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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics" *by* A. M. Makarieva et al.

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We thank Dr. Held for stepping forward to help review our paper (hereafter M10) when others seemed unwilling[1]. Dr. Held raises a number of objections to our paper and presentation. Careful scrutiny suggests that most of the more substantial points have already been raised by other readers. We believe indeed that these have been responded to. Below we address the comments of Dr. Held and use this opportunity to recapitulate the major points of the preceding discussions as well as to highlight our major findings.

[1] http://wattsupwiththat.com/2011/01/21/an-appeal-to-the-climate-science-blogosphere/

1 Latent heat and Section 2

When gas disappears somewhere in the atmosphere, the local pressure is lowered and a compensating air inflow from the surrounding areas is initiated. In M10 we derive the magnitude of a stationary horizontal pressure gradient that is associated with water vapor condensation – the process by which the vapor gas molecules are packed into a thousand of times smaller liquid volume and thus effectively disappear from the atmosphere.

Dr. Held recommends our paper to be rejected because he does not *see any cogent arguments that overturn the conventional wisdom* that *the heat release associated with condensation dominates over the effect of the mass loss*. To quantitatively support this statement, Dr. Held referred to the calculations made by Spengler et al. (2011).

Heat (Joule) and mass (kg) are magnitudes of different dimensions. To compare the two factors, one needs a constant of transitional dimension. Such a constant can be obtained from an established physical law by applying it to a process where both factors influence one and the same variable. We emphasize that the considered process must not be in conflict with the fundamental physical laws and it should be of relevance to the real atmosphere.

The process considered by Spengler et al. (2011) is adiabatic condensation that spontaneously occurs at constant volume, with latent heat released in sensible form warming the atmosphere[2]. The *latent heat dominance* is quantified by calculating the pressure rise due to heating and comparing it to the pressure drop due to vapor removal from the gas phase. While apparently belonging to the standard perspective, this argument is incorrect. Why it is incorrect is discussed in detail in Section 2 of M10. Dr. Held characterized Sections 2 and 3 as having *no direct connection to the main claim of the paper*. The connection of Section 2 to the main claim of our paper is to show

[2] Recall that latent heat is called *latent* because it is released when the gas actually cools.

that the common (and only) quantitative argument against the vapor sink dominance is not valid, being based on consideration of a process that is prohibited by the laws of thermodynamics.

There are three fundamental equations that govern condensation: the first law of thermodynamics [1], the Clausius-Clapeyron equation [3], [8] and the equation of state [5], [6] (formula numbers in square brackets refer to M10). We can write them as follows:

$$c_p dT - RT\frac{dp}{p} + L d\gamma \equiv \frac{RT}{\mu}\left(\frac{dT}{T} - \mu\frac{dp}{p} + \mu\xi d\gamma\right) = 0, \quad \mu \equiv \frac{R}{c_p}, \quad \xi \equiv \frac{L}{RT}. \quad (1)$$

$$\frac{dp_v}{p_v} = \frac{dT}{RT^2}, \quad \frac{d\gamma}{\gamma} = \xi\frac{dT}{T} - \frac{dp}{p}, \quad \gamma \equiv \frac{p_v}{p}. \quad (2)$$

$$pV = RT, \quad \frac{dp}{p} + \frac{dV}{V} = \frac{dT}{T}. \quad (3)$$

Equations (1)-(3) are written for molar quantities. They include four variables, T, p, V and γ and thus unambiguously determine the relationship between any pair of variables, (γ, T), (γ, p), (γ, V), (T, p), (T, V) and (p, V):

$$\frac{d\gamma}{\gamma} = \frac{dp}{p}\frac{\mu\xi - 1}{1 + \mu\gamma\xi^2}, \quad (4)$$

$$\frac{d\gamma}{\gamma} = \frac{dT}{T}\frac{\mu\xi - 1}{1 + \gamma\xi}, \quad (5)$$

$$\frac{d\gamma}{\gamma} = -\frac{dV}{V}\frac{\mu\xi - 1}{1 - \mu + \mu\gamma\xi(\xi - 1)}. \quad (6)$$

Eqs. (4) and (6) coincide with [11] and [14], respectively, in M10. Equating the right-hand parts of Eqs. (4)-(6) yields the equation for moist adiabat in terms of (p, T) (Eq. [10] in M10), (p, V) and (T, V). Equations [10] and [11] in M10 correspond to Eq. (6).

Multipliers at the relative changes of p, T, V in Eqs. (4)-(6) are all positive. At $T = 288$ K (15°C) we have $\xi = 18$, $\mu = 0.29$, $\mu\xi = 5.3$, such that at $d\gamma < 0$ (vapor condenses) we have $dp < 0$, $dT < 0$ but $dV > 0$. This means that when condensation happens adiabatically, the pressure *drops*, the temperature *drops* and the molar volume *grows*[3]. Adiabatic condensation can neither occur at constant pressure, nor constant temperature, nor constant volume.

In relation to our work, the statement about latent heat dominance was first formulated by Dr. Rosenfeld, see Pöschl (2009, p. S12436), based on consideration of adiabatic condensation at constant volume. The same argument is repeated by Spengler et al. (2011). The core of this argument is as follows. First all water vapor is removed from the considered atmospheric volume by an unknown process. This causes local pressure to fall by a relative magnitude $\Delta p_1/p = \gamma \equiv p_v/p$. Then the physically prohibited warming from latent heat release is calculated from (1) at constant volume $dV = 0$: $c_v\Delta T = L\gamma$. Then the pressure rise at constant volume is calculated from the obtained ΔT: $\Delta p_2/p = \Delta T/T = \gamma L/c_v T$. The ratio $\Delta p_2/\Delta p_1 = L/c_v T \approx 7$ at $T = 288$ K is interpreted as latent heat dominance (Spengler et al., 2011, p. 350). (Dr. Held in his review uses another version of this argument, with c_p instead of c_v. Adiabatic condensation at constant *pressure* is equally prohibited.)

To summarize, the statement that latent heat release is more important for atmospheric dynamics than the vapor sink could only be substantiated by considering a physically plausible process. The available arguments about latent heat dominance do not meet this requirement and thus do not constitute an objection against the proposed major role of the vapor sink in atmospheric dynamics. The error consists in ignoring the Clausius-Clapeyron law[4] and replacing the "cooling causes condensation" physics by

[3]We emphasize that adiabatic condensation is necessarily accompanied by pressure fall and rise of molar volume, but a pressure fall at constant temperature does not lead to condensation.

[4]This basis of atmospheric condensation appears to be neglected rather widely at the conceptual level. For example, McGuffie and Henderson-Sellers (2001) reviewing the "Forty years of numerical climate modeling", Table

the "condensation causes warming" misconception.

2 Latent heat and Section 3

Governed by temperature change, condensation occurs in the atmosphere if and only if one of the following happens: (1) local temperature drops or (2) moist saturated air moves against the temperature gradient (and, hence, cools) in the considered point[5]. In Section 3 of M10 the first of the two possibilities is investigated.

We take two vertically isothermal columns A (moist) and B (dry) with equal surface pressures and surface temperatures T_s set to 303, 293, and 283 K (typical surface temperatures)[6]. We then cool the moist column such that the surface temperature does not change, but the temperature lapse rate becomes moist adiabatic (thus reflecting latent heat release)[7]. We cool the dry column as well, such that in this column the resulting temperature lapse rate is dry adiabatic. We demand that the columns are in hydrostatic equilibrium. Condensation is caused by diabatic cooling of column A.

We then compare the resulting vertical pressure profiles in columns A and B in the lower eight kilometers of the atmosphere, $z \leq 8$ km, see Fig. 1c in M10. Since the total amount of gas in column B has not changed, while in column A it has decreased by the amount of condensed vapor, surface pressure in column A is lower than in column B. The pressure difference caused in the lower atmosphere by the vapor sink is

V, list the main physical laws which circulation models are aimed to obey. Among those, the Clausius-Clapeyron law is not mentioned.

[5]None of these conditions are met in the the thought experiment considered by Spengler et al. (2011).

[6]Spengler et al. (2011) start by considering an isothermal column as well and specify the column temperature at $T = 255$ K.

[7]This setup is physically meaningful because the amount of vapor that condenses due to cooling in column A coincides with the so-called adiabatic liquid water content – the amount of vapor lost to condensation from an air volume as it rises to a certain height – integrated over the atmospheric column.

comparable in magnitude to the pressure difference caused in the upper atmosphere by the different lapse temperature rates (moist versus dry) in the two columns[8]. One can see from Fig. 1c that the vapor sink pressure change (lower pressure in the column where condensation occurs) dominates in the lower atmosphere up to a height of several kilometers.

The results of Section 3 show that considering a physically plausible process (condensation by diabatic cooling) and involving relevant atmospheric parameters (moist versus dry adiabatic lapse rates) one obtains results incompatible with the statement about *latent heat dominance*. At the same time, these considerations do not prove that the calculated pressure differences can actually exist in the atmosphere. This is because the laws of equilibrium thermodynamics do not suffice to predict atmospheric dynamics. This is a more general argument against the *latent heat dominance* meme: a proposition that is based on (incorrect) *thermodynamic* considerations of condensation may have little implications for condensation-induced *dynamics*. This dynamics is considered in Section 4 of M10.

3 Condensation rate: Devil in a detail

Condensation rate $S < 0$ that describes the vapor sink replaces the conventional zero in the right-hand part of the continuity equation. When $S = 0$, the equations of hydrodynamics (Euler/Navier-Stokes equations and the continuity equation) do not carry any information about whether the gas motion occurs or not. This information is contained in the boundary conditions, which can be specified such that $\mathbf{v}(t, \mathbf{r}) = 0$ (motionless

[8]It is further discussed in M10, p. 24045, that in reality such temperature differences are never observed between the column where moist air ascends and condenses and the column where dry air descends. Indeed, even in the warm-core tropical storms – i.e., in intense precipitation events – the horizontal temperature difference between the core and the external environment rarely exceeds a few degrees Kelvin (e.g., Knaff et al., 2000) rather than reaching a few dozen degrees K as in the columns compared in Fig. 1c.

atmosphere) is a solution. When $S \neq 0$, the gas is either produced or disappears somewhere in the atmosphere, which necessitates some motion. The range of solutions to the system is narrowed, because now the system contains the information that a driver of motion does exist.

The pressure gradients produced by a vapor sink should naturally depend on the strength of this sink. In some cases these gradients can be derived considering the formulation of the vapor sink S in the continuity equation. In Section 4 of M10 it is shown how this can be done.

There has been much critical discussion in the blogosphere and further on the ACPD web site of our Equation 34 for condensation rate S that is key to the presented derivation. At various times and places, including Section 4.2 of M10, it was pointed out that if one formulates S in terms of water vapor mixing ratio $\gamma_d \equiv N_v/N_d = p_v/p_d$ one obtains $\partial p/\partial x = 0$. If one instead uses the *relative partial pressure of water vapor*, $\gamma \equiv N_v/N = p_v/p$, a horizontal pressure gradient is obtained that appears to be so significant as to substantiate the claim for a dominant role in the whole planetary dynamics. (Here N_v, N_d, $N = N_v + N_d$, p_v, p_d, $p = p_v + p_d$ are molar density and pressure of water vapor, dry air and air as a whole, respectively.)

A typical value of water vapor partial pressure p_v in the lower atmosphere is around 1-3 per cent. This means that the mixing ratio and relative partial pressure γ_d and γ differ insignificantly. Dr. Held referred to this difference as to *a detail*. We are unsure whether Dr. Held has overlooked Section 4.2 (as well as several clarifying comments[9]) where it is discussed why the γ/γ_d dichotomy is crucial and likely responsible for the fact that the condensation-induced dynamics has not so far received the full attention it deserves. Here we briefly revisit these arguments.

Consider the stationary continuity (mass conservation) equations written for dry air and

[9]http://www.atmos-chem-phys-discuss.net/10/C10922/2010/
http://www.atmos-chem-phys-discuss.net/10/C12836/2011/

water vapor (Eqs. 32 and 33 in M10):

$$\nabla N_d \mathbf{v} = 0, \quad \nabla N_v \mathbf{v} = S.$$

These equations only tell us that while the dry air mass is conserved for sure, the vapor mass may be conserved or it may be not: there can be a local source or sink of vapor S. *Irrespective of the existence/nature/magnitude* of the vapor sink/source S, the above equations can be combined with use of elementary algebra such that their left-hand parts take various forms. In his review Dr. Held chose $N_d \mathbf{v} \nabla (N_v/N_d) = S$, which is equivalent to

$$\mathbf{v}(\nabla N_v - \gamma_d \nabla N_d) = S. \tag{7}$$

In M10 a horizontally uniform surface temperature is considered, which dictates a constant saturated pressure of water vapor, such that

$$\mathbf{u} \nabla N_v = 0. \tag{8}$$

(If water vapor is not saturated, this assumption corresponds to a horizontally uniform surface temperature and constant relative humidity.) Here $\mathbf{u}$ is horizontal velocity, $\mathbf{v} = \mathbf{u} + \mathbf{w}$, $\mathbf{w}$ is vertical velocity.

Combining (7) and (8) we obtain

$$\mathbf{u} \nabla N_d = (S - S_d) \frac{1}{\gamma_d}, \quad S_d \equiv \mathbf{w} \left(\nabla N_v - \gamma_d \nabla N_d \right). \tag{9}$$

Equation (9) has two important implications for any given horizontal velocity $\mathbf{u} \neq 0$. First, it shows that when $S = S_d$, the horizontal density gradient is zero, $\mathbf{u} \nabla N = \mathbf{u} \nabla N_d = 0$. Second, it shows that if S and S_d differ by *a small relative magnitude* of the order of $\gamma_d \ll 1$, this magnitude is multiplied by *a large relative magnitude* $1/\gamma_d \gg 1$ to determine the horizontal density gradient and, hence, horizontal pressure gradient.

We emphasize that these conclusions do not depend on the formulation of condensation rate: S in (9) is unknown. Equation (9) shows that any minor difference of the order of γ_d in the theoretical formulation of S – whatever the latter might be – is not *a detail* but the zeroth order term in determining the horizontal density and pressure gradients associated with vapor condensation. The fact that the difference between N_d and N, γ and γ_d is commonly perceived as an unimportant *detail* helps understand how a major driver of atmospheric motions could have been overlooked.

4 Condensation rate formulation

As discussed in Section 4 and the relevant comments[10], the formulation of condensation rate, Eq. (34) in M10, is based on three statements: (1) it is proportional to the amount N_v of condensing vapor;

2) it is proportional to vertical velocity w (because condensation is due to cooling, hence it is proportional to the velocity of movement along the temperature gradient); 3) it is proportional to the degree by which the vertical distribution of vapor deviates from equilibrium:

$$S = wN_v(k_o - k_E). \tag{10}$$

Here $k_o \equiv (1/N_v)(\partial N_v/\partial z)$ is the inverse scale height of the observed vapor distribution and k_E is the inverse scale height of the equilibrium distribution that the vapor would have had in the absence of condensation. As discussed in Section 4, in Eq. (34) use is made of the fact that moist air as a whole is in hydrostatic equilibrium. This allows one to calculate k_E from the distribution of moist air, i.e., to put $k_E = (1/N)\partial N/\partial z$.

[10]http://www.atmos-chem-phys-discuss.net/10/C10922/2010/
http://www.atmos-chem-phys-discuss.net/10/C12836/2011/

This determines condensation rate as

$$S = w\left(\frac{\partial N_v}{\partial z} - \frac{N_v}{N}\frac{\partial N}{\partial z}\right), \tag{11}$$

which is Eq. (34) of M10.

Some readers were apparently confused by their perception that Eq. (34) is *similar* to the right-hand part of (7) (the continuity equation) if one puts there horizontal velocity $u = 0$. We discussed both in the paper, in the comments and in the preceding section that this formal similarity is misleading (note also that u is not zero in the general case). The independent physics contained in Eq. (34) may appear more obvious to the reader when the suggested formulation (10) of condensation rate is generalized for motion over a non-isothermal surface (Makarieva and Gorshkov, 2010). The resulting expression $S = \mathbf{v}\nabla N_v - \gamma\mathbf{w}\nabla N + \gamma(N/T)\mathbf{u}\nabla T$ contains the temperature gradient term which is absent from the continuity equation. (At $\mathbf{u}\nabla T = 0$ this expression coincides with Eq. (34)).

It is pertinent to note that while the discussion of Eq. (34) was extensive, detailed and rather critical, it did not reveal any arguments that would prove the equation wrong. It was not possible to demonstrate that Eq. (34) is in conflict with any physical laws or observations. Earlier critics[11] did attempt to formulate such objections. E.g., it was suggested that Eq. (34) must be wrong because it predicts zero condensation rate in a vapor-only atmosphere (when $N = N_v$). This argument was repelled by noting that in a vapor-only atmosphere *that is in hydrostatic equilibrium* condensation rate must indeed be zero and the prediction of Eq. (34) is correct. No objections of similar kind were later put forward. Rather than poking to specific errors, the readers tended to mention that they *did not understand* Eq. (34) and asked for greater clarity.

Accordingly, we did our best to clarify the physical bases of Eq. (34). In the absence

[11]See, e.g., here http://2s3c.wordpress.com/2010/11/08/grl-submission-files/ and here
http://2s3c.files.wordpress.com/2010/10/grlreview3.pdf

of any exposed controversies, further testimony in favor of our propositions must come from comparing our theoretical predictions with observations. The pressure gradient produced by condensation (it is obtained by combining Eqs. (7), (11) and the ideal gas law $p = NRT$)

$$\frac{\partial p}{\partial x} = \left(\frac{\partial p_v}{\partial z} - \frac{p_v}{p}\frac{\partial p}{\partial z}\right)\frac{w}{u} \qquad (12)$$

yields a physically relevant magnitude when the parameters of tropical circulation (Hadley cell) are fed into it. When applied to hurricanes (circulations that differ greatly from Hadley cell in both geometry, linear size and condensation intensity) the same equation satisfactorily describes the observed hurricane pressure profiles (Makarieva and Gorshkov, 2011).

Dr. Held mentions in his review that *to make a connection with the pressure gradients that drive horizontal winds, one has to talk about pressure differences at fixed height, or something more or less equivalent*. This and related comments in the review that describe the readers' expectations, as well as the reference to the work by Spengler et al. (2011), confirm that the community's effort to investigate the vapor sink dynamics is in its incipient stage. This effort is apparently hindered by the standard perspective which has long held that the vapor sink just cannot matter as long as the latent heat dominates[12]. In our paper the misconceptions comprised by the conventional wisdom are exposed and a coherent formulation of the vapor sink is presented for the first time in the literature, the one which has passed the test for relevance to atmospheric processes. This allows us to consider our work as a timely and meaningful contribution.

[12]For example, a physically plausible setup to study relaxation of pressure perturbations by condensation, which is the focus of Spengler et al. (2011), would be to cool a saturated atmosphere. But then, by definition, there would be no warming in such an atmosphere and no way of advancing the statement about heat dominance. There will be no upward displacement of the upper atmosphere either, cf. Fig. 2c of Spengler et al. (2011).

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