Editorial

Winds and Rain: The Role of the Biotic Pump

By Peter Bunyard

In 2007, Anastassia Makarieva and Victor Gorshkov came up with the *Biotic Pump Theory* (Makarieva A. a., 2007). The two scientists, mathematician/physicists at the Petersburg Nuclear Physics Institute, St Petersburg, Russia, described the Biotic Pump Theory (BPT) in terms of the fundamental laws of physics pertaining to the phase change when water evaporates and then condenses through the process of cloud-forming, as humid air rises in the troposphere and chills with altitude. The degree of water vapour saturation follows the Clausius-Clapeyron equation for ideal gases, taking into account temperature (Kelvin), relative humidity and barometric pressure.

In essence, Makarieva and Goshkov took exception to the standard climatological idea that the Hadley Cell air mass circulation between Africa and South America was caused primarily by latitudinal differences in temperature between the tropics and the equatorial zone of the Amazon Basin. They theorized instead that air mass changes, brought about through condensation and precipitation, would lead to atmospheric pressure changes such as to draw air upwards to the cloud-forming region, more or less at an altitude of 2.5 km and beyond. They then proposed that the air which replaced that moving upwards would come from surface air flowing over the ocean, bringing humid air to the continent interior. They suggested that the biotic pump theory provided the correct explanation for the conundrum of the western reaches of the Amazon Basin, such as that of Colombia, receiving as much rainfall, if not more, than at the Atlantic Coast 2,500 km distant.

For them, the Trade Winds (*vientos alisios*), flowing between tropical Africa and converging at the Intertropical Convergent Zone (ITCZ) over the Amazon Basin, were drawn in by the high rate of evapotranspiration and then condensation over the closed-canopy rainforest. They based their conclusion on the evapotranspiration rate per square metre of the rainforest, with its multi-levels of leaves, being an order of magnitude greater than the rate of evaporation over the ocean at the same latitude. Makarieva and Gorshkov describe the force generated by the partial pressure change as the evaporative force F_e in hPa/km and they postulate that a gradient is created between the F_e over the ocean and that over the rainforest, acting to draw in the air from the ocean to the continent (Makarieva A. M., 2013).

If the Biotic Pump theory is correct, the consequences of widespread deforestation in the Amazon Basin will be considerably more devastating in terms of the hydrological cycle and reduction in precipitation compared with a scenario where the air mass circulation, including the Hadley Cell and Walker circulation, results primarily from latitudinal differences in air temperature.

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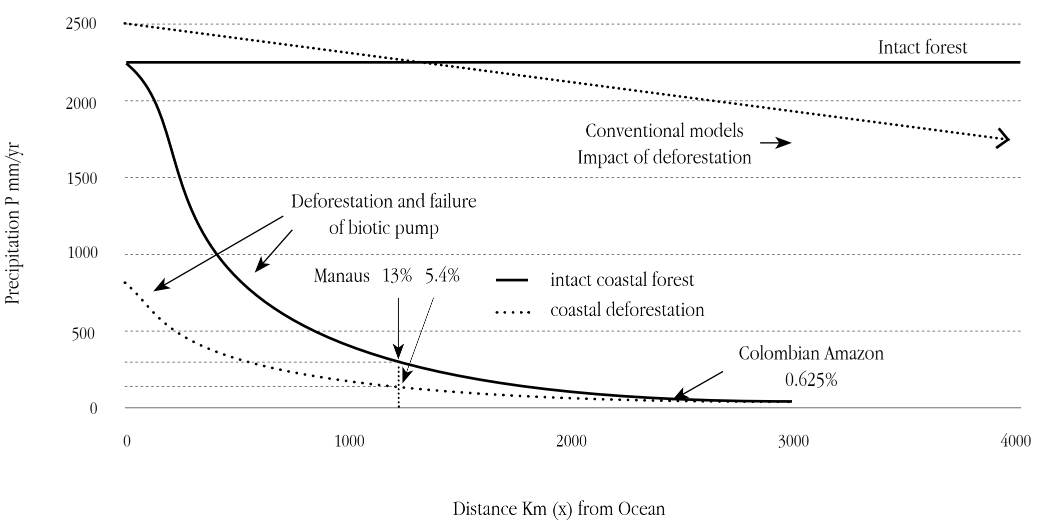
Based on measurements that the average distance of fall-out of a molecule of water vapour, as it evaporates and then precipitates, is some 600 km, Makarieva and Gorshkov calculated that the central and western regions of the Amazon Basin would desertify. That claim of desertification, with rainfall reduced over the Colombian Amazon to less than 1 per cent of today's value, is to be contrasted with the projection of only a 12 to 15 per cent reduction in rainfall according to those climate models, primarily temperature-based, which determine that the flow of humid air from the tropical Atlantic ocean and over the rainforest will continue, irrespective of whether the land is forested or not. In general, climate models predict that the mid and western regions of the Amazon Basin would convert to savannah. On the basis of the BPT, deforestation of the Amazon Basin would remove the F_e gradient and, therefore, would reduce the flow of the Trade Winds. Such a reduction in the flow of humid air from the ocean would result in the forming of desert rather than savannah.

Figure 1. *Deforestation impact according to the biotic pump theory. Makarieva & Gorshkov (Makarieva A. M., 2007) use a length, l, of 600 km, as the distance over which a molecule of water will evaporate and fall-out through precipitation. The formula,* $P_X = P_0 \exp\left[-x/l\right]$ *describes the reduction in precipitation as the distance increases between the coast and inland.*



Makarieva and colleagues then cite, as evidence for the BPT, the precipitation history of those river basins that are forested compared with those that lack forest (see Fig. 2 below). They find that river basins such as those of the Amazon, Congo and Yenisei show no decline in rainfall and even a slight increase with distance inland. That finding is in sharp contrast to river basins without forest: they show an exponential decline in rainfall with distance from the coast, just as the formula in Fig. 1 indicates. For example, the West African river basin shown in Fig. 2 has a precipitation history of 1600 mm at the Atlantic coast. Some 1,700 km away from the coast, the annual precipitation has reduced to just over 20mm (Fig.2).

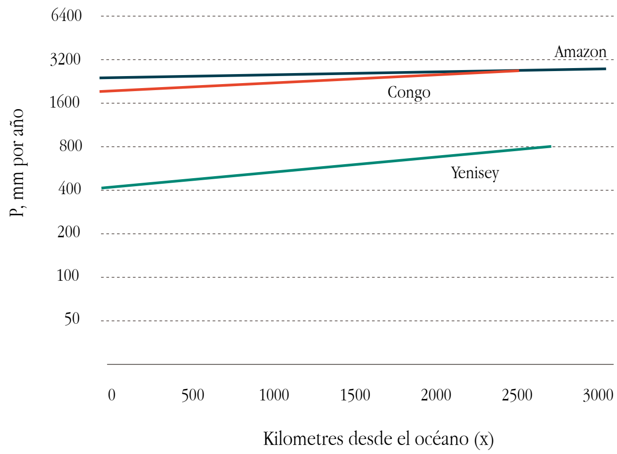
In essence the **Biotic Pump Theory maintains that:**

1. The rainforest provides the moisture for cloud forming by means of a high rate of evapotranspiration (ET);
2. The rising air results in condensation and precipitation;

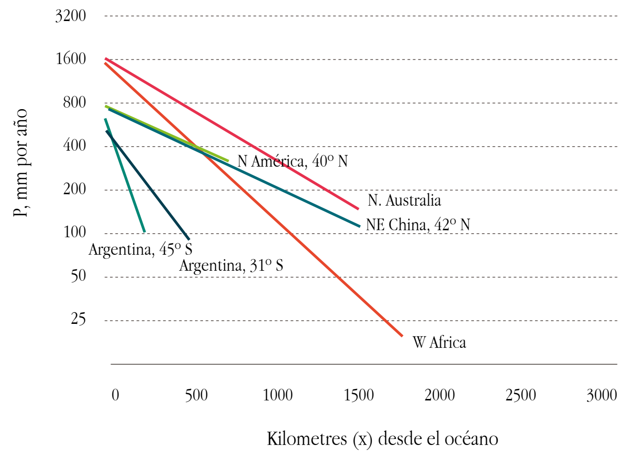
Leading to

3. Monsoon rain;
4. An abrupt reduction in local pressure when clouds form;
5. The vertical motion of air from the forest canopy upwards;
6. The drawing in of horizontal surface air to replace the air flowing vertically upwards.

Figure 2. *The left-hand diagram is for forested river basins, with the X-axis showing distance, x, from the coast and the Y-axis showing an exponential annual precipitation rate. The annual precipitation is seen to rise with distance from the coast. The right-hand diagram shows river basins without forest. In all instances, the annual precipitation rate declines exponentially with distance from the coast.*



Derivado de A.M. Makarieva & V.G. Gorshkov, Hydrol. Earth Syst. Sci., 11, 1013-1033, 2007



Derivado de A.M. Makarieva & V.G. Gorshkov, Hydrol. Earth Syst. Sci., 11, 1013-1033, 2007

By means of the biotic pump, moist trade winds are pulled in and feed moisture to the forest. The forest recycles more than 50 per cent of that moisture by means of evapotranspiration.

Aside from the precipitation data for river basins, what further evidence do we have for the biotic pump? A recent pan-tropical study of rainfall and land-cover, as indicated by the leaf area index (LAI), led Spracklen and his colleagues to the conclusion that satellite-derived rainfall measurements could be positively correlated with the degree to which model-derived air trajectories were exposed to forest cover (Spracklen, 2012).

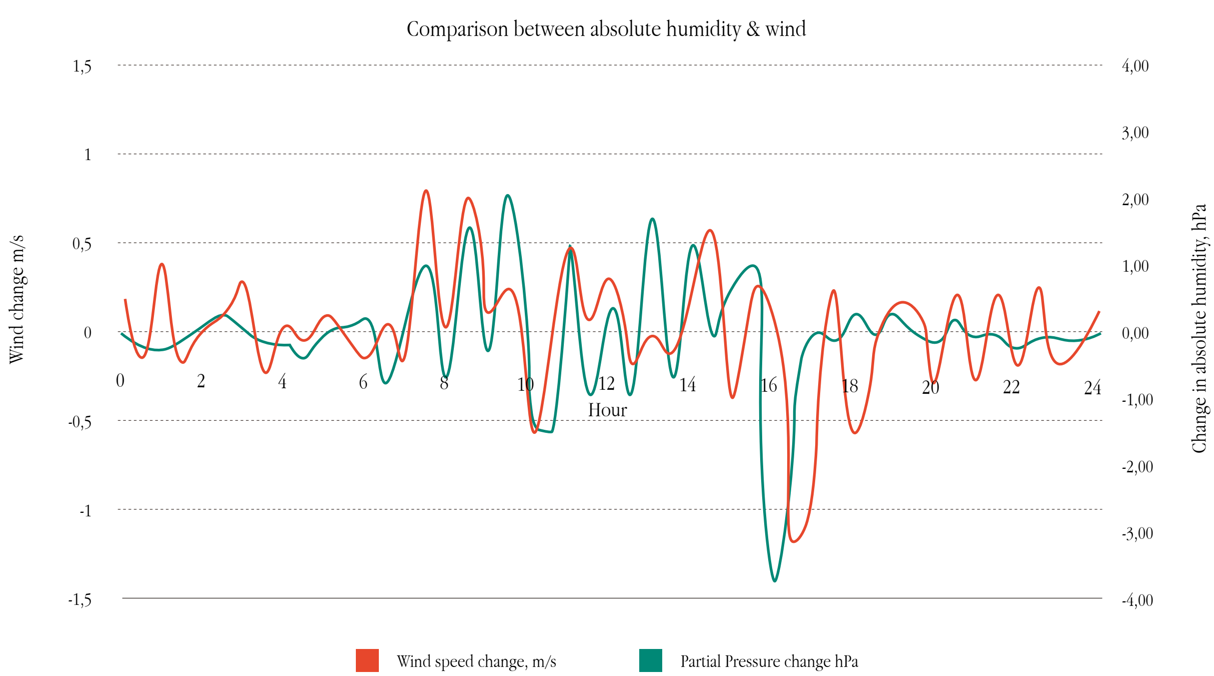
Poveda and colleagues provide evidence that when the low level jet streams pass over forested regions precipitation levels stay high and constant, whereas over regions which lack forest, precipitation levels decline exponentially, just as the BPT suggests should happen. Poveda and his colleagues look at the low level Chocó jet and comment that the change in direction of the Pacific Austral Trade Winds from Easterlies to Westerlies just over the Equator at 4° N, may owe their abrupt switch to the unsurpassed degree of evapotranspiration and subsequent condensation over the Chocó in Colombia (Poveda G. a., 2000) (Poveda G. L., 2014).

With more than 380,000 cubic metres per second of water vapour brought in from the Tropical Atlantic Ocean, the Amazon Basin functions on a far grander scale than the Chocó (Salati, 1987). Marengo showed that evapotranspiration rates were sufficiently high over the rainforest to increase the volume of the Amazonian atmospheric river in the form of the South American Low Level Jet Stream as it approached the western reaches of the Amazon Basin and was then deflected both upwards and southwards on encountering the Andes (Marengo, 2006).

On reviewing daily meteorological date from La Selva Biological Station in Costa Rica, Peter Bunyard found a significant correlation of an association between surface air flow and absolute humidity changes during daylight hours. The absolute humidity changes in hectopascals were suggestive of changes in the rate of evapotranspiration. In reviewing the data on a daily basis between October 2013 and April 2014, Bunyard discovered an average of approximately 10 pulses of absolute humidity during 12 hours of daylight which coincided with an equivalent number of pulses in surface airflow, the wind direction being from the Atlantic Ocean. In general, the airflow pulses came within 30 minutes of the pulses in surface humidity, the lag in time suggesting the time necessary for the humidified air at the surface to flow upwards and reach condensation altitudes.

Figure 3. *Data from La Selva, Costa Rica, October 21st, 2012. The airflow changes are delayed by 30 minutes. The X-axis shows the hours of the day.*

Figure 4. *La Seva, Costa Rica, hydrological data July 14th, 2011.*



The table gives the average monthly rates of peak change of the evaporative/condensation force, f_E, (hPa/km), of windspeed (m/s) and of temperature (°C) between the daylight hours of 6:00am and 19:30pm. For instance, from one day's results as seen in Fig. 3 and Fig. 4, we obtain some 9 to 11 peaks for both variables, namely f_E and windspeed.

Data from La Selva, Costa Rica

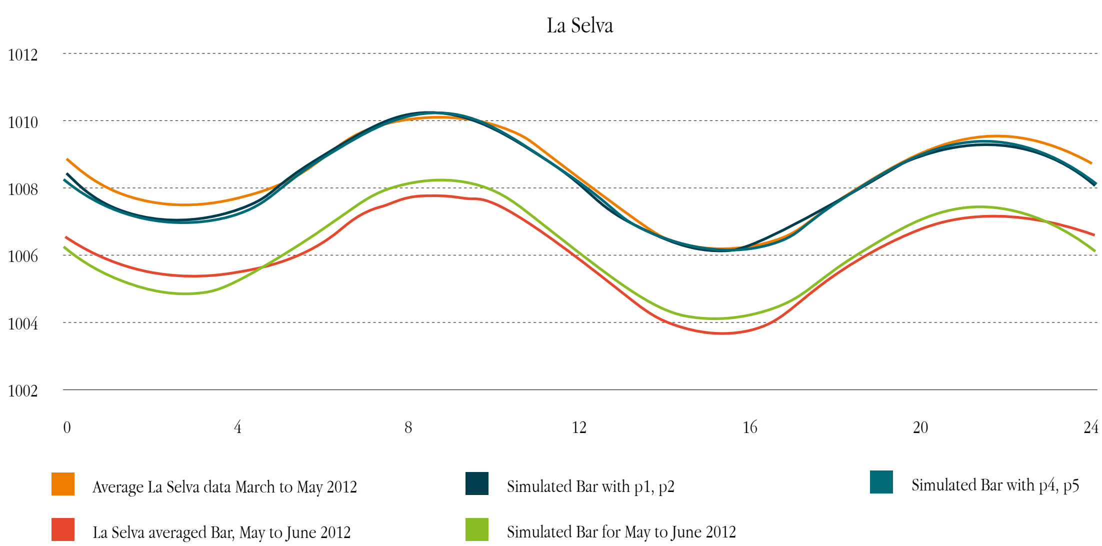
Date	Evaporative/condensation force (hPa/km)	Windspeed (m/s)	Temperature (°C)
October 2013	10.06	9.94	9.55
November 2013	10.47	9.87	9.9
December 2013	10.42	10.68	9.74
January 2014	10.35	10.52	9.58
February 2014	10.14	10.29	9.68
March 2014	10.29	10.29	9.84
April 2014	10.39	10.25	9.71

The meteorological data from La Selva, Costa Rica, also provide insight into the daily gross changes to the barometric pressure. Such changes are typical of the equatorial Tropics and consist of a double sinusoidal wave, with their peaks and troughs following the same pattern throughout the year.

Figure 5. *Data from La Selva, Costa Rica, showing the barometric pressure wave from March to May, 2012 and from May to June, 2012. The peaks and troughs occur at the same time over 24 hours (X-axis). The simulated curve is derived from the formula below (Plamen Netchev & Peter Bunyard), with coefficients,* P_1, P_2.

The coefficients enable the simulated curve to follow closely to the actual data.

Bar pressure $p = p_0 + (p_1 - p_2 \cos\left(\frac{nt}{12}\right)) * \sin\left(\frac{nt}{12}\right)$



As stated before the barometric pressure wave is a phenomenon of the equatorial Tropics with 12 hours of daylight and 12 of night. From observing data from a boreal forest region in Finland, Jokioinen, Latitude 60° 48' 50.44'', Bunyard found that the barometric pressure at the time of the September equinox, when the daylight length was close to 12 hours, followed a similar pattern to that obtained throughout the year for La Selva, Costa Rica., A similar, less clear form of the barometric pattern could be seen in the March equinox data for Jokioinen.

Figure 6. *The barometric pressure wave for Jokioinen, Finland averaged over 10 years during the September and March equinoxes. The pattern is similar to that obtained throughout the year for La Selva, Costa Rica.*

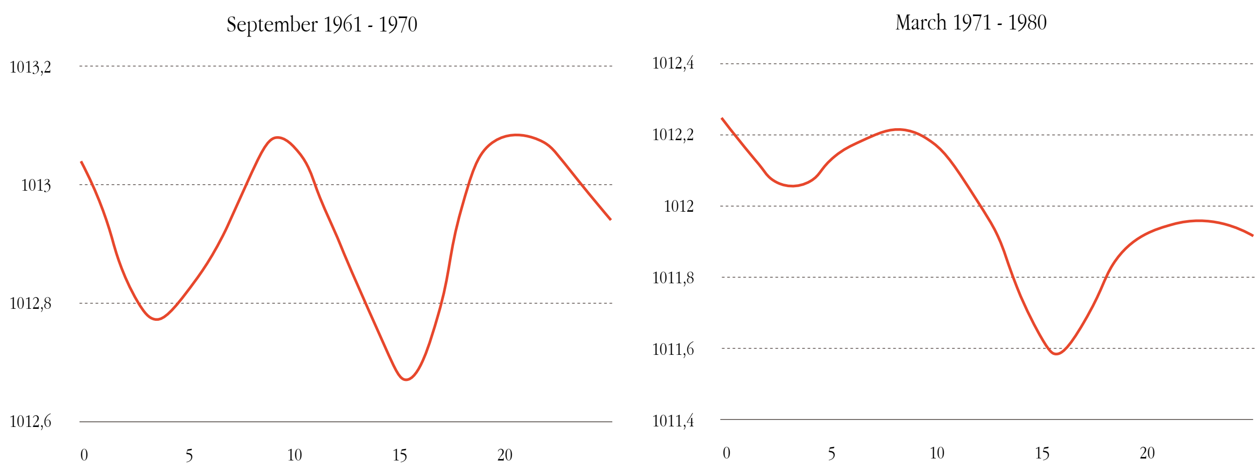
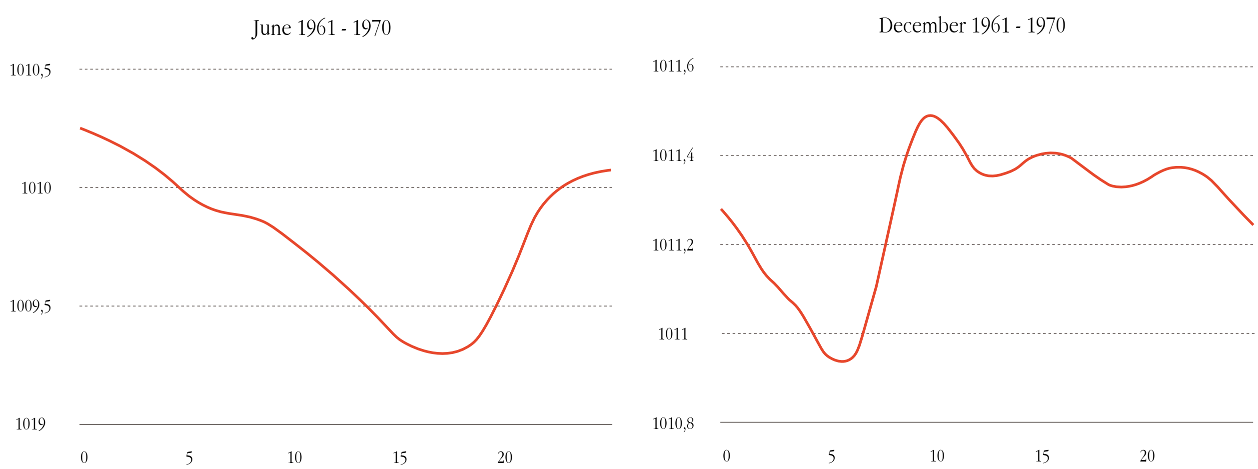


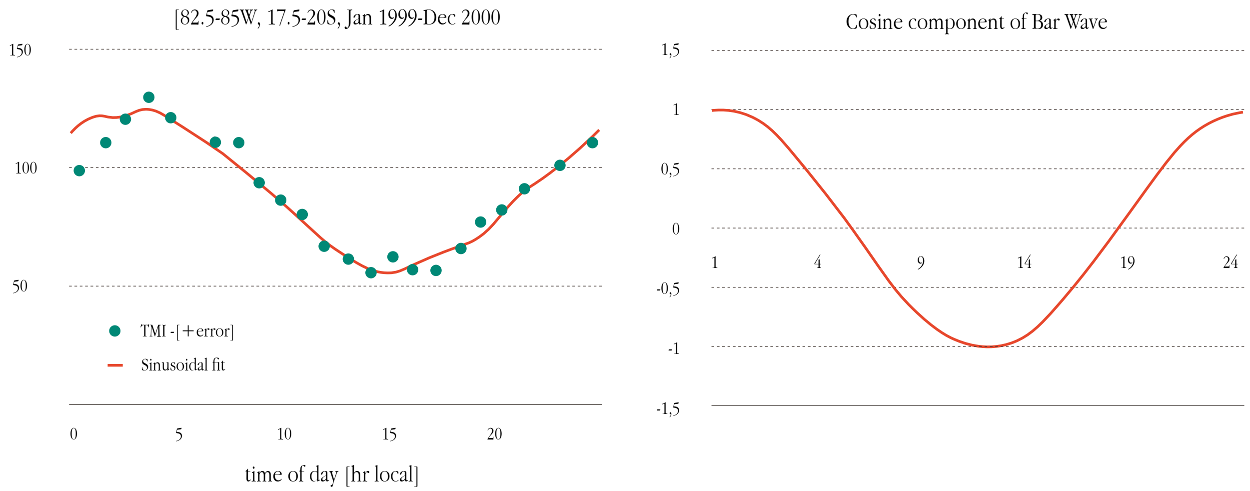
Figure 7. *The data from Jokioenen, showing the barometric wave over 24 hours.*



Could the curves, with their sinusoidal waves, be associated with the solar diurnal cycle and, later in the day, with the hydrological cycle? The pressure wave of Jokioinen in June, when the daytime length is at its maximum, shows a hint of the first part of the wave to be contrasted with a drawn-out second wave. During the 'shortest day' at the time of the December solstice, the second wave does not appear, whereas the first wave does.

Some answer to that question may be obtained from data derived from the tropical Pacific Ocean. Wood, Bretherton and Hartmann, over a two-year period between January 1999 and December 2000, measured the rate of condensation over the Southern Tropical Pacific (17.5 – 20S) and obtained the curve as shown in Fig.8 (Wood, 2002). A comparison of the 'liquid water path' derived from the atmosphere over the Pacific Ocean with the simulated cosine curve of the barometric pressure wave shows an extraordinary coincidence, as in Fig. 8. The indication is that changes in the partial pressure of water vapour are responsible for significant changes to the pressure wave during daylight hours. Those changes, indicating that condensation and cloud-forming are taking place, are of a sufficient magnitude to affect airflow (Bunyard P. P., 2014).

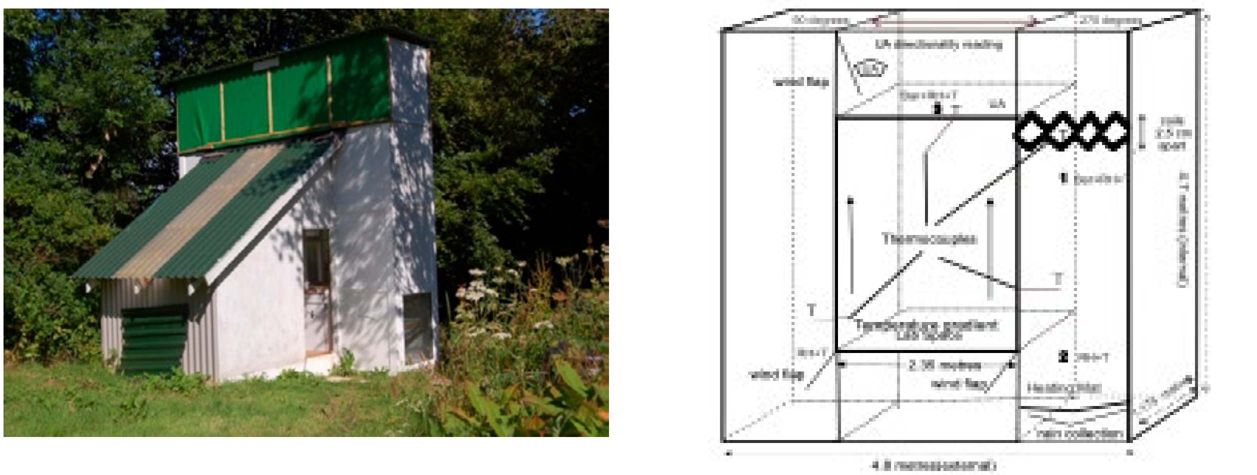
Figure 8. *: Atmospheric liquid water path as determined over 24 hours in the Tropical Pacific reveals similarities with the cosine component derived from the simulated barometric wave for La Selva. Source: Peter Bunyard, 2011; Wood, Bretherton, & Hartmann, 2002.*



Experimental Evidence of the Biotic Pump

To gain further evidence of the association between the condensation of atmospheric water vapour and airflow, Bunyard designed and carried out experiments in a special chamber in which some 20 cubic metres of atmospheric air were enclosed. Refrigeration, by means of a double layer of cooling coils, resulted in the condensation per second of a few grams of water vapour. A Gill ultrasonic 2D anemometer measured any airflow, including its directionality. By applying ideal gas physics to the air in different parts of the structure so as to measure changes in specific (absolute) humidity, correlations between the rate of condensation and airflow can be determined (Bunyard P. P., 2017), (Bunyard P. P., 2019).

Figure 9. *The experimental chamber for measuring absolute humidity changes and airflow. The lean-to is the laboratory.*



When water vapour condenses through cooling the air, a measurable wind can be detected which circulates around the structure. The correlation between the rate of condensation and the unidirectional wind flow is highly significant. By use of basic physics, (Bunyard P. P., 2019), the kinetic energy for the airflow is derived from the implosion of air surrounding the locus of condensation. That energy is some 1000 times greater than that of air density changes, the latter being insufficient by an order of magnitude to account for the measured airflow.

The following physical equations account for the energy derived from condensation:

$$\mathcal{J} = \frac{\Delta Pa}{\Delta t} m^3 = 1000 \Delta T_v and \Delta T_v = 0.621 \Delta q T$$

Where *J* (joules) is equal to the partial pressure change (pascals) over time by volume and is the reduction in temperature by volume as the surrounding air expands into the space vacated by water vapour. The heat capacity of dry air at constant pressure is 1,000 J $kg^{-1}K^{-1}$. Meanwhile, is the absolute humidity change per volume and is the temperature of the surrounding air.

Figure 10. *Experiment June 27th, 2016. The graph shows 4 refrigeration cycles. The left-hand axis shows the partial pressure change in water vapour in watt.seconds during the refrigeration cycle and the right-hand axis shows the anemometer readings. The directionality is clockwise and therefore down from the cooling coils.*

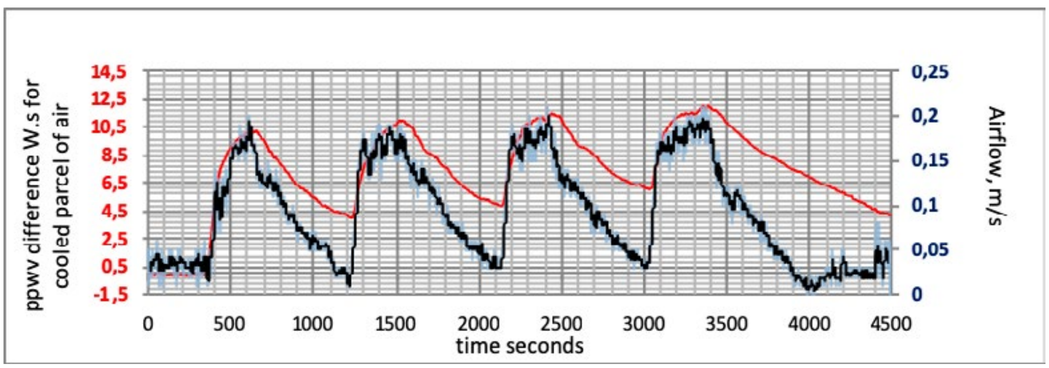
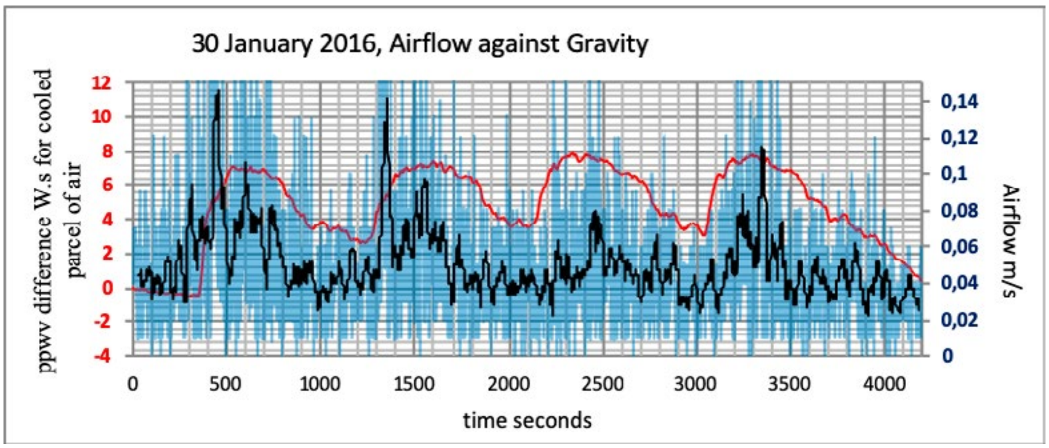


Figure 11. *Experiment 30th January, 2016. The left-hand axis shows the partial pressure change as a parcel of air is cooled. The right-hand axis shows the airflow. During the four refrigeration cycles the airflow is directed upwards, against gravity and therefore requires additional work for the air to move.*



Climate models currently do <u>not</u> account for partial pressure changes from water vapour condensation being a prime cause of air mass circulation, thus raising the possibility that the exclusion of the biotic pump from such models brings about a gross underestimate of the consequences of widespread deforestation (Fig.1).

In addition, the pulsing of the absolute humidity encountered in the meteorological data from La Selva Biological Station in Costa Rica (Figs. 3 & 4) opens the possibility that the rainforest synchronizes the opening and closing of its leaf stomata at particular times of the day. The above experiments show clearly that the airflow velocity depends on the rate of condensation. Consequently, it would be advantageous on evolutionary grounds, were some synchronization of evapotranspiration to take place so as to increase the rate of cloud-forming over the forest.

The evapotranspiration (ET) over the 5 million square kilometres of the Brazilian Amazon amounts to an average of 1,370 mm per year (Maeda, 2017). The kinetic energy associated with the implosion as water vapour from evapotranspiration condenses into clouds (therefore approximately equal and opposite to one-twentieth of latent heat energy) translates to some 5 Ws for every square metre of forested land, as if occurring throughout 24 hours.

Whereas 5 Ws would give airflows of 2.85 ms^{-1}, daytime pulses of absolute humidity from ET (some 10 pulses during daylight hours) could give airflows of 7 ms^{-1} (Trade Winds) and require a condensation rate of 30 pascals per second per cubic metre (30 Ws). The 5 Ws is the average over 24 hours and, on the assumption that transpiration occurred in pulses during daylight hours, the 30 pascals per second of condensation and partial pressure change per cubic metre would be readily obtained.

A preliminary experiment with an isolated hydrangea plant (*Hortensia*) indicates that the absolute humidity measured at the surface of separate leaves on different stems appears to be synchronized in contrast to a control. Further experimentation is required on rainforest species to see whether such synchronization of surface humidity is a shared property both on individual specimens and more widely.

Figure 12. *Experiment on Hydrangea, 5th July, 2019. Tests on separate leaves on separate stems of a Hydrangea potted plant compared to the control.*

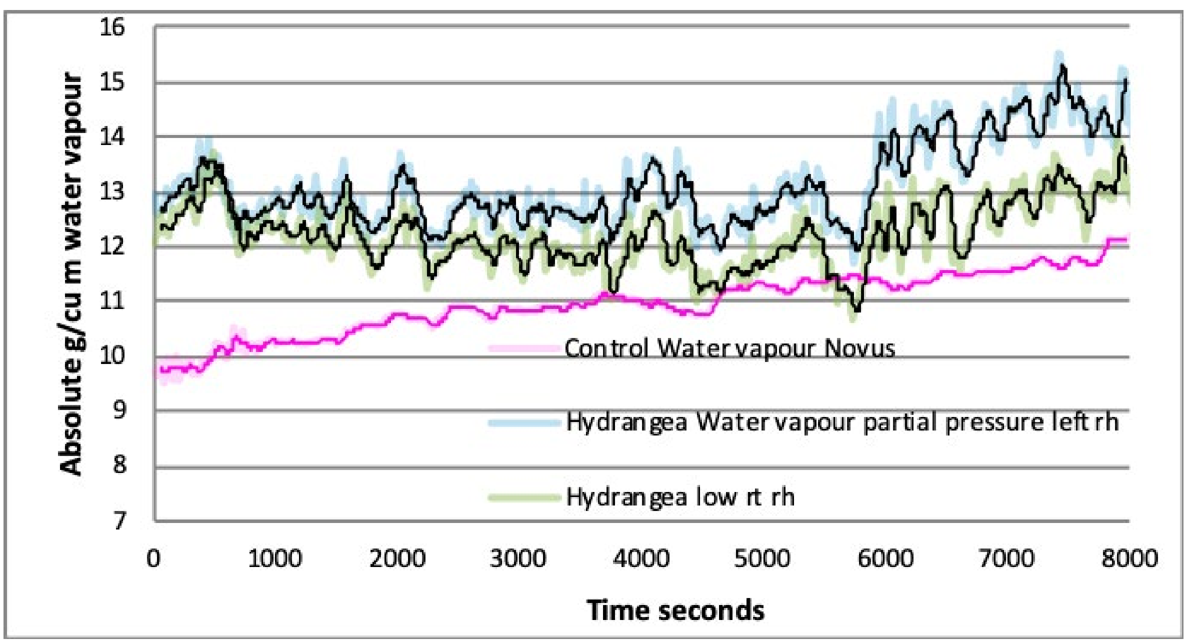
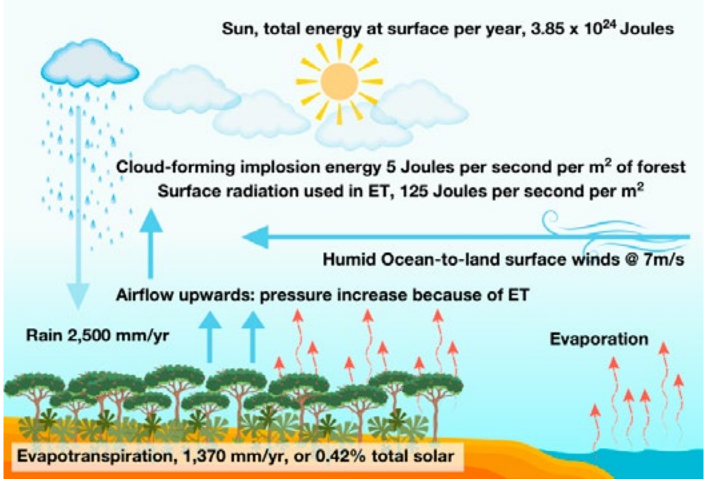


Figure 13. The biotic pump in action. Source: Peter Bunyard, diagram by Andrew Ayres



In conclusion, empirical evidence suggests that the biotic pump is no longer an abstract theory, but is a principle which needs urgently to be accounted for in those climate models which pertain to rainforest regions such as in the Amazon Basin. Were deforestation to continue at its current 2019 pace in the different countries of the Amazon, in particular Brazil, but including Colombia, the consequences for South America could be devastating. Bogotá, for instance, obtains its fresh water via the upper moorland páramos and, in turn, they depend on the air mass circulation over the Amazon to deliver rain. Were that circulation to collapse because of the abrupt reduction in the biotic pump brought on by deforestation, countries such as Colombia would face a dramatic shortage of fresh water.

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