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Interactive comment on “Biotic pump of atmospheric moisture as driver of the hydrological cycle on land” *by* A. M. Makarieva and V. G. Gorshkov

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In response to the comments of H. de Melo Jorge Barbosa:

Dr. de Melo Jorge Barbosa raises a number of questions that we now address in the order of what we envisage as their physical importance, with more fundamental issues discussed first.

1) Evaporative force

Comment to **P3638, L5** (p. S1423) questions the existence of the evaporative force, which constitutes the basis of the physical mechanism of the biotic pump that we proposed. The comment says (quote): "If "dry air" molecules are in a state of hydrostatic balance, they should not move. . . If only water vapor is out of equilibrium, only the H_2O molecules should diffuse upwards trying to bring the vertical profile to equilibrium."

These statements contradict the bases of the kinetic theory of gases. Gas is a physical state where molecules are at large distances from one another as compared to the radius of molecular interaction. The state of gas is determined by the spatial distribution of molecules and by the velocity distribution of molecules that is formed in the course of molecular collisions. At low gas densities, as those in the terrestrial atmosphere, the ideal gas approximation is valid. Pressure of ideal gas does not depend on the properties of molecules (their mass, atomic structure, scattering length etc.) but is exclusively determined by temperature T and molar density N, $p = NRT$, that is, on temperature and the total number of gas molecules of whatever nature.

Therefore, when molar density of a gas mixture deviates from equilibrium in a certain spatial area, local pressure of the gas mixture deviates from equilibrium as well. This leads to the appearance of a force acting on a unit volume of the gas mixture. This force is equal to the difference between the equilibrium pressure gradient and the existing (non-equilibrium) pressure gradient of the gas mixture. This process does not depend on whether the considered gaseous state is represented by only one gas or a mixture of several different gases. In the view of $p = NRT$, it does not matter whether molar density N deviates from equilibrium due to the change of molar densities of all mixture constituents or due to the change of the molar density of only one of them. Thus, when the molar density of water vapor deviates from equilibrium, this leads to the appearance of the evaporative force acting on the gas mixture as a whole, i.e. on the unit volume of moist air.

The same effect can be illustrated by the following simple example. Let us take a closed jar divided into two compartments by a gas-impermeable partition and fill both compartments with atmospheric air. In the initial state molar densities and partial pressures of all gases are equal in both compartments; gases in the two compartments are in equi-

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librium. Let us now partially remove some gaseous component (e.g., oxygen) from the first compartment. This can be done, for example, by initiating a chemical reaction turning oxygen into some non-gaseous oxygen-containing chemical substances (e.g., solid oxides). Partial pressure of oxygen in the first compartment will drop. However, as far as the total pressure of gas mixture is equal to the sum of partial pressures of all its constituents, total air pressure in the first compartment will drop as well as compared to air pressure in the second, intact compartment. When we now remove the partition, acted upon by the force equal to the appeared pressure gradient, all gases from the second compartment (and not only oxygen!) will move to the first compartment to compensate for the oxygen and total pressure shortage there.

Note that if we fill the first compartment in the jar with one gas, and the second compartment with a different gas, both gases having equal temperature and molar densities (and, hence, pressures), then, after removing the partition, a diffusion process will start mixing the gases and equating their molar densities in both compartments. There will be a diffusional flux of molecules of gas No. 1 to the second compartment, and of gas No. 2 — to the first compartment. No pressure gradient, no force and no mass movements of gases will originate. In contrast, the process of equating non-equilibrium *pressures* of the gas mixture in the two compartments in the previous example is not a diffusion process, it is a dynamic mass movement of the gas mixture as a whole.

On a related note, it is several times mentioned in the comments that the non-equilibrium distribution of water vapor induces "upward motion" of water vapor (see comment to **P2636, L7**, p. S1422), while in the considered comment to **P3638, L5** it is said that the non-equilibrium distribution of water vapor will make water vapor "diffuse" to the upper atmosphere. We thus believe it is appropriate to emphasize the distinction between motion of gas as a whole (which may only occur under the action of some force) and the thermal chaotic motion of air molecules. The latter is the driver of molecular diffusion and occurs irrespective of whether a force is acting on the gas or not. In atmospheric physics the word "motion" (vertical motion, upward motion etc.)

is conventionally applied to denote dynamic mass movements of air (i.e. motion of air as a whole). In this sense there cannot be any dynamic motions of water vapor in the otherwise motionless atmosphere, but only motions of moist air as a whole.

To summarize, when the dry air constituents are in hydrostatic equilibrium, while water vapor is not, there is an upward-directed evaporative force acting on a unit volume of the entire gas mixture, moist air = dry air + water vapor. This force creates mass movement (or a dynamic (not diffusional) flux, as we referred to this movement in our response to Dr. Dovgaluk) of moist air in the atmosphere.

As requested in the comment to **P3638, L5**, we now clarify how expression (14) (p. 2638) for the evaporative force acting on moist air is obtained from the Euler equation of the hydrodynamics. When there is a force f acting on a unit gas volume with mass density ρ, this volume starts to accelerate in accordance with Newton's law: $\rho dw/dt = f$, where w is velocity. The time derivative dw/dt describes the change of velocity of the unit air volume, which moves in space. Hence, in the case of vertical movement $\dfrac{dw}{dt} = \dfrac{\partial w}{\partial t} + \dfrac{\partial w}{\partial z}\dfrac{\partial z}{\partial t} = \dfrac{\partial w}{\partial t} + w\dfrac{\partial w}{\partial z}$. In the stationary case $\dfrac{\partial w}{\partial t} = 0$ and we have $\rho w\dfrac{\partial w}{\partial z} = f$, or, as far as z is the only independent variable, $\rho\dfrac{1}{2}\dfrac{dw^2}{dz} = f$. In the presence of the gravitational force, total force acting on unit gas volume is $f = -dp/dz - \rho g$ (z increases upwards), so we have:

$$\rho\frac{1}{2}\frac{dw^2}{\partial z} = -\frac{dp}{dz} - \rho g. \qquad \text{(C1)}$$

We do not have the English text of Landau and Lifshitz (1987) at hand, but from our Russian edition we believe that equation (C1) can easily be located by its number, (2.4), in Section 2 "Euler equation" of Chapter 1 "Ideal liquid".

Writing this equation for moist air (low index m), $p_m = p + p_{\mathrm{H_2O}}$, $\rho_m = \rho + \rho_{\mathrm{H_2O}}$, and taking into account that $\rho = MN$ and that in hydrostatic equilibrium for dry air

$-dp/dz = MNg = \rho g$ (Eq. 7, p. 2633), we can see that the dry air terms cancel in the right-hand part of Eq. (C1). The only terms that remain, $-dp_{\mathrm{H_2O}}/dz - \rho_{\mathrm{H_2O}}g$, pertain to water vapor. Now making elementary substitutions $p_{\mathrm{H_2O}} = (\rho_{\mathrm{H_2O}}/M_w)/RT$ and $h_w = RT/(M_w g)$, one arrives at expression (14) for the evaporative force acting on moist air as a whole. See also our reply to S. Sherman, pp. S1130-S1132. Note also that, as we mentioned in our reply to S. Sherman (p. S1131, L20-21), the minus sign at the first term in the right-hand side of the first equality in Eq. (14) was lost by mistake.

Concluding this issue, if there is no water vapor in the atmosphere, the evaporative force is zero. However, the evaporative force acting in one local area (e.g., over the ocean) can make the water-poor air in other areas (e.g., deserts) move as well, as prescribed by the continuity equation that governs atmospheric circulation.

2) Saturation of surface air and atmospheric column

(comments to **P2634, L14** on p. S1419 and to **P2636, L7** on p. S1421)

The condition $\Gamma > \Gamma_{\mathrm{H_2O}}$ leads to saturation of the entire atmospheric column if only water vapor is saturated at the surface. In the absence of horizontal air movements this condition is always fulfilled when the rate at which water vapor is removed from the surface layer by vertical updrafts is less than the rate at which it is added to the surface layer in the course of evaporation. It is easy to show that at the considered vertical velocities of the order of 10^{-3} m s^{-1} this is always the case.

To be brief, we start from the physically transparent formula (42.5) of Feynman et al. (1963), which gives the flux F_e of molecules (mol m^{-2} s^{-1}) evaporating from unit of water surface area per unit time:

$$F_e = \frac{vX}{V_a}\exp(-Q_{\mathrm{H_2O}}/RT), \qquad \text{(C2)}$$

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where v is molecular velocity ($\sim$500 m s^{-1} at room temperature for water molecules), $1/V_a$ is the number of molecules per unit liquid volume (5.6 $\times$ 10^4 mol m^{-3} for water), and X is a dimensionless coefficient of the order of unity.

When $\Gamma < \Gamma_{\mathrm{H_2O}}$, water vapor is in hydrostatic equilibrium, there are no upward fluxes, so flux F_e of molecules leaving the liquid (water) is balanced by the flux F_s of molecules that enter the liquid state from the saturated area above the surface, $F_e = F_s$.

When $\Gamma > \Gamma_{\mathrm{H_2O}}$, there appears an upward dynamic flux $F_w = N_1 w$, where N_1 is the current concentration of water vapor at the surface. This flux removes water vapor from the surface layer. The stationary mass balance equation for water vapor in the surface layer thus becomes $F_e = F_s(N_1/N_s) + F_w$. Here F_e is given by (C2), $F_s(N_1/N_s)$ is the flux of water molecules returning from the gaseous to liquid phase, $F_s = F_e$ is this flux when the surface layer is saturated ($N_1 = N_s$), N_s is the saturated concentration of water vapor. We thus obtain for N_1:

$$N_1 = \frac{F_e}{w_e + w}, \qquad w_e \equiv \frac{F_e}{N_s}. \qquad \text{(C3)}$$

From (C3) it is clear that when $w << w_e$, then $N_1 = N_s$, i.e. concentration of water vapor at the surface is always saturated. Given $N_s \sim 0.7$ mol m^{-3} at 15 $^{\mathrm{o}}$C and $F_e \sim 0.3$ mol m^{-2} s^{-1} as estimated from (C2) at $Q_{\mathrm{H_2O}}/R = 5300$ K, we obtain $w_e \sim 0.4$ m s^{-1} $>> w \sim 10^{-3}$ m s^{-1}. Since the empirically determined velocity w describes the net flux of water vapor from the surface, it is clear that, contrary to the qualitative statement made in the comment to **P2634, L14** on p. S1419, vertical turbulent mixing cannot perturb saturation of water vapor at the surface.

At the same time our estimate indicates that horizontal air fluxes with characteristic global wind speeds of the order of 10 m s^{-1} $> w_e$ can substantially change relative humidity at the surface by mixing surface air from "drier" surfaces like poorly vegetated land with air from "wet" surfaces like oceans. The resulting mean global relative humidity at the surface, ~80% (Held and Soden, 2000), remains, however, fairly close to saturation, which reflects the spatial dominance of the hydrosphere on our planet.

Distribution $p_1(z)$ suggested in the comment to **P2634, L14**, p. S1422, is physically unrealistic. In this distribution water vapor is compressed even further as compared to the saturated case and has a scale height $h_{\mathrm{H_2O}}/2 < h_{\mathrm{H_2O}}$. Water vapor is not saturated anywhere in the atmosphere.

The non-equilibrium distribution of water vapor with $h_{\mathrm{H_2O}} << h_w \sim$ 15 km can persist solely due to the fact that any additional amounts of water vapor needed to restore the equilibrium cannot be sustained in the atmosphere and are removed via condensation and precipitation, as far as otherwise the atmosphere would have been permanently oversaturated. Thus, distribution $p_1(z)$ could be created only artificially, for example, by arranging a vertical profile of chemical processes removing water vapor from the gaseous phase. These chemical processes would play then the role of condensation and precipitation. Notably, in this case the value of lapse rate Γ will have no impact on the vertical distribution of water vapor. The latter will be totally determined by the spatial distribution of the intensity of those chemical reactions. However, as soon as these artificially maintained processes are stopped, while trying to reach the equilibrium water vapor will immediately fill the atmospheric column until saturation is reached at any height, when further accumulation of water vapor in the column becomes impossible. This will result in a saturated column and a vertical (still non-equilibrium) distribution with a scale height of $h_{\mathrm{H_2O}}$.

Concluding our response to these comments: for questions regarding the origin of lapse rate $\Gamma > \Gamma_{\mathrm{H_2O}}$ we refer the reader to the Appendix of our paper, where this issue is discussed. Briefly, atmospheric lapse rate arises due to the presence of greenhouse substances; the release of latent heat of the upwelling water vapor is already "taken into account" in the observed lapse rate of 6.5 K km^{-1}.

3) Specific issues

Comment to **P2633, L20**, p. S1419

The first phrase of this paragraph can be changed to: "Hydrostatic equilibrium of dry air represents the basis of theoretical considerations of atmospheric processes".

Comment to **P2634, L8**, p. S1419

Change of absolute air temperature in the lower troposphere $z \sim h_{\mathrm{H_2O}}$ relevant for our consideration is of the order 10% of surface temperature. This means that in formula (8) the approximation of isothermal atmosphere is valid to the accuracy of 10%. To have the idea of the exponential drop of pressure with height is useful for further reading of the paper. With this idea in mind, it becomes clear from formula (8) that the account of the fact that air temperature drops with height makes pressure drop more rapidly than the isothermal exponent.

Comments to **P2634, Eq. 9**, p. S1419 and **P2634, Eq. 10**, p. S1420

For a change of temperature from 0 to 100 $^{\circ}$C the value of $Q_{\mathrm{H_2O}}$ changes by only 10%. In the temperature interval of interest, from $z = 0$ to $h_{\mathrm{H_2O}}$ it changes by a magnitude of the order of 1%. Constancy of $Q_{\mathrm{H_2O}}$ is therefore a very good approximation for our analysis. It is mentioned in the comment that the exact Eq. (10) can be derived directly from the differential form of the Clausius-Clapeyron equation, which is valid for any dependence of $Q_{\mathrm{H_2O}}$ on T; we agree. However, we do not think that such a change in our derivations would be appropriate, because formula (9) obtained by integrating the differential Clausius-Clapeyron equation at constant $Q_{\mathrm{H_2O}}$ is similar in its form to the fundamental Boltzmann's distribution, is well-known and widely used in atmospheric analyses.

Comment to **P2635, L14**, p. S1420

The exact equation (11) obtained from formulae (8) and (10) has the form $-\dfrac{dT}{dz} = \dfrac{T}{H}$. Hence, we have $T = T_s \exp(-z/H)$ and, consequently, $dT/dz =$

$(dT/dz)_s \exp(-z/H) = \Gamma_{H_2O} \exp(-z/H)$. The exponent $\exp(-z/H) \approx 1$ is omitted in Eq. (11), as is stated in the text.

Comment to **P2635, last paragraph**, p. S1420

The reasoning in the comment is based on the incorrect premise that the amount of water vapor in the unsaturated atmosperic column at $\Gamma < \Gamma_{H_2O}$ is less than the amount of water vapor in the fully saturated atmospheric column at $\Gamma = \Gamma_{H_2O}$ at equal surface temperatures. In reality, the amount of water vapor in the column at $\Gamma < \Gamma_{H_2O}$ is larger than at $\Gamma = \Gamma_{H_2O}$, as far as pressure drops more slowly when the temperature lapse rate is smaller, see formula (8) and our response to comment **P2634, L8**, p. S2429 above.

The general point that is overlooked in the comment is that in the first case of temperature dropping only slowly with height, $\Gamma < \Gamma_{H_2O}$, the atmosphere is on average warmer than in the second case when, due to the more rapid decrease of temperature with height, it is on average colder. The saturated amount of water vapor at low temperature is not necessarily higher than the unsaturated amount of water vapor at a higher temperature. Therefore, the conclusions about the non-equilibrium state of water vapor and existence of upward fluxes of water vapor at $\Gamma < \Gamma_{H_2O}$ do not hold.

Comment to **P2636, L1**, p. S1421

We do not state anywhere in the paper that it is the same molecules that evaporate into the atmosphere that immediately condense.

Comment to **2636, L11**, p. 1421

$p_w(z) = p_{H_2O}(z)$ means that in the stationary case there is no excessive water vapor; but there can be moisture in the form of liquid or solid water (cloudiness, fog).

Comment to **2631, L21**, p. S1422

Our statement that the Archimedes force cannot drive atmospheric motions over areas exceeding h^2 is based on the physically transparent fact that h is the only relevant vertical length scale of the atmosphere. In our paper we show how the evaporative force can drive large-scale atmospheric circulation. We do not base our consideration on the Archimedes force and, hence, we do not need to prove this statement. This statement would need to be *disproved* in an attempt to show that the Archimedes force *is* able to drive large-scale atmospheric motions. The example of the observed extensive updraft regions in the real atmosphere is not a counter-example to our statement. We have shown (p. 2641, L3-19) that the evaporative force can lead to strong updrafts with vertical velocities of up to several dozens m s^{-1}.

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