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Hydrology and
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Discussions

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 second set of comments by H. de Melo Jorge Barbosa:

1) Latent heat

Condensation and evaporation are reversible processes. If at a given temperature in a closed system "liquid water" — "saturated water vapor" there occurred condensation, the released latent heat would warm the system. This would immediately lead to additional evaporation accompanied by the corresponding drop of temperature to its initial value, so that on average the net flux of molecules from the gaseous to liquid state (condensation) is zero. Therefore, condensation can only occur when the system's

temperature is externally lowered, for example, when the system loses heat or moves to a colder environment. In accordance with the Le Chatelier principle, the release of latent heat can only decrease the drop of temperature that initiated condensation, but it cannot in principle make the air warmer than it had been before its temperature started to drop.

In the stationary case (and namely this case is considered in our paper, p. 2638) the release of latent heat due to condensation of the upwelling water vapor is taken into account in the stationary value of the observed lapse rate of air temperature Γ_{ob}, which would have been larger if the atmosphere had been dry. Expression for the evaporative force (14), as can be seen from formulae (10)-(12), includes both the latent heat of evaporization $Q_{\mathrm{H_2O}}$ and the value of Γ_{ob}.

It should be noted that, as was discussed in our reply to Dr. Sherman (p. S1133, lines 20-29), condensation and latent heat release do not directly generate dynamic processes in the atmosphere. Introduction of the evaporative force provides clue to the so far unresolved fundamental physical question of the atmospheric circulation theory (Lorenz, 1967), namely by means of which physical processes solar energy, the apparent driver of atmospheric processes, is converted into the kinetic energy of moving air masses. The energy of solar radiation spent on the evaporation increases the amount of water vapor in the atmosphere; this enhances the evaporative force, which accelerates air masses to the observed velocities. The dynamic energy of moving air masses is transformed to heat due to friction. The energy conversion process is completed with the release of latent heat in the course of condensation of the upwelling water vapor. Latent heat is transformed into thermal energy of air molecules and ultimately leaves into space in the form of thermal radiation. As is well-known, the power of the flux of latent heat significantly exceeds the dynamic power of air circulation.

2) Precipitation before RH = 100%

Relative humidity is defined with the reference to the saturated water vapor concentration above a plane surface of pure water. Saturated water vapor concentration above the curved surface of pure water droplets is higher than the reference concentration. Saturated concentration of water vapor above various solutions (e.g., NaCl) is lower than the reference concentration. Due to this fact the observed values of relative humidity corresponding to the initiation of condensation in the atmosphere can be somewhat lower or higher than 100%. If, on average, condensation occurred “well before” 100%, as stated in the comment, for example, at 80%, which is the mean relative humidity at the surface, we would have seen precipitation originating just at the surface rather than at a certain height in the atmosphere. This is apparently not the case and condensation occurs at RH close 100%. In any case, condensation of water vapor at RH $<$ 100% would have only enhanced the evaporative force, as it would lead to even further compression of the vertical distribution of atmospheric water vapor.

3) Shallow cumulus parameterization

The principal difference between the established tradition of describing convection and the evaporative force theory, as referred to in the comment, lies in the following. In the conventional consideration the force that generates air movements is lacking. Instead, one operates with the notion of instability leading to turbulence; properties of turbulent eddies are further considered from the statistical viewpoint by considering various order moments of the studied variables. As mentioned in the paragraph on the Archimedes force in our paper (p. 2637), when averaged over a spatial scale linked to the vertical scale of the convective region, in the employed parameterization schemes there are no force-induced movements of air masses (see, e.g., Moeng and Wingaard, 1989). Since there is no dynamic driver of air motions, the major quantitative parameters and functional dependencies, including those on the subgrid scale, have to be borrowed directly from, or fitted to, observations, with little or no theoretical clues as to why they are such as they are and what physical processes and fundamental physical characteristics of the Earth’s environment could determine their values. Reflecting this situation, it is widely admitted that the modern representation of atmospheric convection in GCMs

is a *parameterization*, not a theory.

The proposed physical approach based on the evaporative force aims at describing air motions based on the fundamental physical principles. In our paper we have introduced the evaporative force acting in the troposphere and described its large-scale implications, including the continental biotic pump. The planetary boundary layer, where the processes of shallow cumulus convection develop, has its well-known peculiarities. They are manifested, in particular, in the diurnally variable vertical lapse rates that are often much larger in absolute magnitude than the mean tropospheric lapse rate. In section 3.4 “Water preservation by closed canopies” we discussed several issues regarding the implications of the evaporative force mechanism at the surface layer, see also (Gorshkov and Makarieva, 2006; Makarieva, Gorshkov and Li, 2006, in press). In our response to Dr. Dovgaluk we showed how the regional mean Bowen ratio can be quantified using this approach; the problem of hurricane formation, also outlined in our paper, awaits further studies. Generally, we believe that the application of the evaporative force mechanism to every atmospheric problem, including the description of shallow convection, can be expected to yield meaningful results, as would do consideration of an important process previously unaccounted for.

4) Precision

As can be deduced from the paper’s text, we do not neglect the change of tropospheric temperature. Formula (8) that describes the decrease of equilibrium pressure with height does take into account the change of temperature with height. The approximate formula for isothermal atmosphere, that is given in the text (p. 2634, line 11) and lacks a number, is not used in any derivations. As we explained in our previous response, this formula is retained in the text for the explanatory sake, as it helps to visualize, by comparison with the exact formula (8), that an account of the temperature drop makes pressure decrease with height more rapidly than in the exponent describing the isothermal atmosphere. Regarding the value of $Q_{\mathrm{H_2O}}$, its value in the troposphere ($h \sim 8$ km) changes by only 5%. Moreover, Eq. (10), which is the basis for estimating the fundamental parameter $h_{\mathrm{H_2O}}$, is exact with respect to temperature-related changes of $Q_{\mathrm{H_2O}}$, as noted also by Dr. de Melo Jorge Barbosa in his first comment.

5) Downward diffusion

It is rightly noted in the comment that the action of the evaporative force making moist air rise should change the vertical distribution of the other atmospheric gases as well. This question has been already quantitatively tackled in this discussion, see the responses to Dr. Sherman (pp. S1131-S1132) and to Dr. Dovgaluk (pp. S1179-S1180).

Briefly, the evaporative force acting on moist air as a whole make air parcels rise; when they expand, the relative amount of various dry air constituents does not change, yielding a constant mixing ratio of the dry air (p. 2643). When dry air has a constant mixing ratio and hence constant molar mass of $M = 29$ g mol^{-1} and a single scale height $h = RT/(Mg)$, all dry air gases appear out of hydrostatic equilibrium. Gases with $M_i < M$ (such as N_2) appear to be vertically compressed as compared with their equilibrium distribution with a scale height $h_i = RT/(M_i g) > h$; these gases diffuse **upward.** Gases with $M_i > M$ (as O_2, CO_2 etc.) are "overstretched" compared with their equilibrium distributions; these gases diffuse **downward.**

As we have shown, osmotic forces acting on dry air gases, that can be introduced in a manner similar to the evaporative force, precisely compensate each other in case of height-independent M (response to Dr. Sherman, pp. S1131-S1132), yielding hydrostatic equilibrium of dry air as a whole. Moreover, diffusional fluxes caused by the non-equilibrium distribution of dry air gases are all significantly smaller by their absolute value compared to the upward dynamic flux of moist air induced by the evaporative force (response to Dr. Dovgaluk, pp. S1179-S1180), which therefore appears to be the dominant vertical process.

6) Other issues

Discussing the box horizontally divided into two compartments filled with different

gases at equal pressure. While it is said in the comment that the center of mass will move to the center of the box, it will only do so in the case when the gases have different molar masses. If these are different gases having equal molar masses (e.g., isomers), the center of mass will not move anywhere being in the center of the box from the very beginning. Generally, speaking of motion in the atmosphere one usually does not mean motion of the center of mass, but motions of air masses, i.e. winds. No wind will occur in the box where two compartments are filled with different gases at equal pressure. Moreover, in the course of the diffusion process the vertical position of the center of mass does not change. Thus, if the box is much heavier than the gases within it (as is Earth with respect to the atmosphere), the impulse of the moving center of mass will be absorbed by the box and no motion of whatever object will be observed, even if the gases have different molar masses.

Regarding the water that evaporates and undergoes condensation "immediately at a microscopic distance above the surface" (p. 2636). We now see that this is a language issue. As follows from both comments of Dr. de Melo Jorge Barbosa, this phrase can be interpreted as implying that those very molecules that evaporate immediately condense. (Note that due to the quantum principle of identity of molecules, it is impossible to tell for the condensing molecules whether they are the same molecules that have just evaporated, or they are those having resided in the atmosphere for some time, unless the gas and the liquid have different isotopic composition).

To our knowledge, the word "immediately" has at least two meanings, a temporal — "at once" and a spatial — "just there", see, e.g., the Princeton University vocabulary (wordnet.princeton.edu), which gives an example of the usage like "he passed immediately behind her". It is in this second sense that we used this word, emphasizing that condensation occurs at a microscopic distance of the order of one path length from the liquid surface, right there and not further up in the atmosphere.

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