A conceptual approach to estimate the effects of heterogeneity and lateral transfer on ET

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How important and where?

Large-scale Earth system models average over land surface heterogeneity and overlook lateral transfer of water.
Nonlinearity in land-atmosphere processes: Budyko as a simple nonlinear estimator of ET

Water and energy limits constrain ET rates → downward convex curve

Budyko relations describe ET as a nonlinear function of P and PET.

\[ ET = \frac{P}{\left( \left( \frac{P}{PET} \right)^n + 1 \right)^{1/n}} \]

\( n \) is catchment specific parameter that modifies the partitioning of P between Q and ET.

The blue cloud is a smoothed scatterplot of the 30 arc sec. mean annual P, ET, and PET for continental Europe. ET and PET data are from MODIS (Mu et al., 2007), P dataset is from WorldClim (Hijmans et al., 2005).
Spatial averaging biases estimates of ET

The averaging bias is approximated as:

$$\bar{ET} - f(\bar{P}, \bar{PET}) \approx \frac{1}{2} \frac{\partial^2 f}{\partial P^2} var(P) + \frac{1}{2} \frac{\partial^2 f}{\partial PET^2} var(PET) + \frac{\partial^2 f}{\partial P \partial PET} cov(P, PET)$$

The heterogeneity bias depends on how strongly curved the function is and how widely its inputs are scattered.

- In a convex-downward curve like Budyko, the true average of the two columns always lies below the curve.
- Function of average inputs (open circle) is larger than average of the function evaluated at individual inputs (grey circle) in any convex-downward curve.
- This leads to overestimation bias due to spatial averaging (overlooking spatial heterogeneity).

Rouholahnejad freund and Kirchner, 2017, Hydrol. Earth Syst. Sci.
Lateral transfers affect average ET rates as seen from the atmosphere

Here, transfer of water from a wet, energy limited area (loc 1.) to a dry, water limited area (loc. 2) increases average ET

The net ET effect depends on the amount of lateral redistribution (how far the points move along the Budyko curve) and on the degree of curvature between them.

Budyko equation, with Available Water (AW=P+net transfer) instead of P:

\[
ET = \frac{P + \text{net transfer}}{\left(\left(\frac{P + \text{net transfer}}{PET}\right)^n + 1\right)^{1/n}}
\]
Lateral transfer may increase or decrease average ET rates as seen from the atmosphere.

- Water transfer from higher, wetter locations to lower, drier places increases average ET (a).

- The lateral transfer increases ET if the source location is energy limited and recipient location is water limited (a).

- Water transfer from higher, drier locations to lower, wetter places decreases average ET (b).

- If both of the locations are water-limited or energy-limited, water transfer would not alter average ET significantly (c and d).
What is the maximum effect of lateral transfer on average ET?

Lateral transfers affect ET rates if one of the sites is water-limited and the other site is energy-limited.

Average ET depends on the amount of lateral transfer.

Average ET of the two columns is maximized at the transfer at which Available Water/PET in the two columns are equal.

The maximum effect of redistribution on average ET is equal to the heterogeneity effect on average ET (one can prove this mathematically).

\[
\begin{align*}
\text{ET}_{\text{avg}} & = 595 \, \text{mm yr}^{-1} \\
\text{ET'}_{\text{avg}} & = 680 \, \text{mm yr}^{-1} \approx 14 \%
\end{align*}
\]
Heterogeneity bias at global scale: a first assessment

WorldClim data at 1 km resolution is available at global scale

We calculated ET at 1km resolution with Budyko relations and then averaged at 1 degree grid cell (avg of functions)

We also averaged P and PET over each 1 degree grid cell and then calculated ET from these averaged values (function of avg)

The difference between these two ET estimates is a measure of the likely heterogeneity bias
Averaging over heterogeneity in P and PET at 1 degree grid resolution leads to slight overestimation of ET

The overestimation of ET is associated with areas with sharp gradients in aridity index within 1 degree by 1 degree grid cells.

The likely heterogeneity effect in a physically based model could be larger than this, because Budyko curves already subsume heterogeneity effects at catchment scale and (and also in time).

The results depict the biases in long-term average ET estimates. Given the fact that P and PET can vary temporally (i.e., seasonality), the estimated bias could be much larger, particularly where P and PET are out of phase.

The maximum effect of redistribution on average ET is equal to heterogeneity effect on average ET.
At the scale of the US, the heterogeneity bias in average ET estimates at 1 degree scale varies with input data.
The averaging bias is greater in climate zones with dry summers.
Characteristic scale at which averaging errors are minimized

PCP mm/yr, 500 m

PET mm/yr, 500 m

Altitude m, 500 m

ET avg error at 1/32 degree

ET avg error at 1/16 degree

ET avg error at 1/8 degree

ET avg error at 0.25 degree

ET avg error at 0.5 degree

ET avg error at 0.75 degree

ET avg error at 1 degree

ET avg error at 2 degree

% averaging error
Spatial averaging overestimates ET in heterogeneous landscapes (example from Himalayas)

In the middle grid cell:
- A sharp gradient in P, PET, and altitude
- Averaging at 1 degree grid cell, leads to 12% overestimation in ET estimates

Including all the neighbouring grid cells:
- Heterogeneity bias strongly depends on SD of aridity
- SD of aridity strongly depends on topography

\[ \bar{E}(P_i, PET_i) = 812 \text{ mm yr}^{-1} \]
When aridity index increases (decreases) with altitude, lateral transfer increases (decreases) ET: Himalayas case study

1. High altitude, low PCP, low PET
2. Mid altitude, high PCP, low PET
3. Low altitude, moderate PCP, high PET

Gravity could move water from 1 to 2 and from 2 to 3

Transfer from 1 to 2 decreases average ET (a)

Transfer from 2 to 3 increases average ET (b)