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Hydrology and Earth System Sciences Discussions

Interactive comment on "Comment on "Biotic pump of atmospheric moisture as driver of the hydrological cycle on land" by A. M. Makarieva and V. G. Gorshkov, Hydrol. Earth Syst. Sci., 11, 1013–1033, 2007" *by* A. G. C. A. Meesters et al.

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Here we provide a brief overview of the biotic pump theory (BPT) from the condensation viewpoint – that is, on the basis of the phenomenon which physics was neglected both in the DP, in the so far available comments of the DP authors, and in the review of the DP by Anonymous Referee No. 3.

In a nutshell, BPT makes use of the simple physical fact: condensation of atmospheric water vapor leads to drop of local air pressure in the region where condensation occurs.

This pressure drop initiates a dynamic air flow directed towards the region of condensation. Depending on particular conditions, this condensation-induced dynamic flow takes a variety of atmospheric circulation forms. These are the most general statements. Below under items 1-6 we list the most essential particularities. For more details, interested readers are referred to Makarieva & Gorshkov (2007, HESS 11: 1013), Makarieva et al. (2008, ACPD 8: 17423) and the relevant Author Comments in the accompanying HESSD and ACPD discussions.

1. *Water vapor condensability.* Water vapor, a condensable gas under terrestrial conditions (i.e., in the presence of liquid hydropshere), is unique among atmospheric gases in that its partial pressure cannot exceed a certain maximum (saturated) value. The latter is dictated by air temperature and drops twofold per each 10 °C of temperature decrease. When moist saturated air enters a region with lower temperature, water vapor undergoes condensation and partially disappears from the gas phase. Temperature of the troposphere declines approximately linearly with height by 6.5 °C km^{-1}. E.g., at a 6 km height the saturated pressure of water vapor drops about 16-fold, while air pressure drops only twofold. Therefore, to a very good approximation, all water vapor that ascends from the Earth's surface to the upper troposphere undergoes condensation.

2. *Energy spent for evaporation.* Evaporation of one mol of water is associated with energy L_v spent on breaking the intermolecular bonds of molecules in the liquid phase and energy RT spent on "squeezing" the vapor molecules into the atmospheric air, R is the universal gas constant. Total molar energy of evaporation (latent heat) is equal to $L = L_v + RT$. In the atmosphere of Earth $L_v/(RT) \approx 17$. Both types of energy, L_v and RT, are consumed during the process of evaporation on one and the same microscopic time scale, when an H_2O molecule breaks out from the liquid phase of water and intrudes into the gaseous phase of atmospheric air.

3. *Energy released from condensation (latent work).* As air temperature drops, macroscopic amounts of liquid water are formed during condensation via formation of long-range correlations between vapor molecules. Energy L_v released during this process

HESSD

6, S59–S68, 2009

Interactive Comment

partially offsets the initial temperature drop, but it cannot warm the air above the temperature at which condensation started. Condensation occurs nearly instantaneously compared to the time scale of atmospheric circulation processes, so the time scale of L_v release is also microscopic. In contrast, the second part of latent energy L, $p_v V_v = RT$ (latent work, ACPD 8: S8340), where p_v is partial pressure and V_v is molar volume of water vapor at the surface, as the gaseous phase disappears, is not immediately converted to heat. The condensation-induced drop of air pressure leads to formation of dynamic air flow, which dissipates into smaller turbulent eddies and ultimately to heat on a macroscopic time scale, i.e. much more slowly. In summary, the ascent of one cubic meter of moist saturated air from the surface to the upper troposphere makes approximately $p_v = RT/V_v$ J m^{-3} available for conversion into kinetic energy of air. This potential energy exponentially depends on temperature and doubles per each ten degrees of temperature rise; at $\gamma_v \equiv p_v/p = 0.02$ (corresponding to global mean surface temperature of 15 °C) it is equal to 2×10^3 J m^{-3} ($p = 10^5$ J m^{-3} is air pressure at the surface).

When turbulent friction is negligible, all available potential energy is converted into kinetic energy of air, thus producing maximum velocities, $p_v = \Delta p = \rho u^2/2$, ρ is air density. This relationship correctly predicts the observed maximum wind velocities u in hurricanes ($\gamma_v \approx 0.05$) and tornadoes ($\gamma_v \approx 0.1$). In hurricanes and tornadoes water vapor that has slowly accumulated by evaporation at the expense of the absorbed solar energy (power $\sim 10^2$ W m^{-2}) undergoes condensation over a hundreds of times shorter time period, thus generating a wind power hundreds of times greater ($\sim 10^4$ W m^{-2}) than the solar radiation power. Therefore, hurricanes and tornadoes rapidly disappear after all potential energy of water vapor is used up; their next occurrence is only possible after a long time period of water vapor accumulation in the atmosphere.

4. *Turbulent friction and stationary circulation.* When turbulent friction is considerable, all potential energy $p_v = \Delta p$ (dimension J m^{-3} $\equiv$ N m^{-2}) released during condensation of water vapor can, instead of accelerating the air mainstream up to the maxi-

mum possible velocities, be spent on generation of small turbulent eddies. Force F_T of turbulent friction per unit surface area (surface friction pressure or surface friction stress, dimension $\mathrm{J\,m^{-3}} \equiv \mathrm{N\,m^{-2}}$) having the nature of friction of rest does not depend on wind velocity and is proportional to the weight of atmospheric column. From dimensional considerations surface friction is written as $F_T = \rho g z_T$, where g is acceleration of gravity and z_T is a scale height characterizing formation of turbulent eddies at the atmosphere/surface interface. Mean power of surface turbulent friction is $F_T u$ (dimension $\mathrm{W\,m^{-2}}$), where u is velocity of horizontal wind. Mean power of condensation is $\Delta p w$ ($\mathrm{W\,m^{-2}}$), where w is velocity of vertical wind: potential energy Δp ($\mathrm{J\,m^{-3}}$) becomes available as soon as a unit air volume ascends to the characteristic scale height h_v where condensation occurs; this takes a time period of $t = h_v/w$, hence the power released per unit surface area in the entire atmospheric column of height h_v is $\Delta p h_v/t = \Delta p w$. Stationarity of circulation and absence of acceleration of air masses correspond to the condition when the powers of condensation and surface friction coincide. This condition and the continuity equation for the air flow have the form

$$\Delta p w = F_T u, \quad L_E w = h_v u; \quad K \equiv \frac{\Delta p}{F_T} = \frac{\Delta p}{\rho g z_T} = \frac{u}{w}, \quad L_E = K h_v. \tag{1}$$

Here L_E and h_v are lengths of the horizontal and vertical parts of the streamline, respectively; condition for the equality of the horizontal and vertical air fluxes is $D L_E w = D h_v u$, where D is circulation width perpendicular to the streamline. Taking global mean values $\overline{w} = 1.3$ mm s^{-1} (calculated from the observed global mean precipitation rate), the observed value of $h_v = 2$ km, $\overline{u} = 7$ m s^{-1} and $\Delta p = p_v = 2 \times 10^3$ J m^{-3}, we obtain $\overline{z_T} \approx 0.1$ m, $\overline{K} = 5400$ and $\overline{L_E} \sim 10^4$ km. We now discuss the physical content of Eq. (1).

4a) *Direction of surface wind.* Since we are discussing air motion initiated by the condensation-induced pressure drop, it is obvious that air will move from the area with less intense condensation (donor region) to the area where condensation is more in-

HESSD

6, S59–S68, 2009

Interactive Comment

tense (acceptor region). In the stationary case condensation is more intense where evaporation is more intense, so that the donor region is a region with lower evaporation, while the acceptor region is a region with higher evaporation. In the stationary case linear sizes of the donor and acceptor regions should be of one and the same order of magnitude. Horizontal difference in the evaporation rate can be associated with **(1) systematic differences in surface properties**: ocean (donor) – forest (acceptor), desert (donor) – ocean (acceptor); **(2) systematic differences in solar flux**, e.g. Hadley circulation: tropics (donors) – equator (acceptor), with an account of seasonal shifts; **(3) or both**, e.g. monsoonal circulation: summer ocean (donor) – summer grasslands (acceptor), winter grasslands (donor) – winter ocean (acceptor).

Surface air moves from the donor region and carries water vapor that undergoes condensation in the acceptor region. This sustains the input of potential energy Δp available for the flow maintenance, increases precipitation in the acceptor region and makes the regional difference (precipitation minus evaporation) positive. In particular, this difference compensates for the river runoff in a forested river basin. (Note that in the case of stationary circulation, unlike in hurricanes and tornadoes, evaporation and precipitation fluxes in the acceptor region are of one and the same order of magnitude.) Deprived of precipitated moisture, dry air returns to the donor region in the upper troposphere, where its accumulation results in increased air pressure and subsidence. Therefore, the acceptor region where condensation occurs, features precipitation and lowered air pressure; the donor region features increased air pressure and fair weather. Far from the equator, where Coriolis acceleration becomes considerable, the horizontal air flow curves into cyclones at the surface in the acceptor regions and into anticyclones in the upper troposphere of the donor regions.

4b) *Spatial distribution of pressure difference.* Because of air continuity, pressure drop $\Delta p = p_v$ that arises in the course of water vapor condensation, is uniformly distributed along the entire streamline. As the vertical part of the streamline is much shorter than the horizontal part, $h_v \ll L_E$, practically all pressure drop falls on the horizontal part of

HESSD

6, S59–S68, 2009

Interactive Comment

the streamline L_E, $\Delta p_L \approx \Delta p$. Pressure drop along the vertical part of the streamline is negligibly small, $\Delta p_h \sim \Delta p(h_v/L_E) \ll \Delta p$, $h_v/L_E \sim 10^{-3}$.

4c) *Length of the horizontal part of the streamline in the stationary circulation.* This length is strictly defined, see Eq. (1), and on a global average it is very large, $\overline{L_E} \sim 10^4$ km. The existence of a spatially uniform region of length comparable to Earth's diameter is not a realistic condition on modern Earth with its scattered continents. Therefore, even in the largest existing acceptor regions the stationarity of circulation is observed only approximately, with large wind structures (cyclones) continuously arising, slowly moving along and dissipating. Remarkably, from Eq. (1) it follows that in the tropics where evaporation and, hence, vertical velocity w increase almost fourfold compared to the global average $\overline{w}$, so that length L_E in the tropics can be reduced to $(2-3) \times 10^3$ km. This means that large regions with intact forest cover like the Amazon and Kongo river basins should enjoy stable stationary circulation without any extreme events.

5) *Occurrence of intense circulation patterns and velocity of their movement.* When length L_E of the acceptor region is reduced to less than a thousand kilometers, the power of turbulent friction becomes negligibly small compared to the power of condensation, $L_E < 0.1\overline{L_E}$, $F_T u < 0.1 \Delta p w$, see Eq. (1). (The continuity equation for air $L_E w = h_v u$ holds.) Therefore, practically all potential energy $\Delta p = p_v$ released during condensation is converted to the kinetic energy of wind. Horizontal velocity $u = (2\Delta p/\rho)^{1/2}$ becomes over ten times larger than the global average $\overline{u}$. Hurricanes satisfy $L_E \gg h_v$, so most part of pressure difference Δp still falls on the horizontal part of the streamline L_E. Vertical velocity w of ascending air remains much smaller than horizontal velocity $u = (L_E/h_v)w \gg w$. At the same time it is hundreds of times larger than the global mean vertical velocity $\overline{w}$ determined by stationary evaporation: $w/\overline{w} = (\overline{L_E}/L_E)(u/\overline{u})$, $\overline{L_E}/L_E > 10$, $u/\overline{u} > 10$. Condensation power $\Delta p w$ and precipitation rate also increase hundredfold compared to the global averages. Condensation power and wind velocities in horizontal and vertical directions, $w \sim u$, reach maximum

possible values in tornadoes at $L_E \sim h_v$. Air convergence from a large donor region of volume $L_d^2 h_v$ to a small acceptor region of volume $L_a^2 h_v$ ($L_a \ll L_d$) (inevitably) produces a rotational structure of air masses with a calm eye in the center.

Length $L_E = L_a$ of the acceptor region is much smaller than length L_d of the donor region in all wind structures where wind velocities significantly exceed global averages. All potential energy of water vapor accumulated in the donor region is converted into kinetic energy of wind in the acceptor region. As soon as the local store of water vapor in the donor region is depleted, the wind structure must either dissipate or move to another area. This condition allows one to determine velocity U of movement of the wind structure as a whole. Evaporation increases the store of potential energy at a rate of $p_v \overline{w}$, where $\overline{w} \sim 10^{-3}$ mm s^{-1} is global mean vertical velocity. Total store of condensational potential energy in the atmospheric column above the donor region is $A_d = p_v(L_d^2 h_v)$. The power at which this potential energy is released during the process of condensation in the acceptor area is $W_a = p_v(w - \overline{w})L_a^2$, where w is the vertical wind velocity in the considered wind structure (cyclone, hurricane, tornado). Time τ during which all potential energy accumulated in the donor region is released in the acceptor region is given by $\tau = A_d/W_a = L_d^2 h_v/[L_a^2(w - \overline{w})]$. During this time the wind structure must move to the neighboring donor region (if such exists), i.e. it must move at velocity $U = L_d/\tau = (w - \overline{w})L_a^2/(h_v L_d)$. For the stationary case of a large-scale circulation pattern, the latter remains immobile: $w = \overline{w}$ and $U = 0$. For a hurricane with $w \sim 0.1$ m s^{-1} $\gg \overline{w}$ we have $U = wL_a^2/(L_d h_v)$. Taking $L_d \sim 10^3$ km, $L_a \sim 4 \times 10^2$ km, $h_v \sim 2$ km, we obtain $U = 2$ m s^{-1}. Conversely, knowing vertical velocity w of air masses in the hurricane, velocity of hurricane movement U and hurricane linear scale L_a, it is possible to estimate the linear dimension of the donor region $L_d = (w/U)L_a^2/h_v$. For tornado with $w \sim u \sim 10^2$ m s^{-1} and $L_a \sim L_d \sim h_v$ we have $U \sim u$, where u is the horizontal wind speed. The same relationship connects condensational vertical velocities w with movement velocity U and sizes of the donor and acceptor regions L_d and L_a for cyclones and atmospheric fronts.

If there were no extensive donor and acceptor regions on Earth with systematically different evaporation rates, that is, if evaporation were largely uniformly distributed over the planetary surface, then the atmospheric circulation would take the form of episodic violent events with intense condensation and precipitation like hurricanes and tornadoes. These events would be intermitted by prolonged periods of dry fair weather with no precipitation, during which the store of water vapor in the atmosphere would be slowly replenished by evaporation.

6. *Summary: why evaporation and precipitation occur in the atmosphere of Earth.* We have shown that the power of condensation is significant enough to numerically explain the observed wind velocities in all circulation phenomena, both stationary and episodic, that are registered in the atmosphere of Earth. This suggests that the contribution of horizontal differential heating, conventionally considered as the main cause of circulation, into the origin of the observed circulation patterns is minor in comparison or, at best, in the unlikely case of random coincidence of independent factors, of the same order of magnitude as the contribution of the condensation power.

The so far described physics of condensation-driven different-scale atmospheric motions, items (1)-(5), defining the general atmospheric circulation constitutes the essence of the biotic pump theory. This physics is based on a single observed fact – that the vertical distribution of atmospheric water vapor (exponential scale height ~ 2 km) is compressed by several times compared to the vertical distribution of atmospheric air (exponential scale height ~ 8 km). This compression is caused by the observed condensation of water vapor and precipitation known to everybody.

The biotic pump theory asks and answers a question that has remained both unasked and unanswered: why does the hydrosphere of Earth evaporate, why it rains, why rivers flow on land. These phenomena have been considered as self-evident, demanding no explanation. The biotic pump theory shows that the processes of evaporation and precipitation are caused by the non-equilibrium distribution of atmospheric water vapor in the gravitational field of Earth **in the presence of a large vertical lapse rate** Γ

HESSD

6, S59–S68, 2009

Interactive Comment

of air temperature. At $\Gamma \leq \Gamma_v \equiv T_s M_v g/L = 1.2$ K km^{-1} water vapor and moist air as a whole would have been in hydrostatic equilibrium. (Here T_s is surface air temperature, $M_v = 18$ g mol^{-1} is molar mass of water, $L = 44$ kJ mol^{-1} is molar latent heat.) Water vapor would have had an exponential scale height of $h_{ve} = RT_s/(M_v g) = 13.5$ km. Global atmospheric circulation as intense as one knows it today would not exist. Surface air would have been saturated with water vapor, but no vertical flux of water vapor would have been present in the static atmosphere. Evaporation and precipitation would not exist.

The ultimate cause of a non-zero vertical lapse rate of air temperature is the presence of greenhouse gases in the atmosphere of Earth, which creates a non-zero lapse rate $\Gamma_b \geq \Gamma$ of brightness temperature (related to the local intensity of thermal radiation). At $\Gamma > \Gamma_v$ the vertical dynamic movement of air is governed by the condensation-induced non-equilibrium pressure shortage; it is fundamentally different and unrelated to the buyoancy effects of Archimedes force. This process of air ascent can modify the lapse rate of air temperature accordingly (making it closer to the dry or moist adiabatic lapse rate Γ_a), thus giving a classical example of a boot-strap. Persistence of the condensation-induced motion is secured by condition $\Gamma_a > \Gamma_v$, i.e. in no case the modified lapse rate becomes smaller than the critical value necessary for the initiation of condensation. Note also that the condition $\Gamma_a < \Gamma_b$ is necessary for the described processes to be possible (since the ultimate sink of thermal energy into which all atmospheric processes ultimately dissipate is thermal radiation, brightness temperature at any height must be lower that air temperature).

The observed mean tropospheric value of lapse rate of air temperature $\Gamma = 6.5$ K km^{-1} exceeds the critical value of $\Gamma_v \equiv 1.2$ K km^{-1} by nearly six times. From this fact the vertical scale height of atmospheric water vapor was theoretically estimated as $h_v = h_{ve}\alpha = 2.4$ km, $\alpha \equiv \Gamma_v/\Gamma = h_v/h_{ve} = 0.18$, which is in agreement with observations. Values $p_v h_{ve}$ and $p_v h_v$ characterize the store of water vapor potential energy in the static and real atmospheric column, respectively. This consideration allows for a more precise estimate of the condensation-related potential energy available for conversion to the kinetic energy of air as $\Delta p = (1-\alpha)p_v = 0.82p_v$ instead of approximate equality $\Delta p \approx p_v$ used throughout this comment. At $\alpha = 1$ we have $\Delta p = 0$, condensation and precipitation are absent.

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