ORIGINAL PAPER

Revisiting forest impact on atmospheric water vapor transport and precipitation

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Abstract Using a robust global precipitation database, we analyze coast-to-interior seasonal precipitation distributions over the world's major forest regions. We find that the active functioning of boreal forests in summer is associated with an intense ocean-to-land moisture transport, which declines in winter when forest functioning is minimal. This seasonal switch manifests itself as a change in the exponential scale length of precipitation distribution, which exceeds 15×10^3 km in summer but decreases to $(3–4) \times 10^3$ km in winter. In equatorial rainforests, which are photosynthetically active throughout the year, annual precipitation remains approximately constant, while the coefficient of variation of monthly precipitation significantly declines toward the continent interior. Precipitation over forest during the periods of active forest functioning is always higher than over the adjacent ocean. Such precipitation patterns support the biotic pump concept according to which forest cover drives the ocean-to-land atmospheric moisture transport on a continental scale.

1 Introduction

Precipitation is indispensable for life to thrive on land. Water comes to land from the ocean as atmospheric water vapor and

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returns to the ocean in the liquid form as river runoff. The role of vegetation cover in the maintenance and control of the various terms in the terrestrial water budget is receiving growing attention from a range of research perspectives. On the one hand, *for a given pattern of air flow*, the recycling of precipitated moisture by evaporation from the vegetation cover increases aerial runoff, thus enhancing precipitation downwind (Savenije 1995; van der Ent et al. 2010; Keys et al. 2012). However, as the local liquid runoff is reduced by the same amount, there is a discussion as to whether such moisture recycling actually depletes rather than enhances the water cycle (e.g., Lane et al. 2005; McVicar et al. 2007; Cao et al. 2010) as recently reviewed by Ellison et al. (2012). On the other hand, research is now showing that the ocean-to-land air flow can itself be a function of the state of the vegetation cover (e.g., Goessling and Reick 2011; Chikoore and Jury 2010; Cook et al. 2011; Poveda et al. 2011). In that case, the water cycle disturbance associated with a land cover change manifests itself as a change in the moisture-carrying winds. The biotic pump concept (Makarieva and Gorshkov 2007; Makarieva et al. 2009; Sheil and Murdiyarso 2009) belongs to the latter category: It posits that large-scale forests drive the coast-to-interior atmospheric moisture transport. In this concept, high evaporation from the forest canopy maintains an intense water vapor condensation over land such that low-pressure zones are formed on land causing the moisture-rich oceanic air to flow inland. Conversely, a deforestation-induced drop in land evaporation results in erosion of the low-pressure zones and weakening of the coast-to-interior moisture transport.

The biotic pump concept has a physical and an ecological component. The physical component describes water vapor condensation as a driver of air circulation. Any area where condensation occurs becomes a zone of low pressure and leads to the appearance of air flows converging to the condensation centre. As we have explained elsewhere, this physical mechanism permits a quantitative description of several

purely physical patterns of atmospheric circulation, including hurricanes and tornadoes (Makarieva and Gorshkov 2011; Makarieva et al. 2010, 2011). The ecological component is an analysis of how forest ecosystems function on the basis of the physical laws relating to condensation-induced dynamics to meet their water needs by pumping moist air from ocean to land (Makarieva and Gorshkov 2007, 2010). It addresses why the same cannot be achieved efficiently by other vegetation types with a low leaf area index and shallow root system as we find, for example, with pastures or tree-plantations.

Quantitative analysis of ecological and biological variables is complicated by the complexity of living systems. While one cannot hope to describe quantitatively the patterns of forest–atmosphere interaction based on physical laws alone, such patterns can be established empirically from comparison of the hydrological cycle in natural versus disturbed ecosystems (e.g., forests versus croplands) and further analyzed within the corresponding physical framework. In this context, Makarieva and Gorshkov (2007) and Makarieva et al. (2009) point out that in forest-covered regions, annual precipitation does not decline with increasing distance from the ocean or and may even grow as one proceeds several thousand kilometers inland, whereas, in contrast, where forests are lacking, precipitation decreases with an exponential scale length of just a few hundred kilometers. Recently, Angelini et al. (2011) re-analyzed three of the six forest transects studied by us (Makarieva and Gorshkov 2007; Makarieva et al. 2009), using a different precipitation dataset and considering *seasonal* rather than annual precipitation. They questioned our findings and concluded that the results of their re-analysis did not support the biotic pump concept.

We agree with the general motivation outlined by Angelini et al. (2011) for their study, namely that the question of how forests impact atmospheric moisture transport is very important and will benefit from extensive research. In our view, Angelini et al. (2011) have made an important and informative contribution to the topic through their analysis of the seasonal dimension of the spatial precipitation patterns over forests. However, we find that their analyses suffer from several inconsistencies. Here we present an extended analysis of seasonal precipitation patterns in all forest transects studied by us (Makarieva and Gorshkov 2007; Makarieva et al. 2009) and by Angelini et al. (2011) (Fig. 1). We also analyze the most recent data on temporal changes in precipitation in tropical regions affected by deforestation. We show that all the available evidence is strongly consistent with and reaffirms the biotic pump concept; moreover, we clarify the misunderstandings that might have led Angelini et al. (2011) to conclude otherwise.

The paper is structured as follows: In Section 2, we discuss what kind of precipitation dependence on distance from the source of moisture (ocean) can be predicted from the biotic pump concept. In Sections 3 and 4, we analyze seasonal precipitation distributions along tropical rainforest and boreal forest transects, respectively, with their comparison to follow in Section 5. In the concluding section, we discuss other evidence analyzed by Angelini et al. (2011) including temporal precipitation changes and provide a synthesis of all the results.

2 The logic of the biotic pump concept

The *physical* basis of the biotic pump concept lies in the process by which condensation leads to reduced atmospheric pressure as the water vapor disappears from the gas phase (Makarieva et al. 2010; Makarieva and Gorshkov 2010). In consequence, the surrounding air moves into the reduced pressure zone. If the incoming air also carries enough water vapor, condensation continues and is sustained together with the pressure gradient generating the inflow. Condensation occurs where there is the highest concentration of water vapor. Since evaporation from the open water surface of the world ocean, which covers two thirds of the Earth's surface, is a major source of atmospheric water vapor, in the absence of water stores on land the ocean would remain the single predominant place for condensation to occur.

Consequently, to move a condensation area from the ocean to land, it becomes necessary to create a terrestrial water store on land to serve as a source for evaporation and to create a surface that can evaporate water into the atmosphere more effectively per unit area than the oceans. But evaporation diminishes the amount of moisture in soil. Moisture is additionally lost from soil by gravitational runoff. If all the soil moisture is gone, evaporation stops, local water vapor concentration diminishes, condensation ceases, and so does the atmospheric moisture transport. This requires that a non-trivial balance must be maintained for the condensation zone to persist over land: Indeed, evaporation should not deplete soil moisture but should be enough to ensure that the amount of moisture brought from the ocean by condensation-induced winds compensates moisture losses in the soil.

Looking now from the other—*ecological*—side, we notice that natural forests are well equipped to be able to implement all the above processes of water handling. Synthesis of organic matter by trees involves significant inputs of water vapor into the atmosphere (evapotranspiration); tree root systems allow for the accumulation and redistribution of moisture in soil (e.g., Nadezhdina et al. 2010); the large cumulative surface area of leaves allows for a biotic control of evaporation fluxes above the forest canopy; the moist air flow is modified by drag caused by the large height of trees; trees produce biogenic condensation nuclei to seed condensation over the forest, etc. Forests can indeed be viewed as a green ocean on land (e.g., Williams et al. 2002; Andreae et al. 2004) with the rates of
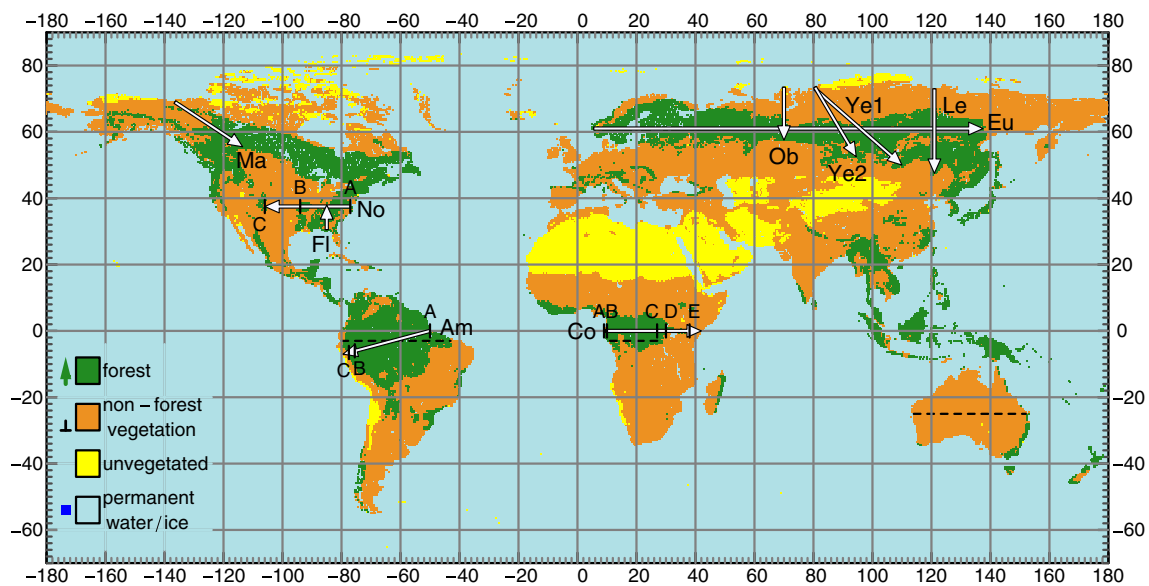
Fig. 1 Precipitation transects analyzed in this paper. *White arrows* indicate transects across forested regions: *Am* Amazon region, *Co* Congo region, *Ye1* Yenisey basin transect of Angelini et al. (2011), *Ye2* Yenisey basin transect of Makarieva and Gorshkov (2007) and Makarieva et al. (2009), *Le* Lena basin, *Ob* Ob basin, *Ma* Mackenzie basin, *Fl* Florida Panhandle transect of Angelini et al. (2011), *No* North American transect at 37.5°N, *Eu* Eurasian boreal forest. *Dashed lines* indicate the additional Amazon, Congo, and Australian transects shown in Fig. 6a, c. Land cover categories are based on the IGBP 0.5×0.5° 2000–2001 land cover data set (Friedl et al. 2010; see Online Resource for details). *Symbols to the left of the map legend* are used in Figs. 2, 3, 5, and 6 to refer to the corresponding land cover classes

phase transitions of water exceeding those over the ocean and remaining under biotic control. Rather than being just an incidental collection of water-related properties, the existence of these traits is consistent with the proposition that they ensure the functioning of the biotic pump—the natural biological mechanism that regulates condensation intensity and the associated air flow to keep soil optimally moistened. Notably, as with all life processes, the biotic pump should be a highly organized and complex process. It cannot be meaningfully analyzed other than within an interdisciplinary framework with knowledge sharing between and insights from diverse scientific disciplines including atmospheric physics, biochemistry, ecology, and evolutionary biology.

If the moisture transport on land is controlled by forests, what kind of spatial precipitation patterns do we expect to find there? When there is no water deficit, the productivity of natural ecosystems (that are capable of controlling the amount of biogens in soil, e.g., Gorshkov et al. 2004) is limited only by solar radiation and temperature, both of which are a function of latitude. If in the process of evolution forests had been able to saturate their water demand fully, evaporation from the forest canopy should be approximately the same at any given latitude irrespective of how far the forest is from the ocean. On a regional scale, the long-term approximation of the water budget is $P=E+R$, where P is precipitation, E is evaporation, and R is runoff determined by the amount of precipitation and regional topography. Assuming the latter to be generally independent of distance from the ocean, we would expect that the biotic pump functioning should, at any given latitude, produce

a constant cross-continental P that is independent of distance from the ocean. The same reasoning leads to the conclusion that precipitation in a forest region with a biotic pump should, independent of distance from the moisture sources, increase from poles to the equator as determined by the corresponding increase in temperature and solar radiation.

We emphasize that these predictions stem from our proposition that the biotic pump is an outcome of forest evolution, which resulted in a situation when the forest ecological community has been able to fully control its moisture supply. There are no other grounds and, importantly, no a priori geophysical considerations which could make one expect to observe such patterns. On the contrary, where the biotic control of moisture flow is absent and moisture transport is largely determined by geophysical factors alone, one would expect that precipitation should decline with growing distance from the primary source of moisture (ocean coast) to the continent interior. Indeed, as the air flows inland, its moisture content is depleted by precipitation and runoff. Assuming that precipitation is proportional to the moisture content in the air flow (e.g., Bretherton et al. 2004), this yields an exponential decline in precipitation with distance from the coast along the moist wind streamline (Savenije 1995, 1996; Makarieva and Gorshkov 2007)—a pattern common in world's unforested regions. Thus, insights into the question of how vegetation impacts moisture transport can be gained from two perspectives: first, by considering the physical bases of air circulation and the role of vegetation-induced condensation processes and, second, by comparing the patterns of moisture transport and precipitation distribution

between forested versus unforested/deforested regions and between periods of active vegetation functioning versus periods when the ecosystem is relatively inactive. If the biotic pump operates in the manner we have described, we expect to see that the presence of large-scale forest cover is the cause and not the consequence of large-scale rainfall patterns and that the forest ecosystems will exert their influence in any time of year when the vegetation is vigorous but not when they are relatively dormant.

3 Precipitation in tropical rainforests

For their analyses, Angelini et al. (2011) used the global precipitation climatology of Legates and Willmott (1990), which is a 0.5×0.5° latitude/longitude grid interpolation of quality-controlled station observations spanning the period from 1920 to 1980. Makarieva and Gorshkov (2007) and Makarieva et al. (2009) used data from various sources, predominantly the 0.5×0.5° gridded precipitation data bank Carbon Cycle Model Linkage Precipitation (McGuire et al. 2001) that corresponds to the period from 1950 to 1995. The data used in this study are described in greater detail in Online Resource.

Two equatorial rainforest transects analyzed by Angelini et al. (2011) in the Amazon and Congo River basins are shown in Fig. 2. The Amazon transect of Angelini et al. (2011) goes from 0°S 50°W to 5°S 70°W (region AB in Fig. 2a) and covers 2,300 km. Makarieva and Gorshkov (2007) and Makarieva et al. (2009) studied an Amazon transect from 0°S 50°W to 5°S 75°W, a total of 2,800 km (transect Am2 in Table 1). In the Congo basin, the transect of Angelini et al. (2011) goes along the equator from 9°E to 30°E, which is about 2,300 km (region AD in Fig. 2b). The same transect was studied by Makarieva and Gorshkov (2007), while Makarieva et al. (2009) analyzed a smaller part of this transect from 10°E to 27°E (region BC in Fig. 2b). We did this for two reasons: first, because the coastal part of the equatorial transect belongs to a deforested area which spans from approximately 0°N to 1.5°N and from 9°E to 10.5°E and second, because starting from 27°E eastward, the topography of the transect changes abruptly from a plateau with height above the sea level between 500 and 800 m to the mountains over 3 km above the sea level (Fig. 2d).

It is pertinent to dwell on how the precipitation transects should generally be chosen. To discriminate between exponential precipitation decline along the moisture transport path in the absence of biotic pump and distance-independent precipitation in its presence, it is desirable to know the trajectory of the ocean-to-land moisture flow. For example, in the equatorial zone, moisture transport involves both zonal and meridional components as it is significantly influenced by the seasonal migration of the Intertropical Convergence Zone.

Although the moisture path could be in principle deduced from the direction of the prevailing winds, it turns out to be difficult to implement this in practice: For example, a large proportion of moisture can be delivered by winds of an infrequent direction (e.g., Wu et al. 2012) or the information on the wind patterns as related to moisture transport can be of insufficient quality. The latter is especially true for the Amazon River basin where no match exists between the value of moisture transport estimated from atmospheric data and that estimated from the runoff measurements (Marengo 2005). To minimize the uncertainty associated with the unknown or changing directions of the prevailing atmospheric moisture transport, the coast-to-interior transect should be chosen in such a manner that as one moves along the transect inland, distance grows to both the meridional and zonal borders of land with the ocean. As shown in Fig. 2c, the Amazon transect, which has a meridional component from 0° to 5°S, satisfies this condition: Distance counted from each point of the transect to the nearest coastal point to the North grows with the corresponding distance to the east over most part of the transect. As there are no water sources either to the north or to the south from the Congo rainforest, the choice of the transect direction along the equator in the Congo basin is relatively straightforward (Fig. 1).

The analysis of Angelini et al. (2011) revealed that in the Amazon and Congo rainforests, precipitation during the wet (dry) season decreased (increased) from coast to interior (Fig. 2a, b). From this, Angelini et al. (2011) inferred that the data for tropical rainforests did not support the biotic pump concept. According to Angelini et al. (2011), during the wet season, precipitation decreases inland which would be against what the concept predicts, while whatever happens during the dry season does not matter, as in this period the vegetation functioning is inhibited and the biotic pump (even if it existed) should be switched off anyway.

This conclusion stems from several misinterpretations of the biotic pump concept and the data. First, the biotic pump concept does not predict an increasing precipitation inland for a given latitude. As discussed in the previous section, the biotic pump should cause precipitation at a given latitude to remain constant. Second, the seasonal time scale when this pattern of biotically controlled precipitation is to be observed should coincide with the seasonality of the vegetation functioning. Rainforests of the Amazon and Congo basins are photosynthetically active year round. They arguably represent Earth's terrestrial ecological communities with the *least* pronounced seasonality of biological functioning. Indeed, through all the year, these forests enjoy high temperatures and solar radiation flux. Moreover, contrary to one of the basic premises of Angelini et al. (2011), in undisturbed tropical rainforests, the dry season is *not* the time when transpiration is the lowest. This is the season of intense photosynthetic activity that occurs at the expense of significant moisture
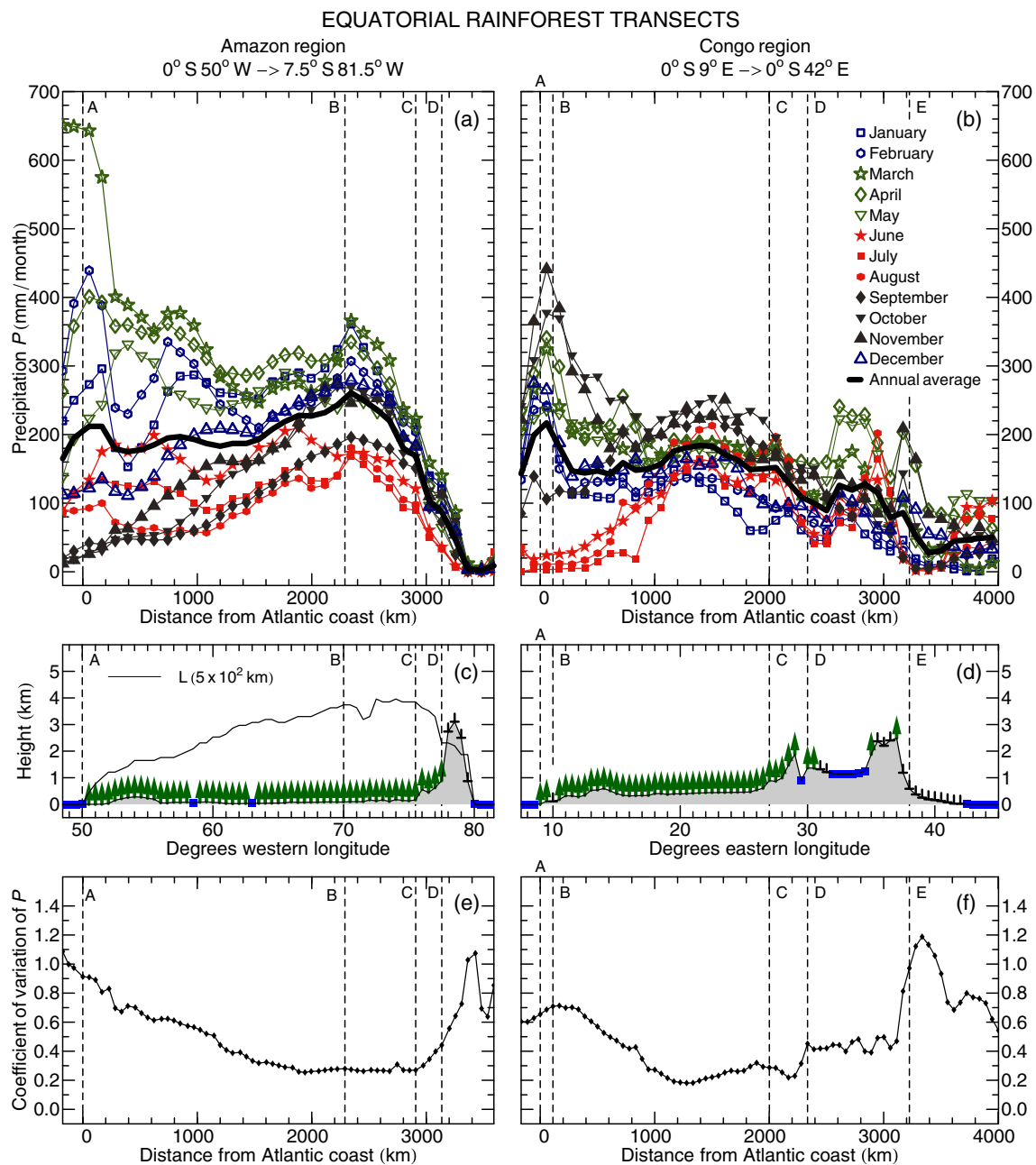
EQUATORIAL RAINFOREST TRANSECTS

Fig. 2 Equatorial rainforest transects along the Amazon and Congo River basins. **a**, **b** Monthly and annual precipitation versus distance from the ocean based on Legates and Willmott (1990). **c**, **d** Land cover classes as in Fig. 1 and mean height above the sea level in each half degree cell (Verdin 2011); *L* in **c** is the meridional distance from a given point on the Amazon transect to the northern oceanic coast. **e**, **f** Coefficient of variation of monthly precipitation (it is equal to zero when precipitation is the same every month) versus distance from the ocean based on Legates and Willmott (1990) data. *Dashed lines* indicate the following regions: **c** *AB* the part of Amazon transect analyzed by

Angelini et al. (2011) (0°S 50°W→5°S 70°W), *AC* the lowland forest part of the transect (0°S 50°W→6°S 75.5°W), *AD* (0°S 50°W→6.5°S 77.5°W) total forest part of the Amazon transect including mountains. **d** *AD* Congo forest transect of Angelini et al. (2011) and Makarieva and Gorshkov (2007) (0°S 9°E→0°S 30°E), *BC* Congo forest transect of Makarieva et al. (2009) (0°S 10°E→0°S 27°E), *AE* transect shown in Fig. 8 of Angelini et al. (2011) that spans over 3,000 km. The rapid precipitation decline in the *ED* section of the transect shown in Fig. 8 of Angelini et al. (2011) occurs over unforested areas

stores accumulated in soil during the wet season and is facilitated by clear sky conditions of the dry season (Nepstad et al. 1994; Huete et al. 2006; Saleska et al. 2003; Poveda and Salazar 2004; Baker et al. 2008; Ghazoul and Sheil 2010;

Davidson et al. 2011). For example, during much of the dry season, there is active shooting and fruiting of tropical trees (Myneni et al. 2007). In forests that are active year round, the biotic pump should control *annual* precipitation, a statistic

Table 1 Dependence of precipitation on land (P, millimeters per month) on distance from the ocean (x, kilometers) in word's major forest regions, $\text{Log } P = a + bx$

Transect	Mon	Data	$\overline{P} \pm \text{SE}$ (mm month^{-1})	P_0 (mm month^{-1})	l (10^3 km)	$a \pm \text{SE}$	$(b \pm \text{SE}) \times 10^3$ (10^3 km^{-1})	R^2	p
Am-AB	Ann	McGuire et al. (2001)	193±2.9	177	13.4	5.174±0.025	0.0748±0.019	0.28	<0.001
Am-AB	Ann	Legates and Willmott (1990)	202±3.4	180	10.4	5.195±0.025	0.0958±0.019	0.4	<0.001
Am-AC	Ann	McGuire et al. (2001)	192±2.6	185	41.7	5.22±0.027	0.024±0.016	0.04	0.142
Am-AC	Ann	Legates and Willmott (1990)	206±3.5	186	15.8	5.227±0.029	0.0632±0.017	0.21	<0.001
Am-AD	Ann	McGuire et al. (2001)	188±3.4	196	−29.1	5.278±0.04	−0.0343±0.022	0.04	0.124
Am-AD	Ann	Legates and Willmott (1990)	198±4.9	206	−26.5	5.328±0.057	−0.0378±0.032	0.03	0.236
Am2	Ann	McGuire et al. (2001)	196±3.2	176	14.1	5.173±0.027	0.0708±0.017	0.27	<0.001
Am2	Ann	Legates and Willmott (1990)	206±3.2	181	11.5	5.2±0.023	0.0867±0.014	0.44	<0.001
Co-AD	Ann	McGuire et al. (2001)	145±3.1	167	−7.6	5.115±0.041	−0.1316±0.031	0.31	<0.001
Co-AD	Ann	Legates and Willmott (1990)	157±3.7	173	−10.4	5.156±0.045	−0.0962±0.034	0.16	0.008
Co-BC	Ann	McGuire et al. (2001)	151±1.7	152	−106	5.021±0.022	−0.0094±0.02	0.01	0.647
Co-BC	Ann	Legates and Willmott (1990)	162±2.8	156	35.3	5.053±0.033	0.0283±0.03	0.03	0.355
Ye1	Ann	McGuire et al. (2001)	40±1.3	41	−37.9	3.709±0.065	−0.0264±0.038	0.01	0.491
Ye1	Ann	Legates and Willmott (1990)	38±1.5	52	−4.36	3.95±0.057	−0.2292±0.033	0.53	<0.001
Ye1	Jan	McGuire et al. (2001)	25±1.5	44	−2.38	3.778±0.084	−0.4205±0.049	0.63	<0.001
Ye1	Jan	Legates and Willmott (1990)	24±2.	53	−1.53	3.961±0.109	−0.6544±0.064	0.71	<0.001
Ye1	Jul	McGuire et al. (2001)	71±3.1	43	3.22	3.751±0.052	0.3106±0.03	0.71	<0.001
Ye1	Jul	Legates and Willmott (1990)	67±1.6	63	26	4.137±0.05	0.0384±0.029	0.04	0.199
Ye2	Ann	McGuire et al. (2001)	46±3.5	31	3.29	3.419±0.108	0.3038±0.076	0.5	<0.001
Ye2	Ann	Legates and Willmott (1990)	44±1.7	51	−8.55	3.924±0.064	−0.1169±0.045	0.3	0.019
Ye2	Jan	McGuire et al. (2001)	32±2.	29	21	3.381±0.132	0.0477±0.093	0.02	0.613
Ye2	Jan	Legates and Willmott (1990)	30±3.1	49	−2.04	3.898±0.147	−0.4892±0.103	0.59	<0.001
Ye2	Jul	McGuire et al. (2001)	70±6.7	35	1.96	3.549±0.068	0.5092±0.047	0.88	<0.001
Ye2	Jul	Legates and Willmott (1990)	72±3.3	61	7.6	4.103±0.071	0.1315±0.049	0.31	0.017
Le	Ann	McGuire et al. (2001)	30±1.2	19	3.47	2.957±0.042	0.2879±0.026	0.72	<0.001
Le	Ann	Legates and Willmott (1990)	32±1.2	21	3.61	3.026±0.039	0.2767±0.023	0.74	<0.001
Le	Jan	McGuire et al. (2001)	9±0.6	14	−2.2	2.656±0.111	−0.4549±0.068	0.47	<0.001
Le	Jan	Legates and Willmott (1990)	10±0.8	14	−3.17	2.609±0.144	−0.315±0.087	0.21	<0.001
Le	Jul	McGuire et al. (2001)	76±5.	32	1.84	3.45±0.046	0.5437±0.028	0.89	<0.001
Le	Jul	Legates and Willmott (1990)	75±4.3	33	1.98	3.509±0.04	0.5041±0.024	0.9	<0.001
Ob	Ann	McGuire et al. (2001)	34±1.3	23	2.35	3.126±0.025	0.4249±0.025	0.91	<0.001
Ob	Ann	Legates and Willmott (1990)	42±1.7	34	4.38	3.514±0.074	0.2282±0.071	0.25	0.003
Ob	Jan	McGuire et al. (2001)	22±0.5	18	4.99	2.881±0.027	0.2005±0.026	0.65	<0.001
Ob	Jan	Legates and Willmott (1990)	27±2.3	29	−0.73	3.362±1.158	−1.3614±1.118	0.05	0.233
Ob	Jul	McGuire et al. (2001)	53±2.9	29	1.62	3.373±0.028	0.6185±0.027	0.94	<0.001

Table 1 (continued)

Transect	Mon	Data	$\overline{P} \pm SE$ (mm month^{-1})	P_0 (mm month^{-1})	l (10^3 km)	$a \pm SE$	$(b \pm SE) \times 10^3$ (10^{3}km^{-1})	R^2	p
Ob	Jul	Legates and Willmott (1990)	51±5.2	35	−0.98	3.562±1.241	−1.0254±1.199	0.02	0.399
Ma	Ann	McGuire et al. (2001)	25±1.4	16	2.57	2.798±0.064	0.3898±0.057	0.71	<0.001
Ma	Ann	Legates and Willmott (1990)	27±1.1	21	4.09	3.054±0.045	0.2447±0.041	0.66	<0.001
Ma	Jan	McGuire et al. (2001)	14±1.	8	2.11	2.119±0.124	0.4746±0.11	0.49	<0.001
Ma	Jan	Legates and Willmott (1990)	18±0.7	14	4.64	2.666±0.046	0.2156±0.041	0.59	<0.001
Ma	Jul	McGuire et al. (2001)	51±2.8	33	2.46	3.509±0.022	0.4059±0.019	0.96	<0.001
Ma	Jul	Legates and Willmott (1990)	52±3.3	38	3.42	3.629±0.088	0.2925±0.079	0.42	0.001
Fl	Ann	McGuire et al. (2001)	110±0.8	113	−15.5	4.723±0.012	−0.0645±0.024	0.34	0.017
Fl	Ann	Legates and Willmott (1990)	116±1.4	120	−14.9	4.785±0.023	−0.0672±0.047	0.13	0.173
No-AB	Ann	McGuire et al. (2001)	93±1.5	85	9.18	4.444±0.028	0.1089±0.032	0.26	0.002
No-AB	Ann	Legates and Willmott (1990)	101±1.	98	26	4.58±0.019	0.0384±0.021	0.09	0.078
No-BC	Ann	McGuire et al. (2001)	52±4.5	101	−0.7	4.610±0.025	−1.4284±0.04	0.98	<0.001
No-BC	Ann	Legates and Willmott (1990)	58±4.8	107	−0.76	4.670±0.061	−1.3196±0.098	0.89	<0.001
Eu	Ann	McGuire et al. (2001)	44±1.2	68	−7.65	4.218±0.025	−0.1308±0.006	0.66	<0.001
Eu	Ann	Legates and Willmott (1990)	48±1.4	77	−6.83	4.35±0.025	−0.1464±0.006	0.71	<0.001
Eu	Jan	McGuire et al. (2001)	32±1.7	66	−4.08	4.192±0.036	−0.2448±0.009	0.77	<0.001
Eu	Jan	Legates and Willmott (1990)	38±1.9	81	−4.02	4.39±0.037	−0.2487±0.009	0.77	<0.001
Eu	Jul	McGuire et al. (2001)	70±0.8	83	−20	4.422±0.018	−0.05±0.004	0.37	<0.001
Eu	Jul	Legates and Willmott (1990)	72±1.	87	−17.4	4.467±0.024	−0.0574±0.006	0.29	<0.001

In the first column, the first two letters denote the transect as in Fig. 1; letters after dash denote the corresponding part of the transect. P_0 (millimeters per month)≡exp(a) is the estimated precipitation at $x=0$ (at the coast); $P_0 < \overline{P}$ indicates that precipitation grows inland; $P_0 > \overline{P}$ indicates that precipitation grows inland. l (kilometers)≡1/b indicates the exponential scale length of precipitation change; $l>0$ indicates that precipitation grows inland. Complete statistics for all months in all regions is given in Online Resource Table 4

Transect regions where precipitation was studied, *Mon* period for which precipitation data are reported, *Data* precipitation data set used, $\overline{P} \pm SE$ mean precipitation in the region ±1 standard error, R^2 the squared correlation coefficient, p the probability value of the OLS regression Log $P=a+bx$, *Ann* annual

which Angelini et al. (2011) did not analyze for their tropical transects.

As pointed out by Makarieva and Gorshkov (2007) and Makarieva et al. (2009), in agreement with this expectation, annual precipitation in the equatorial zone in the Amazon and Congo forests remains approximately constant from coast to interior. The data of Legates and Willmott (1990) unequivocally support this conclusion (Table 1 and Fig. 2a, b). Annual precipitation in the Amazon is found to grow inland very slightly in both transects studied by Makarieva and Gorshkov (2007) and Makarieva et al. (2009) on the one hand and by Angelini et al. (2011) on the other. No statistically significant decrease in precipitation from coast to interior can be discerned across the largest transect Am-AD that spans over 3,000 km (Fig. 1). There is no significant dependence of the annual precipitation on distance from the ocean in the Congo basin either (Table 1). Indeed, precipitation slightly increases inland along the transect Co-BC as can be derived from both Legates and Willmott (1990) and McGuire et al. (2001) datasets; meanwhile, over the larger transect Co-AD which includes the mountains, we find a slight decline. This decline is characterized by an exponential scale length l of about 10,000 km (Table 1), which is one order of magnitude larger than the typical scale length of precipitation decline over deforested areas (Makarieva and Gorshkov 2007; Makarieva et al. 2009).

The observed seasonal changes in precipitation in the two rainforest regions have remarkable properties that can be analyzed within the biotic pump framework. First, as also mentioned by Angelini et al. (2011), we find a coast-to-interior decline in the seasonality of precipitation measured as the coefficient of variation of monthly precipitation based on Legates and Willmott (1990) data (Fig. 2e, f). In both the Congo and Amazon forests, we perceive a minimum of seasonal coefficient of variation at around 0.2 that pertains to over a thousand kilometers in the forest core. In the forest-flanking regions in both river basins, the seasonal variation increases sharply irrespective of whether precipitation in these bordering regions is high (the Atlantic Ocean) or low (the Pacific coast of South America and the Indian Ocean coast of Africa) (Fig. 2e, f).

Second, the biotic pumps of the Congo and Amazon forests function to some degree in an opposite phase. For example, October and November are the driest months at the Atlantic coast of the Amazon basin, while they are the wettest months at the Atlantic coast of the Congo basin (Fig. 2a, b). In the absence of forest impact, the condensation zones in the ocean should undergo regular seasonal changes in location and intensity that are governed by the similarly regular seasonal changes in solar radiation at any given latitude. Meanwhile, the observed seasonal precipitation patterns and their differences between the two equatorial forests suggest that these patterns may not be directly related to geophysical seasonal

factors and are therefore not "seasonal" in the common geophysical sense of this term. Rather, they may result from the presence of two large-scale biotic pumps that share the same moisture source (the Atlantic Ocean) and have evolved to function asynchronously (see also Fig. 6a and discussion in Section 5 below). On the other hand, the coast-to-interior decline in precipitation seasonality (Fig. 2e, f) reflects the declining influence of oceanic oscillations and other remote processes in the interior forest regions where moisture transport is stabilized by the surrounding forests. On a smaller temporal scale, the same stabilizing impact of rainforests as compared to unforested regions was recently quantified by Millán et al. (2011) in an analysis of daily precipitation statistics: Rainforest precipitation in Ecuador was the highest among several regions studied across the world, but its coefficient of variation was the lowest.

To conclude the discussion of seasonal rainfall patterns in the annually active tropical rainforests, it is pertinent to note the following: In view of the fact that land covers a considerably smaller area than the ocean, moisture transport from ocean to land by forests is an uneasy "tug-of-war" with the ocean where the physically similar condensation-driven atmospheric dynamics is also operating. Thus, depending on seasonal and geographic conditions (temperature, solar radiation, size, and location of the forest area with respect to the major oceanic condensation zones), the atmospheric moisture transport from ocean to land by the biotic pump can be either more or less efficient. In the unfavorable periods when such transport is physically unfeasible, functioning of the ecological community may occur at the expense of soil moisture accumulated during the more favorable periods—if the ecological community is able to store moisture efficiently. The coastal forests of the Amazon and Congo basins apparently realize such a strategy. Returning to the evolutionary context of the biotic pump concept, we note that a *time-invariable* distance independence of precipitation (i.e., the constancy of precipitation per se) could not have been a goal of natural selection during forest evolution. The prerequisite of land colonization by life was to meet the water needs of the ecological community and to guarantee its water supply against fluctuations like extreme floods and droughts. Other conditions being equal, an ecological community with trees capable of ensuring high and stable rates of water supply would be able to maintain a higher productivity than an ecological community incapable of controlling its water regime (and so would out-compete the latter, see discussion in Makarieva and Gorshkov (2007), Section 4). Will that goal be achieved by continuously transporting moist air from the ocean year round, or by efficiently storing moisture during the periods when the ocean-to-land transport is easier and then spending it to maintain high productivity during the more difficult periods, are just different forms of the biotic pump mechanism.

4 Seasonal forests

Unlike the equatorial rainforests, seasonality in the functioning of boreal forests is very clear-cut as it is associated with significant temperature changes between seasons. In winter at low temperatures, the biochemical machinery of the forest ecosystem is virtually shut down. In summer at high temperatures, it functions at its most active. Comparing precipitation distribution between winter and summer months can yield important insights into the peculiarities of the biotic pump mechanism. However, surprisingly, having studied *seasonal* precipitation in the equatorial rainforests that are active year round, Angelini et al. (2011) only analyzed *annual* precipitation in the boreal forest of the Yenisey River basin, despite the latter exhibiting perhaps the most extreme seasonality among the world's forests.

In the Yenisey basin, Angelini et al. (2011) considered a somewhat different transect than did Makarieva and Gorshkov (2007) and Makarieva et al. (2009) (Fig. 1 and Table 1). They found that, according to Legates and Willmott (1990) data set, annual precipitation along the transect declines southward with growing distance from the ocean. The McGuire et al. (2001) data confirm this trend (Fig. 3a). Annual precipitation in three other meridional boreal transects in the Lena, Ob, and Mackenzie river basins (these regions were omitted by Angelini et al. (2011) from their analysis) increases with distance from the ocean according to both McGuire et al. (2001) and Legates and Willmott (1990) data (Fig. 3c–e). For the original transect of Makarieva et al. (2009), the McGuire et al. (2001) data show a growing trend, while Legates and Willmott (1990) data show no significant trend (Fig. 3b and Table 1). However, these differences in annual precipitation between the various data sets and various transects turn out to be minor compared to differences in the seasonal distribution of precipitation (Fig. 3f–j).

In Fig. 3f–j, January and July precipitation is shown for all the five meridional boreal forest transects. As can be seen from Fig. 3f–j and Table 1, summer precipitation either grows significantly (the slope of the semi-log curve log P versus distance is positive) or it does not show any trend. In contrast, winter precipitation either conspicuously decreases or remains nearly constant (Fig. 4a). One area in the Ob transect displays zero precipitation during some months (Fig. 3i) in Legates and Willmott (1990) data. Another significant discrepancy between the two data sets is associated with tundra precipitation in the Yenisey transect. In Legates and Willmott (1990) data, the tundra precipitation is nearly twice as high as in the McGuire et al. (2001) dataset. It is also significantly higher than elsewhere in the tundra zone, e.g., in Lena, Ob, or Mackenzie regions (cf. Fig. 3a–e). It may well be that the natural tundra ecosystem which is evolutionarily adapted to low temperatures and low absolute humidity functions as a high latitude analog of the forest moisture pump. More research is needed to establish spatial precipitation patterns over tundra given the current discrepancies between the data. For the time being, we separately analyzed data for the forest parts of the transects (Fig. 4b). The pattern is confirmed: In all summer months when the forest ecosystem actively functions, precipitation grows southward with increasing distance from the ocean. This pattern is robust with respect to the dataset used (Legates and Willmott (1990) or McGuire et al. (2001)).

Angelini et al. (2011) also studied a meridional forest transect from the Florida Panhandle to Ohio River (about 840 km) (Fig. 1 and Table 1) and observed that precipitation in April, March, and June drops as one moves northward. It was interpreted by Angelini et al. (2011) as evidence against the biotic pump. However, as discussed in Section 2, the biotic pump would cause precipitation to decrease from equator to the poles irrespective of distance from the ocean. Therefore, the northward decrease of precipitation in the subtropical forest region of the USA would be consistent with the biotic pump concept. On the other hand, in the absence of the biotic pump, precipitation should decrease from coast to interior as the geophysical water vapor fluxes become depleted of moisture at they travel inland. Therefore, logically, analysis of precipitation distribution along a northward coast-to-interior transect is not well suited to expose the presence or absence of the biotic pump because precipitation should decrease northward either way. Concluding the discussion of North American transects, we note that the data of Legates and Willmott (1990) confirm the conclusion of Makarieva et al. (2009) about the approximately constant coast-to-interior precipitation in the forest region between 35° and 40°N and a sharp decline of precipitation over the non-forested part of the transect (Table 1).

It was noted by Angelini et al. (2011) that the meridional orientation of the boreal transects analyzed by Makarieva and Gorshkov (2007) and Makarieva et al. (2009) does not coincide with the predominant transport of atmospheric moisture that occurs from west to east in high latitudes (van der Ent et al. 2010). This question was addressed during open discussion of Makarieva and Gorshkov (2006, p. S1709, 2007). Here we extend our analysis and explore precipitation distribution across the 61°N parallel, which harbors the most extensive forest coverage in Eurasia that spreads over 7,000 km (Fig. 1). In summer, with forest actively functioning, precipitation over the forest is nearly constant over several thousand kilometers and exceeds the mean precipitation over the Atlantic Ocean at the same latitude (Figs. 4c and 5a). For example, in July the exponential scale length of precipitation decline exceeds 17,000 km (Fig. 4c and Table 1). Moisture evaporated from the ocean is transported inland feeding the water cycle on land and thereby leading to reduced precipitation over the ocean.

In winter, the situation changes radically. Now precipitation over the Atlantic Ocean greatly exceeds precipitation over the dormant winter forest (Fig. 5b). Moreover, the oceanic
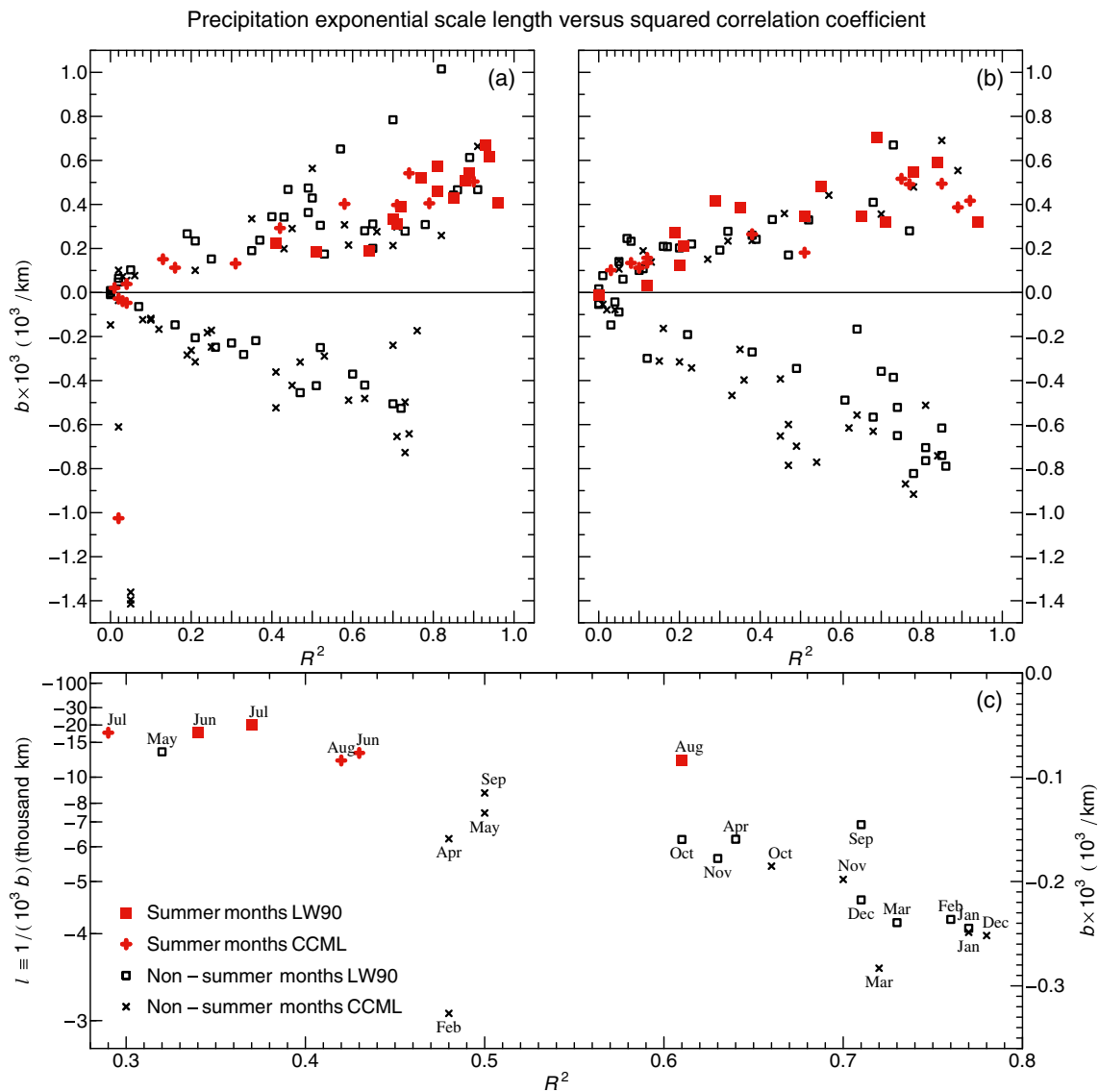
Fig. 3 Annual and seasonal (July, January) precipitation in the meridional boreal forest transects according to Legates and Willmott (1990) (*LW90*) and McGuire et al. (2001) (*CCML*) data. **k–o** The topography and land cover with the same symbols as in Fig. 2c, d. *Dashed line* marked "T" indicates the tundra–forest transition

precipitation in winter becomes three times larger than it is in summer. Land is apparently locked for oceanic moisture: Winter precipitation drops abruptly at the coast and then gradually decreases eastward (Fig. 2b) with an exponential scale length of 3 to 5,000 km (Fig. 4c).

Notably, this length still significantly exceeds the scale length of no more than 10^3 km established by Makarieva and Gorshkov (2007) and Makarieva et al. (2009) for major unforested regions. Owing to the accumulation of snow on tree branches, forests in the boreal zone retain a high evaporative surface index ("branch area index") in winter. Interception of winter precipitation by trees increases the evaporative surface area and enhances total evaporation. This makes the biotic pump work to some degree even in winter forests when the plants are in anabiosis and no photosynthesis nor other active biochemical processes are occurring in plant tissues. Evaporation of moisture intercepted by trees constitutes a significant part of total forest evaporation (Savenije 2004; Cuartas et al. 2007; Murakami 2009), and in winter when transpiration is absent, this part may play a major role in total evaporation over a snow-covered forested terrain. From an evolutionary viewpoint, the amount of intercept and winter precipitation should be regulated by tree morphology to keep the spring high waters within biologically safe limits, but at the same time allow for accumulation of a sufficient store of moisture to be used by plants in the spring. It remains to be investigated how the observed large-scale changes in the morphology of the dominant tree species, from the evergreen spruce in eastern Eurasia to deciduous larch over Siberian permafrost, attenuates the biotic pump functioning in winter.

Precipitation exponential scale length versus squared correlation coefficient

Fig. 4 Exponential scale length of monthly precipitation P (millimeters per month) in boreal forest transects estimated from OLS regression $LogP = a + bx$, where x (kilometers) is distance from the ocean and P for each grid cell is taken from either Legates and Willmott (1990) (*LW90*) or McGuire et al. (2001) (*CCML*) dataset and R^2 is the squared correlation coefficient. Inverse value of $l \equiv 1/b$ represents the exponential scale length of precipitation change. **a** Data for the five meridional boreal transects (tundra/forest) (Fig. 3), a total of $5 \times 12 \times 2$ points. **b** Data for the forest parts of the five meridional transects excluding Legates and Willmott (1990) precipitation for Ob because of its abrupt change over the forest region (Fig. 3i). **c** Data for the Eurasian latitudinal boreal forest transect (Fig. 5). Notations shown in **c** hold for all panels. Numerical data are given in Online Resource Table 4

5 Comparing boreal and tropical forests

Precipitation P is the best studied term in the stationary water budget equation $P = E + R$, where E is evaporation and R is the amount of moisture delivered to the considered area by winds and lost by that area in the form of liquid runoff. However, the precipitation databases that are used in climate studies are not perfect and may feature systematic discrepancies as illustrated in our analysis on the example of the difference in tundra precipitation between the Legates and Willmott (1990) and McGuire et al. (2001) data (Fig. 4). Like Angelini et al.

(2011), we used the available precipitation data at their face value: In the statistics shown in Table 1, precipitation values in all grid cells are treated as independent data points. In reality gridded precipitation databases are constructed by spatial interpolation of precipitation station records on land (or ship observations in the ocean) that are scattered in a highly non-uniform manner across the planetary surface. In particular, the least populated forested areas are characterized by a much lower density of observations than the industrial areas (see, e.g., Figs. 1 and 2 of Legates and Willmott 1990). We, however, believe that the large-scale trends established for our
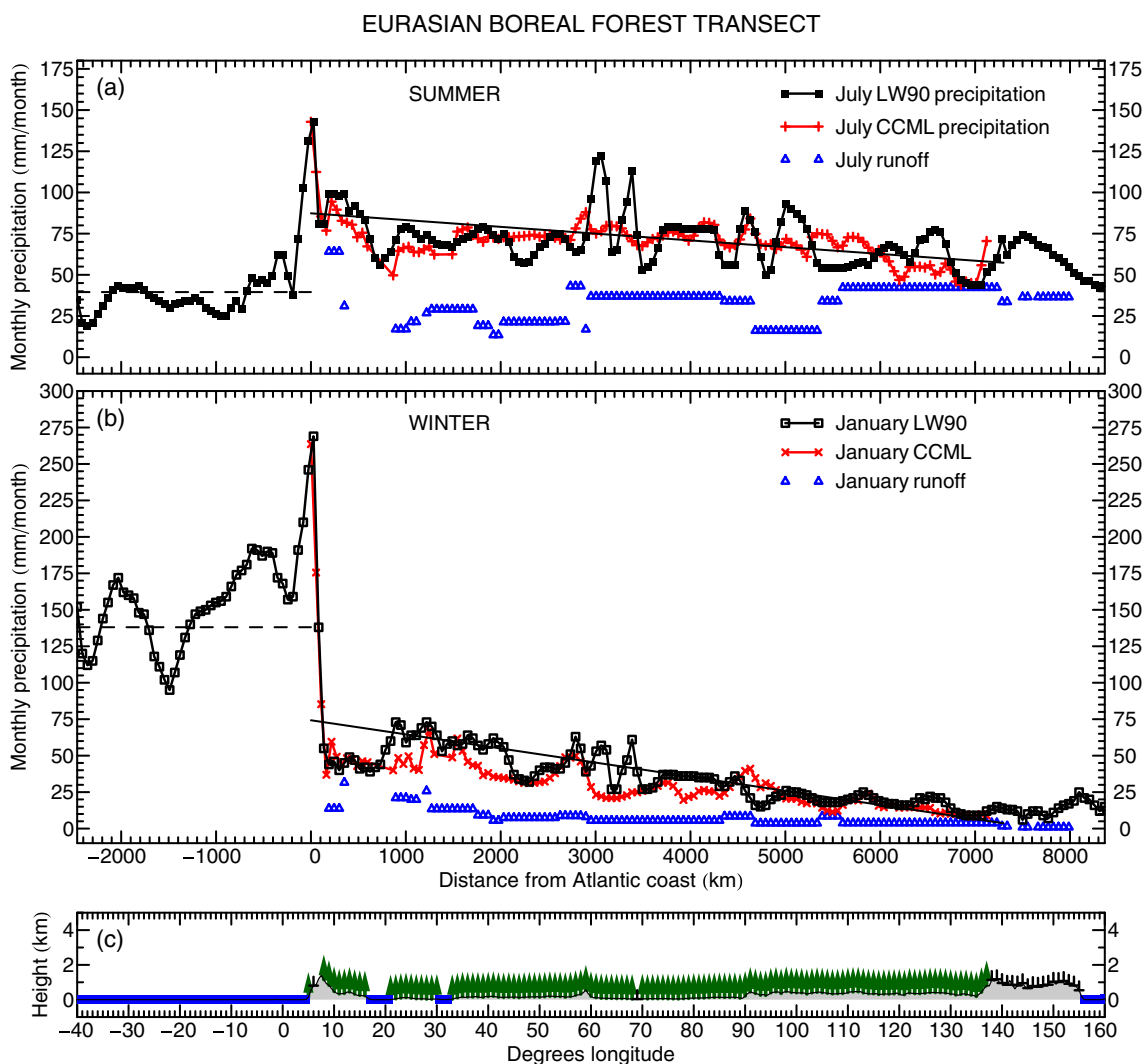
EURASIAN BOREAL FOREST TRANSECT

Fig. 5 Summer (July) and winter (January) precipitation in the Eurasian boreal forest transect at 61°N according to Legates and Willmott (1990) (*LW90*) and McGuire et al. (2001) (*CCML*) data. Additionally shown is river runoff during the same periods. *Solid lines* indicate linear regressions of Legates and Willmott (1990) forest precipitation P over distance x from $x=0$ to $x=7,150$ km (a total of 252 values for 0.5° grid cells) in the form $P=c+dx$: **a** $c=87\pm2$ mm month^{-1}, $d=-0.0041\pm0.0004$ mm month^{-1} km^{-1}, $R^2=0.25$. **b** $c=74\pm3$ mm/month (±1 SE), $d=-0.0097\pm0.0007$ mm month^{-1} km^{-1}, $R^2=0.43$. *Dashed lines* indicate

mean Legates and Willmott (1990) precipitation over the Atlantic ocean at 61°N: **a** 40 mm month^{-1}; **b** 139 mm month^{-1}. **c** The topography and land cover; *symbols* same as in Fig. 2c, d (note that a narrow precipitation peak at the land–ocean border like the one in **a** at 5° E appears to be a common feature across the globe and is attributed to local topography (e.g., Álvarez-Villa et al. 2011, Fig. 8) or to the local impact of land breezes (e.g., Heiblum et al. 2011) that is imposed on large-scale synoptic patterns)

forest transects which spread over more than a thousand kilometers should not be significantly affected by the station spacing: Even in the regions with the lowest station density, neighboring stations are separated by no more than a few hundred kilometers (for example, there are over 40 stations along the Eurasian forest transect to the west of 90°E and about a dozen—to the east.) Moreover, for boreal forests, our main results pertain to seasonal changes in the precipitation distribution (Fig. 4), which are recorded by one and the same set of stations.

Further improvement in the precipitation data quality is obviously highly desirable. In the meantime, another way to

check for the robustness of the established patterns is to back up the investigation of precipitation data by independent runoff measurements. The long-term average runoff of a river basin is equal to the long-term average net advection of moisture by the winds. Therefore, river runoff is not only a crucial hydrological variable but it is also a crucial meteorological variable. However, while precipitation is measured locally, runoff estimates made on rivers by definition pertain to the water budget of the entire catchment. Moreover, when the precipitation transect is located within a single large river basin, as is the case with the Congo and Amazon transects, runoff estimates made along one and the

same river at different points of the transect may suffer from spurious spatial and temporal correlations.

The Eurasian boreal forest transect is unique in this aspect as it runs across several major independent river basins, including the Great Siberian rivers. This allows one to gain additional independent information about the net moisture transport in the region. In Fig. 5, we plotted July and January runoff observations corresponding to 61°N from the gridded UNH, GRDC, and Global Composite Runoff Data Set (v1.0) (see Online Resource for details). It can be seen from Fig. 5a that the runoff data are consistent with the statement that the amount of moisture, which is delivered to each region along the forest transect, is approximately independent of distance from the ocean along the boreal forest Eurasian transect when the forest is photosynthetically active (note that the runoff in July is minimally affected by the seasonal discharge of precipitation accumulated during the winter). Runoff in January resembles January precipitation in showing a conspicuous decline from west to east (Fig. 5b). The agreement between the independent runoff and precipitation data strengthens the validity of using precipitation as a proxy for large-scale moisture transport.

As discussed above, the role of vegetation in atmospheric moisture transport becomes clear from comparison of the land/ocean precipitation ratios (LOPR) in regions/time periods with or without biotic pump. For the Amazon and Congo forests at 3°S, the ratio of precipitation at a given longitude to the mean Atlantic precipitation at the same latitude (i.e., mean precipitation between 45°W and 10°E at 3°S) is shown in Fig. 6a. It can be seen that the point of minimal oceanic precipitation coincides with the point of minimal LOPR, which undergoes periodic zonal migration between the two forest basins throughout the year. The LOPR minimum is closer to the Amazon basin in November, when the coastal precipitation there is at its minimum (Fig. 2a), and it is closer to the Congo basin in March, when coastal precipitation in the Amazon is at its maximum. It would be interesting to investigate how the seasonal drift of the LOPR minimum is temporally and spatially correlated with the photosynthetic activity of both Congo and Amazon forests, e.g., by comparing the normalized difference vegetation index climatology between the basins—so far it has been predominantly studied in either one basin or another (e.g., Anyamba et al. 2001; Poveda and Salazar 2004).

It is clear from Fig. 6a that independent of the season condensation is predominantly concentrated over the forests, with a difference of two to three times between precipitation over the forest and over the adjacent ocean. An essentially identical pattern is observed during summer months over the Eurasian boreal forest (Fig. 6b). Since the flux of evaporation from either forest or the ocean is limited by solar radiation, it cannot differ several times between the ocean and the forest. Such precipitation differences unambiguously testify for a

significant moisture transport from ocean to the forest. Meanwhile, winter precipitation over the boreal forest not only decreases downwind but it is lower than oceanic precipitation. For comparison, in the unforested regions of Australia, precipitation over land remains lower than over the ocean both in the dry and, more importantly, during the wet season (Fig. 6c). Thus, it is not the absolute availability of moisture that distinguishes forested regions from unforested ones, but the presence/absence of an efficient ocean-to-land moisture transport. Unforested land regions are locked to oceanic moisture all year round even when moisture is abundant over the adjacent ocean.

6 Discussion

The overall conclusion of Angelini et al. (2011) (p. 251) was that the basis of the biotic pump concept is not borne out with observations of the internally consistent precipitation climatology of Legates and Willmott (1990) because (1) precipitation actually decreases, rather than increases or remains constant, as one moves inland along the forested transects and (2) seasonal variation in the coast-to-interior precipitation trends vary in a manner that is inconsistent with the biotic pump concept because constant or increasing precipitation can be found only during some dry seasons in some locations, which, according to Angelini et al. (2011), is "the time when transpiration is lowest and presumably the biotic pump mechanism would be weak." Additionally, Angelini et al. (2011) generalized that the distance–decay model of mean precipitation decreasing inland from the ocean is not dependent upon the local vegetation type.

In this paper, we have addressed all these issues, clarified the misinterpretations of the biotic pump concept by Angelini et al. (2011), and demonstrated that the precipitation climatology of Legates and Willmott (1990) consistently supports the biotic pump concept:

1. In natural science, there cannot be such a thing as an absolute constancy of a variable, e.g., precipitation: It always changes somewhat from location to location. The focus of Makarieva and Gorshkov (2007) and Makarieva et al. (2009) was on a *quantitative comparison* of precipitation distributions between forested and unforested areas. Precipitation in the latter was found to drop exponentially from coast to interior with a length scale of the order of 10^3 km. This reference length scale allowed us to speak about the relative constancy of spatial precipitation distribution in forested regions, which quantitatively means that the scale length of coast-to-interior precipitation change in forests significantly exceeds the "unforested" reference. Angelini et al. (2011) did not provide any quantitative backup for

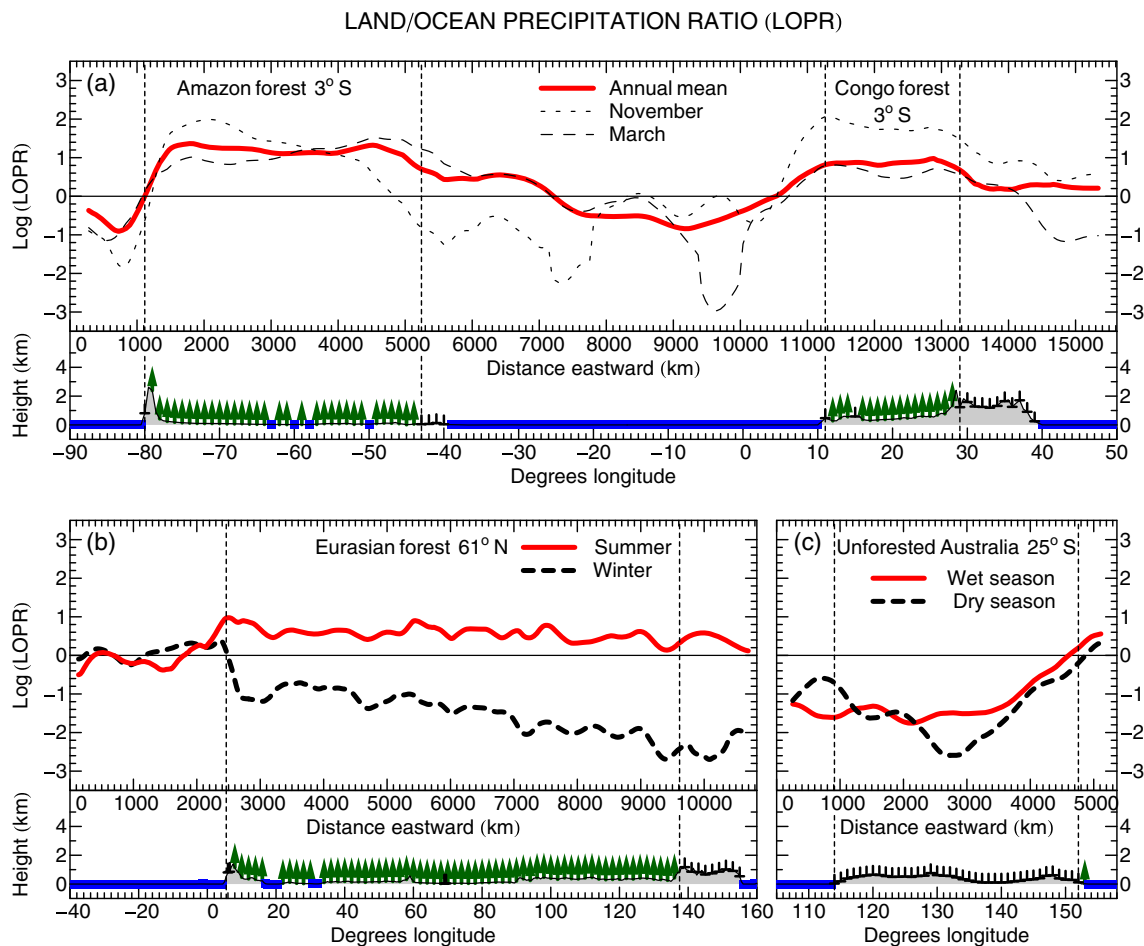LAND/OCEAN PRECIPITATION RATIO (LOPR)

Fig. 6 Natural logarithm of land/ocean precipitation ratio (*LOPR*) in forested and unforested regions. **a** Annual mean, November, and March precipitation at a given longitude at 3°S divided by mean Legates and Willmott (1990) precipitation over the Atlantic Ocean at the same latitude during the same period (63, 41, and 104 mm month^{-1} annual mean, November, and March, respectively). Note the relatively constant precipitation over the forests at this latitude as well (cf. Figs. 1 and 2a, b dashed transects). **b** Summer (July) and winter (January) precipitation at a given longitude at 61°N divided by mean Legates and Willmott (1990) precipitation over the Atlantic ocean at the same latitude and over the same period (139 and 40 mm month^{-1} in January and July, respectively). **c** Precipitation over Australia at 25°S (dashed transect in Fig. 1) during the wet (January) and dry (July) seasons divided by mean oceanic Legates and Willmott (1990) precipitation at the same latitude over the same period (140 and 70 mm month^{-1} in January and July, respectively). Legates and Willmott (1990) data for half degree grid cells are smoothed by moving average over 11 cells (5.5°). Topography and land cover *symbols* same as in Fig. 2c, d

their analyses, such that their generalization on the distance–decay of precipitation being independent of vegetation type remains unfounded.

2. As confirmed by Legates and Willmott (1990) data, in tropical and equatorial rainforests that are photosynthetically active year round, *annual* precipitation remains approximately constant as one moves from the oceanic coast over several thousand kilometers inland (Figs. 2 and 6; Table 1). This is in agreement with the biotic pump concept (Section 2) and consistent with our previous results (Makarieva and Gorshkov 2007; Makarieva et al. 2009).

3. The dry season is not the time when transpiration is the lowest in undisturbed rainforests but an active season when the forest functions at the expense of moisture

previously accumulated and stored in soil. Seasonal precipitation in tropical rainforests displays a complex spatial distribution reflecting the interaction between oceanic and forest condensation zones and a possible coupling between the Congo and Amazon forests. Coastal forests are affected most by condensation processes in the ocean and thus display most pronounced seasonality in precipitation patterns. This seasonality diminishes from the coast toward the region interior where the stabilizing impact of the forest cover becomes dominant (Fig. 2e, f). All these patterns are consistent with the biotic pump concept.

4. Angelini et al. (2011) did not investigate seasonal precipitation in boreal forests. In the meantime, the data of Legates and Willmott (1990) testify to a sharp contrast

in the spatial distributions of summer precipitation when the boreal forest ecosystem is active and precipitation during the rest of the year when the biological processes in plants are inhibited or completely shut down (Fig. 4a–c). In agreement with the biotic pump concept, summer precipitation grows toward lower latitudes.

5. Investigation of the world's longest forest transect—the Eurasian boreal forest which spreads over 7,000 km at 61°N (Fig. 5)—illustrates the biotic pump most vividly (Fig. 6). First, summer precipitation is nearly constant along the transect (exponential scale length 10–20,000 km, Fig. 4c and Table 1), while winter precipitation declines more conspicuously from west to east. Second, summer precipitation over the forest exceeds mean precipitation over the Atlantic Ocean at the same latitude, while in winter the opposite is true. Precipitation over the Atlantic Ocean in winter, when the biotic pump does not draw moisture away from the ocean, is larger than it is in summer.

Aside from considering large-scale spatial precipitation distributions, Angelini et al. (2011) reviewed some evidence on local precipitation patterns. For example, from the observation that rainfall in the Amazon occurs more frequently in close proximity to rivers rather than far from them (Fitzjarrald et al. 2008), Angelini et al. (2011) concluded that the rainfall is a complex process that is influenced but not controlled by vegetation contrary to what the biotic pump concept implies. However, the biotic pump concept does not predict that rainfall must be the same over the rivers and over the forest. It predicts that if there are no large-scale forests, there will be no coast-to-interior atmospheric vapor transport and no rivers in the continental interior (an extreme example of such a situation is the now unforested Australian continent). The data discussed by Angelini et al. (2011) relate more to the intrinsic peculiarities of what kind of a rainfall regime a large-scale forest can induce rather than to the foundations of the biotic pump concept itself.

It should be further noted that the most recent satellite data analysis (Paiva et al. 2011) does not support the conclusions of Fitzjarrald et al. (2008) for higher precipitation over rivers in the Amazon. Rather, precipitation over the water bodies is found to be several per cent lower than over the adjacent forest. This effect stands in contrast with the pattern observed in the southeast USA that is largely unforested. There, on the contrary, precipitation over the water bodies is larger than over land (Tian and Peters-Lidard 2007). These patterns are in agreement with the biotic pump concept that postulates higher convective capacity of the atmosphere above the forest canopy than over the open water surface. On the other hand, the open water surface should have a higher convective potential than bare land or scarce non-forest vegetation.

Finally, Angelini et al. (2011) dwelled on the question of the temporal changes of precipitation with time in the regions affected by deforestation. They noted that Satyamurty et al. (2010) observed only a slight precipitation reduction in the Amazon basin during the last century using data for 18 meteorological stations with long-term records. However, conclusions based on reconstructing the precipitation trends for the very large Amazon basin on a small number of stations should be interpreted with caution. Using a much wider quality-controlled station network, Espinoza et al. (2009a) established a decline in the basin precipitation between 1974 and 2003 at an approximate rate of 0.33%/year, i.e., about 10% over the studied period. Given that the forest losses of about 30% occurred in the basin in the last half a century and considering that the these losses mostly affected the southern and southeastern part of the basin where precipitation is generally lower than in the basin core, this means that the mean precipitation decline observed since the beginning of the deforestation roughly corresponds to the loss of the biotic pump power. Notably, the analysis of Espinoza et al. (2009a) had not yet included 2005 and 2010, the 2 years when exceptional droughts hit the Amazon region (Marengo et al. 2011). In studies pertaining to a smaller regional scale, deforestation in the Amazon basin is also found to be associated with increase in temperature but decrease in precipitation (Dubreuil et al. 2012).

Espinoza et al. (2009a) observed that the precipitation decline is least manifested in the southern part of the basin. However, one should take into account that with progressing deforestation, the precipitation bias of the meteorological stations may change its sign. If stations that are situated near water channels report lower than average precipitation when surrounded by forests (Paiva et al. 2011) but higher than average precipitation when located in unforested areas (Tian and Peters-Lidard 2007), deforestation may cause a spurious increase in rainfall in the readings of such stations. Analysis of runoff trends (Espinoza et al. 2009b) indicates a conspicuous decrease in runoff in southern regions. In the Congo region while the precise value of the decline rate is debated, the declining trend itself is undoubtedly present especially in the Greater Horn region that is situated downwind the Congo forest (Yin and Gruber 2010; Williams et al. 2011). On an historical time scale, recent studies of past climates increasingly suggest that human-induced deforestation was likely cause of desertification and subsequent civilization collapses (Beresford-Jones et al. 2009; Oglesby et al. 2010).

One can expect the biotic pump degradation to be accompanied by an increase in the frequency of extreme events and weather unpredictability, as the stabilizing impact of forest ecosystems is diminished and the region is exposed to uncontrolled fluctuations of the oceanic water cycle. When the biotic transport of water vapor from ocean to forest stalls or weakens, from the mass conservation law, it follows that moisture evaporated from the ocean must, if not over the forest, precipitate somewhere else. In the ultimate case, when moisture transport from ocean to land is completely absent, all moisture

evaporates from and precipitates over the ocean. Interpolating between the states of a perfect biotic pump and its complete absence, one can expect that deforestation-induced degradation of the biotic pump should primarily affect the farthest downwind areas. Owing to the weakening of the coast-to-interior air flow and reduced convection the air that would otherwise rise over the forest and return to the ocean in the upper atmosphere can instead follow a horizontal path affecting nearby regions. This may lead to a temporary enhancement of the water cycle in the drier areas bordered by forests. For example, a recent precipitation increase in Sahel and the precipitation decline in the Greater Horn region in Africa (Williams et al. 2011) can both be associated with the continuing degradation of the Congo forest.

Since with the stalling of the biotic pump, moisture increasingly remains over the ocean rather than is drawn far inland, one may also expect a transient increase in coastal precipitation as a long-distance outcome of deforestation: In the result of a reduced transport of moisture to the deeper continental interior, precipitation in the coastal zone may rise. The analysis of Satyamurty et al. (2010) tends to support this pattern. Among the 18 rainfall stations investigated, six display a statistically significant difference in the mean annual precipitation between the periods prior to and after the year 1970 (the year when deforestation started to affect the Amazon basin). Three stations show a drop in rainfall, of which two (Iauaretê and Benjamin Constant) are among the innermost locations that are the farthest from the Atlantic Ocean. Among the remaining three stations that show a rise in precipitation, two (Belém and Soure) are located near immediately at the Atlantic coast. The only other coastal station studied by Satyamurty et al. (2010) (Macapá) does not display a statistically significant annual precipitation change.

Angelini et al. (2011) concluded their paper by noting that their analyses did not support the existence of any vegetation-induced driving mechanism of rainfall but *instead* testified for a strong dependence of Amazon rainfall on the water drawn from the ocean and on the large-scale weather systems coupling the continental interior and the ocean. As we clarified in this paper, such an opposition does not really exist but represents a misinterpretation of the biotic pump concept. Indeed, those large-scale moisture-carrying weather systems would not be there without the biotic pump. The very existence of the Amazon, Congo, and the Great Siberian rivers as well as all the data analyzed by Makarieva and Gorshkov (2007), Makarieva et al. (2009), and Angelini et al. (2011) indicate that a large-scale transport of oceanic moisture to the forested continents does occur. The biotic pump concept (1) reveals the physical mechanisms (condensation-induced atmospheric dynamics) behind this transport and quantifies parameters of those large-scale weather systems that couple the land and the ocean and (2) clarifies the principles of the biotic control of those physical mechanisms and how they may change upon the anthropogenic disturbance of the natural vegetation cover. Deforestation can be expected to erode the low-pressure zones on land that are associated with forest functioning and are responsible for the coast-to-interior moisture transport. Further studies of the physical and ecological bases of the biotic pump are important for safeguarding a stable and intense hydrological cycle on land and protecting populations from unfavorable regional changes in the hydrological cycle.

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