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Atmospheric
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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. Judith Curry for her open review and her suggestions. Below we address the four concerns raised by Dr. Curry.

1 The physics of Equation 34

Dr. Curry indicated that we should provide a clearer and more extensive justification for Eq. 34. We believe we have addressed this in three comments submitted to this discussion[1]. As advised by Dr. Curry, we have compiled these comments as an appendix (see Appendix A below).

2 Significance of the effect

Dr. Curry comments that while she thinks that *"the mechanism described by M10 is correct and real, the issue is its significance in the atmosphere. It is not clear to what extent this mechanism "matters"; their thermodynamic analysis is insufficient to demonstrate the relative magnitude of this effect."*

Condensation-induced dynamics was first introduced to ACPD in a previous submission of Makarieva et al. (2008) where it was invoked to explain hurricanes. At that time the handling editor Dr. Haynes recommended[2] that if *"you wish to publish a paper on your ideas in a journal such as Atmospheric Chemistry and Physics then you need to put much more emphasis on careful (and very basic) physical discussion — perhaps presenting one or two clear, simple (and physically relevant) thought experiments in which the novelty and correctness of your approach is clear."* Likewise, Dr. Rosenfeld[3] confined himself to estimating the magnitude of latent heat release to question the significance of the vapor sink. While we disagree with the particular conclusions of that critique, we do agree with the general idea that the primary arguments for a significant new driver of atmospheric circulation should be based upon physical fundamentals.

Thus our paper presents several physical arguments building from established basic principles (plus an extensive physical discussion) in favor of the statement that the vapor sink is not only real but significant in magnitude:

(1) We compared the relative contributions of the condensational vapor sink versus

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[1] http://www.atmos-chem-phys-discuss.net/10/C10922/2010/ http://www.atmos-chem-phys-discuss.net/10/C11046/2010/ http://www.atmos-chem-phys-discuss.net/10/C12836/2011/

[2] http://www.atmos-chem-phys-discuss.net/8/S12168/2009/ p. S12172

[3] http://www.atmos-chem-phys-discuss.net/8/S12426/2009/ p. S12436

latent heat release into the formation of horizontal pressure differences (Section 3.2, Fig. 1c). We used a transparent thought experiment comparing pressure distributions between air columns with moist adiabatic and dry adiabatic lapse rates.

(2) For a horizontally isothermal surface we derived the horizontal pressure gradients associated with condensation and show them to coincide in magnitude with observed gradients (Section 4.1).

(3) We estimated the mean global power of the condensation mechanism and showed it to be of similar magnitude to the dissipative power of general atmospheric circulation (Section 4.4).

All these are new arguments.

Later in the open discussion we analyzed[4] the assumptions and conclusions of several numerical models of a moist atmosphere, including the studies of Lackmann and Yablonsky (2004), Bryan and Rotunno (2009) and Bryan and Fritsch (2002). These analyses indicate that models built and calibrated without a theory regarding the dynamic effects of a vapor sink cannot be used to evaluate such a sink.

There are other ways to respond to Dr. Curry's concerns. One way of advancing the case that a physical process is important is to compare it with a process conventionally accepted as important, and showing that that the first has a similar or greater "importance" (i.e. influence) than the latter. For this reason we chose to compare the forces that arise due to vapor sink ("condensation") and latent heat release ("buoyancy") mechanisms. We added a figure to show how each force depends on height in the atmosphere and surface temperature. This new text is attached to this reply as Appendix B "Comparing forces due to condensation and buoyancy".

Furthermore, we can now refer to a recently published study where our approach

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[4] http://www.atmos-chem-phys-discuss.net/10/C10926/2010 http://www.atmos-chem-phys-discuss.net/10/C12008/2011/ http://www.atmos-chem-phys-discuss.net/10/C13260/2011/

(and, in particular, Eq. 34) allows us to predict hurricane velocity and pressure profiles that are in good agreement with observations. This approach also explains the size of the hurricane eye, a feature that has resisted previous explanation (for more details of these derivations and associated justifications and comparisons see (Makarieva and Gorshkov, 2011)).

These additional arguments, results and publications that have become available while our paper has been under discussion support our key proposition: that the condensation-induced dynamics deserve serious scrutiny. A wider evaluation by many scientists as well as analysis of the empirical evidence will determine the exact place and importance of condensation-induced dynamics for the atmospheric circulation on Earth.

3 The Hadley argument

Dr. Curry notes that *"the Hadley circulation argument is unconvincing, and it needs to be placed in context of other ideas about the Hadley circulation."* We wish to clarify the purpose of this example (p. 24032 in M10). In Section 4.1 we present a theoretical derivation linking the horizontal pressure gradient produced by vapor sink to the ratio of the vertical to horizontal velocities and the vertical profile of water vapor. The outcome is Eq. 37. We then use the empirical data for the Hadley cell, put them into Eq. 37 and obtain a pressure gradient that is in satisfactory agreement with observations.

This was a test that the condensation theory could have failed. Estimating the pressure gradient using Eq. 37 and known atmospheric parameters we could have obtained a negligible value, e.g., a value a thousand times smaller than the observed gradient. One would then have sufficient grounds to argue, on the basis of that result, that the vapor sink makes little contribution to these atmospheric dynamics and can be safely neglected. This did not not happen. The condensational theory passed this test.

In our opinion, therefore, the fact that Eq. 37 yields a pressure gradient sufficient in magnitude to explain actual observations stands by itself. Logically, this particular argument cannot be made more or less convincing by listing other ideas about the Hadley circulation other than noting, as we do, that climate scientists have long recognised concerns and weaknesses in previous explanations. At the same time, in our paper we do quote the comprehensive review of Schneider (2006) where the reader can find most ideas (though not our condensational theory) that currently dominate theories concerning general atmospheric circulation, including Hadley circulation.

In line with Dr. Curry's recommendation we could clarify what our estimate achieves and emphasize the value of our ideas for offering alternative explanations for recognised phenomena as follows (see p. 24032):

"This estimate illustrates that our approach when coupled to fundamental atmospheric parameters, yields horizontal pressure gradients of magnitudes similar to those actually observed in large-scale circulation patterns. Should we have obtained a much smaller magnitude from our theoretical derivation, Eq. (37) we could argue that the impact of the vapor sink is negligible and cannot explain the observations. This did not happen. Rather the result adds credibility to our proposal that the vapor sink is in fact a major cause of atmospheric pressure gradients.

Not incidentally, accepted difficulties in the understanding of atmospheric circulation relate to circumstances where uncertainty over the dynamics of water vapor play a role - even if the nature of that role remains debatable. For example, modern global circulation models do not satisfactorily account for the water cycle of the Amazon river basin, with the estimated moisture convergence being half the actual amounts estimated from the observed runoff values (Marengo, 2006). We also emphasise that so far it has not been possible to derive a quantitatively realistic theory of Hadley circulation based on current theories and the effects of differential heating alone (Held and Hou, 1980; Fang and Tung, 1999; Schneider, 2006). Efforts to address this challenge are ongoing but progress is limited (e.g., Lindzen and Hou, 1988; Robinson, 2006; Walker and Schneider, 2005, 2006). In one recent review concerning theories of general circulation the undertsanding of atmospheric moisture and its influences, particularly, *lack of relevant theoretical concepts*, were identified as a persistent challenge (Schneider, 2006) .

Furthermore, many climate researchers readily acknowledge that the current incomplete understanding of the general circulation precludes a theory-based analysis, from fundamental physical principles, of the role of latitudinal atmospheric mixing in stabilizing the Earth's thermal regime important – this is not a minor and thus neglected detail but is central in debates concerning climate sensitivity (e.g., Lindzen and Choi, 2009; Trenberth et al., 2010). It would seem to many that new ideas are needed. If these ideas were obvious, and followed directly from current paradigms, they would have already been identified and accepted – thus we should not be surprised that the new ideas we all seek may challenge conventional perspectives. In view of our results concerning the potential of condensation-induced dynamics to remedy the existing theoretical problems we conclude that these approaches are a promising avenue for further examination."

4 Condensation and evaporation: volume and surface

Dr. Curry commented: *"I disagree with the authors regarding evaporation vs. condensation. They identify "salient differences" between them which in fact do not exist. Evaporation is not a surface specific process. When a cloud forms in the atmosphere, the condensed water has one of two fates: fallout in the form of precipitation or evaporation. The precipitation efficiency of clouds is rather low, much less than 10%. So most of the condensed water in the atmosphere eventually evaporates in the atmosphere. But I don't see that this has much impact on their overall argument."*

These are interesting issues. Here we offer some clarifications. On p. 24040 we say: "Evaporation is a surface-specific process. It is predominantly anchored to the Earth's surface." These are two independent statements. Evaporation is, fundamentally, a surface-specific process because it represents a flux of water molecules via the surface of liquid. In contrast, condensation is a volume-specific process that affects vapor molecules distributed in a certain volume. The balance between condensation and evaporation demands that to compensate for the amount of moisture condensed in a certain volume vapor must be transported to that local volume via its borders. Adding more gas to a gas volume where condensation has occurred is associated with doing work on the gas volume.

The second statement is that the surface of predominant importance for evaporation is the planetary surface and not the surface of liquid drops that are present in the atmosphere. In the stationary state the evaporation and condensation rates are equal: neither vapor nor liquid accumulates anywhere in the atmosphere. Evaporation from the planetary surface accounts for about one third of the total flux of solar radiation absorbed by the planet. Thus, the energy budget considerations prohibit the existence of a ten times more intense evaporation flux at a certain height in the atmosphere. Precipitation efficiency of clouds can be defined in several different ways that pertain to different spatial and temporal scales. Depending on how it is defined precipitation efficiency ranging from less than -100% to over 100% are reported in the literature (Anip and Market, 2007; Shusse and Tsuboki, 2006; Sui et al., 2007; Snodgrass et al., 2009).

A good question in this context is what the rates of condensation and evaporation actually are if we speak of a steady state? In the stationary state the evaporation and condensation rates are equal: neither vapor nor liquid accumulates anywhere in the atmosphere. Therefore, by measuring the mean rainfall rate at the surface we can estimate the flux of evaporation from the surface. But how can we know how much moisture recycles – condenses/evaporates – in the atmosphere? While each droplet is surrounded by a microscopic layer with saturated vapor, where the water molecules travel there and back via the liquid-gas interface, such equilibrium exchange occurring within one mean free path length from the liquid surface does not matter to atmospheric

processes.

Condensation is associated with adiabatic ascent of saturated air and happens at relative humidity equal to unity. Evaporation occurs when the relative humidity is lower than unity. Therefore condensation and evaporation must occur in different locations. The rate of vapor/liquid turnover between such areas will determine the stationary rates of evaporation/condensation in the atmosphere. One region of relative humidity lower than unity is just below the cloud base. However, observations show that evaporation from hydrometeors normally represents a small correction (at around 6%) to the rainfall rate measured immediately below the cloud base (Snodgrass et al., 2009): that is, practically all rainfall reaches the ground. Another opportunity for droplets to evaporate is in the regions of downdrafts. If droplets are sufficiently small and the downdrafts are sufficiently slow, the droplets could, in principle, fully evaporate before they reach the ground. In this case the rate of air exchange between the updrafts and downdrafts could serve as an estimate of the intra-atmospheric condensation/evaporation turnover.

In this case one would observe that the amount of condensed water in the atmosphere would be on average close to the adiabatic liquid water content. In reality, the amount of liquid in the atmosphere is much less, both in updraft and downdraft areas (e.g., Rangno and Hobbs, 2005; Wood et al., 2002). This shows that most water that condenses in the atmosphere as the moist air ascends originates from the planetary surface and ultimately precipitates back to the surface.

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A On the physical meaning of Eq. 34 for condensation rate

Equation (34) expresses condensation rate as the difference between (a) the total change of vapor density with height and (b) the density change caused by adiabatic expansion. Here we explore the physical meaning of this expression from a different perspective. We shall show that Eq. (34) follows directly from the condition that the vertical distribution of moist air remains in equilibrium under the assumption that that condensation rate S is linear over the amount of vapor (i.e., condensable gas) in the atmosphere.

A.1 Linearity of condensation rate over the molar density N_v of water vapor

The linearity assumption is justified by the particular physical nature and stoichiometry of condensation, with gas turning to liquid: condensation is a first-order reaction over saturated molar density N_v of the condensing gas. This can be experimentally tested by considering condensation of water with different isotopic composition (e.g., Fluckiger and Rossi, 2003). (Note, for example, that the reverse process (evaporation) is a zero-order reaction over N_v.)

The rate of first-order reactions is directly proportional to the molar density of the reagent, with the proportionality constant having the dimension of inverse time: $S = CN_v$, where C (dimension s^{-1}) is in the general case independent of N_v. In chemical kinetics C depends on temperature and the molecular properties of the reagent as follows from the law of mass action. Since the saturated concentration N_v of condensable gas depends on temperature as dictated by the Clausius-Clapeyron law, we can ask what the proportionality coefficient C physically means in this case. Different substances have different partial pressures of saturated vapor at any given temperature – this is controlled by the vaporization constant L and the molecular properties of the substance. Note too that for any given substance (like water) the saturated concentration depends on various additional parameters including the curvature of the the liquid surface and availability of condensation nuclei. Therefore, a range of saturated concentrations is possible at any given temperature. This allows one to consider C and N_v as independent variables in the space of all possible combinations of C and N_v.

A.2 The equilibrium

The notions of equilibrium and deviation from it are key to determining the rate of any reaction. For example, in the case of evaporation the deviation from equilibrium is measured by the water vapor deficit: the deviation of relative humidity from the (equilibrium) unity value. Atmospheric condensation is peculiar in being physically associated with air movement in a particular direction – water vapor condenses as the air moves vertically towards a lower temperature.

Here, in the context of our work, by invoking the concept of *equilibrium* we mean the vertical distribution that the water vapor would locally take in the absence of condensation, all other conditions being equal. Let us denote the inverse scale height of such an

equilibrium distribution for k_E. Condensation rate S is then proportional to the first order deviation k_v of the *observed* vertical distribution of water vapor from the equilibrium:

$$k_v = -\frac{1}{N_v}\frac{\partial N_v}{\partial z} - k_E. \tag{A1}$$

The physics of Eq. (A1) consists of the fact that the character of the considered equilibrium distribution is not affected by condensation. For example, for the case of *hydrostatic equilibrium* any gas having molar mass M, temperature T and finding itself on a planet with acceleration of gravity g in the presence of a temperature gradient $\partial T/\partial z$ will have a distribution of its molar density following $-\partial N/\partial z = k_E N$, where $k_E = Mg/RT + (1/T)\partial T/\partial z$. (But note that Equation (A1) can also be applied to describe physical equilibria of a different nature. For example, in a vertically isothermal atmosphere in the absence of gravity $k_E = 0$.)

Such a formulation (proportionality of condensation rate to k_v) presumes that the deviation k_v of the vertical distribution of water vapor from equilibrium is due to condensation alone. (This premise is empirically testable: where condensation is absent, the vertical water vapor distribution should have the same scale height as the non-condensable gases and moist air as a whole.) This removes the need to consider N_v as the saturated vapor concentration. When $k_v = 0$, the condensation rate is zero independent of whether water vapor is saturated or not. When $k_v \neq 0$, N_v is saturated water vapor by formulation.

A.3 Distribution of vapor, dry air and moist air as a whole

We write the condition that moist air with molar density N is in equilibrium in the vertical dimension as:

$$-\frac{1}{N}\frac{\partial N}{\partial z} \equiv k = k_E, \quad N = N_v + N_d. \tag{A2}$$

Condensation causes the distribution of vapor N_v to deviate from the equilibrium distribution. The condition that moist air as a whole must nevertheless remain in equilibrium causes dry air N_d to also deviate from the equilibrium – but in the opposite direction to the vapor:

$$-\frac{\partial N_v}{\partial z} = (k + k_v)N_v, \ \ -\frac{\partial N_d}{\partial z} = (k + k_d)N_d, \tag{A3}$$

$$k_v N_v + k_d N_d = 0, \tag{A4}$$

$$k_v = -\frac{1}{N_v}\frac{\partial N_v}{\partial z} - k, \ k_d \equiv -\frac{1}{N_d}\frac{\partial N_d}{\partial z} - k. \tag{A5}$$

The value of k_v describes the intensity of the mass sink. In the case of water vapor $k_v > 0$ is caused by a steep vertical temperature gradient that causes vapor to condense (Makarieva and Gorshkov, 2007, Sec. 3). From consideration of the Clausius-Clapeyron law and hydrostatic equilibrium (see also Eqs. (20), (24) and (25) in our paper, pp. 24024, 24026) one can see that

$$k_v = \frac{L\Gamma}{RT^2} - \frac{Mg}{RT}, \tag{A6}$$

where L is molar vaporization constant, $\Gamma \equiv -\partial T/\partial z$ is temperature lapse rate, and M is molar mass of air.

The value of k_v is controlled by temperature lapse rate Γ – keeping all other variables constant, changing Γ it is possible for k_v to take any value, $-\infty < k_v < \infty$. This validates our assumption that k_v can be kept independent of N_v when investigating the limit behavior $N_v \to 0$ in Eq. (A10): for any N_v (e.g., set by ambient temperature) any value of k_v can be prescribed by changing Γ.

A.4 The limit behaviour $\partial N_d/\partial x \to 0$

Using Eqs. (32), (33) and $\partial N_v/\partial x = 0$ we obtain:

$$u\frac{\partial N_d}{\partial x} = (S_d - S)\frac{1}{\gamma_d}, \tag{A7}$$

where

$$S_d \equiv w\left(\frac{\partial N_v}{\partial z} - \gamma_d\frac{\partial N_d}{\partial z}\right), \ \ \gamma_d \equiv \frac{N_v}{N_d}. \tag{A8}$$

The magnitude of condensation rate S in (A7) remains unknown. Note that under terrestrial conditions $1/\gamma_d \gg 1$.

Putting (A3) into (A7) using (A4) we obtain:

$$u\frac{\partial N_d}{\partial x} = -wk_v N_d\left(1 + \frac{N_v}{N_d} + \frac{S}{wk_v N_v}\right). \tag{A9}$$

Now putting $S = CN_v$ into (A9) we have

$$\frac{\partial N_d}{\partial x} = -wk_v\frac{N_d}{u}\left(1 + \frac{N_v}{N_d} + \frac{C}{wk_v}\right). \tag{A10}$$

We require that $\partial N_d/\partial x \to 0$ at $N_v \to 0$ (no horizontal density gradient in the absence of condensable substance). This condition follows from considering that, aside from condensation, there are no processes in the atmospheric column that would make the air distribution deviate from a static equilibrium. This limit is general and should apply to all conditions, including cases where all other variables in (A10) are independent of N_v. From this condition we obtain $C = -wk_v$ and

$$S = -wk_v N_v, \tag{A11}$$

which is Equation (34). An experiment to test this relationship would be to consider a circulation with given vertical and horizontal velocities w and u, set k_v and N_d and change the saturated molar density N_v by either changing the condensable gas or the amount of condensation nuclei in the atmosphere or temperature (see below) or both. One will observe that as the condensable gas disappears from the atmosphere, the horizontal pressure gradients vanish. (It is interesting to note the following. Given that the spatial distribution of N_v is exponential, $N_v(z) = N_0 \exp(-z/h_N)$, the local condition $N_v \to 0$ corresponds to complete disappearance of the condensable component from the atmosphere and restoration of equilibrium in the horizontal plane. In comparison, the local condition $k_v \to 0$ does not presume that condensation is absent everywhere else in the atmosphere (it is plausible that k_v changes stepwise at the point where condensation commences).)

In the obtained formulation (A11) condensation rate S is a linear function of three independent variables: vertical velocity w, local amount of vapor N_v and deviation k_v of vapor from the equilibrium distribution (k_v can be characterized as the "condensability strength" of atmospheric vapor). Note an interesting relationship: with S given by (A11) and $\gamma \equiv N_v/N$ we have $S_d - S \equiv S\gamma_d \equiv S_d\gamma$.

A.5 Conclusions

Eqs. 32 and 33, taken together, contain the information that it is water vapor and not dry air that undergoes condensation. Eq. 34 contains information about the magnitude of deviation from equilibrium that causes condensation. Jointly considered, these facts are sufficient to determine the horizontal pressure gradient produced by the vapor sink.

Note that in Eq. (A7) any small difference of the order of γ_d between S and S_d is multiplied by a large magnitude $1/\gamma_d \gg 1$ and thus has a profound influence on the magnitude of the horizontal gradient $\partial N_d/\partial z$. We emphasize the point we made in Section 4.2: if it were dry air to be in equilibrium, i.e. $k_E = -(1/N_d)\partial N_d/\partial z$, the same

consideration of the same equations would give $\partial N_d/\partial x = 0$ instead of $\partial N_d/\partial x = S/u$ as in the case when it is moist air that is in equilibrium. This profound impact of the nature of equilibrium on the dynamics associated with condensation has never been expored in meteorological theory.

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A Comparing forces due to condensation and buoyancy

Fig. 1c describes the relative contributions of latent heat release and the condensational vapor sink to the *horizontal* pressure differences. This result can also be illustrated by comparing the *vertical* forces associated with phase transitions of water vapor.

The buoyant force acting per unit moist air volume can be written as

$$f_B = \rho_p g \left(\frac{\rho}{\rho_p} - 1 \right) = \rho_p g \left(\frac{T(z)}{T_d(z)} \frac{1}{1 - (M_v/M_d)\gamma(z)} - 1 \right). \qquad \text{(B1)}$$

Here ρ_p is the density of the air moist air parcel that ascends in the environment with density ρ. (Note when f_B is taken per unit mass by dividing by density ρ_p and integrated over z, one obtains the *convective available potential energy* (Glickman, 2000), which represents work performed by the buoyant force.)

Fig. 2a shows the buoyant force acting on an air volume from column A that rises moist adiabatically in the dry adiabatic environment of column B: $\rho_p = p_B(z)M/RT$, $\rho = p_B(z)M_d/RT_d$. Here p_B is given by (31), T_d follows the dry adiabatic profile $T_d(z) = T_s - \Gamma_d z$, where $\Gamma_d = 9.8$ K km^{-1}, while temperature $T(z)$ and molar mass $M(z) = M_d[1 - (M_v/M_d)\gamma(z)]$ of the rising air satisfy Eqs. (22)-(23). The positive value of the buoyant force at the surface is due to the lower molar density of the moist versus dry air.

The same figure shows the condensational pressure gradient force that acts in the column where moist saturated air ascends adiabatically.

$$f_C = \frac{p_v}{p}\frac{\partial p}{\partial z} - \frac{\partial p_v}{\partial z} = -p\frac{\partial \gamma}{\partial z}. \tag{B2}$$

Here p and γ conform to Eqs. (22)-(23).

As Fig. 2a shows, the two forces have different spatial localization. The condensational force has a maximum in the lower atmosphere where the amount of vapor is maximized. The buoyant force grows with height following the accumulating difference between the moist adiabatic and dry adiabatic temperatures. At $T_s = 300$ km at $z = 8$ km the difference theoretically amounts to over 50 K.

The buoyant force estimated in Fig. 2 represents a theoretical upper limit that assumes zero heat transfer between the ascending air and its environment. Maximum temperature differences observed in the horizontal direction in real weather systems are typically much smaller than 50 K at any height. In Fig. 2b the same forces are plotted, but for the buoyant force estimated for an environment having a mean tropospheric lapse rate of 6.5 K km^{-1} (rather than the dry adiabatic lapse rate 9.8 K km^{-1}). As Fig. 2b shows, the magnitude of the buoyant force drops rapidly with diminishing differences in temperature. Convective available potential energy associated with the buoyant force shown in Fig. 2a is $\int_0^{8\,\mathrm{km}}(f_B/\rho_p)dz = 8.5 \times 10^3$ J kg^{-1}. This is several times higher than the typical values calculated from the lapse rate soundings of the atmospheric

column of 12 km height in the most intense convection events like thunderstorms and tornadoes (e.g., Thompson et al., 2003; Kis and Straka, 2010). This shows the degree by which the theoretical buoyant force is overestimated in Fig. 2b.

The key message from Fig. 2 is that the condensational force remains comparable in magnitude to the buoyant force even when the latter is allowed (for the sake of argument) to take unrealistically high values. Furthermore the condensational force dominates in the lower atmosphere with the buoyant force more pronounced only in the upper atmosphere. We note that both the buoyant and condensational forces are vertically directed. But we emphasise that their action in the atmosphere is manifested in the formation of horizontal pressure gradients. This follows from the independent stipulation that the atmosphere is vertically in approximate hydrostatic equilibrium. In Section 4 we derive the horizontal pressure gradients associated with the condensational force.

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Legend to Fig. 2. Condensational force f_C (B2) (solid curves) and buoyant force f_B (B1) (dashed) acting at height z on a moist air volume ascending in an environment with dry adiabatic lapse rate 9.8 K km^{-1} (a) and mean tropospheric lapse rate 6.5 K km^{-1} (b) for different values of surface temperature T_s.

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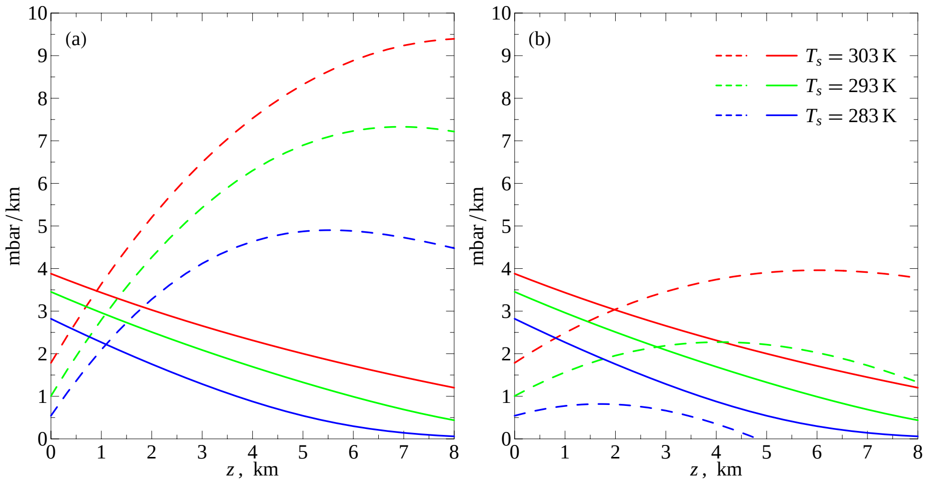

Fig. 2.