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Precipitation on land versus distance from the ocean: Evidence for a forest pump of atmospheric moisture

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ABSTRACT

Flux of oceanic moisture brought inland by winds has been conventionally considered as a geophysical parameter practically unaffected by vegetation; accordingly, models predict only slight post-deforestation precipitation reductions. Here we show that the dependence of annual precipitation on distance x from the ocean differs markedly between the world's forested and non-forested continent-scale regions. In the non-forested regions precipitation declines exponentially with distance from the ocean with an established global mean e-folding length of $l \sim 600$ km. In contrast, in the forest-covered regions precipitation does not decrease or even grow along several thousand kilometers inland. Using a novel physical mechanism involving the non-equilibrium distribution of atmospheric water vapor it is explained how the high transpiration fluxes developed by forests enable them to pump atmospheric moisture from the ocean to any distance inland to compensate for the gravitational runoff of water. Our results indicate that forest cover plays a major role in the atmospheric circulation and water cycling on land. This suggests a good potential for forest-mediated solutions of the global desertification and water security problems.

1. Introduction: precipitation dependence on distance from the ocean

Investigating the role of forests in sustaining the terrestrial water cycle is important in the current situation of rapid global elimination of the natural vegetation cover. Comparative global analysis of the precipitation dependence on distance from the ocean in forested versus non-forested areas is lacking. Using the available meteorological data for the second half of the 20th century and continental vegetation maps (Bryant et al., 1997; Ni and Zhang, 2000; Loveland et al., 2000; Watersheds of the World, 2003), here we show that the dependence of annual precipitation on distance from the ocean differs markedly between the world's forested and non-forested continent-scale regions. In the non-forested regions, precipitation declines exponentially with distance from the

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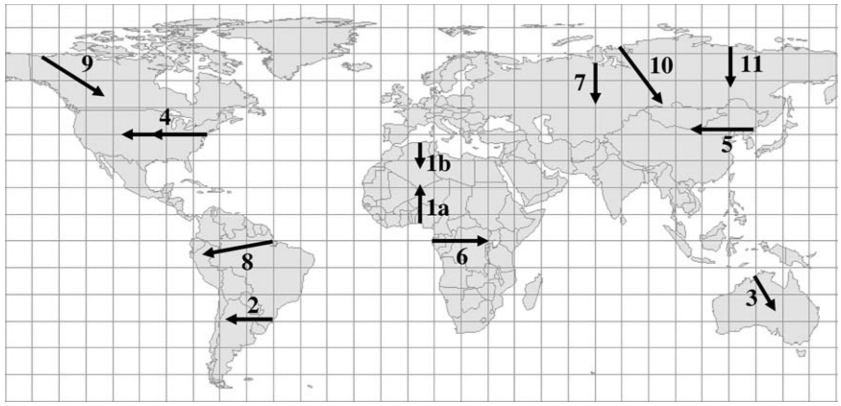

Fig. 1 – Geography of the regions where the dependence of precipitation *P* on distance *x* from the ocean was studied. Numbers near arrows correspond to regions as listed in Table 1. Arrows start at $x = 0$ and end at $x = x_{max}$, Table 1.

ocean. In contrast, in the forest-covered regions precipitation does not decrease or even grow along several thousand kilometers inland. On the basis of a new physical mechanism involving the non-equilibrium distribution of atmospheric water vapor it is explained how the high transpiration fluxes developed by forests enable them to pump atmospheric moisture from the ocean to any distance inland to compensate for the gravitational runoff of water. Our results indicate that forest cover can play a major role in the atmospheric circulation and water cycling on land and suggest a good potential for forest-mediated solutions of the global desertification and water security problems.

In world's non-forested regions, Fig. 1, mean annual precipitation P declines exponentially with distance x from the ocean, Fig. 2a–c and Table 1. Estimated from parameter b of the linear regression $\ln P = a + bx$ as $l = -1/b$ (x is distance from the ocean), the precipitation e-folding length l assumes the values of several hundred kilometers with a global mean of 600 km, in agreement with the available estimates for some regions (Savenije, 1995; Makarieva and Gorshkov, 2007).

We studied the dependence of precipitation on distance along the 40°N in North America and in the world's seven major river basins, all greater than 10^6 km^2 (Dai and Trenberth, 2002), that retain a substantial percentage of the original forest cover (in the Congo river basin 44% area is currently covered by forest; Ob 34%, Amazon 73%, Mackenzie 66%, Yenisey 40%, Lena 65%) (Watersheds of the World, 2003). The transects were chosen to run from the ocean inland across the forest-covered parts of the basins, Fig. 1, including the natural tundra wetlands in the subpolar zones of regions 7, 9, 10, and 11. The North America transect goes approximately parallel to the northern border of the forested region confined within the eastern part of the Mississippi river basin and further eastward to the oceanic coast (Bryant et al., 1997). The forest cover of the regions studied is characterized as undisturbed, except in the Congo and North America regions, where forests are mostly secondary (Bryant et al., 1997).

The results obtained, Fig. 2d–f and Table 1, reveal a significant difference between the precipitation–distance relationships in the non-forested versus forest-covered regions, where precipitation does not decline with distance from the ocean. The only exception is the North America region, Fig. 2c, where the degree of the anthropogenic disturbance of the forest cover is the largest among the regions studied (Bryant et al., 1997). In this region precipitation does diminish in the inland direction, but it does so significantly more slowly (l = 14,000 km) than in the non-forested regions (mean l = 600 km), including the non-forested region at the same latitude in North America, Fig. 2c, for which l = 830 km. As expected, there is no statistically significant dependence of precipitation on distance along the equatorial transects of the Amazon and Congo river basins, Fig. 2d and e. Precipitation over the other forest-covered regions with a predominantly meridianal orientation, regions 7, 9, 10 and 11, grows towards the inner parts of the continents. With the estimated e-folding lengths of $l = -(2, 2, 3 \text{ and } 4) \times 10^3$ km for Ob, Mackenzie, Yenisey and Lena river basins, respectively, Table 1, the regional precipitation increases by approximately twofold per two thousand kilometers inland, Fig. 2d–f. This growth of precipitation is well matched by the twofold increase of the absorbed solar radiation, which, in the North Hemisphere, changes from about 50–100 W m^{-2} over the two thousand kilometers from 70 to 50°N (Hatzianastassiou et al., 2005).

High precipitation creates high soil moisture content, which, in its turn, is coupled with large losses of water to gravitational runoff, since continents are elevated above the sea level. This means that forests should be able to transport moisture inland from the ocean in quantities sufficient for compensation of the high runoff losses associated with the maintenance of high soil moisture content. Since the major part of solar energy used by the biota is spent on transpiration (i.e. evaporation of water through leaf stomata during photosynthesis), it can be expected that namely transpiration should be the key process of such forest moisture pump.

2. Physical principle of the biotic pump of atmospheric moisture

Atmospheric air is in approximate hydrostatic equilibrium, which means that at any height z air pressure is balanced by the weight of atmospheric column above z:

$$\frac{dp_a}{dz} = -\frac{p_a}{h_a}, \quad p_a = p_{as} \exp\left\{-\int_0^z \frac{dz'}{h_a}\right\}, \quad h_a \equiv \frac{RT}{M_a g}, \qquad (1)$$

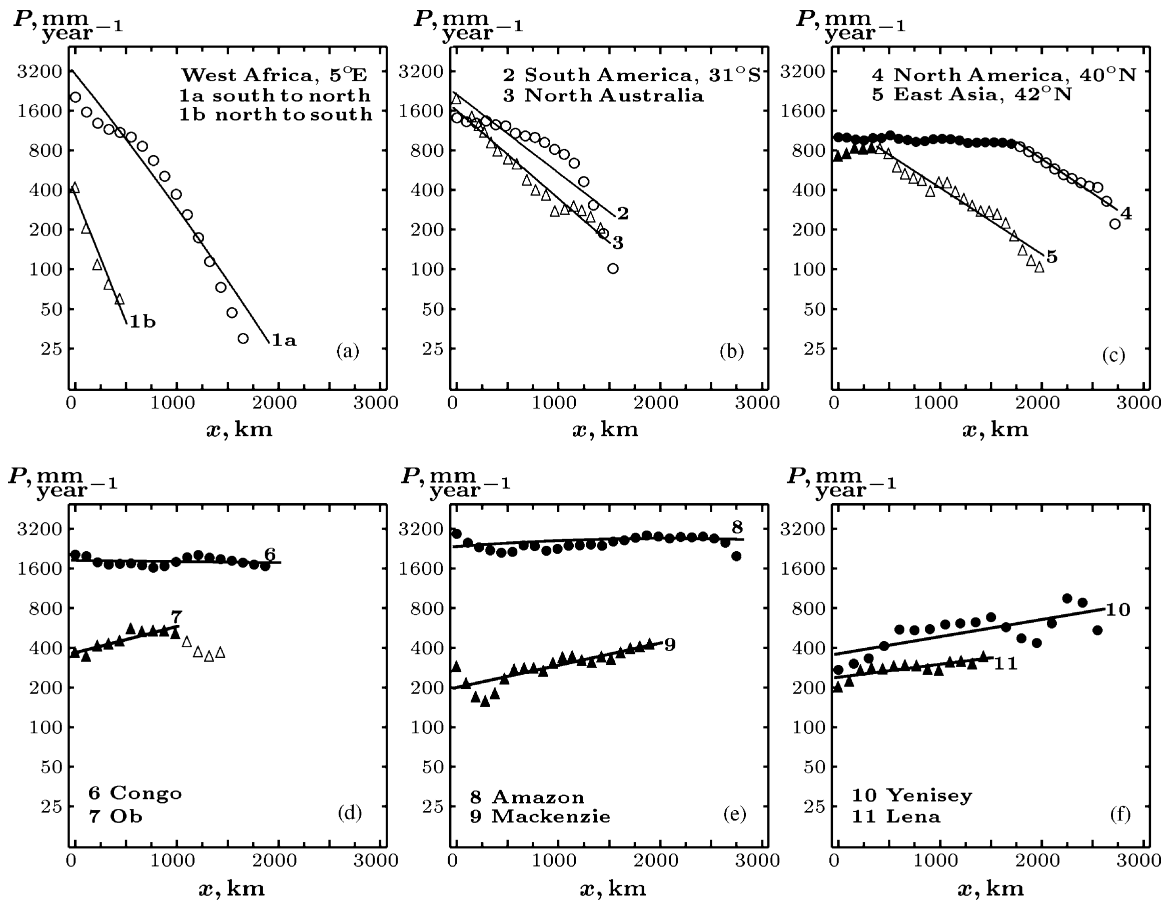

Fig. 2 – Dependence of annual precipitation P (mm year^{-1}) on distance x (km) from the ocean over non-forested territories (open symbols) and forest-covered territories (closed symbols). Regions are numbered as in Table 1, where parameters of the linear regressions are also given.

Table 1 – Precipitation on land P (mm year^{-1}) versus distance from the ocean x (km) as dependent on the absence/presence of forests.

Region					Parameters of linear regression $\ln P = a + bx$			
#	Name	Location $x = 0$	Location $x = x_{max}$	x_{max} (km)	$a \pm 1$ S.E.	$(b \pm 1$ S.E.$) \times 10^3$	r^2	$l \equiv -1/b$ (km)
Non-forested regions								
1a	West Africa, south to north	6°N5°E	21°N5°E	1650	7.99 ± 0.16	−2.46 ± 0.17	0.94	400
1b	West Africa, north to south	36°N5°E	32°N5°E	440	5.87 ± 0.15	−4.44 ± 0.54	0.96	230
2	South America, 31°S	31°S52°W	31°S68°W	1540	7.65 ± 0.18	−1.37 ± 0.20	0.76	730
3	North Australia	11.5°S130°E	25°S137°E	1400	7.37 ± 0.05	−1.54 ± 0.06	0.96	650
4	North America, 40°N	40°N95°W	40°N106°W	940	6.78 ± 0.06	−1.20 ± 0.10	0.93	830
5	East Asia, 42°N	42°N125°E	42°N106°E	1570	6.70 ± 0.06	−1.16 ± 0.07	0.94	860
Forest-covered regions								
4	North America, 40°N	40°N74°W	40°N95°W	1790	6.92 ± 0.01	−0.068 ± 0.001	0.66	14×10^3
6	Congo river basin	0°S10°W	0°S27°W	1870	7.52 ± 0.03	+0.020 ± 0.029	0.03	n.d.
7	Ob river basin	67°N70°E	58°N70°E	990	5.91 ± 0.05	−0.46 ± 0.09	0.77	-2×10^3
8	Amazon river basin	0°S50°W	5°S75°W	2800	7.76 ± 0.04	+0.045 ± 0.024	0.13	n.d.
9	Mackenzie river basin	69°N136°W	55°N113°W	1900	5.27 ± 0.06	+0.40 ± 0.06	0.72	-3×10^3
10	Yenisey river basin	73°N81°E	52°N95°E	2550	5.89 ± 0.11	+0.30 ± 0.07	0.52	-3×10^3
11	Lena river basin	72°N121°E	59°N121°E	1430	5.46 ± 0.04	+0.24 ± 0.05	0.67	-4×10^3

Statistics are significant at the probability level $p < 0.00001$ for all regions except regions 1b ($p = 0.004$), 6 ($p = 0.5$), 7 ($p = 0.001$), 8 ($p = 0.07$), 10 ($p = 0.001$) and 11 ($p = 0.0003$). Negative values of l indicate an exponential increase of precipitation with distance from the ocean.

where z is height, p_a and T are the air pressure and absolute air temperature at height z, R = 8.3 J K^{-1} mol^{-1} is the universal gas constant, M_a = 29 g mol^{-1} is air molar mass, g = 9.8 m s^{-2} is the acceleration of gravity. Low index s everywhere stands for the corresponding values at the Earth surface. In contrast, atmospheric water vapor is out of hydrostatic equilibrium. Since water vapor is a condensable gas, when the air temperature drops sufficiently rapidly with height, the upper atmosphere appears to be too cold to hold enough water vapor for its weight to balance the high partial pressure of water vapor in the lower, warmer atmosphere. As far as the cumulative pressure of the moist air exceeds the weight of atmospheric column, there appears an upward-directed force, which causes air and water vapor to ascend.

The dependence of the partial pressure p_{H_2O} of saturated water vapor on air temperature T, which depends on height z, is dictated by the Clausius-Clapeyron law, which can be written in the form similar to that of the hydrostatic equilibrium Eq. (1):

$$p_{H_2O} = p_{H_2Os} \exp\left\{-\int_0^z \frac{dz'}{h_{H_2O}}\right\}, \quad h_{H_2O} \equiv \frac{T^2}{(-dT/dz)T_{H_2O}}, \qquad (2)$$

where $T_{H_2O} \equiv Q_{H_2O}/R \approx 5300\,K$, $Q_{H_2O} = 44\,kJ\,mol^{-1}$ is the latent molar heat of evaporation. Low index s everywhere stands for the corresponding values at the Earth surface. (The common form of the Clausius-Clapeyron law can be obtained from Eq. (2) performing the integration.)

Saturated water vapor remains in hydrostatic equilibrium in the atmospheric column when $h_{H_2O} = h_w = RT/M_w g$ (M_w = 18 g mol^{-1} is water molar mass, h_{ws} = 13.5 km); in this case Eq. (2) formally coincides with the hydrostatic equilibrium Eq. (1). The condition $h_{H_2O} = h_w$ fixes the vertical air temperature gradient Γ as $\Gamma \equiv (-dT/dz) \equiv \Gamma_{H_2O} = T_s/H = 1.2\,K\,km^{-1}, H \equiv RT_{H_2O}/M_w g = 250\,km$, $h_{ws}/H \approx 0.05 \ll 1$.

At $\Gamma < \Gamma_{H_2O}$ atmospheric water vapor is in hydrostatic equilibrium but is saturated at the Earth's surface only; the moist air remains still. At $\Gamma > \Gamma_{H_2O}$ (which is the case in the troposphere, where on average $\Gamma \approx 6.5\,K\,km^{-1}$), water vapor is out of hydrostatic equilibrium, but is close to saturation (Makarieva et al., 2006; Makarieva and Gorshkov, 2007). The scale height for water vapor vertical distribution $h_{H_2O} \approx 2\,km$ obtained from Eq. (2) agrees satisfactorily with observations and is about six times smaller than the hydrostatic equilibrium scale height for water vapor h_{ws} = 13.5 km.

The difference between the non-equilibrium vertical gradient of water vapor partial pressure and the weight of a unit volume of water vapor (these magnitudes cancel each other in hydrostatic equilibrium) is equal to the upward-directed force f, which causes moist air to rise. At the surface, the ascending air volumes must be replaced by the air flowing horizontally from the neighboring areas, where this force is weaker, into the region of ascent. The stationary value of this force, which can be termed the evaporative force (Makarieva and Gorshkov, 2007), is determined by the rate at which water vapor is added to the atmosphere to compensate for its condensation, i.e. by the rate of evaporation. Hence, *horizontal fluxes of air and water vapor should be directed from areas with weak evaporation and small evaporative force to areas with intensive evaporation and large evaporative force*. It is here where the significant role of the vegetation cover in atmospheric circulation becomes evident.

3. Vegetation cover and ocean-to-land atmospheric circulation

A conspicuous feature of the organization of natural forests is their high leaf area index (Lieth, 1975), when there are several (up to a dozen or more) leaf blades along the vertical. It is physically possible for the local evapotranspiration from the several leaf planes of the forest canopy to greatly exceed evaporation from the one plane of the open water surface of the ocean (provided that local temperature is maintained by an adequate heat input). The evaporative force is then larger over the natural forest canopy than over the ocean, which, according to the above-formulated principle, causes the moisture-rich surface oceanic air to flow to the forest-covered continent. As this air ascends and its moisture precipitates, the air dries out and returns to the ocean in the upper atmosphere. This forest-induced atmospheric circulation constitutes the essence of the biotic pump of atmospheric moisture (Makarieva and Gorshkov, 2007). If stability of water cycle is biotically maintained, one can expect natural forests to react to the lack of moisture (droughts) by increasing transpiration in order to enhance the moisture-rich ocean-to-land atmospheric fluxes and reduce moisture shortage. This somewhat counterintuitive prediction was recently found to be matched with evidence for natural Amazonian forests, which were observed to green up during droughts (Saleska et al., 2007).

In the extreme reverse case, when the vegetation cover on land is completely absent as in deserts, evaporation from the ground surface is practically zero. The upward-directed evaporative force is always greater over the ocean than in the desert. It makes oceanic air rise and effectively ‘‘sucks in’’ the desert air to the ocean, where it replaces the rising oceanic air masses at the oceanic surface. Due to the absence of evaporation from the ground surface, deserts appear to be locked for oceanic moisture year round. In the intermediate case when the natural forests with their high leaf area index are eliminated, but there remains some vegetation cover on land, horizontal air fluxes can be directed either from the ocean to land or vice versa depending on the environmental conditions, in particular, surface temperature, e.g., the monsoon climate.

In the theory of atmospheric circulation the assumption of hydrostatic equilibrium has been traditionally applied to moist air as a whole (Lorenz, 1967). This implies that the shortage of weight of one gas (water vapor) in the upper atmosphere should be compensated by the excessive weight of the other atmospheric gases. However, according to the kinetic theory of gases, hydrostatic equilibrium corresponds to the balance between the flux of molecules drifting downward under the force of gravity and the upward diffusional flux of molecules working to diminish the vertical concentration gradient (Feynman et al., 1963). In equilibrium, equal numbers of molecules of each gas cross any horizontal plane in the upward and downward directions. Therefore, if one gas in a mixture deviates from equilibrium, this deviation cannot in principle be compensated by the reverse deviations of other gases from the equilibrium. In meteorology, the barometric Eq. (1) has been conventionally derived from the balance of weight and pressure gradient with no discussion of the equilibrium concentration of gases (Lorenz, 1967), a possible reason for why the proposed evaporative force has not been included into the atmospheric circulation theory.

So far in the theory of atmospheric circulation the horizontal barometric gradient, the driver of atmospheric motions, has been invariably linked to the horizontal air temperature gradient. The described physical mechanism provides new clues to the observed atmospheric circulation phenomena and opens a wide field for further research. For example, it can help resolve the problem of the theoretical description of Hadley circulation, where the traditional consideration of air fluxes associated with the observed horizontal temperature gradient yields lower circulation intensity than actually observed (Fang and Tung, 1999). Additional consideration of the difference in the evaporation fluxes and evaporative forces between the equator and higher latitudes, caused by the corresponding difference in the absorbed solar flux, will lead to enhancement of the circulation. Generally, our findings indicate that air circulation can arise in the absence of the horizontal temperature gradient at the expense of the horizontal gradient of evaporation flux alone. And, conversely, even a very large horizontal temperature gradient (e.g., between the surfaces of the ocean and a desert) may not be sufficient to generate a monsoon-like surface circulation from the cold to the warm, if the gradient of the evaporative force is larger in magnitude and works in the opposite direction. As recently shown, the same physical mechanism can explain the origin of high wind speeds observed in hurricanes and tornadoes (Makarieva et al., 2008).

Interesting information can be gained from comparison of precipitation distributions in the temperate zones of USA, where secondary forests persist within a nearly 2000 km belt along the coastline, and temperate East Asia, where most forests were eradicated in prehistoric times (Bryant et al., 1997), Fig. 2c. It is remarkable that over the non-forested parts of the two regions precipitation diminishes with distance from the ocean in practically identical ways, starting from approx. 10^3 mm year^{-1} in both cases and having *e*-folding lengths of 830 and 860 km in the USA and East Asia, respectively, Table 1. The present-day gap between the North American and East Asian lines describing the dependence of precipitation on distance from the ocean numerically describes the price that East Asia pays, in terms of precipitation shortage, for its ancient deforestation. It can be expected that if the continental forests of North America are destroyed or self-degrade, the semi-logarithmic line describing the dependence of precipitation on distance in this region, Fig. 2c, will gradually move down towards the East Asian line, so that currently reasonably well-moistened continental areas can lose up to 800 mm year^{-1} of annual precipitation. Conversely, as suggested by our results, gradual restoration of the natural forest cover can lead to significant intensification of the water cycle even in the present-day zones of aridity and mitigate and reverse the processes of desertification (where they have recently started) by means of enhancing the incoming flux of atmospheric moisture from the ocean to the content. The proposed major role of forests in the global change of water resources appears as conceptually novel to match the emerging scientific focus on forests in climate change studies (Bonan, 2008).

4. Methods

Precipitation data for all regions except Australia and Amazon were taken from the gridded monthly precipitation data bank Carbon Cycle Model Linkage-CCMLP (McGuire et al., 2001), time period 1950–1995, grid size 0.5 × 0.5 degrees; statistics are based on *P*-values for 5–22 grid cells spaced by 85–110 km along the straight line from $x = 0$ to $x = x_{max}$. Precipitation data for Australia are from Cook and Heerdegen (2001) and Miller et al. (2001). Precipitation data for the Amazon river basin are from the gridded monthly precipitation data bank LBA-Hydronet v1.0 (Water Systems Analysis Group, Complex Systems Research Center, University of New Hampshire), time period 1960–1990, grid size 0.5 × 0.5 degrees.

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