CORRESPONDENCE

Comments on "Is Condensation-Induced Atmospheric Dynamics a New Theory of the Origin of the Winds?"

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ABSTRACT

Here we respond to Jaramillo et al.'s recent critique of condensation-induced atmospheric dynamics (CIAD). We show that CIAD is consistent with Newton's laws while Jaramillo et al.'s analysis is invalid. To address implied objections, we explain our different formulations of "evaporative force." The essential concept of CIAD is condensation's role in powering atmospheric circulation. We briefly highlight why this concept is necessary and useful.

1. Introduction

Jaramillo et al. (2018) critiqued our theory of condensation-induced atmospheric dynamics (CIAD). CIAD results from the difference between evaporation and condensation. While most evaporation occurs at Earth's surface, and is a slow, widely distributed process, condensation in contrast occurs within the atmospheric volume and, depending on vertical air velocity, can be orders of magnitude more rapid than evaporation. In simplified form, water vapor with partial pressure p_v is added to the atmosphere at the surface and removed at the mean condensation height h_γ in air ascending with vertical velocity w. The product $p_v w/h_\gamma$ ($\mathrm{J\,m^{-3}\,s^{-1}}$) gives the rate of the release of available potential energy p_v ($\mathrm{J\,m^{-3}}$) equal to the rate of generation of the kinetic energy of wind (Makarieva and Gorshkov 2009, 2010; Makarieva et al. 2013b, 2014a).

Jaramillo et al. (2018) stated that CIAD modifies the equation of vertical motion such that it violates Newton's third law. This is incorrect: CIAD constrains the power of atmospheric circulation; it does not modify "the vertical momentum budget" nor any fundamental equations of hydrodynamics. Furthermore, Jaramillo et al.'s (2018) analysis of the equation of vertical motion is invalid.

2. The equation of vertical motion

Jaramillo et al. [2018, their Eq. (8)] write the equation of vertical motion as

$$F_z = \left(-\frac{\partial p_d}{\partial z} - g\rho_d + F_{vd}\right) + \left(-\frac{\partial p_v}{\partial z} - g\rho_v + F_{dv}\right)$$
$$= -\frac{\partial p}{\partial z} - g\rho + F_{vd} + F_{dv} = \rho a_z\,, \qquad (1)$$

where a_z is the vertical acceleration of air; g is the acceleration of gravity; and p_d, p_v, and $p = p_d + p_v$ and

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ρ_d, ρ_v, and $\rho = \rho_d + \rho_v$ denote, respectively, the pressure p and density ρ of dry air, water vapor, and moist air as a whole. The terms grouped in each set of parentheses are interpreted by Jaramillo et al. (2018) as "the forces on each component"—dry air and water vapor. "Internal forces" F_{vd} and F_{dv} are defined as "respectively the force of the vapor on the dry air and the force of the dry air on the vapor," which cancel because of Newton's third law: $F_{vd} = -F_{dv}$.

Equation (6) of Jaramillo et al. (2018) gives the definition of the evaporative force f_e as introduced by Makarieva and Gorshkov [2007, their Eq. (16)]:

$$f_e \equiv -\frac{\partial p_v}{\partial z} - \frac{p_v}{h_v}, \tag{2}$$

where $h_v \equiv RT/M_v g$, R is the ideal gas constant, T is temperature, and M_v is molar mass of water vapor. Force f_e quantifies the deviation of the vertical distribution of water vapor from equilibrium (discussed in the next section). Since $\rho_v = M_v N_v$ and, according to ideal gas law, $p_v = N_v RT$, where N_v is molar density of water vapor, f_e [Eq. (2)] can also be written as

$$f_e = -\frac{\partial p_v}{\partial z} - \rho_v g. \tag{3}$$

Jaramillo et al. (2018) state that "if the air parcel is not undergoing vertical acceleration, then

$$F_{vd} = f_e, \tag{4}$$

as defined by (6)." From this, they conclude that CIAD "includes F_{vd} in the vertical motion equation while omitting F_{dv}," which represents "a clear violation of Newton's third law."

This conclusion is not supported by evidence. First, Jaramillo et al. (2018) did not quote any equation from our works that would represent the alleged modified equation of vertical motion. Jaramillo et al. (2018) incorrectly attribute their Eq. (11), which is an adiabatic version of $\rho a_z = -\partial p/\partial z - \rho g + F_{vd}$, to Gorshkov et al. (2012). Everywhere in our works, the equation of vertical motion is $\rho a_z = -\partial p/\partial z - \rho g$; see, for example, Eq. (15) of Makarieva and Gorshkov (2007), where $\rho a_z = -\partial p/\partial z - \rho g = f_e$, and Eqs. (13) and (19) of, respectively, Gorshkov et al. (2012) and Makarieva et al. (2013b), where $\rho a_z = -\partial p/\partial z - \rho g = 0$ (hydrostatic equilibrium). CIAD does not modify the equations of motion.

Second, while Jaramillo et al. (2018) characterize their analysis as "rigorous," they do not explain how their key statement—Eq. (4)—was obtained. Indeed, F_{dv} and F_{vd} cancel and thus cannot be retrieved from Eq. (1). We speculate that Jaramillo et al. (2018) separated the equation of motion [Eq. (1)] into two "component" equations, for water vapor and dry air:

$$\rho_v a_{zv} = -\frac{\partial p_v}{\partial z} - \rho_v g + F_{dv} = f_e + F_{dv}, \tag{5}$$

$$\rho_d a_{zd} = -\frac{\partial p_d}{\partial z} - \rho_d g + F_{vd}, \tag{6}$$

where a_{zv} and a_{zd} are vertical accelerations of water vapor and dry air. Our suggestion is supported by Jaramillo et al. (2018, p. 3307) interpreting f_e [Eq. (2)] as "a force on the water vapor component." If, as Jaramillo et al. (2018) assume, "the air parcel is not undergoing vertical acceleration," $a_{zv} = a_{zd} = 0$ and Eq. (4) follows from Eq. (5) and $F_{dv} = -F_{vd}$.

The problem with this assumed derivation is that Eqs. (5) and (6) are incorrect. Separate equations of motion can be justified for such components of moist air as the gas and the condensate as they have distinct velocities (Makarieva et al. 2017), but not for the various components of a mixture of ideal gases that all move at the same velocity. In the case of Eqs. (5) and (6), the error is to assume that $\partial p_d/\partial z$, the partial pressure gradient of dry air, acts exclusively on dry air, while the partial pressure gradient of water vapor $\partial p_v/\partial z$ acts exclusively on water vapor.

Molecules of all gases adjacent to the considered unit volume of moist air collide and exchange momentum: dry air and water vapor molecules outside the volume collide with both dry air and water vapor molecules within it (Fig. 1a). The difference in the rates of these collisions above and below the volume determines the vertical pressure gradient $\partial p/\partial z$, which is an external force acting on the considered air volume. The vertical difference in the rates of collisions of *water vapor molecules* outside with *any molecules* within determines $\partial p_v/\partial z$, which is likewise an external force acting on the same air volume. Thus, when $\partial p_v/\partial z$ is perturbed, *all* air, and not just the water vapor, will accelerate (Fig. 1b).

Since the external forces in Eqs. (5) and (6) are incorrectly specified by Jaramillo et al. (2018), Eqs. (5) and (6) are also incorrect as equations of motion: the sum of the forces on the right-hand side of these equations, taken per unit mass, is not equal to accelerations a_{zv} and a_{zd}. Therefore, F_{vd} cannot be retrieved from the condition $a_{zd} = a_{zv} = 0$ and remains unspecified. With F_{vd} unspecified, Jaramillo et al.'s (2018) conclusion that CIAD "includes F_{vd} in the vertical motion equation while omitting F_{dv}" is meaningless.

3. CIAD and potential energy

Jaramillo et al. [2018, their Eqs. (6) and (7)] correctly note that we used two different expressions for the

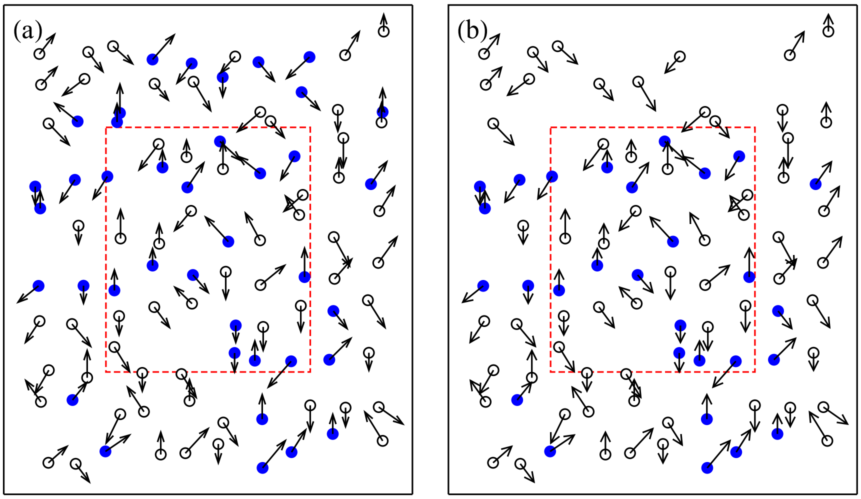

FIG. 1. Momentum exchange among gas molecules (open circles: dry air; filled circles: water vapor; dashed frame denotes the considered unit volume). (a) The cartoon is a reminder that all types of molecules collide with each other (arrows show the chaotic velocities of molecular motion). (b) The gradient of water vapor is perturbed from the initial equilibrium state in (a) by an instantaneous removal of water vapor from the upper quarter of the vessel; the gradient of dry air is not perturbed; and within the unit volume, nothing changes either—in particular, interactions between the molecules remain the same. In this case, Eqs. (5) and (6) would lead to the unphysical scenario where only water vapor will accelerate upward to fill the void, while the dry air as a whole will remain motionless.

evaporative force f_e in our publications. We use this opportunity to clarify. Because of the condensation that occurs in rising moist air, the negative partial pressure gradient of saturated water vapor is several times larger than its weight. Makarieva and Gorshkov (2007) proposed that the resulting "evaporative force" f_e drives atmospheric motion:

$$f_e \equiv -\frac{\partial p_v}{\partial z} - \rho_v g = \frac{p_v}{h_c}\left(\frac{h_v - h_c}{h_v}\right),$$

$$h_c \equiv \frac{RT^2}{L\Gamma} \ll h_v \equiv \frac{RT}{M_v g}, \qquad (7)$$

where L (J mol^{-1}) is the latent heat of vaporization and $\Gamma \equiv -\partial T/\partial z$. The magnitude of

$$\Delta p(z) \equiv \int_z^{\infty} f_e \, dz \lesssim p_v(z) \qquad (8)$$

(J m^{-3}) was interpreted as a store of potential energy available for conversion to kinetic energy (Makarieva and Gorshkov 2009, 2010). An analogy is a spring compressed from an equilibrium state with length h_v to $h_c < h_v$; this spring decompresses in the upward direction until Hooke's force associated with its deformation $(-\partial p_v/\partial z)$ becomes balanced by spring's weight $(-\rho_v g)$.

The magnitude of the available potential energy depends on how the state with minimum potential energy is defined (Lorenz 1955). Definition (7) assumes that such a minimum corresponds to a static atmosphere where every ith gas with partial pressure p_i and molar mass M_i has its own scale height $h_i \equiv -p_i/(\partial p_i/\partial z) = RT/M_i g$. In the real atmosphere, very small motions are sufficient to counteract molecular diffusion and keep the air well mixed: in the absence of condensation, the air molar mass M is independent of altitude, and all gases have the same scale height $h_i = h = RT/Mg$. Accordingly, in later CIAD publications, the definition of the evaporative force (also termed the "evaporative–condensational" or "condensational" force) was modified, with h_v in definition (7) replaced by h [Gorshkov et al. 2012, their Eq. (15)]:

$$f_e \equiv \frac{p_v}{h_c} - \frac{p_v}{h} = \frac{p_v}{h_\gamma}, \qquad (9)$$

where

$$\frac{1}{h_\gamma} \equiv -\frac{1}{\gamma}\frac{\partial \gamma}{\partial z} = \frac{1}{h_c} - \frac{1}{h}, \quad \gamma \equiv \frac{p_v}{p}. \qquad (10)$$

Equation (9) attributes the minimum of condensation-related potential energy to well-mixed air. By analogy, the state with minimum available potential energy as defined by Lorenz (1955) is not a static isothermal atmosphere, but an atmosphere with an adiabatic vertical lapse rate, which requires some motion. Defining f_e as in

Eq. (9) likewise presumes that some small motion (not generated by condensation) is required to keep $M = \text{const}$ and $h_i = h$.

The key statement of CIAD is that condensation provides power to atmospheric circulation: the rate at which the kinetic energy of wind is generated is equal to the rate at which the condensation-related potential energy is released. The latter rate is equal to the work per unit time $\mathbf{v} \cdot \mathbf{f}_e = wf_e$ of the evaporative force, where $\mathbf{v}$ and $\mathbf{w}$ are the total and vertical air velocities. It is in this sense that the evaporative force drives winds. Accordingly, the key equation of CIAD is the equality between wf_e and the local rate of generation of kinetic energy (and, in the steady state, its dissipation). For a hydrostatic atmosphere, this equation takes the form

$$w\frac{p_v}{h_\gamma} = -\mathbf{u} \cdot \nabla p, \tag{11}$$

where $\mathbf{u}$ is the horizontal velocity ($\mathbf{v} = \mathbf{w} + \mathbf{u}$); see Eqs. (4), (17), and (5) of, respectively, Makarieva and Gorshkov (2009, 2010, 2011), Eq. (16) of Gorshkov et al. (2012), and Eq. (37) of Makarieva et al. (2013b). Equation (11) presumes that condensation is associated with the vertical movement and temperature gradient.

We have shown that Eq. (11) can explain and describe the observed wind and pressure profiles in hurricanes and tornadoes (Makarieva and Gorshkov 2009, 2011; Makarieva et al. 2011). When Eq. (11) is generalized to account for horizontal temperature gradients (Makarieva and Gorshkov 2010; Makarieva et al. 2014a), it can also explain the wind power in the Amazon rain forest (Makarieva et al. 2014b). The global integral of Eq. (11) produces an estimate of condensation-driven global circulation power that likewise matches observations (Makarieva et al. 2013b).

4. Conclusions

While Jaramillo et al.'s (2018) criticisms are unsupported, we value any interest and discussion of CIAD and its implications. As in the steady-state kinetic energy production is balanced by dissipation, CIAD by constraining atmospheric power can guide the parameterization of turbulence (which in current models is fitted to observations). Furthermore, CIAD implies that removing major terrestrial sources of water vapor, for example, through deforestation, will influence atmospheric circulation, modify ocean-to-land moisture transport, and impact the terrestrial water cycle (Makarieva and Gorshkov 2007; Makarieva et al. 2013a, 2014b).

Many observation-based studies have shown a significant impact of vegetation cover on ocean-to-land circulation and moisture import (e.g., Levermann et al. 2009; Chikoore and Jury 2010; Andrich and Imberger 2013; Poveda et al. 2014; Herzschuh et al. 2014; Levermann et al. 2016; Boers et al. 2017). The relevant discussions are controversial, since current circulation models cannot explain abrupt changes in air circulation following changes in vegetation (e.g., Levermann et al. 2016; Boos and Storelvmo 2016). If modeled turbulence could be reparameterized so as to account for CIAD, we expect the simulated atmospheric reactions to vegetation degradation/recovery to become more realistic, resolving the mismatch between models and observations.

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