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Interactive Comment

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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1 Reply to comments

We thank Dr. Nick Stokes for his critical comments. Dr. Stokes has concentrated his comments on Eqs. (32)-(36). We have reviewed this part of our paper in our recent comment[1] (hereafter M10-C1), dwelling also on some of the points raised by Dr. Stokes. Here we first provide our response to specific comments (italicized) of Dr. Stokes. We then use this opportunity to overview the physical meaning of Eq. 34.

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

1. "I think Eqs 32 and 33 do correctly express conservation of mass. The argument for 34 also seems to be in terms of conservation of mass; no other physics seems to be introduced. But independent equations cannot be derived from the same physics. ... My view is that Eq 34 is not independent of 32 and 33, and cannot be used as an extra equation."

The physics contained in Eq. 34 is explained on p. 24034, lines 20-23. It is explained that Eq. 34 is based on the condition of hydrostatic equilibrium of *moist air*. In M10-C1 we showed how it can be derived from that condition assuming linearity of condensation rate over molar density of water vapor.

"2. An equation very like Eq 34 does follow from 32, 33."

Eqs. 32-33 do not contain any information about hydrostatic equilibrium or absence/presence of condensation in the atmosphere. Eq. 34 cannot be derived from Eqs. 32-33 or vice versa. As discussed in M10-C1, expression for condensation rate obtained by Dr. Stokes, $S = S_d \equiv wN_d\partial\gamma_d/\partial z$, corresponds to hydrostatic equilibrium of *dry air*.

3. "Assuming $\partial N_v/\partial x = 0$ and presumably on the same basis $\partial N_d/\partial x = 0$..."

Our physical basis for assuming that $\partial N_v/\partial x = 0$ in M10 is our proposal that a horizontally isothermal surface is considered along which water vapor is assumed to be saturated. In the real atmosphere this corresponds to a constant relative humidity which agrees well with observations. Since the saturated concentration of vapor depends on temperature, over an isothermal surface we have $\partial N_v/\partial x = 0$. Concentration of dry air does not depend on temperature. The assumption $\partial N_d/\partial x = 0$ made by Dr. Stokes while deriving $S = S_d$ has no grounds.

Another way to derive this expression is by putting horizontal velocity $u = 0$. For a one-dimensional vertical motion we then have from the system (32)-(34) that $S = S_d$. This equation is only satisfied at $S = 0$. This reflects the fact that a steady-state vertical

ACPD
10, C11046–C11050, 2010

Interactive Comment

motion with mass removal cannot be hydrostatic.

4. "Trying to derive 35. It is said to be a result of Eq 32 and 34, with $\partial N_v/\partial x = 0$. But 34 comtains S and 32 does not, so I don't see how S can be eliminated, without bringing in 33."

Dr. Stokes correctly concludes that Eq. 33 is used. To explain how Eq. 35 is derived, it is said in M10, p. 24031, line 6, that: "The mass of dry air is conserved, Eq. (32). Using this fact, Eq. (34) and $\partial N_v/\partial x = 0$" – then Eq. 35 follows. The phrase could read more explicitly: "Using this fact, Eq. (34) and $\partial N_v/\partial x = 0$ in Eq. (33)". The reason why we thought our formulation was sufficient is that $\partial N_v/\partial x$ can be found in Eq. 33 only.

5. "In fact it is clear something is wrong with the math. If you combine Eq. 34 and Eq. 36, you get $S = u\partial N/\partial x$. This gives a finite value for condensation rate S even if the air is dry.

This is incorrect. For dry air we have $N_v = 0$, then, as shown in M10-C1, $S = S_d = 0$ and $\partial N_d/\partial x = \partial N/\partial x = 0$. Conversely, as shown in the comment of Dr. Stokes (p. C9175), at $\partial N_d/\partial x = 0$ we have $S = S_d$ and, consequently, $S = 0$. Thus, the system (32-34) never yields a a non-zero condensation rate in dry air. The physical meaning of equation $u\partial N/\partial x = S$ is clear: the density gradient $\partial N/\partial x$ produced by a mass sink is proportional to the condensation rate (the intensity of the mass sink).

2 Overview of the physical meaning of Eq. 34

Since Eq. 34 in M10 has provoked a lot of discussion we shall next summarize its origin and physical meaning.

There are arguments given in M10 why Eq. 34 is as it is. These arguments rely on the existence of a reference concentration that can be used to pinpoint the effect of condensation on vapor density and discriminate it from other, condensation-unrelated,

ACPD
10, C11046–C11050, 2010

effects (adiabatic expansion). This reference equilibrium concentration is that of total moist air (not dry air, because dry air is not in equilibrium due to condensation).

Next we clarified (M10-C1) how Eq. 34 is derived from the condition of hydrostatic equilibrium of moist air under the assumption that condensation rate is linear over vapor concentration. This assumption is in agreement with the law of mass action that describes condensation rate as a first-order reaction over H_2O. This is observed in experimental studies (e.g., Flückiger, Rossi (2003) J. Phys. Chem. A 107, 4103).

Our next argument for Eq. 34 is that it produces a physically meaningful result: it shows that if we demand vertical equilibrium, the disequilibrium pressure difference magnitude will be re-located onto the horizontal direction. We do know the magnitude $\Delta_z p$ of vertical pressure disequilibrium due to condensation that would have been observed in the absence of hydrostatic adjustment in a column of moist ascending air – it would be of the order of $\Delta_z p \sim p_v$. Eq. 37 for pressure gradient[2], derived with help of Eq. 34, is $\partial p/\partial x = -[p_v/h_\gamma]w/u$. Here w/u can be approximated as h/L, where h and L are circulation height and length scales, respectively.

For total horizontal pressure drop $\Delta_x p \approx [\partial p/\partial x]L$ we have $\Delta_x p \approx -p_v(h/h_\gamma) \sim -p_v \sim \Delta_z p$. Thus, having demanded vertical equilibrium, we can see that the non-equilibrium pressure difference has translated to the horizontal dimension. This is a meaningful result, because except for $\Delta_z p$ there is no other pressure scale to describe the horizontal pressure disequilibrium. (Furthermore, we find the same equation allows one to explain hurricanes and gives a rather accurate picture of the radial profiles.)

The magnitude of the condensation rate, as for the rate of any reaction, depends on the corresponding equilibrium conditions. In M10 and M10-C1 we performed our derivations assuming the hydrostatic equilibrium of moist air in the vertical dimension, constant temperature in the horizontal dimension and the absence of any other factors that can drive circulation. The requirement that water vapor is saturated can only be

[2] In the last equality of Eq. 37 it should be $\partial p/\partial x = -(\gamma p/h_\gamma)(w/u)$.

ACPD
10, C11046–C11050, 2010

Interactive Comment

ensured by turbulent eddies (similar to horizontal convective rolls). Such eddies are observed to have linear scale of the order of several kilometers. This and the fact that the atmosphere is observed to be in vertical equilibrium, means that Eq. 34 should be losing its validity on a horizontal scale of a few kilometers and less.

Since the process of condensation is governed by temperature, it follows from consideration of symmetries that condensation rate should depend on the velocity component that is directed along the temperature gradient, i.e., is perpendicular to the surface of constant temperature. In the case we are considering, that is, a horizontally isothermal surface, this velocity component is the vertical velocity w. Eq. 34 reflects this fact. In a general case when the surface of constant temperature is not horizontal, condensation rate should depend on $\mathbf{w}_0 \nabla N_v$, where $\mathbf{w}_0$ is the velocity vector parallel to the temperature gradient. We are currently working to develop these more general formulations. However, the basic horizontally isothermal surface considered by M10 remains physically important. In particular, its role is to highlight the difference between the conventional differential heating paradigm and the condensation-induced mechanism that can generate pressure gradients across an isothermal surface.

We hope that these considerations may help better communicate our message and nourish further interest in condensation-induced atmospheric dynamics.

Interactive comment on Atmos. Chem. Phys. Discuss., 10, 24015, 2010.