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Cloud Phase Changes Induced by CO_2 Warming—a Powerful yet Poorly Constrained Cloud-Climate Feedback

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Abstract We review a cloud feedback mechanism that has so far been considered of secondary importance, despite a body of research suggesting that it represents a powerful climate feedback that can control the sign of the overall cloud feedback simulated in global climate models (GCMs). The feedback mechanism is associated with phase changes in clouds triggered by a warming atmosphere, which in turn yields optically thicker clouds. Output from the latest generation of GCMs suggest that this is the dominant cloud feedback at high latitudes, with obvious implications for climatically sensitive regions such as the Arctic and the Southern Ocean. Here, we present an overview of the relatively few modeling studies that have investigated this particular feedback mechanism to date, along with new results suggesting that the cloud-climate feedback simulated by a GCM can change dramatically depending on its cloud phase partitioning.

Keywords Clouds · Cloud phase · Global climate modeling · Satellite observations · Cloud-climate feedback

Introduction

Twenty-five years ago, a pioneering study by Mitchell et al. [1] brought the scientific community's attention to a climate feedback mechanism that had been missing in climate model simulations of the time. The "missing feedback" was associated with the cloud phase change that comes about when the atmosphere warms in response to increased concentrations of atmospheric CO_2. A warmer atmosphere can sustain more liquid clouds at the expense of ice clouds relative to the unperturbed preindustrial atmosphere. Liquid clouds generally consist of a high number of liquid droplets, implying that each cloud droplet is very small (~10 μm) [2]. In contrast, ice clouds consist of very few but larger ice crystals that are approximately an order of magnitude larger (~100 μm) than liquid droplets. For a given cloud water content, liquid clouds are therefore generally optically thicker than ice clouds. The difference in size between liquid droplets and ice crystals arises because of the vastly more abundant cloud condensation nuclei (CCN) than ice nuclei (IN) in the atmosphere. Given the non-linear increase in hydrometeor fall speed with size, the larger ice crystals can grow more rapidly through collisions and collection of other hydrometeors, and the result is that ice clouds precipitate far more efficiently than liquid clouds [2]. Taken together, these contrasting properties between liquid and ice clouds can have profound effects on the Earth's radiative budget. Mitchell et al. had included a rudimentary representation of these effects in the cloud microphysical scheme in their global climate model (GCM) and found that accounting for the phase change approximately halved the simulated climate sensitivity (global mean surface temperature change due to a doubling of atmospheric CO_2) from 5.2 to 2.7 K. This astonishingly large and negative change in climate sensitivity implied that the phase change feedback was negative, a result that could potentially be extremely powerful. A follow-up study by Li and Le Treut a few years later qualitatively confirmed this finding [3] and reported that depending on the temperature at which liquid was assumed to convert to ice in their GCM simulations, the cloud

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feedback as a whole could change sign. It should be noted that the study calculated the cloud feedback based on so-called Cess experiments [4, 5], in which the cloud response to uniform sea surface temperature perturbations of 2 °C is evaluated. The puzzling finding by Li and Le Treut can be understood with the help of Fig. 1, which was originally published by Zelinka et al. [6] (their Fig. 1c). The figure shows the change in the top-of-the-atmosphere (TOA) radiation budget in response to cloud cover changes for all combinations of seven different cloud top pressure and optical depth categories.

As atmospheric temperatures increase, the isotherm at which clouds transition from liquid to ice moves upward in altitude, leaving behind a layer of the atmosphere dominated by liquid clouds after the warming, where ice clouds prevailed before. As a result, this layer of the atmosphere will have optically thicker and potentially longer-lived clouds, for reasons explained above. The former effect, which can be thought of as a "phase change feedback" (illustrated with schematic in Fig. 2), corresponds to moving from left to right in Fig. 1 at the relevant constant pressure level, which will be latitude dependent. The latter effect, which has been reported in multiple modeling studies but not confirmed observationally, would add cloud cover at the relevant pressure level, which would generally increase (decreases in altitude) with latitude.

Li and Le Treut were able to generate cloud feedbacks of opposing sign in their model simulations solely by changing the liquid-to-ice transition from −15 to 0 °C. They found that, in the latter case, the cloud coverage and thickness of low- to mid-level clouds increased everywhere except in the low-latitude lower troposphere (always a cooling effect, according to Fig. 1), while in the former case, the increased cloudiness or cloud optical depths occurred at mid- to high levels (cooling or warming, depending on the optical thickness and exact height, Fig. 1). Shifting the liquid-ice phase transition to colder temperatures has important implications for high latitudes. Since colder isotherms exist relatively lower in the atmosphere at high latitudes, shifting the liquid-ice phase transition to colder temperatures implies that phase changes in low clouds will be constrained to high latitudes, where their impact on the shortwave radiation budget is muted by the polar night. At high latitudes, clouds actually have a net warming effect during polar night, which is thought to be weak at the TOA but substantial at the surface, resulting from downward longwave radiation [7].

In situ and satellite observations have since these early studies demonstrated that the assumption of abrupt phase transitions at a set temperature is rather poor, as will be covered in more detail in the following section. Nevertheless, the finding that the overall cloud feedback simulated by a GCM can switch signs depending on the temperature at which phase changes are assumed to occur is one that is extremely important.

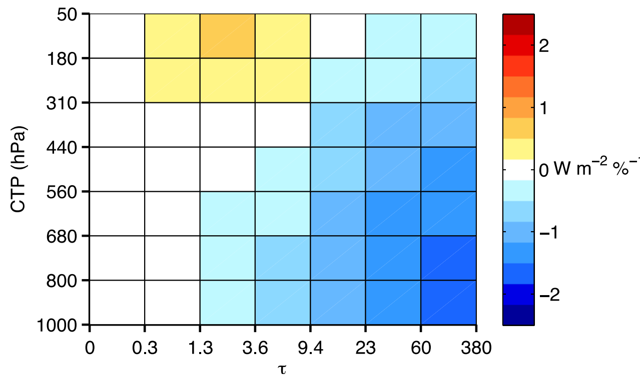

Fig. 1 The net cloud radiative kernel presented in Zelinka et al. [6], showing the net perturbation of the TOA radiation budget corresponding to cloud cover changes, shown separately for all combinations of seven different cloud top pressure and optical depth categories. For further details, see the original publication

Given the gravity of both the above findings, relatively few follow-up studies have been dedicated to fully understanding this evidently important feedback mechanism. This can in part be explained by the complicated and poorly understood processes that govern cloud phase in the temperature range −35°C to 0°C, as well as the lack of observations of cloud phase with good spatial and temporal coverage [8].

The purposes of this paper are to review the limited work that has been done dedicated to the link between cloud phase and cloud-climate feedbacks in GCMs over the last two and a half decades ("Review of Literature") and to summarize related research progress that has been made in laboratories, in the field and with numerical modeling, and satellite data recently ("Recent Relevant Research Progress—Satellite Observations, Laboratory and Field Measurements, and Model Parameterizations"). This progress has now brought us to a stage where we can revisit the feedback mechanism related to phase changes in clouds in a more thorough and comprehensive manner. New results from a recent modeling study dedicated entirely to this problem are presented in "Reexamining the Importance of the Cloud Phase Feedback" section. Finally, in the "Conclusion" section, we conclude that more research on this particular feedback mechanism is overdue and urgently needed, as it pertains to one of the most fundamental and controversial questions of our time, namely how sensitive Earth's climate is to increased atmospheric levels of CO_2.

Review of Literature

As much as the Mitchell et al. study was pioneering, the results were based on GCM simulations that were very crude in today's standard. The horizontal resolution of 5×7.5° (latitude×longitude) and 11 vertical levels for the atmosphere is far coarser than the current standard GCM resolution of 1–2°

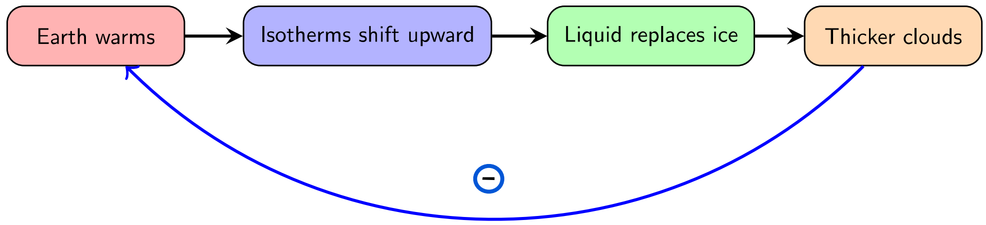

Fig. 2 Flow chart illustrating the cloud phase feedback, which in isolation represent a negative climate feedback

in the horizontal and 30–40 levels in the vertical [9]. Furthermore, model cloud parameterizations have undergone rapid development and generally now all include separate prognostic equations for cloud liquid and ice, with source and sink terms that represent our best knowledge of cloud microphysics, whether anchored in theory, laboratory experiments, field observations, or remote sensing. This is in stark contrast to the less sophisticated state-of-the-art GCMs used 25 years ago, when Mitchell et al. were among the first to include total cloud condensate (liquid and ice) as a prognostic variable. Until then, cloud amount had typically been prescribed and the clouds often had pre-specified radiative properties [10]. It was in fact Mitchell et al.'s newly improved microphysics at the time that had allowed the cloud phase change feedback to surface for the very first time.

Given the rapid evolution of GCMs in recent decades, it is not at all clear that these earlier findings are valid for the latest generation of GCMs. An obvious place to look for cloud feedbacks generated by phase changes in modern GCM simulations is the Cloud Feedback Model Intercomparison Project (CFMIP) [11]. Using model output from the CFMIP archive, Zelinka et al. [6, 12, 13] presented a decomposition of the cloud feedbacks simulated by 11 different GCMs into contributions from cloud height, cloud cover, and cloud optical depth. In response to CO_2 doubling, robust features across models included the following: (i) at low latitudes, a reduction in low cloud cover and a decrease in the cloud top pressure of high clouds, both contributing to a positive cloud feedback (see Fig. 1); (ii) at mid- and high latitudes, an increase in mainly cloud optical depth but also cloud coverage, corresponding to a negative cloud feedback. The latter is particularly relevant to this review, as the aforementioned phase transition that accompanies a CO_2 warming is a plausible, but not necessarily the sole explanation for this feature. This explanation is affirmed by Zelinka et al.'s findings of an ensemble mean increase in total water path (TWP, gm^{-2}) at high latitudes, which is dominated by an increase in the liquid water path (LWP, gm^{-2}). Observations consistent with a phase change feedback have also previously been reported from satellite data [14, 15], based on the International Satellite Cloud Climatology Project (ISCCP), and from several thousand in situ profiles of cloud water content and temperature [16]. These measurements all found that cloud water content tends to decrease with temperature for warm stratus clouds (temperature $T>0$ °C), while an increase in water content with temperature was reported for cold stratus clouds (-35 °C$<T<0$ °C). In the early days of climate modeling, Somerville and Remer [17] used the in situ measurements compiled by Feigelson [16] to implement a relationship between temperature and cloud water content in a radiative-convective equilibrium model and found a strong negative cloud-climate feedback as a result. However, the model configuration did not allow for simulation of changes in cloud cover or height, a shortcoming acknowledged by the authors. In state-of-the-art GCMs, the observed relationship between temperature and cloud thickness is in fact reasonably reproduced, albeit with biases [18].

It is worth noting that the poleward shift of mid-latitude storm tracks has also been proposed as a possible explanation for the negative high-latitude cloud feedback [e.g., 19]. While the fact that the high-latitude cloud feedback is dominated by the change in cloud albedo as opposed to cloud amount does not support this hypothesis [6], the relative contributions of the different high-latitude cloud feedback mechanisms in GCMs remain unclear. However, a recent review of the cloud radiative response to mid-latitude jet shifts found that this mechanism can only explain a modest fraction of the mid-latitude cloud feedback in climate models and thus suggested a dominant role for thermodynamic effects [20].

With the introduction of prognostic equations for total cloud condensate, the cloud parameterization in GCMs became much more sophisticated and could begin to account for phase transitions in a warming climate, albeit in a crude manner. However, temperature was generally still the sole factor in determining cloud phase. A handful of GCMs from this generation of models was compared in terms of their cloud water content and implications for climate sensitivity [21]. The study reported an intimate relationship between climate sensitivity and phase partitioning in clouds at temperatures between -35 and 0 °C (the mixed-phase layer). All models responded to a doubling of CO_2 by producing more liquid in this temperature range, and in agreement with Zelinka et al., this increase was mainly constrained to mid- and high latitudes. Until very recently, this was, to our knowledge, the only study to attempt to follow up on the ideas put forth two decades earlier. The study attributed the stronger response at high latitudes to the presence of more cloud ice in the mixed-phase layer there. Because of the decrease in insolation with latitude, the resulting increase in cloud albedo, and thus its effect on climate sensitivity, becomes less powerful with increasing latitude. This was demonstrated in the study by focusing on cloud albedo over the Southern Ocean, a region considered to be particularly sensitive and important for global climate change [22]. Cloud feedbacks over the Southern Ocean were also the focus of a recent study using several satellite data sets to estimate what albedo changes could be expected to accompany CO_2-induced warming [23]. Taking advantage of observed changes in cloud phase with the seasonal cycle, an increase in reflected shortwave radiation of 0.1–1 W m^{-2} per Kelvin of warming was deduced. These values are consistent with values reported from the CFMIP archive [12], but the negative feedback was estimated to extend further equatorward relative to the models.

A more recent modeling study presented model simulations that were dedicated specifically to the investigation of the cloud phase feedback and reported a higher climate sensitivity in simulations that had more liquid relative to ice in mixed-phase clouds [24]. However, the difference was more subtle compared to the few previous comparable model experiments [1, 3, 21]. The study pointed out that compensating changes in climate feedbacks in the tropics and extratropics could explain the more modest global mean response.

Recent Relevant Research Progress—Satellite Observations, Laboratory and Field Measurements, and Model Parameterizations

Cloud phase for temperatures between −35 and 0 °C is generally understood to be determined by the presence of IN and the subsequent growth and deposition of ice crystals. Field and satellite observations support the understanding that temperature is not the only factor that determines cloud phase and thus that the modeling approach of diagnosing cloud phase based on temperature alone is an oversimplification. Field measurements of cloud phase as a function of temperature differ significantly depending on the regions and seasons in which they were made [25] and represent snapshots of the atmosphere that are not necessarily generally valid in space and time. However, field measurements are of crucial importance for process understanding and testing of model parameterizations and therefore critical for improved GCM simulations and understanding of the cloud phase feedback. Figure 3 presents the revised statistics on phase composition of clouds for 61,765 km of in-cloud measurements [22], covering maritime and continental environments in the mid- and high latitudes of the Northern Hemisphere. The data were reanalyzed to account for the effect of bouncing on ice water content measurements based on [26].

Complementing field measurements, cloud phase can now for the first time be retrieved from space globally and over any land covers, with the launch of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite [27], carrying the first space-borne lidar for measurements of aerosols and clouds, Cloud and Aerosol Lidar with Orthogonal Polarization (CALIOP), in 2006 [27, 28]. The heterogeneity of cloud phase for a given isotherm has been confirmed based on CALIOP measurements, and land-sea contrasts as well as differences between high and low latitudes have been revealed [28, 29]. Prior to the CALIPSO era, the space-borne POLDER radiometer had been used to retrieve cloud phase from space based on angular and polarization signatures of cloud-reflected radiances, but the instrument could not retrieve cloud phase over bright surfaces and temporal coverage was poor [30, 31]. Figure 4 shows cloud phase in the form of supercooled cloud fraction (SCF) as measured at cloud tops by the CALIOP instrument throughout its lifetime (2007–2014) at the −20 °C isotherm. The SCF is here calculated by dividing the number of CALIOP pixels with liquid cloud tops by the number of total cloud tops (liquid and ice) within 2.5×2.5 grid boxes at −20+/−1 °C. Temperatures corresponding to cloud top heights were obtained from the NOAA/NCEP reanalysis data set. CALIOP data used throughout the manuscript were from versions 3.01 and 3.02 of its level 2 vertical feature mask. For more details, see Tan et al. [32].

Evident from Fig. 4 is the heterogeneity of the SCF at a fixed temperature, with high latitudes generally associated with high SCFs and low and mid-latitudes generally exhibiting low SCFs. In mixed-phase clouds (clouds that exist at temperatures below freezing but at temperatures warmer than approximately −35 °C), ice formation can only occur with the aid of IN, insoluble particles with the ability to lower the energy barrier associated with the liquid-ice phase transition at these temperatures, which would otherwise prohibit freezing. The most abundant and potent source of natural IN in the atmosphere is mineral dust, but primary organic particles and possibly black carbon have also been shown to have ice-nucleating ability [33]. Evidence suggests that differences in IN abundance and efficiency between various aerosol species are partly responsible for the heterogeneity of SCF shown in Fig. 4 [20, 29]. While this underscores the powerful effect that perturbations in IN, whether natural or anthropogenic, could have on climate, this is not the focus of the present review. The scope of this paper is limited to fast climate feedback mechanisms involving warming-induced phase changes.

The CALIOP observations as well as in situ cloud phase profiles from around the world have demonstrated that diagnosing cloud phase as a function of temperature alone is a modeling approach that is oversimplified and therefore inappropriate. This practice is now gradually being abandoned and replaced by more sophisticated cloud microphysics schemes that carry both cloud liquid and ice as prognostic variables, both in terms of mass and hydrometeor number concentrations [34–36]. This was in turn made possible by a tremendous effort to develop parameterizations of cloud microphysical

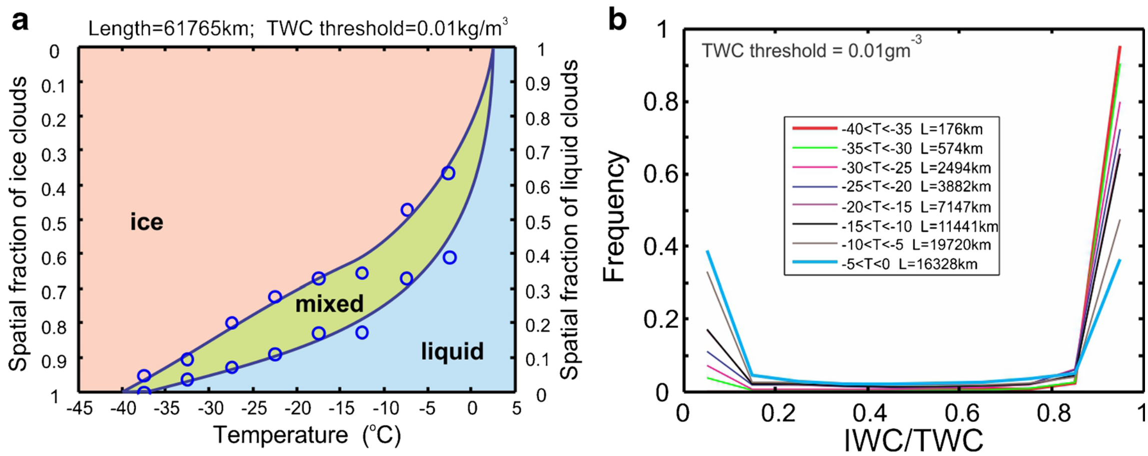

Fig. 3 **a** Spatial fraction of ice/liquid/mixed clouds and **b** cloud phase frequency of occurrence, measured as the ratio of ice water content (IWC) to total water content (TWC), with spatial averaging of 100 m. Ratios larger than 0.1 but below 0.9 are categorized as "mixed". Frequency of occurrence is provided for seven temperature intervals, and the length of in-cloud legs for each temperature interval is provided. Measurements were made in mid- and high-latitude continental and maritime air masses

processes for use in GCMs, particularly when it comes to the complex microphysics of ice crystal nucleation and subsequent growth [37–40].

In a recent study, the cloud phase of six GCMs that included state-of-the-art cloud microphysics schemes were compared to each other and to CALIOP observations [41]. While these models had all abandoned the crude determination of cloud phase based on temperature only, the intercomparison revealed a systematic bias in the simulated cloud phase. All six models produced too much ice relative to liquid compared to the satellite observations, a finding that had previously been reported for comparisons between CALIOP measurements and individual models [42, 43] and has since been confirmed for the CMIP5 modeling archive [44]. The biases were particularly large for the Southern Ocean, which stands out in Fig. 4 as a region of particularly high SCF. High SCF values are expected, because the pristine high Southern latitudes are expected to be essentially free of efficient IN. However, the models do not capture this behavior, and this could partly explain the large bias in cloudiness over the Southern Ocean in most GCMs [45]. While necessary and important, the new and refined microphysics schemes increase the number of sub-grid scale processes that must be parameterized in models, which poses additional challenges. Continued efforts to test microphysics schemes, with a focus on ice crystal formation and subsequent growth, on a range of scales and for different cloud regimes will therefore be important for further progress. Specifically, the extent to which mixed-phase clouds are a homogeneous mixture of droplets and ice crystals as opposed to a non-uniform cloud volume with separate single-phase pockets must be addressed, and parameterizations with the ability to represent such sub-grid-scale features in GCMs should be developed.

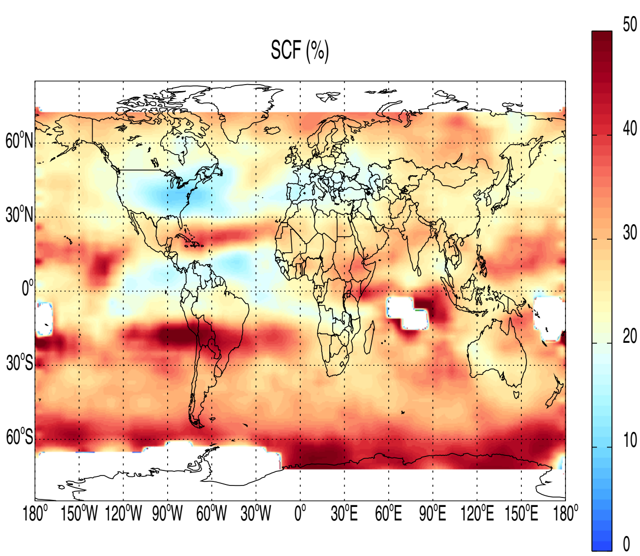

Fig. 4 Supercooled cloud fraction (SCF) observed at cloud tops by CALIOP, averaged over January 2007—December 2014. SCF is calculated by dividing the number of CALIOP pixels with liquid cloud tops by the number of total cloud tops (liquid and ice) within 2.5×2.5 grid boxes at −20+/−1 °C. Temperatures corresponding to cloud top heights were obtained from the NOAA/NCEP reanalysis data set. For more details, see [32•]

As demonstrated by the studies summarized in the previous section, an underestimation of the SCF has implications for the magnitude and potentially even the sign of the cloud feedback simulated by these models. In the following section, we will briefly describe a modeling study specifically designed to address exactly this issue and thereby revisit the modeling study by Mitchell et al. 25 years later.

Reexamining the Importance of the Cloud Phase Feedback

Using the Community Earth System Model (CESM1.0) with the latest version of its atmospheric component, the

Community Atmosphere Model (CAM, version 5), the following simulations have been conducted: (i) a control simulation (CONTROL), (ii) a simulation in which clouds in the mixed-phase layer were mainly liquid (Low-IN), (iii) a simulation in which cloud in the mixed-phase layer were mainly ice clouds (High-IN), and (iv) two simulations in which uncertain parameters in the cloud microphysics scheme were modified so as to match CALIOP SCF observations to the extent possible (CALIOP-1 and CALIOP-2.) Note that CALIOP-observed SCF will be representative mainly of cloud tops, and that the simulated clouds were sampled to reflect that. All simulations were re-tuned to reasonably reproduce present-day observations within uncertainties, with an emphasis on TOA radiation balance and shortwave and longwave radiative forcings as observed from space [46]. Parameters perturbed in order to produce the best possible match to CALIOP observations were atmospheric IN concentrations, parameters controlling wet deposition of mineral dust, the efficiency of the Wegener-Bergeron-Findeisen (WBF) process (i.e., the growth of ice crystals and snow at the expense of surrounding cloud droplets), and ice crystal fall speed. IN concentrations were calculated using the default CAM5 parameterization in the CONTROL simulation [47, 48] and diagnosed based on temperature and the number concentration of large mineral dust particles in all other simulations [49]. Each simulation was run once with atmospheric CO_2 concentrations corresponding approximately to those of the present day (367 ppm) and once again with double the present-day atmospheric CO_2 concentration (734 ppm). The Low-IN and High-IN simulations are not to be considered realistic in terms of their cloud phase and were instead designed to represent the two extremes of the mixed-phase layer containing predominantly liquid or ice, respectively. This was achieved mainly by changing their concentrations of IN, but in Low-IN, we also allowed more liquid detrainment from convection (mimicking the result of low IN abundance for convective clouds) and also made the WBF process less efficient. The Low-IN and High-IN experiments were designed to probe the maximum difference in cloud feedbacks that can be obtained due to different cloud phase representation in models. Table 1 gives an experimental overview and brief description of each of the experiments.

The SCFs produced by the five simulations and those observed by CALIOP, along with the in situ cloud phase measurements presented in Fig. 3, are displayed as a function of temperature in Fig. 5. The field and satellite observations agree quite well, given that the field measurements only covered mid- and high latitudes in the Northern Hemisphere, and probed phase composition in the clouds' interior as opposed to cloud tops. The experiment CALIOP-1 most closely resembles the observations at most of the isotherms.

Evident from Fig. 5 is the markedly lower (higher) SCF in High-IN (Low-IN) relative to CONTROL. However, CONTROL's SCF is consistently lower than those obtained from CALIOP observations, particularly at the warmer mixed-phase cloud temperatures ($T>-25$ °C). Furthermore, the SCF at high latitudes in CONTROL is close to that of High-IN (not shown). CALIOP-1 and CALIOP-2 were both designed to produce similar SCFs to those obtained by CALIOP, and Fig. 5 shows that they do in fact match CALIOP's SCFs relatively well.

A more thorough analysis of the simulations is presented elsewhere.[1] Here, we present only a comparison of the cloud feedbacks in each experiment, calculated based on simulations that have radiation budgets balanced to within 0.3 W m^{-2} in the last 50 years of each simulation. Adopting the method of Zelinka et al. [12], the net cloud feedback has been decomposed into its three components (amount, optical depth, and altitude) using the cloud radiative kernels. The method has the distinct advantage of attributing TOA radiative budget changes to cloud tops the way ISCCP would view clouds. It reveals that the net cloud optical depth feedback parameter in the extratropics monotonically increases with mean state SCF, while the sum of the net cloud altitude and net cloud amount feedbacks in the extratropics remains constant to within 0.06 W m^{-2} K^{-1} in all simulations. This finding is consistent with the cloud phase feedback, where relatively higher SCFs in the initial state reduces the optical depth increase associated with ice-to-liquid transitions, thereby leading to a more positive net cloud feedback. These results imply that realistically constraining mixed-phase cloud SCFs results in a more positive net cloud feedback than would otherwise occur should SCFs not be constrained by observations.

In summary, we find that simulations with a high proportion of cloud ice relative to liquid prior to CO_2 doubling produce a more negative cloud phase feedback, which causes the overall cloud feedback to be weakly positive. On the other hand, simulations with relatively more liquid prior to CO_2 doubling yield a cloud phase feedback that is smaller in magnitude, which causes the overall cloud feedback to be strongly positive (Fig. 6).

The above results confirm that the powerful influence of cloud phase on climate sensitivity first detected in model simulations 25 years ago is still present and equally important in today's much more sophisticated GCMs, here represented by CESM1.0.5-CAM5.

Conclusion

The aim of this review is to bring attention to a potentially crucial feedback mechanism that has so far been considered of secondary importance, namely that associated with phase changes in clouds in a warming climate. The relatively limited

[1] Tan, I., T. Storelvmo, and M. D. Zelinka, Manuscript in prep.

Table 1 Overview of the simulations conducted

Simulation	Description
CONTROL	Standard CESM1.0.5 and CAM5 coupled simulation
Low-IN	Same as CONTROL, except with negligible amounts of IN and revised treatment of ice nucleation and detrainment from convection
High-IN	Same as CONTROL, except revised treatment of ice nucleation and IN are present in abundant concentrations (75 times the default)
CALIOP-1	Same as Low-IN, except that six microphysical parameters have been perturbed to achieve the best possible match[a] to CALIOP observations to the best of the current ability of CESM
CALIOP-2	Same as CALIOP-1, except with different values of the six parameters which produced a roughly equally good match[a] to CALIOP

All simulations were run at a horizontal resolution of 1.9 × 2.5° (latitude × longitude) and 30 vertical levels in the atmosphere and approximately 1 × 1° for the ocean. For details, see Tan, Storelvmo, and Zelinka[1]

[a] We define a perfect match here as a simulation whose differences in 20°-latitudinal averages of SCF at the −10, −20, and −30 °C isotherms with those of CALIOP are zero

body of research carried out to date suggests that this phase change causes an increase in cloud albedo due to increased low cloud water content, particularly at mid- to high latitudes, and it thus represents a negative climate feedback. The strength of the cloud phase feedback is therefore likely to affect the degree of polar amplification of CO_2-induced warming and will disproportionally affect sensitive climatic regions like the Arctic and the Southern Ocean. The research carried out to date also suggests that the strength of this feedback mechanism in GCMs is very sensitive to the way in which models partition cloud water into liquid versus ice. Three previous modeling studies [1, 3, 21] combined with the preliminary results presented in the "Reexamining the Importance of the Cloud Phase Feedback" section of this paper demonstrate that the climate feedbacks and sensitivity simulated by GCMs changes radically in response to changes in cloud phase partitioning. These modeling studies focused specifically on the link between cloud phase and climate feedbacks or sensitivity, and all suggest that an underestimate of liquid in mixed-phase clouds will produce an underestimate of climate sensitivity. It is therefore noteworthy that several recent GCM intercomparison studies have found models to severely underestimate the amount of supercooled liquid relative to satellite observations [28]. This, combined with a recent study reporting that GCMs tend to overestimate the increase in water content with increasing temperature in cold clouds [18], suggests that the negative phase change feedback may be too strong in GCMs. All of the above calls for a serious evaluation of this particular cloud-climate feedback, which should include dedicated model simulations, extensive use of field measurements for testing of new cloud parameterizations, as well as both global and regional comparisons between GCMs and satellite data. Specifically for GCMs, one way to move forward would be to carry out an ambitious model intercomparison project aimed at systematically testing the sensitivity of modeled ECSs to cloud phase. Such projects generally require the coordinated efforts of multiple modeling groups, and as such represent a tremendous challenge that we urge the modeling community to take on.

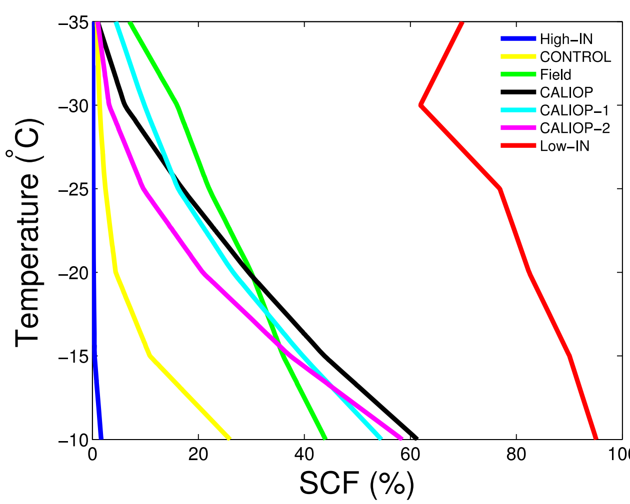

Fig. 5 Supercooled cloud fraction (SCF) in %, averaged over the extratropics (poleward of 30°), from the model simulations summarized in Table 1 and observed by CALIOP and the field measurements presented in Fig. 3. CALIOP observations are global and from the time period 2007–2014. The simulated SCFs are calculated by dividing the liquid mass mixing ratio by the total cloud mixing ratio, averaged only over cloudy time steps, and sampled from cloud tops only, unless cloudy layers above had an optical depth below 3, mimicking what CALIOP observes

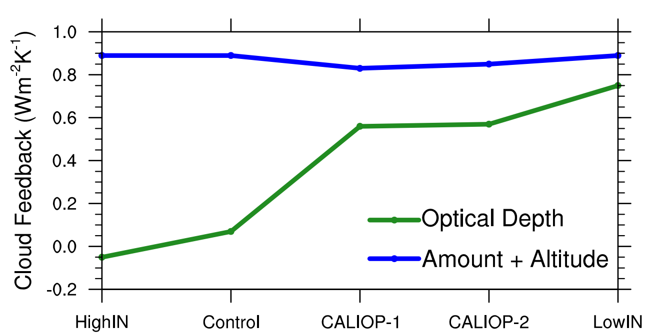

Fig. 6 The cloud optical depth feedback and the combined cloud amount and altitude feedback for each of the simulations in Table 1, calculated according to Zelinka et al. [12]. Figure adapted from Tan, Storelvmo, and Zelinka[1]

Compliance with Ethical Standards

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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