Question:

Radiative forcing plays an important role for the changes in regional water cycles. For example, for the Ob river basin in central Siberia, the runoff ratio is 0.28 under current climate condition. In a numerical experiment with doubled CO_2 concentration, the regional precipitation and net radiation at surface both increase by 10%. At the same time, the regionally averaged Bowen ratio decreases from the current value of 0.5 to 0.4. Use the balance equations for energy and water as well as the definitions of Bowen ratio and runoff ratio to estimate the percent change in regional runoff for the Ob river basin when CO_2 concentration is doubled. The storage and the horizontal flux terms in the balance equations can be ignored.

Solution:

Water balance equation writes: Q = P – E, where Q, P, E represent runoff, precipitation and evapotranspiration, respectively. Apply water balance equation to both current (denoted by subscript 1 thereafter) and doubled (denoted by subscript 2 thereafter) CO_2 conditions, one can obtain:

$$Q_2/Q_1 = (P_2-E_2) / (P_1-E_1) \qquad (1)$$

Now, if we can substitute every term on the right hand side of (2) with P_1, the ratio of runoff between two conditions and therefore the percent change of runoff can be obtained. From the given information, precipitation increases by 10%, thus:

$$P_2/P_1 = 1.1 \Rightarrow P_2 = 1.1P_1 \qquad (2)$$

The definition of runoff ratio is:

$w_1 = Q_1/P_1$, where w_1 is runoff ratio under current CO_2 condition

Apply this relation to the water balance equation:

$$E_1 = P_1 - Q_1 = P_1 - w_1P_1 = (1 – w_1)P_1$$

The runoff ratio under current CO_2 condition is 0.28, thus:

$$E_1 = (1- 0.28)P_1 = 0.72P_1 \qquad (3)$$

The energy balance equation writes:

$$R = SH + LH,$$

where R represents the net radiation at surface, SH and LH represent sensible and latent heat flux, respectively. From the given information, the net radiation increases by 10%, thus:

$$R_2/R_1 = (SH_2+LH_2) / (SH_1+LH_1) =1.1$$

The Bowen ratios for current and doubled CO_2 conditions are 0.5 and 0.4 respectively, thus:

$$SH_1/LH_1 = 0.5 \Rightarrow SH_1= 0.5LH_1$$

$$SH_2/ LH_2 = 0.4 \Rightarrow SH_2= 0.4LH_2$$

Apply these two relations to the energy balance equation, one can obtain:

R_2/R_1 = (0.4 LH_2+LH_2) / (0.5 LH_1+LH_1) =1.1 => 1.4 LH_2/1.5 LH_1 = 1.1
=>LH_2/LH_1= 1.1 · 1.5/1.4 = 1.2

Evapotranspiration and latent heat flux is related as E = LH / $2.5 \cdot 10^6$ (J/kg). Thus:

$LH_2/LH_1 = E_2/E_1 \Rightarrow E_2 = 1.2E_1$

Apply (3) to the above relation:

E_2 = 1.2 * 0.72P1 = 0.86P_1 (4)

So far, we successfully found the relation between P_2 and P_1, E_1 and P_1 and E_2 and P_1. Apply (2), (3) and (4) to (1):

Q_2/Q_1 = (1.1P_1-0.86P_1) / (P_1-0.72P_1) = 0.86

Therefore the percent change of runoff can be obtained:

(Q_2-Q_1)/Q_1 *100%= (Q_2/Q_1 – 1)*100% = (0.86 -1) *100% = -24%

The regional runoff will decrease by 24% when CO_2 concentration is doubled