CORRESPONDENCE

Reply to “Comments on ‘Is Condensation-Induced Atmospheric Dynamics a New Theory of the Origin of the Winds?’”

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ABSTRACT

We respond here to Makarieva et al.’s critique of Jaramillo et al., who showed that the concept of condensation-induced atmospheric dynamics (CIAD) violates Newton’s third law. We confirm here that their analysis is valid and that there is a contradiction in Makarieva et al.’s arguments. We also solve the paradox that CIAD can produce results consistent with observations despite being a flawed theory.

1. Introduction

Jaramillo et al. (2018, hereinafter **JMR**) show that the alleged new force proposed by the hypothesis of the condensation-induced atmospheric dynamics (CIAD) violates Newton’s third law, based on an unbalanced internal force within the atmospheric gas. Makarieva et al. (2019, hereinafter **CIAD19**) argues that **JMR**’s analysis is invalid and explains that the “essential concept” of CIAD is the role of condensation in powering atmospheric circulation.

We will explain and validate the central argument of **JMR** by showing a contradiction in **CIAD19**’s arguments. We will also explain the “essential concept” of CIAD from the perspective of the continuity equation, showing that CIAD confuses a condensation rate with a new force. As a result, we will explain why CIAD’s arguments fit observations despite this flaw.

2. The evaporative force and Newton’s third law

JMR analyzes the “evaporative force” f_e , proposed by CIAD as the main driver of low-level circulations.

They show that this force corresponds to an internal force and, therefore, the central tenet of CIAD violates Newton’s third law. **CIAD19** states that **JMR**’s analysis is not valid, arguing that CIAD does not modify the vertical momentum budget. In this section, we will review and validate **JMR**’s main argument, and why **CIAD19**’s arguments lead to a physical contradiction.

To explain this force, CIAD’s working hypothesis is that condensation prevents the vertical gradient of water vapor partial pressure from decreasing with its proper scale height h_v . Then the vapor out of equilibrium exerts a force f_e on the air expressed as

$$f_e = -\frac{\partial p_v}{\partial z} - \frac{p_v}{h_v}, \quad (1)$$

where $h_v = RT/M_v g$, R is the universal gas constant, T is the absolute temperature, M_v is the molar mass of the water vapor, and g is the gravitational acceleration. This force disrupts the hydrostatic balance of the air column as a whole, and its readjustment is at the expense of horizontal motion toward the condensation area.

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In later studies, [Gorshkov et al. \(2012\)](#) and [Makarieva et al. \(2013\)](#), hereinafter **MG13D**) gave a conflicting definition for f_e :

$$f_e = -\frac{\partial p_v}{\partial z} - \frac{p_v}{h}, \quad (2)$$

that is, (2) uses h instead of h_v in (1), where $h = RT/Mg$ is the scale height for the atmospheric air, which for large-scale motions is to a high degree of accuracy in hydrostatic balance ([Holton and Hakim 2013](#), p. 45). **CIAD19** justifies this change in definition by explaining that, after condensation disturbs the pressure distribution of moist air, the air tends to relax to a hydrostatic distribution with a scale height h .

The key to discovering the failure in CIAD's logic is through understanding the nature of f_e , which, simply stated, is the force that vapor exerts on dry air caused by condensation's effects on the vertical pressure gradients. To address this from a general perspective, **JMR** writes the vertical forces on a parcel of moist air as

$$F_z = -\frac{\partial p}{\partial z} - g\rho = \left(-\frac{\partial p_d}{\partial z} - g\rho_d + F_{vd}\right) + \left(-\frac{\partial p_v}{\partial z} - g\rho_v + F_{dv}\right), \quad (3)$$

where Dalton's law is used in the second equality, with p_d and p_v as the partial pressures of dry air and vapor, and ρ_d and ρ_v are the corresponding densities. For simplicity, (3) ignores the frictional force that the environment exerts on the parcel.

The quantities F_{vd} and F_{dv} are an action–reaction pair that represents the force of the vapor on the dry air and the force of the dry air on the vapor, respectively, as mediated by molecular collisions between the two components. These are internal forces since they act between distinct components of the total system, which is the mixture of dry air and vapor. Newton's third law states that

$$F_{vd} = -F_{dv}. \quad (4)$$

This relationship is unequivocal, no matter the nature of the perturbation: if the water vapor balance is disturbed, the vapor will exert a force on the dry air, and the dry air will react exerting a force equal in magnitude but opposite in direction. Being f_e defined as the force that the water vapor exerts on the air because condensation disturbs the vertical distribution of water vapor, it is clear that this case is covered by the definition of F_{vd} and therefore a dynamics based on this force is not possible, as **JMR** explained.

JMR goes further by explaining the role of condensation in this picture. Using the specific moist entropy equation, they show that the vertical forces on a parcel of moist air including the effect of condensation can be written as

$$F_z = -\rho_d(c_{pd} + r_v^*c_{pv})\frac{\partial T}{\partial z} - \frac{\Lambda}{R_d}p_d\frac{\partial r_v^*}{\partial z} - g\rho, \quad (5)$$

with

$$\Lambda = \frac{L_L(T_F)}{T_F} + c_{pv}\ln\left(\frac{T}{T_F}\right) - R_v\ln\left(\frac{p_v}{e_{SF}}\right), \quad (6)$$

where c_{pd} and c_{pv} are the respective specific heats of dry air and vapor at constant pressure; r_v^* is the mixing ratio of saturated vapor; R_d and R_v are the gas constants for dry air and vapor; L_L and e_{SF} are, respectively, the latent heat of condensation and the saturation vapor pressure at a reference temperature T_F that is usually taken to be the freezing-point temperature; and p_R is a reference pressure usually taken to be 1000 hPa. Under common simplifications, (6) reduces to

$$F_z = -\rho_d c_{pd} \frac{\partial T}{\partial z} - \frac{L_L(T_F)}{T_F R_d} p_d \frac{\partial r_v^*}{\partial z} - g\rho. \quad (7)$$

CIAD19 repetitively states that CIAD does not modify the vertical momentum budget and that **JMR** “did not quote any equation from our works that would represent the alleged modified equation of vertical motion,” suggesting that **JMR** unfairly cited [Gorshkov et al. \(2012\)](#). This opens up an opportunity to explain **JMR**'s motivation in citing [Gorshkov et al. \(2012\)](#) and, at the same time, to point out a contradiction in CIAD's arguments. Using (2), (7) can be rewritten as

$$F_z = -\rho_d c_{pd} \frac{\partial T}{\partial z} + \xi \frac{p}{p_d} f_e - g\rho, \quad (8)$$

with $\xi = L_L(T_F)/T_F R_v$. In this form, $\xi p f_e / p_d$ represents the contribution of latent heat release to the vertical momentum budget, which is different from CIAD's f_e . This difference is stated by [Gorshkov et al. \(2012\)](#), who wrote that “the power of latent heat release which is ξ times larger than the power of dynamic condensation induced circulation.” The statement by [Gorshkov et al. \(2012\)](#) suggests that f_e must appear together with all the other terms in (8) to be able to compare the power of f_e with that of $\xi p f_e / p_d$. Therefore, this leads us to propose

$$F_{z,CIAD} = -\rho_d c_{pd} \frac{\partial T}{\partial z} + \xi \frac{p}{p_d} f_e - g\rho + f_e \quad (9)$$

as the logical consequence of the quoted phrase, which is equivalent to (11) of JMR. Although this equation is not written explicitly in CIAD's references, (9) follows logically from the CIAD theory and represents the newly proposed force in CIAD that must be included in the vertical component of momentum. This fundamental fact seems to go unnoticed in all of CIAD theoretical developments and presents a strong contradiction to their claim that CIAD does not modify the vertical momentum budget.

The fact that CIAD does not include f_e in the momentum budget, but it is used to explain how condensation constrains the power of atmospheric circulation, means that CIAD is confusing their new alleged force with a condensation rate, as we will explain in the next section.

3. The flaw of CIAD's "main dynamic equation"

As CIAD19 states, CIAD's main idea is that condensation provides power to atmospheric circulation, not in the vertical momentum budget but by using the vertical power of f_e for the generation of kinetic energy. Nevertheless, as we explained in section 2, the force that the water vapor makes on the dry air is an internal force, and therefore, it is not possible to define a dynamics based on the power of this force. Also, it is a contradiction to talk about a new force that exerts power that is not present in the momentum budget. From this point of view, we repeat that JMR's arguments are valid and sufficient to expose the flaw in CIAD.

It is interesting to note, however, that despite this flaw, CIAD19 (and references therein) still claim that CIAD describes wind and pressure profiles as consistent with phenomena like hurricanes and tornadoes, the circulation in the Amazon rain forest, or even an estimation of the global circulation power that appears to be consistent with observations. This apparent success in describing a wealth of phenomena across many scales seems to pose a paradox coming from a flawed theory such as CIAD. Here, we show that there is no a paradox but an unnoticed imposition of a well-known observational fact in CIAD's equations.

To that end, we use the continuity equation to explain CIAD's "main dynamic equation," by showing the restrictions that continuity imposes on the horizontal and vertical gradients of pressure for a parcel of moist air in motion. We assume that the parcel conserves its dry component during its motion, but the vapor component is not conserved, because of condensation and evaporation. The water vapor mixing ratio $r_v = \rho_v/\rho_d$, the ratio of the density of water vapor ρ_v and dry air ρ_d , obeys the equation (Raymond 2013)

$$\frac{Dr_v}{Dt} = \frac{1}{\rho_d} \nabla \cdot (K \nabla r_v) + \mathcal{E} - \mathcal{P}, \quad (10)$$

where $D(\cdot)/Dt$ is the usual material derivative of fluid dynamics, K is the dynamic eddy mixing coefficient, and $\mathcal{E}$ and $\mathcal{P}$ are, respectively, the evaporation and precipitation rates per unit mass of dry air.

Using the ideal gas law, the water vapor mixing ratio in terms of the water vapor pressure and the dry air pressure is

$$r_v = \varepsilon \frac{p_v}{p_d}, \quad (11)$$

where $\varepsilon = R_d/R_v = 0.622$. Using (11) and writing the parcel's velocity $\mathbf{v}$ in a reference frame with the x axis directed along the horizontal velocity u and with w as the vertical velocity, that is, as $\mathbf{v} = u\mathbf{i} + w\mathbf{k}$, (10) can be written for the steady state as

$$u \left(\frac{\partial p_v}{\partial x} - \frac{p_v}{p_d} \frac{\partial p_d}{\partial x} \right) + w \left(\frac{\partial p_v}{\partial z} - \frac{p_v}{p_d} \frac{\partial p_d}{\partial z} \right) = \mathcal{E}, \quad (12)$$

where

$$\mathcal{E} = \frac{p_d}{\varepsilon} (\mathcal{E} - \mathcal{P}), \quad (13)$$

and herein, we will refer to $\mathcal{E}$ as a net condensation rate (Pas^{-1}). For simplicity, we ignored the turbulent mixing term proportional to $\nabla \cdot (K \nabla r_v)$.

Equation (12) is the continuity equation together with the state equation for ideal gases and represents the restrictions that the continuity equation imposes on the pressure gradients because of a given condensation rate. There is a simple interpretation of the second term on the left-hand side of (12). For pure vertical motion (i.e., $u = 0$), (12) reduces to

$$\mathcal{E}_z = w \left(\frac{\partial p_v}{\partial z} - \frac{p_v}{p_d} \frac{\partial p_d}{\partial z} \right), \quad (14)$$

where $\mathcal{E}_z$ represents a net condensation rate for pure vertical motion.

Using Dalton's law and (14), (12) yields, after some algebra,

$$u \frac{\partial p}{\partial x} = \frac{p_d}{p_v} (\mathcal{E}_z - \mathcal{E}) + u \frac{p}{p_v} \frac{\partial p_v}{\partial x}. \quad (15)$$

This equation shows that the horizontal pressure gradient is linked to the difference between the net condensation rate of a purely vertical motion $\mathcal{E}_z$ and the real condensation rate $\mathcal{E}$, plus a term proportional to the horizontal pressure gradient of water vapor.

To obtain CIAD's "main dynamic equation," we restrict ourselves to study the continuity equation for the regions where the water vapor is saturated. We use p_v^* to represent the saturated vapor pressure. CIAD also imposes the horizontal gradients of temperature to be zero ($\partial T/\partial x = 0$), implying that $\partial p_v^*/\partial x = 0$ because of the Clausius–Clapeyron equation. CIAD justifies these assumptions by saying that in the real atmosphere this corresponds to a constant relative humidity in a weak temperature gradient approximation (see, e.g., the interactive discussion of MG13D). Under these constraints, (15) reduces to

$$u \frac{\partial p}{\partial x} = \frac{p_d}{p_v^*} (\mathcal{E}_z^* - \mathcal{E}), \quad (16)$$

which is equivalent to (8) of Gorshkov et al. (2012), where $\mathcal{E}_z^*$ represents (14) evaluated for the saturated case.

It is essential to remark that both (15) and (16) describe the restrictions on the pressure and velocity fields for a given condensation rate, but these equations by themselves do not define $\mathcal{E}$. Therefore, to completely resolve the fluid fields, we need to use restrictions coming from the rest of the governing equations like the energy conservation and the equations of motion together with boundary conditions.

Another way to proceed is to parameterize $\mathcal{E}$ by assigning it a reasonable value consistent with observations. For example, one way to parameterize this condensation rate is by using the well-known fact that vertical motions associated with adiabatic cooling are the most important mechanisms that bring moist air to saturation (e.g., Curry and Webster 1999, 172–173); that is, we can propose a parameterization of the form $\mathcal{E} = \alpha \mathcal{E}_z^*$ with $\alpha < 1$. Equation (16) can be written as

$$u \frac{\partial p}{\partial x} = \frac{p_d}{p_v^*} (1 - \alpha) \mathcal{E}_z^*. \quad (17)$$

This latter approach seems to be the one followed by CIAD. Although studies like MG13D and Gorshkov et al. (2012) do not explicitly state this assumption, discussions like MG13D suggest that CIAD proposes that, for a parcel undergoing adiabatic condensation in a hydrostatic atmosphere, the condensation rate must be (i) proportional to the amount of condensing vapor, (ii) proportional to the vertical velocity w , and (iii) proportional to the degree by which the vertical distribution of vapor deviates from equilibrium. From these three points, CIAD proposes a condensation rate:

$$\mathcal{E}_{\text{CIAD}} = w \left(\frac{\partial p_v^*}{\partial z} - \frac{p_v^*}{p} \frac{\partial p}{\partial z} \right) = \frac{p_d}{p} \mathcal{E}_z^*, \quad (18)$$

which expresses the condensation rate as "the difference between the total change of vapor density with height

and the density change caused by adiabatic expansion" (MG13D). In other words, CIAD proposes a parameterization like (17) with $\alpha = p_d/p$, leading to

$$u \frac{\partial p}{\partial x} = \mathcal{E}_{\text{CIAD}} = -w f_e. \quad (19)$$

Equation (19) is what CIAD considers its "main dynamic equation," which would explain how condensation provides power to atmospheric circulations through the power $w f_e$.

CIAD's authors write the term $w f_e$ in (19) to justify the proposal of a "new force" f_e , whose power is used to create horizontal pressure gradients, but as we explain in the previous section, f_e is an internal force and this argument is not physically tenable. Nevertheless, (19) might still correspond to an interesting assumption if we completely abandon the idea of a new force and focus only on (18) as a parameterization of $\mathcal{E}$, like the proposed in (17). Although CIAD's authors still defend the idea of a new force, they seem to be aware of this approach when MG13D states that (19), as a proposal, does not violate the continuity equation.

This analysis shows that the CIAD's "main dynamic equation" is tantamount to proposing a parameterization of the form (17) with $\alpha = p_d/p$, which is consistent with the fact that vertical motions are the most important mechanisms leading to condensation in Earth's atmosphere. This implies that CIAD unknowingly is imposing an agreement with observations through this specific parameterization of $\mathcal{E}$. The fact that CIAD's "main dynamic equation" is just a parameterization is in contrast with CIAD's proposal of a new theory.

4. Conclusions

CIAD19 criticizes JMR by proposing that their analysis about how CIAD violates Newton third law is invalid. Here, we explain that JMR's analysis is valid and that CIAD19 presents a strong contradiction proposing f_e as a new force that exerts power, but at the same time, it is not present in the momentum budget. Ironically, this claim supports the analysis of JMR.

Here, we also address the apparent paradox that, despite being a flawed theory, CIAD's "main dynamic equation" still describes wind and pressure profiles consistent with phenomena like hurricanes and tornadoes, the circulation in the Amazon rain forest, or even an estimation of the global circulation power that seem consistent with observations. We show that there is not a paradox because CIAD unnoticedly forced their main equation to be consistent with observations by proposing a condensation rate that is in agreement

with a well-known fact about condensation being associated with vertical motions.

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