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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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As long as the discussion is open, the authors are kept alert, once again thinking over the available comments and the paper itself. Here we would like to summarize the key difference between the proposed physical mechanism of the evaporative force and the conventional consideration of convective instability and vertical motions in meteorology. With this comment we hope to provide a further and probably more transparent response to the related concerns expressed by Dr. Dovgaluk, Dr. Manuel de Jorge Barbosa and Dr. van den Hurk, in particular, how and why the threshold value of temperature lapse rate, 1.2 K/km, determines the character of atmospheric circulation. Bearing in mind the interests of readers with different backgrounds, an attempt was made of presenting all reasoning in basic physical terms.

1) Equilibrium and stability/instability

If the sum of forces acting on a physical body is zero, it is said to be in static equilibrium. This equilibrium can be either stable or unstable. In the gravitational field a ball in the pit is in stable equilibrium — it can sit there forever; even if there are occasional displacements of the ball, it will return to the initial position. In the meantime, a ball on the top of the hill is in unstable equilibrium. Any fluctuation of its position will make the ball roll down the hill. However, if such fluctuations were absent, the ball could remain motionless on the top of the hill. In contrast, a ball on the *slope* of the hill is not in equilibrium. Such a ball cannot be motionless, it is rolling down the hill under the action of the force of gravity that is not compensated by the pressure force of the hill surface.

This simple example helps illustrate the difference between the conventional meteorological approach to vertical atmospheric motions and the physical approach based on the evaporative force. The meteorological consideration starts from the premise that atmospheric air is — on average — in equilibrium. As is well-known, this equilibrium, called hydrostatic equilibrium in meteorology, consists in the equality of the pressure gradient force of atmospheric air and the weight of a unit air volume (p. 2633, Eq. (7)):

$$-dp/dz = \rho g, \tag{C1}$$

where p is air pressure and ρ is its density.

When there is static equilibrium, it is possible to discuss whether it is stable or unstable. If an air parcel is vertically displaced in the gravitational field and expands adiabatically, it cools (or warms) at a rate that can be easily calculated from thermodynamics and constitutes 9.8 K/km for dry air parcels and around 6 K/km for moist air parcels. If the parcel that was displaced upward becomes colder than its environment, it also becomes more heavy and tends to return downward (as the ball in the pit). Accordingly, an atmosphere with a vertical temperature lapse rate Γ less than ~ 6 K/km is said to be convectively stable. If the displaced parcel cools more slowly than does the surrounding atmosphere, it always remains warmer than the surrounding atmosphere, and, as the ball that was pushed from the top of the hill, continues its vertical motion. An atmosphere with $\Gamma > 9.8$ K/km is considered to be convectively unstable.

An important feature of this conventional theoretical consideration is the average absence of forces. If there were no fluctuations (initial displacements of air parcels, nonuniformities of air density and temperature), the atmosphere, even with a lapse rate $>$ 9.8 K/km, would remain motionless. In the absence of forces, any initial motion ultimately damps out due to dissipation. Thus, in order to obtain a stationary pattern of atmospheric motion, it is necessary to continuously introduce fluctuations to the atmosphere. Namely the character and magnitude of these fluctuations rather than the time-averaged large-scale properties of the atmosphere dictate then the character of atmospheric vertical motions.

By contrast, it was shown in the paper that at sufficiently large values of temperature lapse rate ($\Gamma > 1.2$ K/km) moist air *cannot be in static equilibrium* and, hence, *cannot be motionless*. To further exploit the above comparison with the ball, it is not discussed whether and when the atmosphere is similar to the ball on the top of the hill and whether and when it is similar to the ball in the pit. It was shown that at $\Gamma > 1.2$ K/km the atmosphere is similar to the ball on slope of the hill, along which it is rolling down. Atmospheric air moves under the action of the evaporative force, which can be quantified using the *average* atmospheric parameters (temperature, lapse rate, humidity, evaporation flux etc.).

2) Why the evaporative force has not been previously described

Dr. Nobre in his comment mentioned the issue of why the evaporative force had been so far neglected in meteorology. Here some further insights are provided. Historically, the notion of equilibrium in meteorology was linked to Eq. (C1). This equation can

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be written for any body — solid, liquid or gaseous. If one puts several bricks on one another, the pressure under each brick will decrease in the upward direction — the fewer bricks there are above the considered point z, the lower the pressure. Similarly, pressure decreases in the upward direction within any liquid medium. The term *hydrostatic* equilibrium clearly indicates that Eq. (C1) was borrowed by the atmospheric meteorology from the consideration of the Archimedes' force acting in liquids.

However, as soon as Eq. (C1) is applied to gases, there appears an additional important factor that was not taken into account. In solid bodies and, to a certain degree, in liquids, molecules are stably kept in particular locations by the intermolecular forces. Therefore, the condition of absence of macroscopic forces, Eq. (C1), is both necessary and sufficient for the static state of the body. But molecules of gases move at high velocities having no particular location. Therefore, for the stationary static state of the gas, the absence of macroscopic forces is necessary, but insufficient. Concentrations of gases in the mixture must be in equilibrium as well, i.e. the diffusional flux of molecules through any plane within the gas volume must be zero.

In the gravitational field the diffusional fluxes and macroscopic forces are both zeroed, when each i-th gas conforms to Boltzmann's distribution (see p. 2634, Eq. (8) in the paper and p. S1180, Eq. 2, line 3 in the response to Dr. Dovgaluk):

$$-dp_i/dz = p_i/h_i, \quad h_i \equiv RT/(M_i g). \tag{C2}$$

Here p_i and M_i are the pressure and molar mass of the corresponding gas. When Eq. (C2) is fulfilled for all gases in the mixture, the gas mixture is in equilibrium. The equilibrium state of a gas should be more properly referred to as *aerostatic*, rather than hydrostatic, equilibrium. Note that in aerostatic equilibrium the whole mixture conforms to Eq. (C1) for $p = \sum_i p_i$ and $\rho = \sum_i \rho_i$ (note that $p_i = N_i RT$ and $\rho_i = N_i M_i$, where N_i is molar concentration of the i-th gas).

According to Dalton's law, concentrations of gases in the mixture tend to equilibrium independently of each other. Therefore, if one gas is prevented from equilibrium by some special physical factors acting on it, this fact will not prevent other gases from getting distributed in accordance with Eq. (C2). This fact, lying in the ground of the kinetic theory of gases, is very well-known in many fields of science, as it forms the basis of the wide-spread and life-important phenomenon of osmosis. Indeed, if two solutions with different (i.e. non-equilibrium) concentrations of some substance are put in contact via a semi-permeable membrane, which lets the solvent to pass through it, but retains the dissolved substance, then molecules of the solvent (e.g., water) will pass through the membrane in the direction of the lower concentration of the solvent, to restore its equilibrium (uniform) concentration. In the result, there will appear an excess of liquid pressure in that volume. This osmotic pressure force is, for example, responsible for the turgor (i.e., internal pressure) of living cells.

In the atmosphere the role of such a semi-permeable membrane is played by the temperature lapse rate. Since the maximum concentration of water vapor depends on temperature, a sufficiently rapid drop of temperature with height does not allow water vapor to get vertically distributed along its equilibrium scale height $h_w = 13.5$ km (p. 2634, line 13). The excessive water vapor that is transported upward by eddy diffusion or dynamic fluxes is removed via condensation. Since the atmospheric water vapor is out of equilibrium, moist air as a whole appears to be out of equilibrium as well – the time-averaged moist atmosphere does not conform to Eq. (C1).

3) Virtual temperature, potential temperature and dry air constant mixing ratio

The physical equation of state, $p_i = N_i RT$, where p_i is pressure of the i-th gas, N_i is its molar concentration, R is the universal gas constant and T is temperature, carries the fundamental message that pressure of ideal gas is independent of its nature (e.g., molar mass), but at a given temperature depends on the number of molecules only. In meteorology it is common to write the equation of state in terms of mass density $\rho_i = N_i M_i$, changing the fundamental gas constant R to $R_i \equiv R/M_i$ to obtain $p_d = \rho_d R_d T$ ($\rho_d = N_d M$, $R_d \equiv R/M$) and $p_w = \rho_w R_w T$ ($\rho_w = N_w M_w$, $R_w \equiv R/M_w$) for dry air and water vapor, respectively. In such a representation, where the modified gas constants are no longer constants but depend on molar mass, this fundamental message is lost. The modified gas constant R_d is used for all dry air constituents without further analysis of why the molar mass of dry air, M, is height-independent.

The assumption of the static equilibrium of moist air, Eq. (C1), uncritically adopted in meteorology, is formally manifested in the introduction of the meteorological notion of virtual temperature T_v. It is introduced for moist air and is equal to the temperature of dry air of the same pressure and density. Written in terms of virtual temperature, the modified equation of state for moist air assumes the form of the modified equation of state for dry air. Note that the fundamental physical form of the equation of state, $p = NRT$, is invariant for all gases and their mixtures, where $p = \sum_i p_i$, $N = \sum_i N_i$.

In the consideration of vertical atmospheric movements, the reference equilibrium distribution of atmospheric pressure is calculated by putting the modified equation of state written in terms of density and virtual temperature into Eq. (C1) and integrating it over height (e.g., Zhang et al., 2000). This procedure of using virtual temperature in the equation of hydrostatic equilibrium is equivalent to stating that moist air as a whole is in equilibrium, i.e. it is equivalent to neglecting the evaporative force. After the main force in the aerostatic balance of air is cancelled, it is not unexpected that analyses of observational data yield results that are difficult to interpret.

For example, one can expect from the traditional consideration of convective instability that air volumes participating in the upward atmospheric motions should feature positive buoyancy, while air volumes participating in the downward motions should have negative buoyancy. In reality, the stronger atmospheric updrafts and downdrafts often both have positive buoyancy (e.g., Jorgensen and LeMone, 1989), while large-scale upward atmospheric motions can be both positively and negatively buoyant (Folkins, 2006), etc. Another problem encountered in theoretical meteorology is that the difference in buyoancies between the updrafts and the surrounding atmosphere appears to be too small (up to one order of magnitude) to explain the observed vertical velocities of air masses (Jorgensen and LeMone, 1989). To account for these and similar observations apparently inconsistent with conventional theoretical expectations it is common to involve various additional factors that are often difficult to quantify or theoretically predict, like, e.g., entrainment of surrounding air into the rising or descending air parcels.

But in the view of the omission of the main non-equilibrium force driving vertical motions such inconsistencies are expectable; they can be resolved after taking into account the non-equilibrium state of moist air. In this sense virtual temperature appears to be a misleading term that has been for many years masking the real physics of the gaseous mixture dry air + water vapor. It should also be noted that in the absence of equilibrium, the investigations of whether the equilibrium is stable or unstable lose their meaning. The main formal parameter describing convective instability, potential temperature θ (temperature which a dry air parcel would have if brought adiabatically to a standard pressure of 100 kPa), as well as other related quantities like equivalent potential temperature, liquid water potential temperature, wet-bulb potential temperature, virtual potential temperature, become physically irrelevant.

Returning to the problem of mixing ratio, it is widely stated in the meteorological literature that the constancy of the mixing ratio of the dry air constituents is due to the turbulent mixing of the atmosphere. In the Glossary of Meteorology of the American Meteorological Society (amsglossary.allenpress.com) under the term “mixing” (see also “gradient transport theory”) it is said that “*Gradients of conservative properties such as potential temperature, momentum, humidity, and concentrations of particles and gaseous constituents are reduced by mixing, tending toward a state of uniform distribution*.” However, turbulent mixing restores not the uniform, but the equilibrium distributions. Indeed, for temperature the equilibrium distribution is the uniform one, but for gaseous air constituents in the gravitational field of Earth the equilibrium concentration distribution is not uniform, it is z-dependent. Therefore writing turbulent flux for some quantity S as $F = K\partial S/\partial z$ (K is diffusivity) is possible if S is *not* a concentration of some gaseous air constituent. Otherwise, since air concentration decreases with height, one would come to the conclusion that there is a continuous diffusion flux of air in the upward direction over the entire surface of the planet. For atmospheric gases in the gravitational field the correct equation for turbulent flux (eddy or molecular) is $F = K(\partial N/\partial z - (\partial N/\partial z)_0)$, where $(\partial N/\partial z)_0$ is the equilibrium concentration gradient. In equilibrium, the diffusion flux of gases is equal to zero, while the vertical concentration gradient is not.

Turbulent mixing should work to restore the equilibrium concentrations of gases and, hence, their distributions along the corresponding barometric formulae, Eq. (C2), that are different for each gas. In this state, when concentrations of different gases drop exponentially over different scale heights, mixing ratios of air gases are not constant. The state of constant mixing ratios is non-equilibrium and, hence, cannot be caused by turbulent mixing. Thus, the observed constancy of dry air composition does not seem to have a satisfactory explanation within the traditional meteorological paradigm. Consideration of the evaporative force, as was shown in the response to Dr. Dovgaluk, can provide some clues to the understanding of this important phenomenon.

To conclude, after the notion of hydrostatic equilibrium of moist air was laid in the ground of consideration of vertical atmospheric motions, the subsequent development of meteorological terminology and formalism proceeded further away from the fundamental physical notions and laws like thermodynamic temperature, the universal equation of state and the equilibrium Boltzmann's distribution for gases. This made the task of a critical physical re-analysis of the meteorological principles difficult for the students of meteorology. This task could not in principle be solved within the formalism of virtual and potential temperatures, whose very introduction, as argued above, masked the problem that had to be uncovered. In the result, the evaporative force has not been described in meteorology.

4) Why the lapse rate of 1.2 K/km is the threshold one for the appearance of the evaporative force

Water vapor in the atmosphere is under the action of two *independent* physical factors: **gravitation** and **temperature.** For water vapor to be in the aerostatic equilibrium, when its partial pressure at each height is balanced by the weight of water vapor in the atmospheric column above that height, partial pressure of water vapor must drop with height by approximately twofold per each *nine kilometers* (exponential scale height $h_w = 13.5$ km, p. 2634, line 13). On the other hand, maximum (saturated) concentration of water vapor drops by approximately twofold per each *ten degrees* of temperature decrease. It follows that water vapor can be in aerostatic equilibrium if only air temperature drops with height *not faster* than by *ten degrees* for each *nine kilometers*. Calculated a bit more precisely, this corresponds to the threshold lapse rate of $\Gamma = 1.2$ K/km.

At $\Gamma > 1.2$ K/km, the upper atmosphere becomes too cold to contain enough water vapor to balance the pressure of water vapor in the warmer, lower atmosphere. As noted above, the excessive water vapor that is transported upward by turbulence or dynamic fluxes, is removed via condensation. Water vapor and moist air are out of aerostatic equilibrium, and the evaporative force appears. At $\Gamma < 1.2$ K/km, condensation effects are not manifested. Effectively, water vapor does not behave as a condensable gas; it obeys the aerostatic distribution similar to dry air constituents. Moist air as a whole is in aerostatic equilibrium, the evaporative force is zero.

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