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Hydrology and Earth System Sciences 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 two physical questions posed by S. Sherman:

1. Hydrostatic equilibrium and constant mixing ratio of atmospheric gases.

According to Dalton's law, hydrostatic equilibrium must independently hold for all partial pressures of all air constituents. This follows from the kinetic theory of gases. Kinetic theory describes hydrostatic equilibrium as the state when fluxes of molecules of each gas via any plane (horizontal, in the considered case) in both directions, i.e. up and down, are equal to each other. In this state each gas obeys Boltzmann's distribution (Feynmann et al., 1963). As far as molar masses of dry air constituents are all differ-

ent, the hydrostatic equilibrium should correspond, as pointed out in the comment, to different scale heights of the vertical distribution of different air gases.

The observed constancy of the mixing ratio of dry air constituents in the troposphere, i.e. a single scale height for all gases, means that each of these gases is out of equilibrium. Process when the initially non-equilibrium partial pressure changes towards equilibrium in a gas mixture or liquid solution is the basis of osmosis. For each i-th air gas one can formally introduce the osmotic force f_i equal to the difference of the partial pressure gradient taken with the opposite sign, on the one hand, and weight of the column of this gas above the considered height, on the other:

$$f_i = -\frac{\partial p_i}{\partial z} - \frac{p_i}{h_i} \equiv \frac{p}{h}\gamma_i(1-\beta_i) \tag{1}$$

$$\gamma_i \equiv \frac{p_i}{p}, \;\; \beta_i \equiv \frac{h}{h_i} = \frac{M_i}{M}, \;\; h \equiv \frac{RT}{Mg}, \;\; h_i \equiv \frac{RT}{M_i g}. \tag{2}$$

Here M_i and M, h_i and h, p_i and p are molar masses, scale heights and (partial) pressures of the i-th gas and air as a whole, respectively; γ_i is the mixing ratio of the i-th gas (i.e. its relative contribution into total air pressure: $p_i = N_i RT$, $p = NRT$, $\gamma_i = N_i/N$, where N_i and N are molar densities of the i-th gas and air as a whole, respectively). Taking into account that, according to observations, the gaseous composition and, hence, molar mass of dry air is height-independent, we obtain the following two sum rules:

$$\sum_i \gamma_i = 1, \quad \sum_i \gamma_i\beta_i = 1, \quad \left(\sum_i \gamma_i M_i = M\right). \tag{3}$$

Expression (1) for the osmotic force f_i has the same form as the expression for the evaporative force of the water vapor (p. 2638, Eq. (14), note that the minus sign at the term $dp_{\mathrm{H_2O}}/dz$ in Eq. (14) was lost by mistake).

It is easy to demonstrate numerically that even for the main atmospheric gases N_2 and O_2 their osmotic forces f_i (1) are several times smaller than the evaporative force of the water vapor, because the value of β_i (2) for these gases is close to unity. It is worthy noting, however, that the osmotic forces for N_2 and O_2 are opposite in sign. As far as $\beta_{\mathrm{O}_2} > 1$, the equilibrium Boltzmann's distribution of oxygen would be compressed as compared to the observed vertical air distribution (same as water vapor), while equilibrium nitrogen would be "stretched" as compared to air due to $\beta_{\mathrm{N}_2} < 1$. The cumulative osmotic force acting on dry air appears to be equal to zero as governed by the above sum rules (3):

$$f = \sum_i f_i = \sum_i \gamma_i(1-\beta_i) = 0. \tag{4}$$

Thus, remarkably, from the observed constancy of M it can be derived that dry air as a whole is in hydrostatic equilibrium (4). However, water vapor is not in hydrostatic equilibrium. Therefore moist air as a whole is out of hydrostatic equilibrium as well: each unit volume of moist air is acted upon by the evaporative force conditioned by the non-equilibrium state of atmospheric water vapor.

2. We now discuss the existence of the evaporative force in the presence of cloudiness.

When water vapor undergoes condensation, molar volume of H_2O (i.e. volume occupied by one mole of H_2O) decreases by thousands of times. Partial pressure of water vapor decreases by the same amount and can be neglected. This process corresponds to disappearance ("annihilation") of water vapor from the considered air volume. Thus, even if there is no precipitation and water droplets remain in the air as cloudiness, total pressure of moist air in the region of condensation diminishes. There appears the evaporative force generating air circulation as described in the paper. Moreover, it is namely the evaporative force that in the stationary case supports cloudiness at a particular height in the troposphere. When cloudiness is strong (much liquid water in

the atmospheric column) and covers extensive areas of linear size greatly exceeding height of the tropospere, it can almost completely absorb the vertical impulse imparted to it by the evaporative force, so that practically no horizontal fluxes of air will be formed. Such cloudiness can hang practically motionless or move very slowly.

Formation of patchy cloudiness like stormy clouds is, on the other hand, always accompanied by horizontal winds, as described in the paper. The larger the scale height of the condensation process, the larger the vertical path along which the evaporative force is acting accelerating the air, the higher the final vertical and horizontal velocities that the accelerating air masses ultimately acquire. Hurricanes and tornadoes, as also mentioned in the paper, arise when the condensation process in a local horizontal area spreads to the maximum height in the atmosphere (p. 2641, line 9). There appears a horizontal influx of air into this area, so the local high value of the evaporative force is maintained by the horizontal input of gaseous moisture that evaporated in the neighboring areas. This further enhances moisture condensation in the considered area so that the evaporative force and, consequently, wind speed grow even further. When all water vapor in the region occupied by the tornado (or hurricane) is condensed, the tornado can persist if only it rapidly moves to other areas with large stores of water vapor. The higher tornado wind velocity, the more rapidly the tornado must move to persist (Gorshkov, 1995).

Total power of hurricanes and tornadoes is limited by solar energy that, over a long time, was spent on evaporation of water in the large area along the path of these wind structures. However, the release of latent heat in the course of vapor condensation within the hurricane does not lead to formation of ordered dynamic processes (winds). Energy is transformed in the following order: solar energy leads to water evaporation; water vapor generates the evaporative force which accelerates air masses and creates hurricanes and tornadoes; the dynamic energy of moving air masses undergoes dissipation and heats the air. Most part of energy spent on evaporation is ultimately released in the form of latent heat after condensation of water vapor. Thermal energy of heated air is, with help of greenhouse gases, converted to thermal radiation that leaves into space (pp. 2660, 2661).

References

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 3, 2621, 2006.