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

To cite this article: G Dagan et al 2018 Environ. Res. Lett. 13 054033

View the article online for updates and enhancements.

Related content
- Aerosol effect on the mobility of cloud droplets
  Ilan Koren, Orit Altaratz and Guy Dagan
- How closely do changes in surface and column water vapor follow Clausius–Clapeyron scaling in climate change simulations?
  P A O’Gorman and C J Muller
- CONVECTION IN CONDENSIBLE-RICH ATMOSPHERES
  F. Ding and R. T. Pierrehumbert
Feedback mechanisms of shallow convective clouds in a warmer climate as demonstrated by changes in buoyancy

G Dagan1, I Koren1,3, O Altaratz1, and G Feingold2
1 Department of Earth and Planetary Sciences, The Weizmann Institute of Science, Rehovot 76100, Israel
2 Chemical Sciences Division, NOAA Earth System Research Laboratory, Boulder, CO, United States of America
3 Author to whom any correspondence should be addressed.

E-mail: ilan.koren@weizmann.ac.il

Keywords: cloud feedback, shallow convection, buoyancy

Supplementary material for this article is available online

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):

\[
B \approx g \left( \frac{T'}{T_0} + 0.61 q'_w - q_w \right)
\]

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, \(q'_w\) 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 \(B_H\), and water-loading \(B_E\) (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) (Dave and Austin 2013, Stirling and Stratton 2012), which impacts the buoyancy terms. On the one hand, entrainment enhances 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 entrainment 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.
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 (17–20°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:

$$\Gamma_{\text{moist\_adiabat}} = - \frac{dT}{dZ}_{\text{moist\_adiabat}} = \frac{g}{c_p V} \left[ 1 + \frac{k_B T}{R_d q_e} \right]^{-1} \cdot \frac{\Delta q_e}{\Delta T}$$

(2)

(Rogers and Yau 1989).

Where $Z$ is the height, $c_p$—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, $q_e$—saturation water vapor mixing ratio and $\epsilon$ is the ratio between the molecular weight of water and dry air ($= 0.622$).

Changing the cloud base temperature or pressure (and hence $q_e$) would change $\Gamma_{\text{moist\_adiabat}}$ and hence, for a given environmental lapse rate ($\Gamma_e$), 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 ($H$):

$$\frac{d B_T}{d T} \propto \frac{d (\Gamma_{\text{moist\_adiabat}})}{d T} \cdot H.$$  

(3)

For a given $\Gamma_e$ 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 $^\circ$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 ($q_v - q_e = \Delta q_v$). For a given environmental RH (and assuming that the cloud is at saturation) $\Delta q_v$ increases with increasing temperature.

$$\frac{d B_v}{d T} = g \cdot 0.61 \cdot \left( \frac{dq_v}{dT} \right)$$

(4)

where $q_v$ 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 $^\circ$C increase (Held and Soden 2006).

The adiabatic water lapse rate increases with temperature by about 1%–2%/1 $^\circ$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 $^\circ$C) is smaller
than the relative change in $B_V$ ($\sim 7\%/1^\circ C$). 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 $\sim 295 \text{ cm}^{-3}$, 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 ($-4^\circ C$, $-1^\circ C$, $+1^\circ C$, and $+4^\circ C$) 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 $0.01 \text{ g kg}^{-1}$) 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
reduction in $B_T$ (figure 2(a), a $\sim 7\%$ 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—$\Delta q_v$. For a given environmental RH, $\Delta q_v$ increases by $\sim 7\%$ per 1 °C temperature increase (according to the Clausius–Clapeyron relation). Increasing $\Delta q_v$ 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 $B_T$.

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 $\sim 5.5\%/1$ °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 $\sim 1\%$–$2\%/1$ °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 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.

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

![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).](image-url)
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 $\Delta q_v$ 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 $\Delta q_v$ (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 $\Delta q_v$ is fixed, (see figure S10, supplementary material, for the values of these terms for all simulations). Fixing $\Delta q_v$ 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 $\Delta q_v$, $B_T$ 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 $\Delta q_v$ 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.

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 ($\Delta q_v$) rather than fixed RH conditions.
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 $\Delta q_v$ 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 $\Delta q_v$ 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 $\Delta q_v$ and thus will only increase the reduction in $B_q$ 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 $\Delta q_v$ 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 $\Delta q_v$ (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

Information about the model and the relevant results for this paper are found in the supplementary material. This research was supported by the Ministry of Science and Technology, Israel (grant no. 3-14444).

ORCID iDs

I Koren  https://orcid.org/0000-0001-6759-6265
O Altaratz  https://orcid.org/0000-0002-7923-9000

References

Blossey P N, Bretherton C S, Cheng A, Endo S, Heus T, Lock A P, van der Dussen J J, 2016 CGILS phase 2 LES intercomparison of response of subtropical marine low cloud regimes to CO₂ quadrupling and a CMIP3 composite forcing change J. Adv. Mod. Earth Syst. 8 1714–26
Bony S and Duftresne J L 2005 Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models Geophys. Res. Lett. 32

Bony S, Duvel J P and de Trent H 1995 Observed dependence of the water vapor and clear-sky greenhouse effect on sea surface temperature: comparison with climate warming experiments Clim. Dyn. 11 307–20

Bony S, Stevens B, Corpin D, Becker T, Reed K A, Vugt A and Medeiros B 2016 Thermodynamic control of cirrus cloud amount Proc. Natl. Acad. Sci. 113 8927–32

Boucher O et al 2013 Clouds and Aerosols (Climate change 2013: the Physical Science Basis) (Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change) (Cambridge: Cambridge University Press) pp 371–657

Bretherton C S 2013 Insights into low-latitude cloud feedbacks from high-resolution models Phil. Trans. R. Soc. A 373 20140415

Bretherton C S, Blossey P N and Jones C R 2013 Mechanisms of marine low cloud sensitivity to idealized climate perturbations: a single-LES exploration extending the CGILS cases J. Adv. Mod. Earth Syst. 5 316–37

Charlton P F 1982 Cloud optical feedback and climate stability in a radiative-convective model Tellus 34 245–54

Cotton W R, Bryan G and van den Heever S C 2010 On the scale of deep convection in a two-dimensional cloud resolving model J. Atmos. Sci. 67 686–99

Davis A C III and Rasmussen E N 1994 The effect of neglecting the virtual temperature correction on CAPE calculations Weather Forecast. 9 625–9

Dagan G, Koren I and Altaratz O 2015 Competition between core and periphery-based processes in warm convective clouds—from invigoration to suppression Atmos. Chem. Phys. 15 2749–60

Dagan G, Koren I, Altaratz O and Heiblum R H 2016 Aerosol effect on the evolution of the thermodynamic properties of warm convective cloud fields Sci. Rep. 6 38769

Dagan G, Koren I, Altaratz O and Heiblum R H 2017 Time-dependent, non-monotonic response of warm convective cloud fields to changes in aerosol loading Atmos. Chem. Phys. 17 7435–44

Daw J and Austin P 2013 Direct entrainment and detrainment rate distributions of individual shallow cumulus clouds in an LES Atmos. Chem. Phys. 13 7795–811

Dowell C A III and Rasmussen E N 1994 The effect of neglecting the virtual temperature correction on CAPE calculations Weather Forecast. 9 625–9

Flato G, Marotzke J, Abiodun B, Braconnot P, Chou S C, Collins W J, Cox P, Driouech F, Emori S and Eyring V 2013 Evaluation of models climate model climate change 2013: the physical science basis. Contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change Clim. Change. 5 741–866

Gettelman A and Sherwood S 2016 Processes responsible for cloud feedback. Curr. Clim. Change Rep. 2 179–89

Hartmann D L and Short D A 1980 On the use of earth radiation budget statistics for studies of clouds and climate J. Atmos. Sci. 37 1253–50

Held I M and Soden B I 2000 Water vapor feedback and global warming J. Atmos. Sci. 57 441–75

Held I M and Soden B I 2006 Robust responses of the hydrological cycle to global warming J. Clim. 19 5686–99

Jaenicke R 1988 Aerosol physics and chemistry Meteorology Landolt-Börnstein vol 4b ed G Fischer (Berlin: Springer) pp 391–457

Jiang H, Xue H, Teller A, Feingold G and Levin Z 2006 Aerosol effects on the lifetime of shallow cumulus Geophys. Res. Lett. 33

Kalkos J S 1958 On the structure of the trade wind moist layer (Massachusetts: Cambridge and Woods Hole)

Paltridge G 1980 Cloud-radiation feedback to climate Q. J. R. Meteorol. Soc. 106 895–9

Peixoto J P and Oort A H 1992 Radiation balance Physics of Climate (New York: Springer) pp 91–130

Pruppacher H R and Klett J D 1997 Microphysics of Clouds and Precipitation (Dordrecht: Kluwer)

Qu X, Hall A, Klein S A and Caldwell P M 2015a The strength of the tropical inversion and its response to climate change in 18 CMIP5 models Clim. Dyn. 45 375–96

Qu X, Hall A, Klein S A and Deangels M A 2015b Positive tropical marine low-cloud cover feedback inferred from cloud-controlling factors Geophys. Res. Lett. 42 7767–75

Reisin T, Levin Z and Tzivion S 1996 Rain production in convective clouds as simulated in an axisymmetric model with detailed microphysics. Part I. description of the model J. Atmos. Sci. 53 497–519

Rieck M, Nuijens L and Stevens B 2012 Marine boundary layer cloud feedbacks in a constant relative humidity atmosphere J. Atmos. Sci. 69 2538–50

Rogers R and Yau M 1989 A Short Course in Cloud Physics, International Series in Natural Philosophy (Portsmouth, NH: Heinemann)

Schneider T, Teixeira J, Bretherton C S, Briet F, Pressel K G, Schar C and Siebesma A P 2017 Climate goals and computing the future of clouds Nat. Clim. Change 7 3–5

Sherwood S C, Bony S and Duftresne J-L 2014 Spread in model climate sensitivity traced to atmospheric convective mixing Nature 503 37–42

Singh M S and O’gorman P A 2013 Influence of entrainment on the thermal stratification in simulations of radiative-convective equilibrium Geophys. Res. Lett. 40 4398–403

Small J D, Chuang P Y, Feingold G and Jiang H 2009 Can aerosol decrease cloud lifetime? Geophys. Res. Lett. 36

Soden B J and Held I M 2006 An assessment of climate feedbacks in coupled ocean–atmosphere models J. Clim. 19 3354–60

Somerville R C and Remer L A 1984 Cloud optical thickness feedbacks in the CO2 climate problem J. Geophys. Res. Atmos. 89 9668–72

Stephens G L 1990 On the relationship between water vapor over the oceans and sea surface temperature J. Clim. 3 634–45

Stirling A and Stratton R 2012 Entainment processes in the diurnal cycle of deep convection over land Q. J. R. Meteorol. Soc. 138 1135–49

Tan Z, Schneider T, Teixeira J and Pressel K G 2016 Large-eddy simulation of subtropical cloud-topped boundary layers: 1. A forcing framework with closed surface energy balance J. Adv. Mod. Earth Syst. 8 1565–85

Tan Z, Schneider T, Teixeira J and Pressel K G 2017 Large-eddy simulation of subtropical cloud-topped boundary layers: 2. Cloud response to climate change J. Adv. Mod. Earth Syst. 9 19–38

Tzivion S, Reisin T and Levin Z 1994 Numerical simulation of hygroscopic seeding in a convective cloud J. Appl. Meteorol. 33 252–67

van der Dussen J, de Roode S, Gesso S D and Siebesma A 2015 An LES model study of the influence of the free tropospheric thermodynamic conditions on the stratocumulus response to a climate perturbation J. Adv. Mod. Earth Syst. 7 670–91

Vogel R, Nuijens L and Stevens B 2016 The role of precipitation and spatial organization in the response of trade–wind clouds to warming J. Adv. Mod. Earth Syst. 8 843–62

Wang Y, Gauthier B and French J 2009 Dynamics of the cumulus cloud margin: an observational study J. Atmos. Sci. 66 3660–77

Webb M, Senior C, Sexton D, Ingram W, Williams K, Ringer M, Mcvaney B, Colman R, Soden B and Gudgel R 2006 On the contribution of local feedback mechanisms to the range of climate sensitivity in two GCM ensembles Clim. Dyn. 27 17–38

Webb M J, Andrews T, Bodos-Salcedo A, Bony S, Bretherton C S, Chapwicz R, Chepfer H, Douville H, Good P and Kay J E 2017 The cloud feedback model intercomparison project (CFMIP) contribution to CMIP6 Geosci. Model Dev. 10 359–84



8
Wentz F J and Schabel M 2000 Precise climate monitoring using complementary satellite data sets *Nature* 403 414–6
Xu K-M, Cheng A and Zhang M 2010 Cloud-resolving simulation of low-cloud feedback to an increase in sea surface temperature *J. Atmos. Sci.* 67 730–48
Xue H and Feingold G 2006 Large-eddy simulations of trade wind cumuli: Investigation of aerosol indirect effects *J. Atmos. Sci.* 63 1605–22
Zhao M and Austin P H 2005 Life cycle of numerically simulated shallow cumulus clouds. Part II: mixing dynamics *J. Atmos. Sci.* 62 1291–310
Zhao M, Golaz J-C, Held I, Ramaswamy V, Lin S-J, Ming Y, Ginoux P, Wyman B, Donner I and Paynter D 2016 Uncertainty in model climate sensitivity traced to representations of cumulus precipitation microphysics *J. Clim.* 29 543–60