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Hydrology and Earth System Sciences Discussions

Interactive comment on “Biotic pump of atmospheric moisture as driver of the hydrological cycle on land” *by* A. M. Makarieva and V. G. Gorshkov

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In response to the comments by H. H. G. Savenije:

We are very grateful for the critical reading of our paper and for the constructive comments that raise important issues. Below we adress each of the numbered comments in their original order.

1) We agree that interception, this important term in total forest evaporation, should be discussed on p. 2629, as suggested in the comment. The reason why originally we focused on transpiration is because transpiration, unlike interception, is under immediate, short-term biotic control. For example, as we mention in the paper (p. 2650-2651),

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closure of the stomata in the afternoon results in a drop of the total evaporation flux. As a consequence, the evaporative force diminishes and the upwelling cloud-supportin air flux diminishes as well, leading to formation of precipitation. The daily opening/closure of the stomata and the associated growth/decrease of the evaporative force can be responsible for the diurnal cycle of precipitation in the tropics (Nesbitt et al. 2003), which, remarkably, is observed on land but not in the ocean, where the stomata effects are obviously absent.

Interception, on the other hand, is also dictated by such biotic properties as are, e.g., leaf area index or leaf size. However, these properties, originated in the course of biological evolution, can be only regulated in the long-term, e.g. on a seasonal scale. For a given forest on a short-term scale, the interception term is therefore dictated by physical, rather then biological, regularities: the intercepted water evaporates with no further biotic control. This leads to an interesting idea. Evergreen coniferous forests in the boreal zone retain high leaf area index in winter. The associated high interception of winter precipitation enhances total evaporation thus making biotic pump working even in winter forests where no photosynthesis or other biological processes occur. In other words, being evergreen helps the trees to enhance winter precipitation. This might explain the wide spread of evergreen trees (pines, firs, spruces) in the pristine boreal forests. Secondary boreal forests are composed of deciduous species that lack this feature.

It is remarkable that forest transpiration and interception are close in magnitude and apparently are both significant for the biotic pump functioning. Recently Cuartas et al. reviewed the available interception estimates for Amazonian forests to find that interception ranges from 9 to 26% of total rainfall. If one assumes that runoff, on average, constitutes approximately 50% of Amazonian precipitation (Marengo, 2005), this means that interception constitutes from about 20 to more than 50% of total evaporation, as is also the case in other ecosystems (Savenije, 2004).

Since we do not discuss the resistance to evaporation of the various total evaporation constituents, we would like to modify the text change on p. 2629 (line 10), that was suggested in the comment, as follows:

"When the soil moisture content is sufficiently high, transpiration is dictated by solar energy. Interception, both from the canopy, understorey and the forest floor, which can be more than 50% of the total evaporation (see Savenije, 2004), is also dictated by solar energy. So if there is sufficient soil moisture, then total evaporation from dense forest is constrained by solar radiation. Therefore, when x is counted along the parallel, on well-moistened continental areas we have $E(x) = E(0)$, i.e. evaporation does not depend on the distance from the ocean."

2) To derive the exponential equation (3), p. 2626, for precipitation decline with distance from the ocean one has to make certain assumptions. In Savenije (1995) the exponential equation for precipitation decline ultimately stems from the assumed proportionality between precipitation, on the one hand, and the product of precipiable atmospheric water and air stream velocity (not precipiable moisture content alone), on the other. This assumption is equivalent to our assumption of proportionality between precipitation and flux F in our paper, because flux F is actually equal to moisture content in the atmospheric column multiplied by air stream velocity (which greatly changes with distance).

However, the theoretical question why precipitation over deforested territories declines exponentially with distance, is not of primary concern in our paper. It is enough for our considerations that empirical data strongly confirm this relationship in sharp contrast with natural forests.

The comment says: "In the theory on moisture recycling described by Savenije (1995), which the authors refer to, the decrease of the precipitation along the trajectory of the moisture transport is caused by the runoff and the recharge to groundwater (see Savenije, 1996a). Only if there is 100% moisture recycling can there be constant rainfall along a trajectory. Here lies the main difference between the work of the biotic pump and the theory on moisture recycling. The authors in fact imply that the biotic pump is able to compensate for the drainage of moisture by runoff."

We would like to add that in the theoretical considerations of moisture recycling precipitation P is ultimately related to the horizontal flux of moisture, which is considered as an abiotic geophysical constraint, an independent parameter; evaporation E is known to be affected by vegetation; and runoff R is the residual of P and E. This consideration, where both P and R can be arbitrarily high or low, corresponding to either droughts and floods, should hold well for abiotic environments like deserts, agricultural lands etc.

In our biotic pump consideration we assign a different meaning to the budget $P = E + R$. In the biotically controlled forest environment runoff R is determined by the biotically maintained high soil moisture, total evaporation E is dictated by solar energy, and precipitation P is biotically regulated (via the biotically regulated flux F) to balance the equation. In this consideration it is clear that, as is also confirmed by observations, in natural forests neither floods nor disastrous diminishment of runoff can normally occur throughout the year.

3) By the term $dW/dt = 0$ on the top of page 2629 we indeed meant its long-term average, in agreement with the formulation suggested in the comment: "A high amount of soil moisture (averaged over the year) implies significant runoff, i.e. loss of water by the ecosystem (because R is a function of W)".

We also agree with all further derivations in the comment and in fact it is precisely what is said in the paper in the two upper paragraphs on p. 2629, which should be jointly considered. Indeed, what we say is that if $dW/dx = 0$, then $dR/dx = 0$ ("In areas where neither the surface slope, nor soil moisture content depend on distance x from the ocean, $W(x) = W(0)$, loss of ecosystem water to runoff is spatially uniform as well, $R(x) = R(0)$.")

Since $P = E + R$, $dR/dx = 0$ means, as indicated in the comment, that $d(P - E)/dx =$

0. In the second paragraph on p. 2629 it is essentially said that E in forests is dictated by solar energy, so when x is counted along the parallel, $dE/dx = 0$, while when x is counted along the meridian then $dE/dx > 0$. From this and $d(P-E)/dx = 0$ it is concluded that along the parallel dP/dx should be zero, but it must be positive when x is counted towards the equator (in forested areas).

The concluding lines of the first paragraph on p. 2629, "It follows that in the stationary case precipitation P, which maintains stationary soil moisture content and compensates the runoff, cannot decrease with distance from the ocean either. The conditions $W(x) = W(0)$ and $R(x) = R(0)$ are incompatible with an exponential decline of $P(x)$, Eq. (3).", which disrupt the logic of the above consideration with the premature conclusion about constant P made from $dR/dx = 0$ alone, should be perhaps deleted or moved to the end of the second paragraph.

We would finally formulate the first two paragraphs on p. 2629 as follows (with account of comment 1):

"Change of soil moisture content with time, dW/dt, is linked to precipitation P, evaporation E and runoff R via the law of matter conservation, $dW/dt = P - E - R$. A high amount of soil moisture (averaged over the year) implies significant runoff, i.e. loss of water by the ecosystem (because R is a function of W). In areas where neither the surface slope, nor soil moisture content depend on distance x from the ocean, $W(x) = W(0)$, loss of ecosystem water to runoff is spatially uniform as well, $R(x) = R(0)$.

When the soil moisture content is sufficiently high, transpiration is dictated by solar energy. Interception, both from the canopy, understorey and the forest floor, which can be more than 50% of the total evaporation (see Savenije, 2004), is also dictated by solar energy. So if there is sufficient soil moisture, then total evaporation from natural forest is constrained by solar radiation. Therefore, when x is counted along the parallel, where the amount of the incoming solar radiation does not change, on well-

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moistened continental areas we have $E(x) = E(0)$, i.e. evaporation does not depend on the distance from the ocean. Coupled with constant runoff, $R(x) = R(0)$, this means that precipitation P is similarly independent of the distance from the ocean, $P(x) = E(0) + R(0) = P(0)$. When the considered area is oriented, and x counted, along the meridian, evaporation increases towards the equator following the increasing flux of solar energy. In such areas, provided soil moisture content and runoff are distance-independent, precipitation must also grow towards the equator irrespective of the distance from the ocean. The conditions $W(x) = W(0)$ and $R(x) = R(0)$ are incompatible with an exponential decline of $P(x)$, Eq. (3)."

5) We agree that the term "multiplier" (coefficient k in Eq. (2)), as termed by Savenije (1996b), is appropriate for usage in our derivations.

4, 6) Since our paper was submitted to HESS, we have substantially extended our analyses of precipitation-distance patterns in the large forested regions of the world, including river basins of Mackenzie in North America, Lena and Ob in Siberia (Makarieva and Gorshkov, 2006; Makarieva, Gorshkov, Li, in preparation). In all these meridian-oriented regions we observed an increase of precipitation towards the inner part of the continent, similar to the situation with Yenisey. Moreover, the analysis has shown that this increase, as theoretically predicted, is well-matched in magnitude by the increase in solar radiation with decreasing latitude. As we state in the paper (p. 2628 (lines 6-11), p. 2651 (lines 9-13)), irrespective of the described physical details of functioning of the biotic pump, the analyzed observations unambiguously testify to its existence.

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