Precipitation Efficiency and Climate Sensitivity (Invited Chapter for the AGU Geophysical Monograph Series "Clouds and Climate")

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Abstract

Key Points: * The concept of precipitation efficiency is broad, and can be related to many proposed cloud feedback mechanisms * Microphysical precipitation efficiency of tropical clouds likely increases with warming, but bulk precipitation efficiency and precipitation efficiency of midlatitude clouds could decrease * The impacts of precipitation efficiency on clouds and feedbacks deserve further study and require better evaluation against observations A number of studies have demonstrated strong relationships between precipitation efficiency, particularly its changes under warming, and climate sensitivity. In this chapter, we review the evidence for these relationships, including how they depend on the definition of precipitation efficiency. We identify six mechanisms by which changes in precipitation efficiency may affect Earth's net climate feedback, and also discuss evidence for an inverse relationship between present-day precipitation efficiency and climate sensitivity based on several perturbed physics ensembles. This inverse relationship hints at the possibility of developing emergent constraints on climate sensitivity using precipitation efficiency, though it is put in doubt by studies varying convective entrainment rates, which have found the opposite relationship. More work is required to refine our understanding of the mechanisms linking changes in precipitation efficiency to climate sensitivity and more observational data is needed to validate model results. In particular, the precipitation efficiency of mid-latitude clouds has been relatively understudied, but deserves more attention in light of the importance of extratropical cloud feedbacks for the high climate sensitivities of CMIP6 models.

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- The concept of precipitation efficiency is broad, and can be related to many proposed cloud feedback mechanisms
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Abstract

A number of studies have demonstrated strong relationships between precipitation efficiency, particularly its changes under warming, and climate sensitivity. In this chapter, we review the evidence for these relationships, including how they depend on the definition of precipitation efficiency. We identify six mechanisms by which changes in precipitation efficiency may affect Earth's net climate feedback, and also discuss evidence for an inverse relationship between present-day precipitation efficiency and climate sensitivity based on several perturbed physics ensembles. This inverse relationship hints at the possibility of developing emergent constraints on climate sensitivity using precipitation efficiency, though it is put in doubt by studies varying convective entrainment rates, which have found the opposite relationship. More work is required to refine our understanding of the mechanisms linking changes in precipitation efficiency to climate sensitivity and more observational data is needed to validate model results. In particular, the precipitation efficiency of mid-latitude clouds has been relatively understudied, but deserves more attention in light of the importance of extratropical cloud feedbacks for the high climate sensitivities of CMIP6 models.

1 Introduction

Clouds remain the largest source of uncertainty in Earth's climate sensitivity. While substantial progress has been made in recent years on constraining their response to warming, with a number of lines of evidence pointing to a positive cloud feedback[1] [Sherwood et al., 2020], considerable uncertainty remains as to the cloud feedback's magnitude. Uncertainty in the net cloud feedback reflects the immense complexity of clouds: the variety of cloud types, the multi-scale turbulent interactions within clouds, the microphysics of phase changes and water droplets, the interactions between clouds and large-scale circulations, the difficulties of observing clouds, etc. Recent progress on many of these aspects of cloud physics is reviewed in other chapters of this monograph.

In this chapter, we focus on the relationship between the precipitation efficiency of clouds and climate sensitivity. A number of studies have demonstrated strong relationships between climate sensitivity and either present-day precipitation efficiency or the response of precipitation efficiency to warming[2]. In both cases, the link reflects the variety of processes which determine precipitation efficiency, including the microphysics within clouds, small-scale mixing between clouds and their environment, and the large-scale organization of clouds and convecting systems. All of these contribute to the total cloud feedback, making precipitation efficiency a useful bulk metric for many uncertain cloud processes. Constraining precipitation efficiency and its behavior under warming would not eliminate the uncertainty in climate sensitivity, but it would be an important step.

We begin the chapter by reviewing the concept of precipitation efficiency, including its various definitions, which in turn imply different relationships with climate sensitivity. We then review the connections between the response of precipitation efficiency to warming and climate sensitivity (section 3), including a discussion of the controversial "Iris hypothesis", followed by a discussion of the potential connections between present-

[1] We define a positive climate feedback as a feedback which enhances greenhouse gas-induced warming, and vice-versa for a negative feedback.

[2] Note that these studies, reviewed below, have used various methods for evaluating climate sensitivity. For example, some studies used the Cess & Potter [1988] method for diagnosing climate sensitivity, while others performed coupled model simulations. But these ways of estimating climate sensitivity are well-correlated with each other, and with the net cloud feedback, so we will generally ignore the method used to evaluate climate sensitivity in the discussion.

day precipitation efficiency and climate sensitivity (section 4). Sections 3 and 4 are primarily concerned with tropical clouds, so section 5 addresses the relationship between the precipitation efficiency of extratropical clouds and climate sensitivity, before we end with conclusions in section 6.

We do not attempt to summarize all of the existing literature on precipitation efficiency; the reader is referred to Sui et al. [2020] for a recent overview. Instead, we focus more narrowly on work which has attempted to relate precipitation efficiency and its changes to climate sensitivity. By necessity, this mostly limits our scope to modelling papers, though we touch on observational work where appropriate.

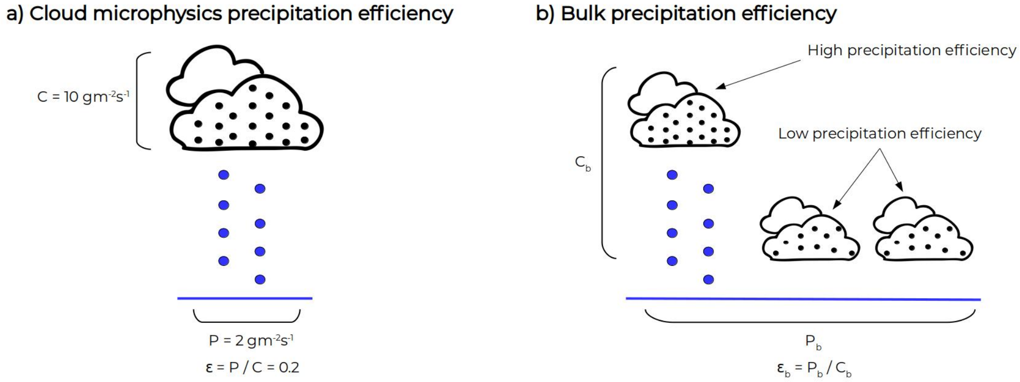

Figure 1. a) Cloud microphysics precipitation efficiency is defined as precipitation P divided by the net condensation in a column C, calculated from microphysical tendencies (vapor condensation, vapor deposition, etc.) only. b) Bulk precipitation efficiency is the average of cloud microphysics precipitation efficiency across a collection of different cloud types, assuming steady-state and averaging over multiple convecting systems.

2 Defining Precipitation Efficiency

Precipitation efficiency can be simply defined as the ratio of surface precipitation to the rate at which cloud particles condense (see Figure 1):

$$\epsilon = P/C, \tag{1}$$

where P is surface precipitation in $\mathrm{kg\,m^{-2}\,s^{-1}}$ and C is the rate of cloud condensation or, equivalently, the sink of atmospheric water vapor, also with units $\mathrm{kg\,m^{-2}\,s^{-1}}$. ϵ is unitless, and can be thought of in a Lagrangian sense as the probability that water which condenses as a cloud droplet reaches the surface as precipitation at some point [Langhans et al., 2015].

The process of cloud condensate reaching the surface can be divided into two stages. First, the condensate must form (or accrete onto) droplets of precipitation—rain, snow or graupel. Next, the precipitation must fall through the atmosphere without re-evaporating. This picture leads to the decomposition of surface precipitation into the condensation rate C multiplied by a "conversion efficiency" and a "sedimentation efficiency" [Langhans et al., 2015; Lutsko & Cronin, 2018]:

$$P = C\alpha(1-\beta), \tag{2}$$

where α represents the efficiency with which cloud droplets are converted into precipitation, of which a fraction β is re-evaporated, so that $1-\beta$ is the sedimentation efficiency. Precipitation efficiency can then be written as

$$\epsilon = \alpha(1 - \beta). \tag{3}$$

Idealized models of the tropical atmosphere often assume a conversion efficiency $\alpha = 1$, so that precipitation efficiency is set entirely by re-evaporation [e.g., Emanuel, 1987; Yano & Emanuel, 1991], but simulations and observations both suggest that α is substantially less than 1.

These simple definitions are difficult to apply in practice. One has to choose the area and time interval over which precipitation efficiency is defined, and how to calculate C. For example, when considering a limited domain, ϵ can be affected by horizontal advection of cloud condensate and precipitation into or out of the domain, changing the value of α and β for reasons not directly related to microphysics. Another question concerns the re-evaporation or sublimation of cloud water, which can be difficult to distinguish from reduced cloud condensation. For simplicity, we follow Zhao [2014] in conceptually separating out two paths for atmospheric water vapor which undergoes phase changes: a rare/fast process in which water vapor condenses/deposits and precipitates out quickly, and a frequent/slow process in which water vapor condenses/deposits and forms clouds, that are eventually recycled back into the atmosphere through evaporation and sublimation. Precipitation efficiency is then a measure of the efficiency of the fast/rare process in the atmosphere's hydrological cycle: if $\epsilon = 0$ no precipitation falls to the surface and if $\epsilon = 1$ any cloud droplets which form fall out instantaneously.

As for the condensation C, Sui et al. [2007] distinguish between "cloud microphysics" precipitation efficiency, ϵ_{cm}, for which C is only calculated from microphysical tendencies (vapor condensation, vapor deposition, etc.), versus "large-scale" precipitation efficiency, ϵ_{ls}, for which C is calculated as the sum of the large-scale horizontal convergence of water vapor, surface evaporation and the change in local water vapor storage. The latter definition represents the total water available for precipitation in a region, instead of the water that condenses as cloud droplets only, and is similar to the early definitions of precipitation efficiency in Emanuel [1987] and Yano & Emanuel [1991], as well as to the "drying ratio (e.g., Eidhammer et al. [2018]), for which C is set equal to the horizontal convergence of water vapor.

Because of our focus on climatological precipitation efficiency, we assume here that all quantities are in steady-state, in contrast to Sui et al. [2007], and thus neglect changes in vapor loading with time. Furthermore, while we otherwise follow the Sui et al. [2007] definition of cloud microphysics precipitation efficiency ϵ_{cm}, we define a "bulk" precipitation efficiency ϵ_b, rather than using ϵ_{ls} for discussing precipitation efficiency at larger scales. ϵ_b is calculated solely from microphysical tendencies, instead of using the total water budget, and integrates P and C over all clouds and updrafts in a given domain. Thus ϵ_b depends on the particular mix of cloud types in the domain, each having a different typical ϵ_{cm}, and takes into account the higher precipitation efficiency of deep convection versus the lower precipitation efficiency of shallow clouds (see Figure 1b; note that because precipitation efficiency is a ratio ϵ_b is not equal to the average of ϵ_{cm} across different cloud types).

3 Changes in Precipitation Efficiency and Climate Sensitivity

Here we discuss the physical basis for changes in precipitation efficiency to play a role in climate sensitivity. There are two conditions for this. First, changes in global temperature must lead to a systematic change in precipitation efficiency or some related microphysical process. Second, the microphysical change must affect cloud or water vapor properties so as to alter the top-of-atmosphere energy budget. We discuss these two conditions in sections 3.1 and 3.2 respectively.

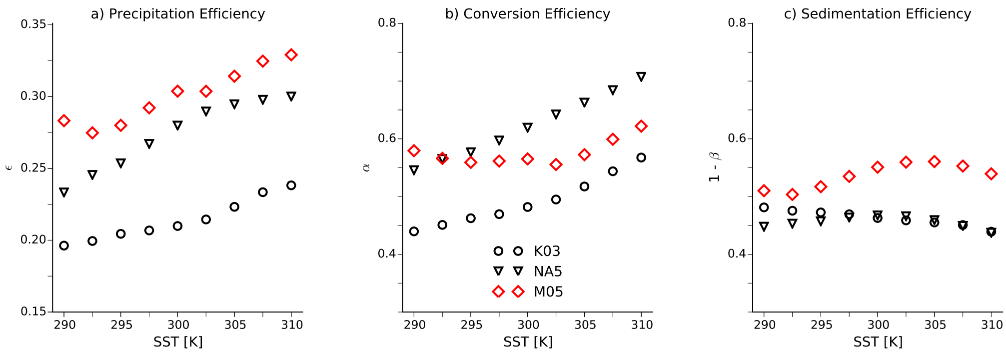

Figure 2. a) Precipitation efficiency ϵ as a function of SST for the three sets of small domain simulations in Lutsko & Cronin [2018] (their Figure 1). Black circles show results with the single-moment microphysics scheme and the parameter settings used by Khairoutdinov & Randall [2003]; black triangles show results with the NOSEDAALIQ5 parameter settings used by Lopez et al. [2009]; and red diamonds show results with the Morrison et al. [2005] microphysics scheme. b) Conversion efficiency α as a function of SST for the same simulations. c) Sedimentation efficiency $1-\beta$ as a function of SST for the same simulations.

3.1 Changes in cloud microphysics precipitation efficiency under warming

Observational evidence and detailed modeling suggest that autoconversion of cloud droplets into rain becomes significant only when liquid water amount and/or droplet radii reach a critical threshold [Freud & Rosenfeld, 2012]. A liquid amount threshold is represented by the simple and very popular Kessler autoconversion scheme, where cloud condensate is converted into precipitation via an equation of the form:

$$\frac{\partial q_p}{\partial t} = max\left[0, \eta(q_c - q_0)\right], \tag{4}$$

where q_p is the mixing ratio of precipitation, η is a rate constant, q_c is the cloud condensate mixing ratio and q_0 is a threshold cloud condensate mixing ratio. Thus denser clouds convert condensate into precipitation more efficiently and a minimum liquid mass is required for the process to occur at all. There is strong evidence that aerosol-induced reductions in droplet size can delay the onset of precipitation [e.g. Andrae et al., 2004; Rosenfeld, 2000], consistent with an increase in droplet collision efficiency when radii exceed 15-20 microns [Rosenfeld & Lensky, 1998]. Nevertheless, given an initial droplet number (i.e., with cloud condensation nucleus (CCN) number held fixed), the droplet radius and total liquid mass will grow jointly as a cloud rises and vapor condenses, such that either a minimum radius or mass requirement can produce the same behavior. Thus, a warmer climate with higher boundary-layer water-vapor concentrations (but no difference in CCN) will produce cloudy updrafts that attain required radii or condensed mass sooner, thereby plausibly increasing the precipitation efficiency, as first suggested by Lindzen et al. [2001, see below]. Whether this actually happens may however depend on factors such as cloud mixing and ice processes not considered in the above simple argument.

Relatively few studies have directly examined the climate-dependence of tropical precipitation efficiency (studies of midlatitude clouds are covered in section 5). Observationally, precipitation efficiency is both difficult to measure and difficult to relate to the large-scale state of the atmosphere. Lau & Wu [2003] suggested that the precipitation efficiency of warm rain increases as the underlying SST increases, but required a microphysical parameterization to convert satellite data into precipitation efficiencies. Conversely, in an analysis of more than 10 years of high quality radar and sounding data from the tropical Pacific, Narsey et al. [2019] found that ϵ_{cm} is inversely related to surface temperature and to convective available potential energy (which is expected to increase with warming), though they noted that these relationships are modulated by co-varying factors such as relative humidity, which may limit the applicability of their findings to warmer climates.

Idealized cloud-permitting simulations in small domains, with several different microphysics schemes, indicate that cloud microphysics precipitation efficiency should increase with warming in the absence of major changes in circulation or convective mixing [Lutsko & Cronin, 2018]. These increases are seen across a wide range of surface temperatures (290K – 310K, see Figure 2) and are primarily driven by increases in the condensation efficiency α, with the sedimentation efficiency $1-\beta$ generally showing small decreases with warming. The increases in condensation efficiency reflect increases in cloud condensate density of ∼2-6%/°C of surface warming at almost all heights, consistent with theoretical expectations for entraining plumes rising along a moist adiabat (Betts & Harshvardhan [1987]; Lutsko & Cronin [2018])

In terms of the sedimentation efficiency, Lutsko & Cronin [2018] suggested that β scales as:

$$\beta \sim (1 - RH)h/w, \tag{5}$$

where RH is relative humidity, h is the average height at which precipitation forms and w is the average fall speed of the precipitation. Analysis of cloud-permitting simulations demonstrated that warming-driven changes in sedimentation efficiency are primarily caused by increases in the height at which clouds form, so that falling precipitation travels a greater distance through the atmosphere and has a greater chance of being re-evaporated, increasing β and decreasing ϵ. However, these changes are small compared to the changes in condensation efficiency α for temperatures in the range 290K-310K (compare panels b and c of Figure 2), so that increases in cloud density lead to increases in the precipitation efficiency of tropical clouds with warming.

A caveat to these results is phase changes. Clouds are increasingly composed of liquid water droplets rather than cloud ice as the atmosphere warms. In turn, the precipitation in a column transitions from being primarily snow and/or graupel to primarily rain. Ice clouds have a higher conversion efficiency than liquid water clouds, because larger ice crystals grow more rapidly than liquid cloud droplets through collisions and collection of hydrometeors, but snow also re-evaporates much more readily than rain because of its slower fall speeds. Hence a change from a predominantly-snow to a predominantly-rain regime results in a decrease in conversion efficiency but an increase in sedimentation efficiency. For relatively warm surface temperatures (c. 290K), the increased sedimentation efficiency generally wins out in cloud-permitting simulations and precipitation efficiency increases with warming [Lutsko & Cronin, 2018], though studies of mixed-phase clouds at higher latitudes have found that the reduction in conversion efficiency wins out at colder temperatures, leading to a reduction in precipitation efficiency with warming (see section 5 for more).

These arguments ignore changes in convective aggregation, which can affect the thermodynamic environment in which precipitation forms as well as the bulk precipitation efficiency (see below), but suggest that, with or without phase changes, the cloud-microphysics precipitation efficiency of tropical clouds should be expected to increase with warming. These arguments apply to the mean precipitation efficiency, rather than the precipitation efficiency of extreme precipitation, but given our focus on the relationship with cloud feedbacks, we speculate that mean precipitation efficiency is most relevant for the discussion (see Muller et al. [2011] and Singh & O'Gorman [2014] for more on the response of extreme precipitation efficiency to warming).

3.2 Precipitation efficiency-related feedbacks on climate

We now consider various ideas for how climate-driven changes in precipitation efficiency could provide feedbacks on climate. Studies investigating this possibility have often been motivated by the Iris hypothesis. First proposed by Lindzen et al. [2001], the Iris hypothesis is a potential negative high cloud feedback, in which a reduction in cirrus cloudiness under warming leads to an increase in outgoing longwave radiation (OLR). The name comes from an analogy to the iris in the human eye, which contracts in the presence of bright light. Based on an analysis of observed changes in cloud cover coincident with higher surface temperatures in a region of the central Pacific, Lindzen et al. [2001] claimed a 22% reduction in cloud cover per degree warming, implying a strongly negative cloud feedback and a climate sensitivity of $\sim$1°C. However, these results were reported for localized regions, which typically involve confounding dynamical changes or atmospheric influences on the ocean [see Sherwood et al., 2010], and relationships can nearly disappear when averages are taken over the whole tropics [Williams & Pierrehumbert, 2017].

One reason for the Iris hypothesis' controversy is the lack of a clear description of what is contracting and why. Lindzen et al. [2001] suggested that increases in conversion efficiency cause decreases in anvil cloud area, but anvil clouds have only a weak net impact on the global energy budget, so a substantial net radiative effect presumably requires a more general contraction of cloudy conditions in favor of expanded clear sky, with implied reductions in other cloud types and/or relative humidity. This links to the concept of convective aggregation, whereby convection can spontaneously cluster into smaller regions; in idealized radiative convective equilibrium (RCE) models aggregation consistently leads to greater OLR [Wing et al., 2020]. Early studies suggested that such aggregation should increase at warmer surface temperatures in some global climate model (GCM) simulations [e.g., Bony, Stevens, et al., 2016] and in small-scale simulations, but due to radiative-dynamical mechanisms rather than anything involving precipitation efficiency [Wing & Emanuel, 2014]. Recent model intercomparisons are more ambiguous as to whether the process is climate-sensitive [Wing et al., 2020], but observational studies suggest that such contractions are generally associated with larger areas of low relative humidity and/or higher OLR [Bony, Semie, et al., 2016; Hohenegger & Jakob, 2020]. Thus, while the tropics appear capable of "Iris"-like fluctuations, it is not clear whether these will deliver a negative feedback on climate. For more discussion of convective aggregation see Chapter 8 in this collection.

We also emphasize that any substantial Iris-like effect on climate sensitivity would likely have to come from the cloud field, rather than from reductions in relative humidity. While stronger convective clustering could lead to a reduction in re-evaporation and hence to a reduction in tropospheric relative humidity, theory and GCM experiments suggest that the sensitivity of tropospheric relative humidity to re-evaporation – to a change in β – is relatively weak (Sherwood & Meyer [2006]; Romps [2014]). Even in the case of a strong Iris effect, the changes in re-evaporation with warming are likely to be modest, and so are the changes in relative humidity.

3.2.1 Model investigations of changing the response of precipitation efficiency to warming

Since the convective processes potentially responsible for an Iris-like effect are crudely represented in climate models, possible Iris effects on climate sensitivity have been explored by varying the response of ϵ_{cm} with warming. In particular, Mauritsen & Stevens [2015] and R. L. Li et al. [2019] modified the autoconversion rate (η) in ECHAM6 and in CESM, respectively, so that

$$\eta(T_s) = \eta_0(1 + I_e)^{T_s - T_0}, \tag{6}$$

where T_0 is a reference temperature, set to 25°C in both studies, η_0 is a reference autoconversion rate and I_e is a parameter which controls the strength of the Iris effect (larger I_e results in a higher ϵ_{cm}). Mauritsen & Stevens [2015] were originally motivated to add this modification to ECHAM6 by their finding that most climate models underestimate the increase in outgoing longwave radiation per °C of tropical surface temperature warming on monthly time-scales, suggestive of a missing Iris-like effect.

Making the autoconversion rate temperature-dependent successfully increased the OLR per degree warming, primarily through negative longwave cloud feedbacks – more negative than any of the CMIP5 models analyzed by Mauritsen and Stevens, even for the smallest value of I_e tested (0.2). But the inclusion of the temperature-dependent autoconversion also resulted in a more positive shortwave cloud feedback, leading to a partial compensation of the longwave cloud feedback and modest reductions in ECHAM6's climate sensitivity, from 2.8°C to 2.2°C. Another factor compensating for the negative longwave cloud feedback was a weakened lapse-rate feedback due to reduced warming of the tropical upper troposphere.

Figure 3. Contributions to the global-mean cloud feedbacks in the Iris simulations of R. L. Li et al. [2019], separated into cloud-amount, cloud-altitude, and cloud-optical-depth components. Control CESM results are shown in red, results from simulation with $I_e = 0.2$ are shown in blue, results from simulation with $I_e = 0.5$ are shown in green and results from simulation with $I_e = 1.0$ are shown in light blue. A separate decomposition is performed for high clouds (<440 hPa), shown with hatched bars. Note that these high-cloud contributions are not additive with the low-cloud (i.e., >440 hPa, not shown) contributions to give back the all-cloud components (all pressure bins). Reproduced, with permission, from R. L. Li et al. [2019] (their Figure 9).

Mauritsen & Stevens [2015] noted that the positive shortwave cloud feedback overcompensated for the negative longwave cloud feedback in unpublished experiments with

CESM, and this was confirmed by R. L. Li et al. [2019]. Using the same modifications as Mauritsen and Stevens, Li et al found that CESM's equilibrium climate sensitivity increased from 3.79°C to 4.59°C as I_e was increased from 0 to 1. The sign of the sensitivity change was robust across different cloud microphysics schemes, and was mostly caused by increasingly large reductions in the optical depth of cirrus clouds, rather than by changes in cloud amount, which were small (Figure 3). The reductions in cloud optical depth were caused by thinning of anvil clouds as a stronger Iris feedback was imposed, though the cloud thinning was itself partially compensated by a negative cloud phase feedback: the liquid water clouds which replace ice clouds in warmer climates are longer-lived and more reflective, because they are made up of a large number of small water droplets, rather than a relatively small number of large ice crystals. We return to the negative cloud phase feedback in section 5.

Finally, in a study not directly motivated by the Iris hypothesis, Zhao et al. [2016] found a strong relationship between cloud microphysics precipitation efficiency and climate sensitivity in their experiments with the GFDL-AM4 model. These experiments involved modifying the scheme by which cumulus precipitation is formed to produce either an increase in ϵ_{cm}, a negligible change in ϵ_{cm} or a decrease in ϵ_{cm} with warming. The configurations each produced good representations of the present-day climate, but had very different climate sensitivities: the version in which ϵ_{cm} increased had a high climate sensitivity, the version in which ϵ_{cm} stayed the same had a moderate climate sensitivity and the version in which ϵ_{cm} decreased had a low climate sensitivity. These differences in climate sensitivity were caused mainly by cloud changes between 800 and 300hPa, with the response of high clouds being weak in each configuration.

4 Present-Day Precipitation Efficiency and Climate Sensitivity

While changes in precipitation efficiency are likely responsible for the relationship with climate sensitivity, studies with several different GCMs have shown strong links between present-day precipitation efficiency and climate sensitivity. These results demonstrate that microphysical parameters related to precipitation efficiency can be used as tuning parameters for controlling models' climate sensitivity, and also imply correlations between baseline ϵ and $\Delta\epsilon$, which could allow observations of present-day precipitation efficiency to be used to constrain its changes.

4.1 Mid- to high-clouds and microphysical mechanisms

The most focused study of the relationship between present-day precipitation efficiency and climate sensitivity is Zhao [2014] who, with the deliberate aim of altering the model's precipitation efficiency, varied two parameters in GFDL's C48HIRAM model: the warm-cloud autoconversion threshold q_0, and c_0, a parameter which controls the cumulus entrainment rate (parameterized as c_0/H). Increasing q_0 means that higher cloud water densities are required to form precipitation, reducing the conversion efficiency and thus decreasing the cloud microphysics precipitation efficiency. Large values of q_0 also decrease the vertical velocities of convective plumes by increasing condensate loading, favoring shallow plumes, rather than the deep convective plumes in which the majority of precipitation forms. Increasing c_0 has a similar effect of decreasing plume vertical velocities because of increases in lateral mixing and entrainment. In both cases, the bulk precipitation efficiency decreases as the relative fraction of shallow plumes increases, and the greater low-cloud fraction decreases the net cloud radiative effect (CRE).

The bulk precipitation efficiency consistently increased when the various model configurations were subject to uniform SST warming, with the largest increases for the configurations with the smallest base-state precipitation efficiencies (Figure 4). Zhao [2014] explained this inverse relationship using a conceptual model of tropical convection in which an ascending parcel rises through the atmosphere, exchanging air with the environment such that the parcel conserves its total mass (although this picture is based on a parcel model, it should be thought of as representing the bulk tropical atmosphere). The parcel is assumed to produce total cloud condensate $q_c = aq_b$, where q_b is the boundary layer specific humidity and a is the fraction of q_b which condenses as the parcel ascends. Of this total condensate, $aq_b - q_0$ reaches the surface as precipitation, where q_0 is again a threshold specific humidity above which precipitation forms (note that the sedimentation efficiency is assumed to be 1, i.e., $\beta = 0$). The bulk precipitation efficiency is then $\epsilon_b = 1 - q_0/(aq_b)$ and the response of ϵ_b to a small perturbation is

$$\Delta\epsilon_b = \frac{q_0}{aq_b}\left(\frac{\Delta a}{a} + \frac{\Delta q_b}{q_b} - \frac{\Delta q_0}{q_0}\right), \tag{7}$$

which can also be written as

$$\Delta\epsilon_b = (1 - \epsilon_b)\left(\frac{\Delta a}{a} + \frac{\Delta q_b}{q_b} - \frac{\Delta q_0}{q_0}\right). \tag{8}$$

Zhao [2014] found that $\Delta\epsilon_b$ was strongly correlated with $1-\epsilon_b$, suggesting that Δa and Δq_b make small contributions to the variations in $\Delta\epsilon_b$ across the model configurations (q_0 is unaffected by warming in this microphysics scheme)[3], and providing the basis for a possible connection between present-day precipitation efficiency and $\Delta\epsilon_b$.

Increases in bulk precipitation efficiency resulted in decreases in liquid and ice water paths with warming in Zhao's experiments, with low and mid-cloud fractions diminishing at faster rates than high cloud fractions because higher precipitation efficiencies favor deep convection, rather than shallow plumes. Hence model configurations with larger $\Delta\epsilon_b$ experienced larger reductions of low and mid-level clouds, which produced larger decreases in shortwave CRE and more positive cloud feedbacks. In this way, configurations with smaller present-day precipitation efficiencies had higher climate sensitivities.

A potential inverse relationship between present-day precipitation efficiency and climate sensitivity across different configurations of a single model is supported by several other studies, though none were directly investigating precipitation efficiency. Tomassini et al. [2015] found that increasing the autoconversion rate, which increases ϵ_{cm} by increasing α, decreases the climate sensitivity of a coarse-resolution version of the MPI-ESM GCM. Similarly, Mauritsen et al. [2012] found that doubling the autoconversion rate in MPI-ESM-LR decreases the model's climate sensitivity from 3.09K to 2.96K, while Bender [2008] found that increasing the autoconversion rate by a factor of 5 decreases CAM3.1's climate sensitivity from 2.50 to 2.26K. These changes are modest, though both sets of experiments involved other changes to the models.

Studies of the connection between the rate of entrainment for deep convection and climate sensitivity have put the inverse relationship into question, however. Tomassini et al. [2015], Mauritsen et al. [2012] and, earlier, Stainforth et al. [2005] found that increasing the rate of entrainment in deep convective plumes led to large decreases in climate sensitivity. This is in contrast to the a priori expectation that higher entrainment rates should produce lower precipitation efficiencies and higher climate sensitivities according to the relationship between ϵ and climate sensitivity established above. However, these studies did not report how ϵ changed in their experiments. We also note that varying the entrainment rate for deep convection is a different modification to Zhao's experiments, in which c_0 governs the entrainment rate throughout the column as part of a bulk plume representation of both shallow and deep convection. Nevertheless, the surprising relationship between deep convective entrainment rates and climate sensitivity indicates that while $\Delta\epsilon$ is often correlated with present-day ϵ, this is not always the case.

[3] The relationship between $\Delta\epsilon_b$ and $1 - \epsilon_b$ holds within different configurations of a single model, but does not necessarily hold when comparing across models. Differences in convective mixing schemes or in microphysics could cause large variations in $\Delta a/a$, $\Delta q_b/q_b$ and $\Delta q_0/q_0$ across models.

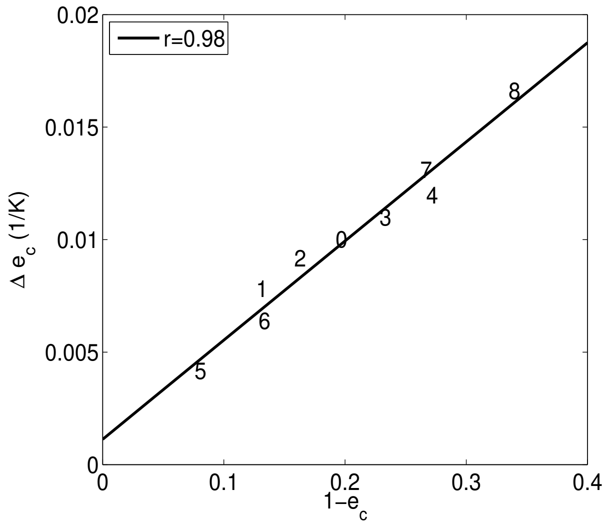

Figure 4. Scatterplot of the change in precipitation efficiency with warming $\Delta\epsilon$ versus the present-day precipitation efficiency (i.e., 1-ϵ) from the perturbed-physics ensemble in Zhao [2014] (their Figure 10). 0 denotes the control simulation while symbols 1-8 denote the perturbed-physics simulations. The line shows a linear regression with the correlation coefficient shown in the legend.

The mechanisms connecting deep entrainment rates and climate sensitivity have not been investigated, except for Mauritsen et al. [2012], who suggested that the reductions in climate sensitivity for higher deep entrainment rates are primarily caused by changes in the rapid adjustments to CO_2 forcing, rather than by changes in temperature-dependent feedbacks. In the absence of follow-up studies, further work is needed to verify this claim.

4.2 Low clouds and convective mixing

A separate set of studies has proposed a connection between the strength of mixing in shallow convection and climate sensitivity. Air lifted out of the boundary layer can either continue ascending, rain out most of its water vapor and eventually return to lower altitudes, or it can be detrained directly at lower altitudes and retain more of its initial water vapor. The latter corresponds to a situation with stronger mixing between the boundary layer and the lower troposphere, resulting in a smaller bulk precipitation efficiency, less boundary-layer cloudiness and a greater net transport of moisture out of the boundary layer for the same mean precipitation rate. Lower tropospheric mixing is expected to strengthen in warmer climates, intensifying the dehydration of the boundary layer and reducing low cloud cover, with the rate of increase in mixing thought to be proportional to the initial mixing strength (Stevens [2007]; Rieck et al. [2012]; Zhang et al. [2013]; Bretherton [2015]; Brient et al. [2016]; Vial et al. [2016]). Hence a model with a lower initial bulk precipitation efficiency for shallow clouds should experience larger low cloud reductions with warming and have a higher climate sensitivity – another inverse relationship between present-day precipitation efficiency and climate sensitivity.

In support of this argument, Sherwood et al. [2014] demonstrated that metrics for the strength of lower tropospheric convective mixing could explain about half the variance in CMIP5 models' climate sensitivity, with mixing rates inferred from observations implying a climate sensitivity greater than 3°C. They also confirmed that convective drying of the boundary layer increased with warming in models with stronger metrics of present-day shallow mixing. However, modelling studies in which mixing into shallow convection is directly altered via the parametrized entrainment rate have found a seemingly different result: in Mauritsen & Roeckner [2020] a developmental version of ECHAM6 exhibited a large decrease in climate sensitivity when the shallow convection entrainment rate was increased by a factor of 10, while in an earlier study, MPI-ESM-LR's climate sensitivity declined from 3.09°C to 2.86°C when the shallow entrainment rate was increased by a factor of 8/3 [Mauritsen et al., 2012].

These results are not necessarily inconsistent with Sherwood et al. [2014] as, for example, increasing the entrainment rate of shallow convection could favor the development of deep convection and thereby increase ϵ_b for reasons unrelated to changes in shallow mixing. More direct tests of the shallow-mixing idea come from Zhao et al. [2016], who found that the indices defined by Sherwood et al. [2014] were not well correlated with climate sensitivity in their perturbed physics ensemble (PPE) simulations, and that clouds above the boundary layer were more important for differences in cloud feedback between the ensemble members (see section 3.2). Finally, Kamae et al. [2016] suggested that the relationship between lower tropospheric mixing and climate sensitivity is model-dependent, as strong correlations between the Sherwood metrics and climate sensitivity were seen in about half the PPEs in their larger multiphysics ensemble. However, PPE ensemble members often exhibit unrealistic feedbacks [e.g. Joshi et al., 2010], reflecting mean-state errors that are typically absent in CMIP-model runs because of model tuning. Thus we feel these PPE results should be interpreted with caution, and that the shallow-mixing mechanism described above cannot be definitely ruled out.

There are other factors that might alter the relationship between shallow mixing and the low cloud feedback. For example, the effects of mixing near the top of the boundary layer on low clouds can be modified by changes in latent heat fluxes and in radiative cooling (Bretherton [2015]; Vial et al. [2016]; Schneider et al. [2019]). Enhanced dehydration of the boundary layer strengthens the surface latent heat flux, which damps the reduction in low clouds. At the same time, low cloud reductions stabilize the lower troposphere by decreasing the cloud-top radiative cooling, which in turn decreases the surface latent heat flux and induces further low cloud reductions. The relative importance of low cloud mixing versus radiative cooling, and the resulting sign of the latent heat flux response, depends on the convective parameterization [Vial et al., 2016]. A convection scheme in which the surface latent heat flux is strongly coupled to low-cloud radiative cooling will have a higher sensitivity of low-cloud fractions to convective mixing parameters, and a stronger low cloud feedback in response to surface warming. But if radiative cooling is less dominant the latent heat flux may increase with warming, weakening the low cloud response and reducing the model's climate sensitivity.

Thus a link between convective mixing and climate sensitivity (or between ϵ_b for low clouds and climate sensitivity) is plausible, but the modelling evidence is inconclusive and the strength of the link is uncertain. The relationship between shallow entrainment rates and climate sensitivity is evidently model-dependent, as is the relative importance of entrainment rates versus other parameters in models' convection and microphysics schemes. Klocke et al. [2011] found that the shallow entrainment rate was the strongest control on climate sensitivity in their PPE and that the rate of autoconversion had a negligible effect, while Tomassini et al. [2015] found that the autoconversion rate exerted a strong control on climate sensitivity and the shallow entrainment rate had a weak effect in their PPE. Putting these model results together, and given the complex mechanisms which govern how shallow entrainment rates affect low cloud cover, the concept of precipitation efficiency as defined here may not be the best way of framing the link between shallow mixing and climate sensitivity.

5 Precipitation Efficiency of Extratropical Clouds

Investigations of the relationship between precipitation efficiency and climate sensitivity have mostly focused on tropical clouds, which are often identified as the leading source of uncertainty in Earth's climate sensitivity. Yet the high climate sensitivities of many of the newest CMIP6 models have been attributed to a reduction of strongly negative extratropical cloud feedbacks compared to CMIP5, particularly over the Southern Ocean [Zelinka et al., 2020], suggesting that the precipitation efficiency of extratropical clouds merits more study. Moreover, while the connection between the precipitation efficiency of extratropical clouds and climate sensitivity has not been investigated explicitly, an inverse relationship between the present-day ϵ_{cm} of extratropical clouds and climate sensitivity has been proposed, mediated by the cloud phase feedback mentioned in section 3.2.

The cloud-microphysics precipitation efficiency of extratropical clouds is expected to decrease with warming because of decreases in conversion efficiency associated with the transition from mostly ice clouds to mostly liquid water clouds. The changes in conversion efficiency win out over increases in sedimentation efficiency due to the transition from snow to rain as the dominant form of precipitation (Kirshbaum & Smith [2008]; Storelvmo et al. [2015])[4]. Cloud phase changes also lead to a negative cloud optical depth feedback as liquid clouds with higher optical depths replace ice clouds (see Chapter 4 in this collection), which may be a substantial effect: Mitchell et al. [1989] found that the cloud phase feedback can alter a model's climate sensitivity by a factor of two (see also Z.-X. Li & Le Treut [1992]; Storelvmo et al. [2015]; McCoy et al. [2015]; Ceppi et al. [2017]; Mauritsen & Roeckner [2020]). Hence models with higher initial ice cloud fractions may experience larger reductions in precipitation efficiency driven by phase changes, and stronger negative cloud optical depth feedbacks under warming. This suggests that models with higher present-day extratropical precipitation efficiencies could have lower climate sensitivities.

Zelinka et al. [2020] noted that one explanation for the weaker extratropical cloud feedbacks in CMIP6 is the increased presence of mean-state supercooled liquid water in mixed-phase clouds in many models. More supercooled water means smaller increases in extratropical cloud optical depth and cloud lifetime compared to models which start with more cloud ice initially. Although Zelinka et al did not calculate ϵ for extratropical clouds explicitly, it is plausible that the high sensitivity CMIP6 models exhibit smaller decreases in extratropical cloud microphysics precipitation efficiency with warming.

6 Concluding Remarks

The general notion of precipitation efficiency is broad, and it can be defined in several different ways, each of which can be related to various cloud feedback mechanisms. Moreover, the relationships between precipitation efficiency and cloud feedbacks are highly model-dependent, and parameters which are important in one model may be less important in another. This is perhaps best illustrated by the multiphysics, multiparameter ensembles of Kamae et al. [2016], in which some model configurations showed strong relationships between lower tropospheric mixing metrics and climate sensitivity, while oth-

[4] We hypothesize that changes in sedimentation efficiency likely become more important at warmer temperatures, when precipitation forms higher in the atmosphere and differences in fall speed lead to larger changes in re-evaporation. We also note that Eidhammer et al. [2018] found that the precipitation efficiency of orographic precipitation decreases with surface temperature in high resolution simulations of a region in the Colorado Rockies, and attributed this to decreases in vertical velocities. However, they defined precipitation efficiency as the drying ratio, which is different from our definitions based on microphysical properties.

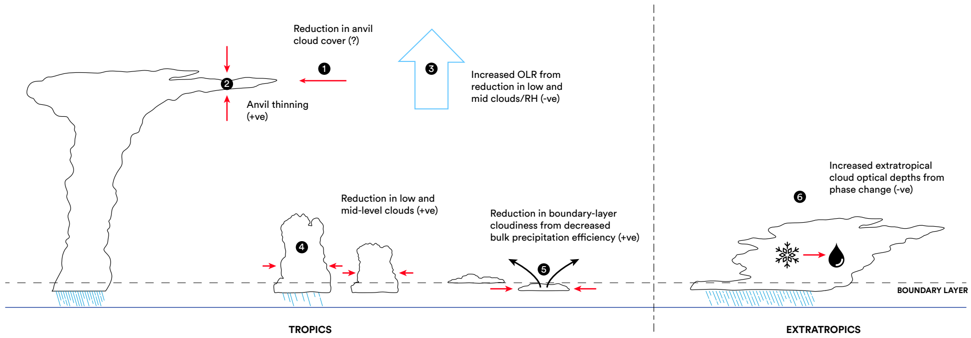

Figure 5. Schematic illustration of the six mechanisms by which changes in precipitation efficiency can alter climate sensitivity, as well as the hypothesized signs of their effect on the net climate feedback.

ers did not. Similarly, Klocke et al. [2011], Zhao [2014] and Tomassini et al. [2015] all demonstrated strong relationships between present-day precipitation efficiency and climate sensitivity, but used different parameter variations to establish these relationships. This model-dependence reflects the fact that precipitation efficiency is a bulk metric for the combined effects of the convective and microphysical processes it represents, and comparing the precipitation efficiencies of models can be deceptive if different processes control ϵ.

Nevertheless, a few robust results do emerge from the literature. For example, there is strong evidence that the cloud microphysics precipitation efficiency of tropical clouds increases with warming, though bulk precipitation efficiency and the cloud microphysics precipitation efficiency of extratropical clouds could decrease. After tracing the various ways in which precipitation efficiency has been connected to climate sensitivity, we also propose that there are six mechanisms by which changes in ϵ could alter the planetary radiative balance (see Figure 5):

1. Increased precipitation efficiency could lead to a reduction in anvil cloud cover. This would increase OLR but also lower albedo, such that the sign of the net feedback is unclear.
2. Increased precipitation efficiency could cause thinning of cloud anvils, producing a positive cloud optical depth feedback.
3. Increased convective organization could produce decreases in cloud cover generally, as well as decreases in relative humidity, such that OLR increases with warming. This could constitute a negative climate feedback, depending on the response of shallow clouds outside the convective area.
4. Increased microphysical precipitation efficiency could lead to reductions in low and mid-level cloud cover (independent of changes in convective organization), a positive feedback on warming.
5. Increased demand on boundary-layer moisture due to decreasing bulk precipitation efficiency via shallow mixing could reduce boundary-layer cloudiness, producing a positive feedback.
6. Decreased mid-latitude precipitation efficiency could be associated with increased extratropical cloud optical depths, a negative mid-latitude cloud feedback.

Mechanisms (1) and (3) correspond most closely to the original "Iris" idea of Lindzen et al. [2001], but (1) is unlikely to produce a strong net radiative feedback while (3) appears to be more of a dynamical than a microphysical mechanism. Changes in anvil cloud amount or tropospheric relative humidity driven by changes in precipitation efficiency are unlikely to be capable of large changes to the planetary radiative balance, leaving changes in other cloud-types as the source of changes in sensitivity. Mechanisms (2), (4), (5) and (6) have all been reported in GCMs, and merit further investigation into how they vary across models and to better understand the magnitude of their effects. For example, evidence that increases in precipitation efficiency could result in thinning of cloud anvils (mechanism (2)) comes from a single modelling study [R. L. Li et al., 2019]. Improving understanding of the precipitation efficiency of extratropical clouds also seems particularly urgent in light of the role of extratropical clouds in the high climate sensitivities of CMIP6 models.

Another important question is clarifying whether there is a relationship between present-day precipitation efficiency and climate sensitivity. A number of model perturbation studies have found inverse relations between present-day precipitation efficiency and climate sensitivity, with the possible exception of modeling studies varying shallow and deep entrainment rates (though these have not actually documented how ϵ changes as parameters are varied). Such a relationship would presumably work through changes in efficiency with warming following one or more of the six mechanisms listed above. A robust relationship in models between present-day precipitation efficiency and climate sensitivity would suggest the possibility of emergent constraints on climate sensitivity, but the link between present-day ϵ and $\Delta\epsilon$ would need to be strengthened before precipitation efficiency could be used in this way, and measuring precipitation efficiency, particularly over large-scales and at the required accuracy, presents many challenges.

Despite the issues around model dependence, the various notions of precipitation efficiency clearly play a central role in many types of likely cloud feedback. The concept of precipitation efficiency is also a useful framework for connecting detailed process studies to emergent properties of climate models. This can be helpful in model development and evaluation, while also suggesting new ways of engineering specific climates to explore hypotheses and to investigate observational constraints. Thus we believe that further study of the impacts of precipitation efficiency on clouds and feedbacks is called for, particularly to refine our understanding of the mechanisms linking changes in precipitation efficiency to climate sensitivity and to provide more observational data with which to validate model results.

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