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LETTER

Feedback mechanisms of shallow convective clouds in a warmer climate as demonstrated by changes in buoyancy

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Abstract

Cloud feedbacks could influence significantly the overall response of the climate system to global warming. Here we study the response of warm convective clouds to a uniform temperature change under constant relative humidity (RH) conditions. We show that an increase in temperature drives competing effects at the cloud scale: a reduction in the thermal buoyancy term and an increase in the humidity buoyancy term. Both effects are driven by the increased contrast in the water vapor content between the cloud and its environment, under warming with constant RH. The increase in the moisture content contrast between the cloud and its environment enhances the evaporation at the cloud margins, increases the entrainment, and acts to cool the cloud. Hence, there is a reduction in the thermal buoyancy term, despite the fact that theoretically this term should increase.

1. Introduction

Cloud response to a warmer climate may determine the overall climate system state (Schneider *et al* 2017). Since clouds are responsible for two thirds of the Earth's albedo and for a large fraction of the outgoing long wave radiation (Peixoto and Oort 1992), even relatively small changes (O 1%) in cloud cover or properties may significantly affect the overall radiation balance. A positive cloud feedback implies that in addition to the induced warming (e.g. by greenhouse gases) the system will be additionally warmed by the cloud response. In contrast, a negative feedback implies an increase in the cooling contribution of clouds (mostly by shortwave reflection back to space by low-level warm clouds (Hartmann and Short 1980, Sherwood *et al* 2014) or less warming by high cirrus clouds (Bony *et al* 2016)). Despite their importance, cloud feedbacks are still considered a significant source of uncertainty in climate sensitivity estimations (Flato *et al* 2013, Schneider *et al* 2017, Soden and Held 2006). For example, warm convective clouds are responsible for the largest uncertainty in tropical cloud feedbacks as treated in climate models (Bony and Dufresne 2005, Webb *et al* 2006). Many recent studies have approached this question in an attempt to better understand the feedbacks and the processes controlling them (Gettelman and Sherwood 2016).

The current hypothesis regarding the amount of atmospheric water vapor in a warmer environment asserts that it will increase with the surface temperature while maintaining roughly constant relative humidity (RH) conditions over large regions of the globe (Held and Soden 2006). This is also supported by observations (Bony *et al* 1995, Stephens 1990, Wentz and Schabel 2000).

Many climate models (Boucher *et al* 2013) and Large Eddy Simulation (LES) models studies (Blossey *et al* 2016, Tan *et al* 2017) predict a positive feedback of shallow clouds to global warming i.e. a reduction in the low-level cloud cover (in response to warming) that enhances the initial warming. However, some contradicting feedbacks of warm convective clouds have also been suggested. For example:

1. With the increase in temperature at constant RH, the adiabatic liquid water content increases and thus drives an increase in cloud water and consequently a larger cloud albedo (Charlock 1982, Paltridge 1980, Rieck *et al* 2012, Somerville and Remer 1984).

This acts as a negative feedback and reduces the warming.

2. An increase in moisture contrast between the boundary-layer and the free atmosphere in a warmer climate (Van der Dussen *et al* 2015) and an increase in surface moisture fluxes (Held and Soden 2000, Xu *et al* 2010) can drive deepening and drying of the boundary-layer due to enhanced vertical mixing with the free troposphere. This feedback will result in a reduction in cloudiness and hence acts as a positive feedback (Bretherton 2015, Rieck *et al* 2012, Sherwood *et al* 2014, Van der Dussen *et al* 2015, Qu *et al* 2015b).

The representation of clouds and microphysical processes in climate models can dramatically affect the cloud feedbacks (Zhao *et al* 2016). For example, it has recently been shown that the positive feedback of the deepening and drying of the boundary-layer under global warming are prevented in case of precipitating clouds (Vogel *et al* 2016). This happens due to reduced evaporation near the inversion layer (Dagan *et al* 2016). Detailed process representation of this kind is not feasible in climate models.

It has previously been noted that both circulations on the global scale (order of 1000 s km) and on the regional scale (order of a grid box in current climate models ~100 km) can contribute to enhanced mixing between the boundary-layer and the free troposphere under global warming (Sherwood *et al* 2014).

Here we explore the smaller scale of a warm convective cloud (~1 km) response to a warmer atmosphere. Focusing on single cloud scale processes allows a separation from larger scales processes, like changes in the thermodynamic conditions of the boundary-layer (Rieck *et al* 2012, Tan *et al* 2016) and hence better understanding of low-cloud feedback mechanisms that are hard to detect in an evolving cloud field. Moreover, studying cloud feedbacks on the cloud field scale (using LES), has been shown to be sensitive to the assumptions regarding the changes in large scale forcing and surface fluxes (Tan *et al* 2016). Focusing on the single cloud scale avoids these sensitivities. We examine the cloud buoyancy response to an idealized representation of a warmer climate, meaning a uniform increase in temperature under a constant RH, similar to what has been done in many previous works (Rieck *et al* 2012, Vogel *et al* 2016, Van der Dussen *et al* 2015). We note that this is a simplified representation of warmer atmosphere and it does not capture all environmental changes, such as changes in large-scale vertical motion and inversion strength (Qu *et al* 2015a). Nevertheless, a simplified view is justified since the changes in the RH and lower atmosphere temperature lapse rates are expected to be bounded (Held and Soden 2006), and such an assumption allows a first approximation of the cloud response. Since buoyancy is the driving force for convection and is directly modulated by the environmental conditions, it could serve as a robust measure of the cloud-scale response to warming.

2. Theoretical framework

The buoyancy of an air parcel (B) is proportional to the deviation of its density from a reference environmental state. Using Lifted Parcel Theory (Pruppacher *et al* 1998), where the pressure of the air parcel is assumed to be equal to that of the environment, the buoyancy of a warm cloud can be written as (Cotton *et al* 2010):

$$B \approx g\left(\frac{T'}{T_0} + 0.61q_v' - q_w\right) \tag{1}$$

where g is the gravitational acceleration, T' is the temperature difference between the air parcel and the reference state of the environment (perturbation), T_0 is the temperature of the environment, q_v' is the perturbation in the water vapor mixing ratio, and q_w is the liquid water mixing ratio. Equation (1) shows that the total buoyancy is composed of three components: thermal (B_T), humidity (B_V—the virtual effect), and water-loading (B_W - i.e. 1st, 2nd, and 3rd term, respectively). For deep convective clouds, the vertical integral of the buoyancy (convective available potential energy, CAPE) is dominated by the thermal component (Doswell III and Rasmussen 1994). On the other hand, for shallow clouds, the virtual effect becomes increasingly important (Doswell III and Rasmussen 1994).

The entrainment rate of unsaturated air into the cloudy moist air depends on the environmental conditions (e.g. RH and stability) (Dawe and Austin 2013, Stirling and Stratton 2012), which impacts the buoyancy terms. On the one hand, entrainment enhance the evaporation and hence reduce the water-loading (reduce the absolute value of this negative term) but on the other hand, the enhanced evaporation cools the cloud and reduces the thermal buoyancy term. As long as the cloud is close to saturation, the humidity term remains roughly the same. The overall change in the thermal term is likely to be larger than the change in the water-loading and therefore the total buoyancy is likely to be reduced (Wang *et al* 2009). The extent to which a given entrainment rate reduces buoyancy (the entrainment efficiency) depends on the water vapor content contrast between the cloud and the environment (Singh and O'Gorman 2013).

We study the competition between the buoyancy components in a warmer environment in two stages. First, we approach the problem analytically for an adiabatic parcel, assuming no entrainement and no sedimentation. Then we add the effects of these processes, using a numerical model of a single cloud. We note that we focus on relatively fast responses, within the lifetime of a single cloud. Such scales have mostly been overlooked in studies that have examined the regional and global response to warming.

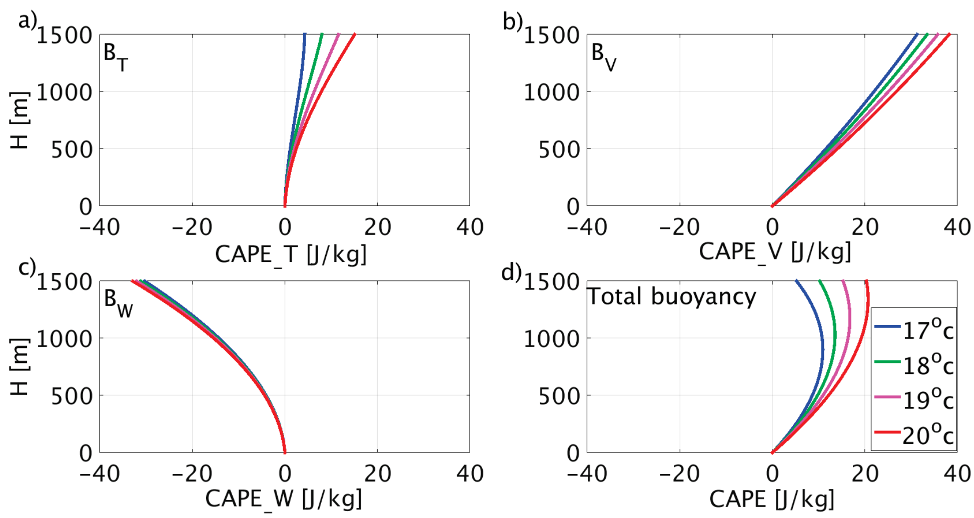

Figure 1. Vertical integral (CAPE) of (*a*) thermal buoyancy term (B_T), (*b*) virtual term (B_V), (*c*) water-loading term (B_V), and (*d*) total buoyancy, for four different cloud base temperatures at 900 mb. The environmental RH in the cloudy-layer in all cases is 70% and the thermal lapse rate is 5 °C km^{-1}. The *y*-axis is the height (*H*) of the upper bound of the integration representing the cloud depth.

3. Theoretical calculations of buoyancy

We start with a simplified case of an adiabatic parcel, assuming no entrainment and no precipitation. Figure 1 presents the profiles of the vertical integral of the different buoyancy terms (CAPE: CAPE_T, CAPE_V and CAPE_W—see equations S1–S3, supplementary material available at stacks.iop.org/ERL/13/054033/mmedia) and the total CAPE, for four different cloud base temperatures (17 °C–20 °C). These four cases represent theoretical clouds forming in progressively warmer profiles with the same RH.

With increasing temperature the thermal buoyancy term (B_T—figure 1(*a*)) increases due to enhanced latent heat release (a warmer air at saturation holds more water vapor and condenses a larger mass for the same increase in height). This is expressed by the dependence of the moist adiabatic lapse rate on the temperature, which is given by:

$$\Gamma_{\text{moist\_adiabat}} = -\left.\frac{dT}{dZ}\right|_{\text{moist\_adiabat}} = \frac{g}{c_{\text{pd}}}\frac{1+\frac{Lq_s}{R_d T}}{1+\frac{L^2\varepsilon q_s}{R_d c_{\text{pd}} T^2}} \qquad (2)$$

(Rogers and Yau 1989).

Where Z is the height, c_{pd}—specific heat capacity under constant pressure, L—heat required for phase transition of unit mass of liquid water to vapor, R_d—gas constant for dry air, q_s—saturation water vapor mixing ratio and ε is the ratio between the molecular weight of water and dry air (= 0.622).

Changing the cloud base temperature or pressure (and hence q_s) would change $\Gamma_{\text{moist\_adiabat}}$ and hence, for a given environmental lapse rate (Γ_e), will change the B_T term.

The change in B_T with an increase in temperature is proportional to the product of the change in $\Gamma_{\text{moist\_adiabat}}$ and the cloud depth (H):

$$\frac{dB_T}{dT} \propto \frac{d(\Gamma_{\text{moist\_adiabat}})}{dT}\cdot H. \qquad (3)$$

For a given Γ_e at the cloudy layer, a uniform increase in temperature will result in an increase in the temperature difference between the cloud and the environment of approximately 0.07 °C·km^{-1} (see figure S1, supplementary material). For a typical shallow convective cloud with a depth of ~1 km the resultant change in B_T will be ~0.0025 m s^{-2}, meaning that for 5 min of the cloud lifetime the vertical velocities in the clouds will increase by ~0.7 m s^{-1}. Such an effect is significant for shallow convective clouds.

The virtual term (B_V—figure 1(*b*)) also increases with temperature. This term is proportional to the difference in water vapor mixing ratio between the cloud and the environment ($q_s - q_e = \Delta q_v$). For a given environmental RH (and assuming that the cloud is at saturation) Δq_v increases with increasing temperature.

$$\frac{dB_v}{dT} = g\cdot 0.61\cdot\left(\frac{dq_s}{dT} - \frac{dq_e}{dT}\right) \qquad (4)$$

where q_e is the environmental water vapor mixing ratio. The change in B_V will follow the Clausius–Clapeyron relation and hence should increase by ~7% per 1 °C increase (Held and Soden 2006).

The adiabatic water lapse rate increases with temperature by about 1%–2%/1 °C (for the relevant temperature range in our case—see equation (2) in Rieck *et al* (2012)) and hence the water-loading buoyancy term becomes more negative (figure 1(*c*)). The relative change of this term (1%–2%/1 °C) is smaller

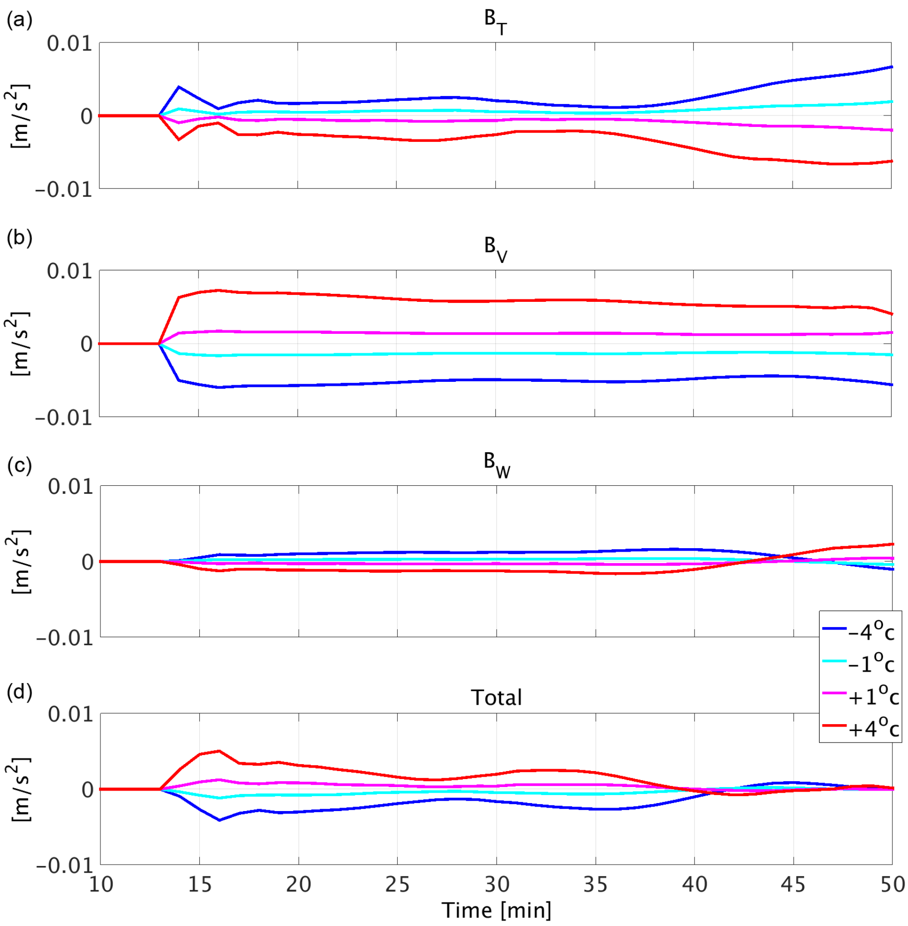

Figure 2. The evolution of the differences from the reference simulation of: (*a*) thermal buoyancy term (*b*) virtual term, (*c*) water-loading term, and (*d*) total buoyancy, for different temperature profiles representing uniform temperature change, compared to the control profile.

than the relative change in B_V (~7%/1 °C). The overall effect is an increase in the total buoyancy with warming (figure 1(*d*)).

As the entrainment rate depends on the environmental conditions (like environmental RH and stability (Dawe and Austin 2013, Stirling and Stratton 2012)), its effect on cloud buoyancy adds another layer of complexity. To test how the buoyancy terms evolve under a warmer climate, including the entrainment and sedimentation roles, we use the Tel Aviv University axisymmetric nonhydrostatic single-cloud model with detailed bin microphysics (Reisin *et al* 1996, Tzivion *et al* 1994). The detailed treatment of sedimentation enables more accurate calculations of the water-loading effect on the total buoyancy. Additional details on the model can be found in the supplementary material.

We use a marine background aerosol size distribution (Jaenicke 1988) with total concentration of ~295 cm^{-3}, which for these soundings allows the clouds to precipitate. In addition to modifying precipitation, changes in the aerosol loading will also impact the entrainment rate (Dagan *et al* 2015, Jiang *et al* 2006, Small *et al* 2009, Xue and Feingold 2006). However, sensitivity tests were conducted with a higher aerosol concentration (1000 cm^{-3}, not shown) and they reveal the same general trend with warming as described below.

We initialized the model with five different idealized atmospheric profiles that produce warm convective clouds (similar in nature to what was shown in (Dagan *et al* 2015, Malkus 1958)). The simulations include a control simulation and four other simulations with a uniform temperature change (−4 °C, −1 °C, +1 °C, and +4 °C) keeping the RH profile the same for all runs (Rieck *et al* 2012, Vogel *et al* 2016) (see supplementary material, figure S2).

Figure 2 presents the temporal evolution of the differences from the control simulation of the cloud-mean thermal buoyancy term (B_T), virtual term (B_V), water-loading term (B_W), and total buoyancy. The values represent the mean buoyancy terms of all cloudy pixels in the domain (with liquid water content above 0.01 g kg^{-1}) weighted by liquid water mass. A simple volume averaging shows the same trend. Figure S3, (supplementary material) presents the values of these terms for all simulations.

As opposed to the theoretical predictions that showed an increase in B_T with the rise in temperature (figure 1(*a*)), when entrainment is included it drives a

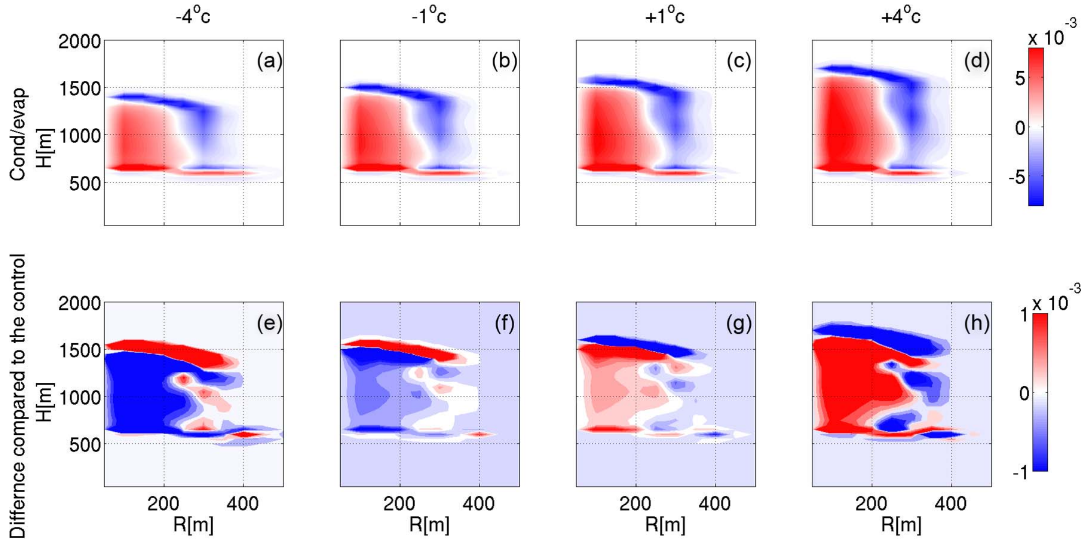

Figure 3. Vertical cross section (as a function of distance from the cloud center (R) and height (H)) of the condensation and evaporation rates [g/kg/s] at $t = 35$ min for the different simulations (*a*)–(*d*) and the differences compared to the control simulation (*e*)–(*h*).

reduction in B_T (figure 2(*a*), a ~7% reduction per 1 °C increase for our simulations). The processes leading to a decrease in B_T (entrainment and evaporative cooling) are fueled by the increased contrast in the humidity content, between the cloud and its environment—Δq_v. For a given environmental RH, Δq_v increases by ~7% per 1 °C temperature increase (according to the Clausius–Clapeyron relation). Increasing Δq_v enhances the evaporation and entrainment rates at the cloud margins. From an eddy diffusivity point of view, the increased water vapor gradient between the cloud and the surrounding drives an increased mixing rate (Peixoto and Oort 1992). Moreover, the extent to which a given entrainment rate acts to cool the cloud also increases with the difference in water vapor mixing ratio between the cloud and its environment (meaning higher entrainment efficiency) (Singh and O'Gorman 2013). Figure 3 presents the condensation and evaporation rates in the different simulations and the differences from the control run. It shows a simultaneous increase in condensation rate in the cloud core and in evaporation rate at the cloud margins in the warmer simulations, which results in a stronger horizontal buoyancy gradient (figure S4, supplementary material) that in turn drives a vortical circulation and enhances the entrainment rate (Jiang *et al* 2006, Small *et al* 2009, Zhao and Austin 2005). This enhanced evaporation at cloud margins overwhelms the benefit of higher latent heat release (figure 1(*a*)), and hence reduces the temperature and the B_T.

This argument at the cloud scale resembles the argument at larger scales regarding the drying of the planetary boundary-layer due to an increase in the humidity contrast (Rieck *et al* 2012, Sherwood *et al* 2014).

A similar mechanism of evaporation-entrainment feedback was previously reported in studies of aerosol effects on warm clouds. Namely, it was shown that increased evaporation rate at the cloud margins in polluted environment enhances the rates of entrainment and mixing between the cloud and its environment (Dagan *et al* 2015, Jiang *et al* 2006, Small *et al* 2009, Xue and Feingold 2006). In our case the enhanced evaporation and hence mixing rate is a result of the increase in the water vapor contrast rather than the decrease in droplet size.

While the B_T response changes sign, B_V does increase with temperature (figure 2(*b*)) as expected by the theoretical calculations (figure 1(*b*)). The rate of increase is ~5.5%/1 °C—smaller than but close to the prediction by the Clausius–Clapeyron relation. Since the liquid water in the cloud acts as a buffer to maintain conditions close to saturation, B_V is much less susceptible to the entrainment effect compared to B_T. As long as there is liquid water in the cloud the difference in water vapor between the saturated cloud and the environment remains roughly constant. In this case, B_T is negative while B_V is positive and dominant (see figure S3 and section S4 in the supplementary material). A theoretical discussion of the sign of B_T and its ratio with B_V is presented in section S4, supplementary material.

The water-loading (B_W—figure 2(*c*)) increases with temperature. This increase is ~1%–2%/1 °C, as expected from the increase in the adiabatic water lapse rate (Rieck *et al* 2012). The increase in B_W in the non-adiabatic case (the cloud model simulations) is also a result of competing processes. On the one hand, it is driven by the increase in the total buoyancy with increasing temperature (figure 2(*d*)) which results in increased condensation in the cloud core (figure 3). On the other hand, due to the increase in humidity and buoyancy contrast between the cloud and its environment the evaporation at the cloud margins

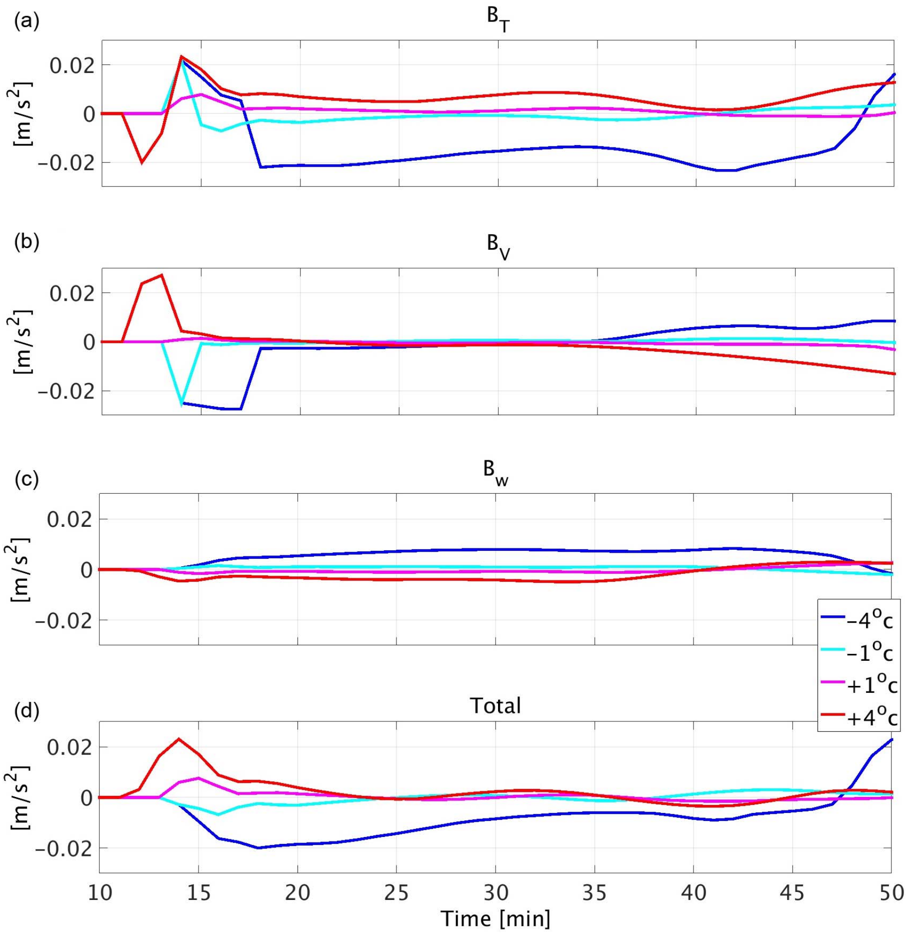

Figure 4. Same as figure 2 but for the second set of simulations, with constant water vapor contrast between the cloud (at saturation) and the environment (Δq_v) rather than fixed RH conditions.

also increases (figure 3). All the buoyancy term responses to temperature change, as presented above, are approximately linear and consistent for both cooling and warming (Webb *et al* 2017).

The decrease in B_T and the increased cloud edge evaporation that accompany the environmental warming can lead to a reduction in cloud cover (if it overwhelms the increase in condensation in the cloud core) and hence to a positive feedback by warm convective clouds to the induced warming. However, in this paper our goal is to clarify basic mechanisms that would affect the cloud feedback, and not the feedback itself.

To further examine the role of increased Δq_v in the resulted decrease in B_T with the environmental warming we conduct additional set of simulations in which we use the same temperature profiles but with fixed Δq_v (as in the control simulation, see figure S9, supplementary material). Figure 4 is similar to figure 2 but it is based on the set of simulations in which Δq_v is fixed, (see figure S10, supplementary material, for the values of these terms for all simulations). Fixing Δq_v results in similar values of B_V in the different simulations (figure 4(*b*)). The large differences in B_V in the first few minutes of the simulations are due to different cloud base heights since they are determined by the RH below cloud base and the differences toward the end of the simulations are due to differences in the rain amount that influence the humidity. However, as opposed to the set of simulations with fixed RH conditions (figure 2(*a*)), in the case of fixed Δq_v, B_T increases with warming (figure 4(*a*)) due to the increase in the latent heat release, as was shown in the adiabatic case (figure 1). These results demonstrate that the decrease in B_T with warming under constant RH conditions is due to the increase in moisture content contrast. We note that under fixed Δq_v conditions the horizontal buoyancy gradient (figure S11, supplementary material) does not increase with warming as in the fixed RH conditions (figure S4, supplementary material).

The relative importance of these competing effects at the cloud scale as presented here depends on the thermodynamic conditions and cloud size. Under different environmental RH and/or thermodynamic instability and/or cloud layer depth, the relative importance of the different buoyancy terms changes (section S4, supplementary material). Therefore, the changes in the processes that are driven by environmental warming may result in different cloud responses.

For example, in a more humid environment, the entrainment effect will be weaker and therefore changes in its magnitude due to warming would be smaller compared to that shown here. Changes in the temperature lapse rate with warming could also affect the predicted cloud properties. In addition, aerosols could modify precipitation, cloud edge evaporation, and influence the way clouds interact with their environment at the scale of the cloud field (Bretherton *et al* 2013, Dagan *et al* 2016, Dagan *et al* 2017).

Our arguments rely on the fact that Δq_v increases with warming (under constant RH conditions). Although the RH is expected to remain roughly constant under global warming (Held and Soden 2006) small changes in it (which are hard to predict) may affect the Δq_v response. Hence, understanding the effect of small changes in RH on the mechanism proposed here is important. Any reduction in RH that will accompany the warming will drive a further increase in Δq_v and thus will only increase the reduction in B_T and increase in B_V (see figures S12–S13, supplementary material). On the other hand, an increase in RH with warming will compensate for the increase in Δq_v and therefore will reduce the effect (see figures 4 and S12–S13, supplementary material). The required magnitude increase in RH to fully compensate for the increased Δq_v (as a function of the initial temperature and the change in temperature) is presented in figure S14, supplementary material.

3. Summary

In this study, we focus on the effects a uniform warming would have on warm convective clouds. To do so, we examine the response of the buoyancy terms, i.e. the drivers of the convection, to a warmer environment. We expose a new low-level convective cloud feedback mechanism—namely enhanced evaporation, which may result in increased entrainment rate and efficiency. Specifically, we show that under specified constant RH profiles, an increase in temperature would drive an increase in water vapor content contrast between the cloud and its environment. This enhanced contrast has opposing effects on the cloud development. On the one hand, it increases the virtual effect, which enhances the cloud development. On the other hand, it enhances the evaporation at the cloud margins and the entrainment rate and efficiency between the cloud and its environment and hence can decrease the thermal buoyancy.

The goal of this paper is to describe the response of the processes acting in a single cloud to warmer environmental conditions. These processes have mostly been overlooked in studies that have focused on the larger scales of cloud-field, synoptic, and global scales. Nevertheless, we cannot determine, based on our current findings, a general response of warm convective clouds to a warmer environment. Both the focus on a single cloud scale and the assumption of a uniform temperature change and constant RH profiles prevent us from doing so. Even though the uniform warming and constant RH conditions are widely used in studies of warm convective cloud feedbacks (Rieck *et al* 2012, Vogel *et al* 2016), they do not capture the range of predicted environmental changes in large-scale circulation and thermodynamic conditions. Within these predicted changes (with their given uncertainty) in the thermodynamic conditions, which impact the cloud response (Tan *et al* 2016), the exploration of the single cloud scale enables a better understanding of the whole system, since the interaction between the cloud scale and the larger scale processes will determine eventually the overall cloud response to warming.

Our argument regarding increased mixing rate between the cloud and its environment due to warming resembles the argument about enhanced mixing between the boundary-layer and the free troposphere in a warmer climate due to an increased humidity contrast (Bretherton 2015, Rieck *et al* 2012, Sherwood *et al* 2014, Van der Dussen *et al* 2015) but at smaller scales. The arguments presented here are applicable both in non-precipitating and precipitating conditions. The clouds presented here are precipitating clouds, however, even in the case of non-precipitating simulations—for example under higher aerosol concentrations—the general trend was found to be the same.

To summarize, this work examines the changes in warm cloud processes in response to global warming. The increased effect of entrainment and evaporation with warming at the single cloud scale should be accounted for, in addition to other known mechanisms at larger scales (see a recent review (Gettelman and Sherwood 2016)) when predicting cloud feedbacks and implications for future climate.

Acknowledgments

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