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Transl. V. Tumanov 23.07.2008

Why Rivers Don't Run Dry

A New Look at the Dynamic Forces that Drive the Continental Water Cycle.

At present, wild, untouched nature has been preserved on only one third of the continental area. The rest consists of tilled land, pasture, forests (made sparse by systematic felling), roads, cities and industrial areas. In the future, economic and demographic growth can lead to the colonization of the natural biota's last bastions. At that point, left-over virgin forests will turn into forestry farms while drained swamps will become agricultural land. This is essentially the aim of the Russian Federation's forestry code. As for wild nature, some people seem to think that it is enough to preserve it in conservation areas. However, this attitude toward natural (primarily forest) ecosystems ignores their extremely important function of maintaining fresh water reserves. All water that has accumulated in lakes, mountain glaciers and swamps on all the continents can be returned to the ocean by river runoff over a period of only four years. The question is why rivers don't run dry. Could it be that one day all the fresh water will flow into the sea and will not come back?

Such questions often intrigue curious children while the wise adults around them appear to have the answer: rain falls over land, and water evaporation from the Earth's surface leads to cloud formation, which in turn leads to new precipitation. However, it ought to be kept in mind that water evaporates over land while rivers flow into the ocean. Water evaporating out of the ocean does not make it to the deserts, for example. The sources of the Yenisei — the seventh biggest river in the world — are so far away from the ocean that no oceanic moisture can reach them on its own. Therefore, an initial glance at the explanation of the fresh water cycle is reminiscent of a yarn by Baron Munchausen who claims to have pulled himself out of a swamp by his own hair. In order for rivers to keep flowing, some sort of permanently active mechanism is required — a process whereby water from the ocean is pumped into any location on land, however remote. The nature of this mechanism has been investigated by two Russian physicists — Drs. V. G. Gorshkov and A. M. Makarieva of the St. Petersburg Institute of Nuclear Physics (RAN). They call it the *forest pump of atmospheric moisture* — a concept outlined below. For a detailed account see http://www.bioticregulation.ru/pump/pump.php.

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Life on land owes its greatest debt of gratitude to plants. Plants can grow only in moist ground. This moisture store must be maintained throughout the entire season of active plant life. However, land is elevated above sea level and is therefore bound by the inevitable laws of physics; soil moisture must flow downward from higher levels, accumulating into rivulets, streams, small and big rivers until it finally reaches the ocean. According to recent data, the volume of this yearly runoff is around 43,000 km.^{2} It has been calculated that within a period of four years, all the land-based water accumulated in lakes, swamps and mountain glaciers would end up in the ocean if it were not replenished by atmospheric precipitation. Some of this precipitation forms right above land from the evaporation of terrestrial moisture sources while approximately 1/3, or to be precise — 35/100 cm — of yearly precipitation (assuming distribution over the entire land surface) corresponds to oceanic evaporation. In other words, if evaporated moisture from the ocean did not fall in the form rain and snow onto land, the latter would become completely free of fresh water within less than 10 years.

Without a doubt the process referred to as “nature’s kitchen” (the displacement of atmospheric fronts, the generation of electrical storms, cyclone formation etc.) constitutes a series of very complex phenomena which still require much study and resist smooth formal mathematical characterization and modeling. Nevertheless, in the past few years a rather promising attempt to use known physical laws in order to connect the functioning of the plant biota with the transfer of ocean moisture to land. This would demonstrate the plant biota’s universal influence on the continental moisture cycle. This model deals with undisturbed forests; in fact Gorshkov and Makarieva refer to the mechanism of this moisture transfer as the *biotic pump of atmospheric moisture* (2007). In order to make sense of the way this mechanism functions, we need to take a closer look at the transpiration process, namely, the release of water from the leaf surface of plants in the course of photosynthesis. This is the key to understanding the phenomenon in question.

Transpiration — akin to blood circulation in animals — is the constant transfer of water and substances dissolved in it, within the plant. This water comes from the soil, traveling through the root system of plants and along the trunk xylem vessels (conductive plant tissue) toward the leaves. The flow from the roots to the leaves occurs along the so-called water potential gradient. This gradient decreases with the increased concentration of salts and other substances in the water, which is facilitated by the selective permeability of cell membranes. The speed of water movement along trunk vessels is quite large, amounting to approximately 1 m/hr in grassy plants and up to 8 m/hr in tall trees. Xylem vessels are dead pipes with narrow openings 0.01-0.2 mm in diameter. The ascent of water along such pipes to the top of a big tree requires pressure of the order of 4,000 kPa.[1] However, even when water is moved along the thinnest of vessels by capillary forces alone, it cannot rise higher than 3 meters, whereas the height of certain trees can reach 50 and even 100 meters as in the case of the Californian sequoia or the Australian eucalyptus.

This phenomenon can be explained by cohesion theory. Thus, the ascent of water from the roots is determined by its evaporation from leaves, which leads to water depletion in leaf cells and consequently — an increase in the concentration of substances dissolved in water. This results in the lowering of the water potential. Therefore, water from xylem fluid with higher water potential enters leaf cells through selectively permeable cell membranes. However, as water leaves xylem vessels, the water column experiences an increase in tension that is transferred down the stalk all the way to the roots. This tension is related to the molecular cohesion capacity of water determined by the polarity of water molecules or the dipole moment. That is, under the influence of electrostatic forces, water molecules are attracted to each other — become "glued" as it were — and are simultaneously held together by hydrogen bonds. Cohesion causes tension in the xylem vessels to reach such great magnitudes that the entire column of water can be drawn upwards. Estimates of tensile strength for a column of xylem fluid vary between 3,000 to 30,000 kPa. The recorded water potential in leaves is of the order of 4,000 kPa. It appears, therefore, that the sturdiness of a xylem fluid column is sufficient to withstand the created tension (Green, N.P.O. et al. 1984, V. 2)

Finally, at the very last stage, water seeks to exit the plant because the water potential of the ambient, moderately moist air is several tens of thousands of kilopascals lower than in the plant itself. However, this departure takes place mainly in the form of water vapor, and this requires additional energy known as the latent

[1] 1 kPa (kilopascal) = 0.01 atm.

heat of evaporation. This energy is provided by sunlight that acts in the end as the force behind the transpiration process at all its stages — from the soil to the roots to the stalks to the leaves. Clearly, water is essential for ensuring the life-sustaining activity of a plant, which includes its photosynthetic needs. What may be less clear is the intensity of this process. After all, the plant itself uses on average less than 1% of the water it takes from the soil whereas the remaining 99% returns directly to the atmosphere. In light of this, the level of transpiration — given sufficient illumination, moisture humidity and ambient air temperature — can be very high. Thus, such herbaceous plants as cotton or sunflowers can lose up to 1-2 l of water within a 24-hour period while a hundred-year-old oak tree can lose more than 600 l (Green, N.P.O. et al., 1984, V. 2). There is some basis for the fact that transpiration is sometimes referred to as a "necessary evil," however, as will be shown below, this is very naïve.

Admittedly, most plants have evolved adaptation strategies which allow the regulation of this process and the retention of moisture if necessary. This would include the shedding of leaves during seasonal cold periods or drought, as well as water stockpiling in mucous cells and the cell walls of various plant parts. This would also include the presence of stomata that are special pores in the epidermis located in leaves and partially in green stalks. Gaseous interchange takes place through these openings – from which up to 90% of water evaporates. Thanks to special guard cells, the stomata can close during dry periods or at night when photosynthesis stops, which slows down the process of transpiration. Another adaptation for reducing transpiration, which formed under dry climatic conditions and moisture deficits, is the thickening of the cuticle — the waxy layer covering the epidermis of leaves and stalks. Nevertheless, under normal conditions and given a large leaf surface typical primarily of forest vegetation, water loss through transpiration can be very great. It can exceed considerably evaporation from water body surfaces equal in area to the tree crown's projection onto the ground. It is therefore not surprising that a natural forest endowed with a high leaf-area index (the ratio of the illuminated leaf area to the area of tree crown projection onto the ground) and given sufficient exposure to solar irradiance, can evaporate moisture much more intensively than the open ocean surface at the same temperature.

However, transpiration is not the only source of water vapor forming above the forest canopy, since trees are capable of using their crowns to accumulate or intercept a significant amount of atmospheric rainwater or snow. These two forms of moisture also make a sizeable contribution (up to 30%) to the evaporation process generated by the forest. The latter circumstance is particularly important with respect to the boreal coniferous forests where layers of snow wrapped around the trunks and crowns of trees ensure continuation of the flow of evaporation even in winter when transpiration is absent. In this manner, a forest that has not suffered a disruption is capable of evaporating moisture practically year-around and much more intensively than the open ocean surface at the same temperature, approaching (on average) the maximum possible magnitude of evaporation which is limited only by the flow of solar energy. Thus, calculations show that the maximal evaporation of water over the forest, corresponding to the flow of solar energy absorbed by the Earth's surface, equals ~ 2 m/yr, whereas the average global evaporation from the ocean surface is only ~ 1.2 m/yr (L'vovitch, M.I., 1979). Furthermore, taking into account that the total leaf surface of the plant biota is 4 times greater than the entire land surface of the planet, we can see that the aggregate transpiration of the forest can successfully compete with oceanic evaporation. From the position occupied by the authors of the forest moisture pump theory, this plays a key role in the formation of the continental moisture cycle.

The point is that the soil layer, as was pointed out earlier, cannot retain moisture for a long time without replenishment, losing it inevitably in the form river runoff that in the end takes it to the ocean. Therefore, the problem of moisture retention on dry land is inextricably linked with compensating for these losses through reverse moisture movement from the ocean. However, the farther we move away from the coastline, the greater is the proportion of precipitation derived from the ocean which returns to the ocean through river runoff because of the continents' elevated position. At the same time, passive atmospheric geophysical currents that transport moisture from the ocean die down as they progress deeper into the continent. This decrease in current strength is exponential. To be accurate, the above-mentioned tendency applies mainly to non-forested areas with low steppe-like vegetation bordering directly on the coastline. In such cases, for every 400 km of penetration into the steppe, savannah or prairie, the flow of moisture and the intensity of precipitation undergoes a diminution of approximately two-fold.

Gorshkov and Makarieva analyzed data on the gradient of precipitation over vast areas of land on five continents corresponding to the indicated criterion. Their findings demonstrate that the passive geophysical transfer of moisture toward bush- or grass-covered land devoid of a continuous tree canopy can provide normal conditions for life only in a zone within a few hundred kilometers of the ocean. In the case of extensive continental areas, the average figure is about 600 km. That said, the water regime in such regions is determined by random fluctuations and seasonal changes in precipitation brought from the ocean, as is the case in monsoon areas with their abundant rains in the summer and very dry winters.

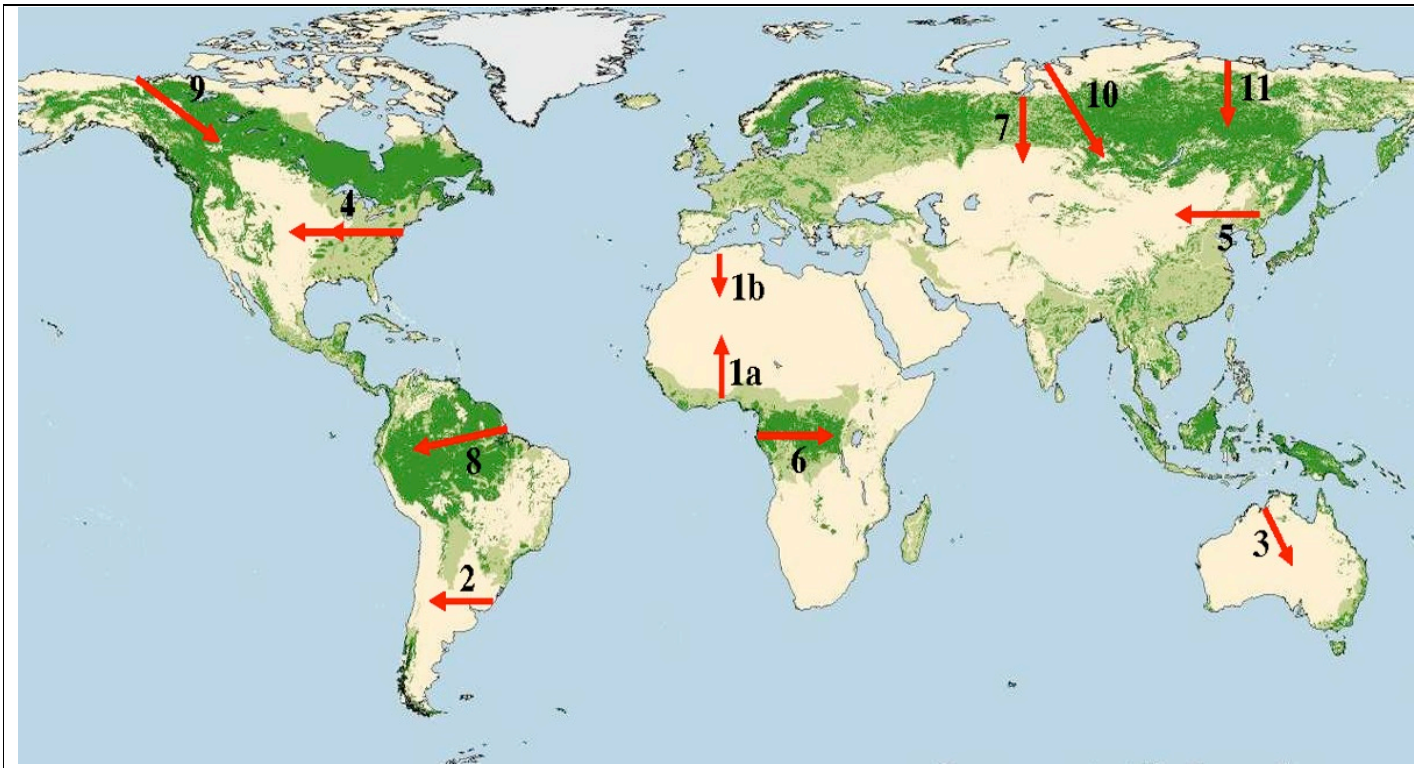

Figure 1: Geophysical regions studied as to dependence of average yearly precipitation on distance from ocean.

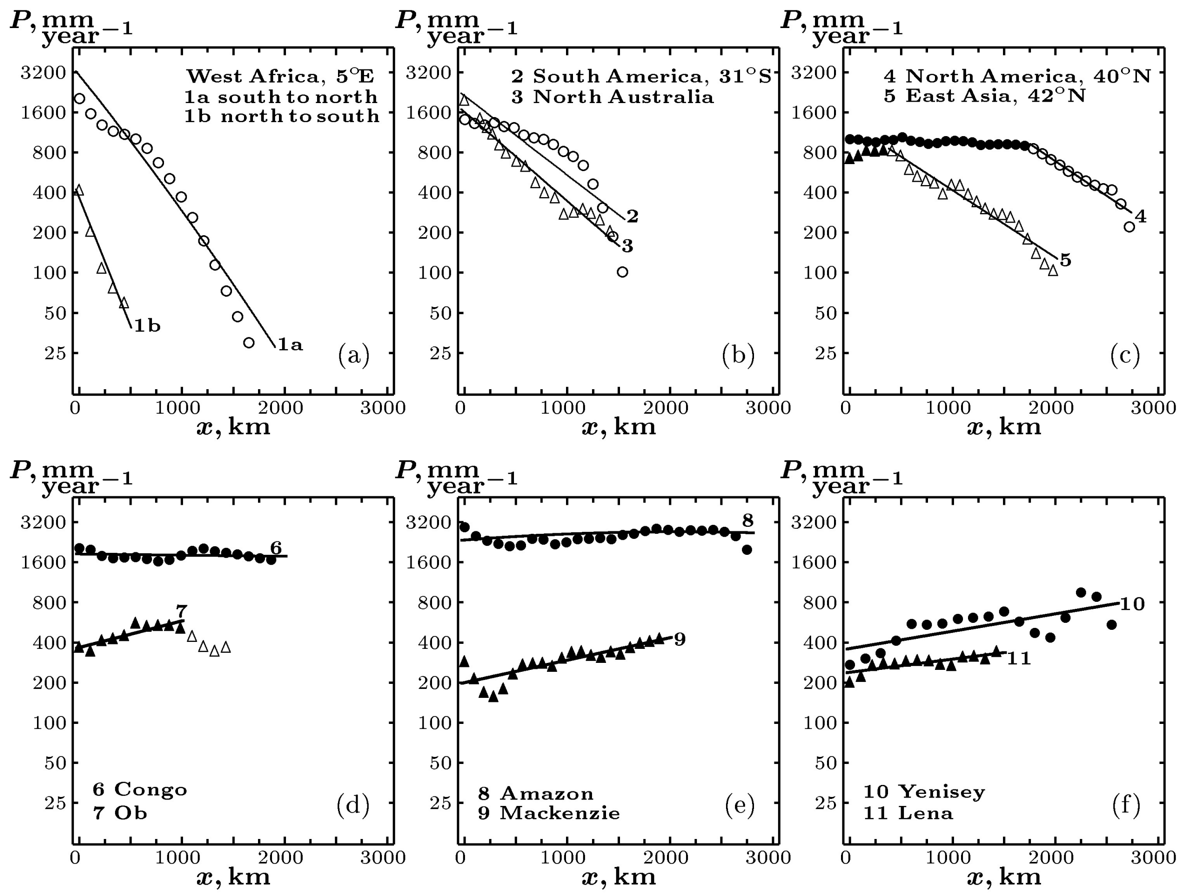

Figure 2: Dependence of precipitation amount P (mm/yr) on distance x (km) from ocean in deforested regions (empty shapes) and forest-covered regions (filled-in shapes). Regions numbered as in Fig. 1.

However, in this case, how is one to explain the existence of well-watered areas deep inside continents — thousands of kilometers removed from the ocean, e.g., Siberia, the Amazon Basin or Equatorial Africa? It would probably be difficult to answer this question if we were to only consider passive geophysical currents, ignoring the active transfer of oceanic moisture based on the forest moisture pump. The essence of these processes can be summarized as follows. With increasing altitude, the atmospheric pressure drops. Anyone acquainted with mountain climbing knows this from personal experience, namely, it is more difficult to breathe in the highlands because the air there is thinner and contains correspondingly less oxygen.

As opposed to the other elements of the air, water vapor can exist in two phases — liquid (rain droplets and fog) and gaseous — and under certain circumstances water vapor can be transformed from gas to liquid. This phenomenon is known as condensation — exemplified by the formation of dew that settles on grass, bushes or certain quickly chilling surfaces and objects in the cool of summer evenings. This happens because a drop in temperature changes the dynamic balance between its gaseous and liquid components shifting in the direction of the liquid. Typically, during daytime, the concentration of water vapor in warm, dry air is likely to be below its possible maximum (the so-called level of saturation). However, when this air cools down at night, it may reach the saturation stage, and water vapor will begin to condense quickly and enter the liquid phase. In physics this critical temperature is known as the dew point, and it can be reached artificially by lowering the temperature of moist air or that of objects coming into contact with the air.

Something similar happens to water vapor with rising altitude. As is well-known, air temperature drops by approximately 6°C / km with increasing altitude. Thus, at an altitude of 10 km where most jets fly, the external temperature is almost 60°C below the surface temperature. For all other gas constituents of air, such a drop in temperature is not critical, but for water vapor the effect is significant. The concentration of water vapor in the air cannot rise above a certain maximum level called *saturated concentration.* This maximum concentration decreases exponentially with decreasing temperature – an approximately two-fold decrease for every 10°C of temperature drop. If water vapor, like the other components of the air, were not a condensable gas, it would remain in gravitational equilibrium at any altitude so that its pressure would undergo a two-fold drop for every increase of 9 km in elevation. But in this case water vapor would be oversaturated in the entire atmospheric column, which is impossible! Therefore, in the real atmosphere, the relative surplus of water vapor continuously condenses and disappears from the gaseous phase. This is accompanied by a decrease in the weight of water vapor in an atmospheric column that can no longer compensate for its pressure in lower atmospheric strata. When condensation occurs, the atmospheric pressure of moist air falls. This causes brings about rising currents of moist air that contains residual water vapor. The latter reaches the upper atmospheric strata and condenses further, forming clouds and precipitation, such as rain and snow. Therefore, as the condensing water vapor leaves the air, this is constantly compensated for by water vapor brought by the rising currents of moist air from the ground level. These currents, to use Gorshkov's and Makarieva's image, are like the ancient Greek titan Atlas — holding up the Earth's cloud cover.

And here we have reached the essence of the forest moisture pump. If the intensity of the rising currents is determined by the amount of water vapor condensation in the upper strata of the atmosphere, the power of these currents will increase with a rising intensity of evaporation from the Earth's surface that feeds them. Therefore, moist surface air will be sucked in from areas with less evaporation into areas with more intense evaporation. If, as has been shown above, evaporation above undisrupted forestland exceeds evaporation above the ocean surface, then ocean moisture will be pumped by the forest farther and farther into the depths of the continents, thereby compensating for river runoff and ensuring year-round soil moisture. However, this presupposes that the tree canopy extends all the way to the coastline, as is the case in the Congo and Amazon Basins or the northern rivers of Russia and Canada. In the latter regions the taiga canopy is adjacent to the swampy areas of the far north that have access to the ocean. At the very least the woodland should be removed from the coastline at a distance below the attenuation distance of passive geophysical transfer.[2]

The destruction of tree cover along the coastline within the attenuation distance (~600 km) interrupts the action of the biotic pump, so that the forest deep within a continent loses its capacity to compensate for river runoff. Soil moisture flows down into the ocean, the forests dry out and river basins cease to exist. All these irreversible changes can happen within a very short period of time — of the order of 4-5 years required for the runoff of fresh water accumulated in mountain glaciers, lakes and swamps.

It appears that something like this took place 50-100 thousand years ago in Australia when the continent was first settled by humans. It is quite natural to

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[2] Since the speed of horizontal air currents is determined by the difference in the intensity of evaporation, the process of pumping moisture from the cold ocean located at higher latitudes than the river basin itself appears to constitute a simpler task for the biota than, for example, the transfer of moisture in the equatorial zone. This would explain the existence of the great Siberian river basins covered by forests that stretch for many thousands of kilometers. As for tropical forests, here the transfer of moisture from the ocean inland requires a much higher level of transpiration which would seem capable of preventing the transfer of atmospheric moisture from the forest to the ocean. In other words, moisture loss diminishes with increasing transpiration, which would explain the rising intensity of the latter noted during dry spells in the Amazon forests (da Rocha et al., 2004).

suppose that the new arrivals acted in the usual manner, namely, they settled the coastline first, all the while destroying forests along the entire perimeter of the continent. When the attenuation distance of the deforested zone reached that of the passive geophysical currents, this turned out to be, alas, sufficient — even in the absence of anthropogenic activity deep within the continent — to cut the biotic pump off from ocean moisture. The result was the demise of the Australian forests and the triumph of the Australian desert that today covers a huge part of the continent — 4 million km^2. Apparently the only way to account for the absence of any paleodata traces left by this transformation is the latter’s brevity. Perhaps this is why most deserts border on oceanic coastlines or have access to inland seas. The foregoing suggests that geography is closely related to the history of human settlement whereby the possession of new territories began from the coastline.

It may seem that Western Europe, which has practically lost its natural forests but has not yet undergone desertification, constitutes a case defying the above line of reasoning. However, this is the proverbial exception that proves the rule. Europe’s felicitous lot is indebted to its unique geographic position. It is surrounded by inland seas, and its coastlines are close from any point. As a result, not a single West European area is farther away from the coastline than the attenuation distance of the geophysical transfer of sea moisture. The latter circumstance is apparently responsible for the illusion that the practice of deforestation can be exported to other regions on the planet where such a policy is sure to be (or has already proven to be) disastrous. At the same time, even in Western Europe we have observed a sharp increase in the number of catastrophic flooding and dry periods, which is the result of deforestation in mountainous regions and the general reduction of forested areas in the first place with the consequent serious disruption of the natural hydrological regime (the melting of mountain glaciers etc.).

The desert environment may be viewed as practically closed off to moisture. This is because the complete absence of transpiration, instead of causing moist air to be sucked inland *from* the ocean, brings about the transfer of dry air *to* the ocean. On the other hand, on steppe- or savannah-like landscapes, as well as artificially irrigated lands and pastures, the intensity of evaporation during the warm season can be greater than the same process over the ocean’s surface. In warmer periods the oceans and seas are the source of a horizontal moist air current whose strength is a negative function of the distance it covers. This current is known as the summer monsoon or the rainy season. In winter or during colder periods, evaporation over bushes and grass stands is less intense than its oceanic counterpart. Therefore the moisture retained here is pulled from the land to the sea, creating the dry winter monsoon (see Figure 3). In this manner, although the vegetation of steppe-like ecosystems ensures the maintenance of a certain moisture reserve and the existence of evaporation currents on dry land, the absence of a continuous forest canopy with a high leaf-area index prevents such areas from increasing evaporation to a level at which the current of moisture from the ocean to land can compensate completely for river runoff. The biotic pump of such ecosystems is not fully functional, and precipitation diminishes exponentially with distance from the coastline.

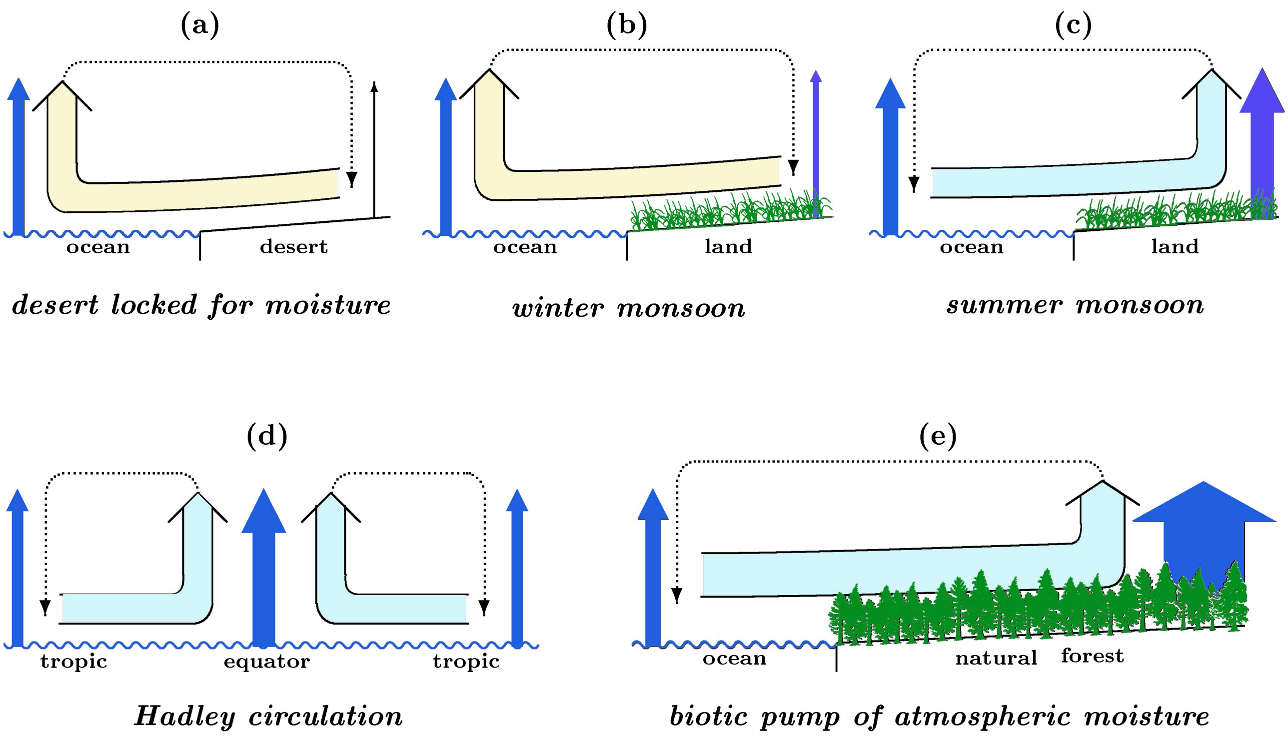

Figure 3: Physical principle of air movement at ground level from regions with less evaporation to those with more evaporation. Dark blue arrows — evaporation currents (current magnitude proportional to arrow thickness). Light blue arrows — horizontal and rising moist air currents. Dotted thin arrows — horizontal and descending dry air currents.

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And so, the short-term thinking and policies leading to the destruction of aboriginal forests — the greatest “invention” of the planet’s biota — can be viewed as nothing short of a crime against life on Earth and humanity itself. As is rightly observed by Gorshkov and Makarieva, ignorance of the “natural” law does not exempt anyone from punishment for disobeying that law. This is how nature deals with humans – making them pay the highest price for their irrational attitude toward the environment. And so, will the rivers flow forever, supported by vast natural forests, or will our collective effort eventually lead to the transformation of our “brave new world” (A.Platonov) into a huge lifeless desert?

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