{1\ \frac{mm}{hr}}\right) = 41.346\ \frac{W}{m^2} = 41.3\ \frac{W}{m^2} \approx 42\ \frac{W}{m^2}$$

42 W m^{-2} is the annual average Q_E value.

Alternatively you could start with a Q_E of 42 Wm^{-2} and show that it is equivalent to the annual evaporation rate of 533 mm *yr* $^{-1}$. Showing this in one equation we get:

$$\left(\frac{42\ \frac{W}{m^2}}{1}\right)\left(\frac{1\ \frac{mm}{hr}}{680\ \frac{W}{m^2}}\right) = \left(\frac{0.06176\ mm}{hr}\right)\left(\frac{24\ hr}{1\ day}\right)\left(\frac{365.25\ hr}{1\ yr}\right) = 541\ \frac{mm}{yr} \approx 533\ \frac{mm}{yr}$$

c) The other mathematical way to show E_t is equal to Q_E is to use the equation $\boldsymbol{Q_E = E_t L_v}$

Using a problem solving approach, we want to:

d) State what our answer should look like
e) Indicate what we know, what we might be able to determine with what we know
f) Indicate what we don't know and would like to know.
g) Attempt a solution.

So:

i. Our answer should show that $E_t \sim Q_E$ (i.e. we must show how these two are related).

ii. We know:

- $Q_E = E_t L_v$
- Q_E is the energy used in evaporation
- L_v = the latent heat of vaporization of water at 20 ^{0}C (i.e. the energy needed to evaporate water at the indicated temperature). By noticing that the units for L_v are kJ kg^{-1} (kilojoules per kilogram of water) you may be able to see ways to solve this problem. L_v @ 20^0C = 2450 kJ/ kg or 2450 kJ kg^{-1}
- E_t = 533 mm yr^{-1} (from Table 3.2). Notice the units of E_t have the dimensions of length per time. However, if $Q_E = E_t L_v$ then E_t must be measured in kg m^{-2} s^{-1} which represents the mass of water evaporated from every square meter each second. How might we get from mm yr^{-1} (length per time) to kg m^{-2} s^{-1} (mass per area per time)?
- We are told that the density of water is 1000 kg per m^3
- We think all this information is relevant in solving this problem

iii. We want to find a way of converting E_t from mm yr^{-1} to kg m^{-2} s^{-1}.

By looking at "basic" units (i.e. dimensional analysis) we can see that:

$$\frac{\textbf{meters}}{\textbf{second}} \times \frac{\textbf{kilograms}}{\textbf{meters}^3} = \frac{\textbf{kilograms}}{\textbf{meters}^2\ \textbf{second}}$$ ← these are the units we want!!

So: (E_t converted to m/second) x (density in kg/meter cubed) = E_t in the form of kg m^{-2} s^{-1}

- So use the equation: $Q_E = E_t L_v$ to determine total energy used to evaporate water in a year (i.e. joules / year). Converting this value to joules/second (a Watt) gives a Q_E value that is consistent with E_t.

iv. **Solution:** Show that Q_E is consistent with E_t (i.e. determine the amount of water evaporated in a year using the annual value of E_t)

$$E_t = 533\frac{mm}{yr} \text{ but understand this indicates } 533\frac{mm}{yr} \text{ evaporates for every square meter}$$

If we convert the millimeters (mm) to meters (m) this can be written as:

$$\left(\frac{533\ mm}{yr}\right)\left(\frac{1\ m}{1000\ mm}\right) = (0.533\ \frac{m}{yr})$$

We are told that the density of water is $\frac{1000\ kg}{m^3}$

We can calculate that

$$\left(\frac{0.533\ m}{yr}\right)\left(\frac{1000\ kg}{m^3}\right) = \frac{533\ kg}{yr\ \ m^2} \text{ of water evaporates in Vancouver}$$

By using the relationship $Q_E = E_t\ L_v$

$$\left(\frac{533\ kg}{yr\ \ m^2}\right)\left(\frac{2450\ kJ}{kg}\right) = 1.306\ \times\ 10^6\frac{kJ}{yr\ \ m^2}$$

$$\left(\frac{1.306\ \times\ 10^6\ kJ}{yr\ m^2}\right)\left(\frac{1\ yr}{365.25\ days}\right)\left(\frac{1\ day}{24\ hr}\right)\left(\frac{1\ hr}{3600\ s}\right) = \left(\frac{0.0414\ kJ}{m^2\ s}\right)\left(\frac{1000\ J}{1\ kJ}\right) = 41.4\ \frac{J}{m^2\ s}$$

Since a watt is a joule per second or $1\ W = 1\ \frac{J}{s}$ then:

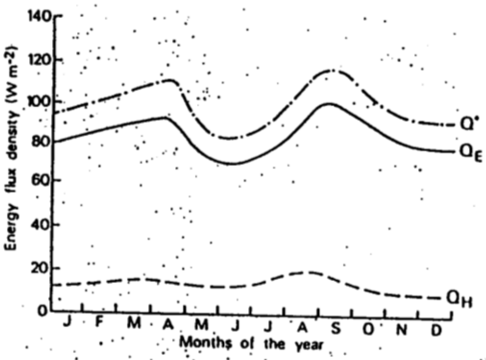
$$41.4\ \frac{J}{m^2\ s} \approx 42\ \frac{W}{m^2} \qquad \text{So } Q_E \text{ is consistent with } E_t$$

8) a) The annual Bowen Ratio (β) for Vancouver is: $\beta = \frac{Q_H}{Q_E} = \frac{17}{42} = 0.40$

b) Vancouver's Bowen ratio *(β)* shows generally evaporation occurs more than sensible heating of the air. The exception is in July and August when heating is just slightly greater. This indicates Vancouver has a moist, humid, relatively cool climate (which is consistent with a temperate rainforest environment).

Comparing Vancouver's with other Bowen Ratios, shows how climates are represented by their Bowen Ratios, (see graphs and summarized in the following table; also see Meteorology Today 2nd Canadian Edition page. 99).

Bowen Ratio *(β)*	**Q_H**	**Q_E**	**Type of Environment** (see examples given in the lab manual)
0.12	~10	~85	Tropical rain forest (example Fig. 3.5)
12	~60	~5	Desert (example Fig. 3.6)
0.4	~15	~40	Humid mid-latitude continental climate (example Fig. 3.7)
- 1	~-15	~15	Polar (example Fig. 3.8); negative as Q_H is always negative; note seasonal trends are reversed in the southern hemisphere

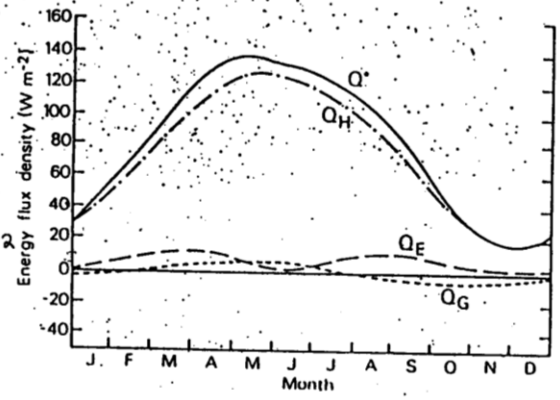


$Q_E \sim 85$

$Q_H \sim 10$

$\beta = \frac{10}{85} = 0.12$

Figure 3.5 Components of the surface energy budget for São Gabriel, Brazil in an equatorial continental climate

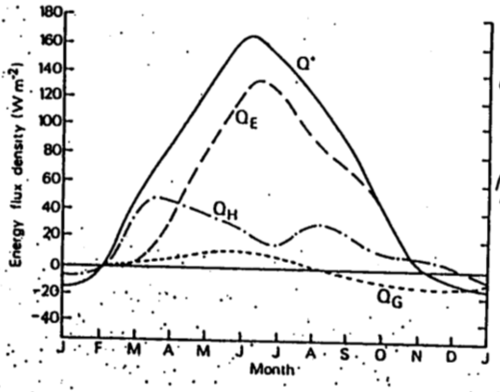


$Q_E \sim 5$

$Q_H \sim 60$

$\beta = \frac{Q_H}{Q_E} = \frac{60}{5} = 12$

Figure 3.6 Components of the surface energy budget for Yuma, Arizona in a desert climate (after Sellers 1965)



$Q_H \sim 15$

$Q_E \sim 40$

$\beta = \frac{15}{40}$
$= 0.4$

Figure 3.7 Components of the surface energy budget for Madison, Wisconsin in a humid mid-latitude climate (after Sellers 1965)

note. seasons reversed.

$Q_H \sim -15$

$Q_E \sim 15$

$\beta = -1$

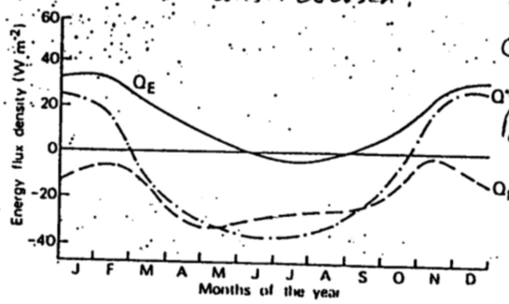


Figure 3.8 Components of the surface energy budget for Mirny, Antarctica (66° 33'S) in a polar climate