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Article

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Cloud feedback mechanisms and their representation in global climate models

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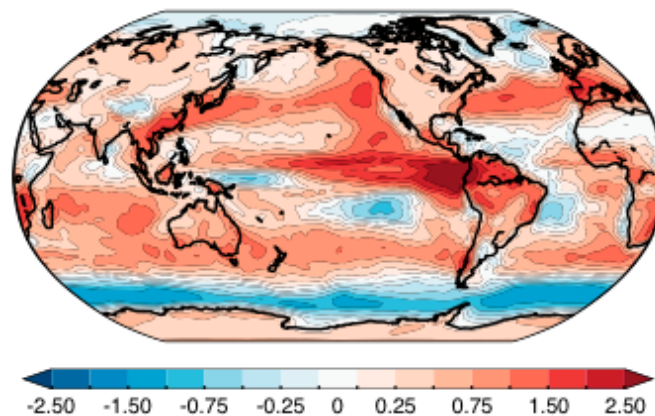
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Abstract

Cloud feedback – the change in top-of-atmosphere radiative flux resulting from the cloud response to warming – constitutes by far the largest source of uncertainty in the climate response to CO₂ forcing simulated by global climate models (GCMs). We review the main mechanisms for cloud feedbacks, and discuss their representation in climate models and the sources of inter-model spread. Global-mean cloud feedback in GCMs results from three main effects: (1) rising free-tropospheric clouds (a positive longwave effect); (2) decreasing tropical low cloud amount (a positive shortwave effect); (3) increasing high-latitude low cloud optical depth (a negative shortwave effect). These cloud responses simulated by GCMs are qualitatively supported by theory, high-resolution modeling, and observations. Rising high clouds are consistent with the Fixed Anvil Temperature (FAT) hypothesis, whereby enhanced upper-tropospheric radiative cooling causes anvil cloud tops to remain at a nearly fixed temperature as the atmosphere warms. Tropical low cloud amount decreases are driven by a delicate balance between the effects of vertical turbulent fluxes, radiative cooling, large-scale subsidence, and lower-tropospheric stability on the boundary-layer moisture budget. High-latitude low cloud optical depth increases are dominated by phase changes in mixed-phase clouds. The causes of inter-model spread in cloud feedback are discussed, focusing particularly on the role of unresolved parameterized processes such as cloud microphysics, turbulence, and convection.

Graphical/Visual Abstract and Caption



Spatial distribution of cloud feedback (in W m⁻² per K surface warming) predicted by a set of global climate models subjected to an abrupt increase in CO₂. Redrawn with permission from Zelinka et al. (2016).

2 INTRODUCTION

3 As the atmosphere warms under greenhouse gas forcing, global climate models (GCMs) predict that
4 clouds will change, resulting in a radiative feedback by clouds^{1, 2}. While this cloud feedback is
5 positive in most GCMs and hence acts to amplify global warming, GCMs diverge substantially on its
6 magnitude³. Accurately simulating clouds and their radiative effects has been a long-standing
7 challenge for climate modeling, largely because clouds depend on small-scale physical processes that
8 cannot be explicitly represented by coarse GCM grids. In the recent Climate Model Intercomparison
9 Project phase 5 (CMIP5)⁴, cloud feedback was by far the largest source of inter-model spread in
10 equilibrium climate sensitivity, the global-mean surface temperature response to CO₂ doubling⁵⁻⁷.
11 The important role of clouds in determining climate sensitivity in GCMs has been known for
12 decades⁸⁻¹¹, and despite improvements in the representation of cloud processes¹², much work
13 remains to be done to narrow the range of GCM projections.

14 Despite these persistent difficulties, recent advances in our understanding of the fundamental
15 mechanisms of cloud feedback have opened exciting new opportunities to improve the
16 representation of the relevant processes in GCMs. Thanks to increasing computing power,
17 turbulence-resolving model simulations have offered novel insight into the processes controlling
18 marine low cloud cover¹³⁻¹⁶, of key importance to Earth's radiative budget¹⁷. Clever combined use of
19 model hierarchies and observations has provided new understanding of why high-latitude clouds
20 brighten¹⁸⁻²⁰, why tropical anvil clouds shrink with warming²¹, and how clouds and radiation respond
21 to storm track shifts²²⁻²⁴, to name a few examples.

22 The goal of this review is to summarize the current understanding of cloud feedback mechanisms,
23 and to evaluate their representation in contemporary GCMs. Although the observational support for
24 GCM cloud responses is assessed, we do not provide a thorough review of observational estimates
25 of cloud feedback, nor do we discuss possible "emergent constraints"²⁵. The discussion is organized
26 into two main sections. First, we diagnose cloud feedback in GCMs, identifying the cloud property
27 changes responsible for the radiative response. Second, we interpret these GCM cloud responses,
28 discussing the physical mechanisms at play and the ability of GCMs to represent them, and briefly
29 reviewing the available observational evidence. Based on this discussion, we conclude with
30 suggestions for progress toward an improved representation of cloud feedback in climate models.

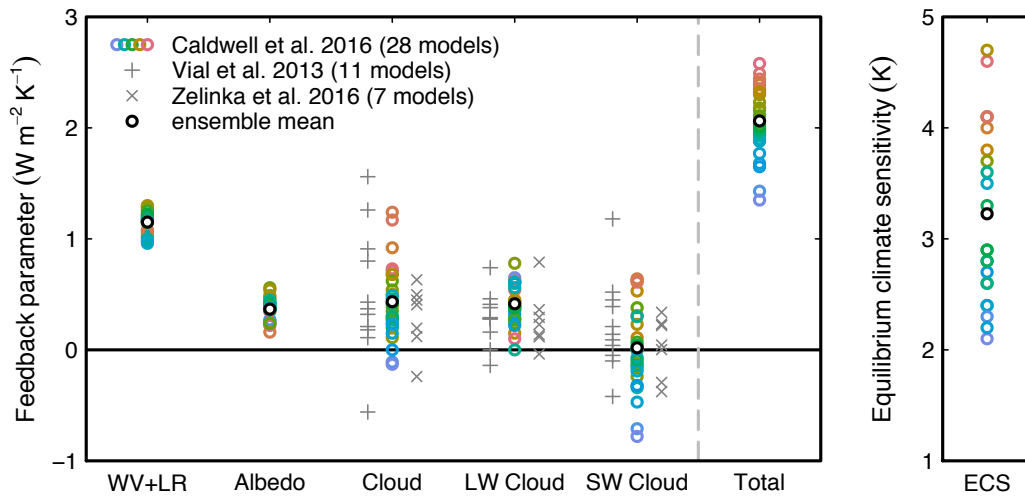
31 DIAGNOSING CLOUD FEEDBACK IN GLOBAL CLIMATE MODELS

32 We begin by documenting the magnitude and spatial structure of cloud feedback in contemporary
33 GCMs, and identify the cloud property changes involved in the radiative response. Although clouds
34 may respond to any forcing agent, in this review we will focus on cloud feedback to CO₂ forcing, of
35 highest relevance to future anthropogenic climate change.

36 Global-mean cloud feedback

37 The global-mean cloud feedback strength (quantified by the feedback parameter; Box 1) is plotted in
38 Fig. 1, along with the other feedback processes included in the traditional decomposition. The
39 feedback parameters are derived from CMIP5 experiments forced with abrupt quadrupling of CO₂
40 concentrations relative to pre-industrial conditions. In the following discussion we quote the

41 numbers from an analysis of 28 GCMs⁵ (colored circles in Fig. 1). Two other studies (grey symbols in
 42 Fig. 1) show similar results, but they include smaller subsets of the available models.



43
 44 Fig. 1. Strengths of individual global-mean feedbacks and equilibrium climate sensitivity (ECS) for CMIP5
 45 models, derived from coupled experiments with abrupt quadrupling of CO₂ concentration. Model names and
 46 feedback values are listed in the Supporting Information, Table S1. Feedback parameter results are from
 47 Caldwell et al.⁵, with additional cloud feedback values from Vial et al.⁶ and Zelinka et al.²⁶ ECS values are taken
 48 from Andrews et al.²⁷, Forster et al.²⁸, and Flato et al.²⁹ Feedback parameters are calculated as in Soden et al.³⁰
 49 but accounting for rapid adjustments; the cloud feedback from Zelinka et al. is calculated using cloud-radiative
 50 kernels³¹ (Box 2). Circles are colored according to the total feedback parameter. The Planck feedback (mean
 51 value of -3.15 W m⁻² K⁻¹) is excluded from the total feedback parameter shown here.
 52

53 **Box 1: Climate feedbacks**

54 Increasing greenhouse gas concentrations cause a positive radiative forcing F (W m⁻²), to which the
 55 climate system responds by increasing its temperature to restore radiative balance according to

56
$$N = F + \lambda \Delta T.$$

57 N denotes the net energy flux imbalance at the top of atmosphere, and ΔT is the global-mean
 58 surface warming. How effectively warming reestablishes radiative balance is quantified by the total
 59 feedback parameter λ (in W m⁻² K⁻¹). For a positive (downward) forcing, warming must induce a
 60 negative (upward) radiative response to restore balance, and hence $\lambda < 0$. When the system reaches
 61 a new steady state, $N = 0$ and thus the final amount of warming is determined by both forcing and
 62 feedback, $\Delta T = -F/\lambda$. A more positive feedback implies more warming.

63 The total feedback λ equals the sum of contributions from different feedback processes, each of
 64 which is assumed to perturb the top-of-atmosphere radiative balance by a given amount per degree
 65 warming. The largest such process involves the increase in emitted longwave radiation following
 66 Planck's law (a negative feedback). Additional feedbacks result from increased longwave emission to
 67 space due to enhanced warming aloft (negative lapse rate feedback); increased greenhouse warming
 68 by water vapor (positive water vapor feedback); and decreasing reflection of solar radiation as snow
 69 and ice retreat (positive surface albedo feedback). Changes in the physical properties of clouds affect

70 both their greenhouse warming and their reflection of solar radiation, giving rise to a cloud feedback
71 (Box 2), positive in most current GCMs.

72 The multi-model-mean net cloud feedback is positive ($0.43 \text{ W m}^{-2} \text{ K}^{-1}$), suggesting that on average,
73 clouds cause additional warming. However, models produce a wide range of values, from weakly
74 negative to strongly positive (-0.13 to $1.24 \text{ W m}^{-2} \text{ K}^{-1}$). Despite this considerable inter-model spread,
75 only two models, GISS-E2-H and GISS-E2-R, produce a (weakly) negative global-mean cloud
76 feedback. In the multi-model mean, this positive cloud feedback is entirely attributable to the
77 longwave (LW) effect of clouds ($0.42 \text{ W m}^{-2} \text{ K}^{-1}$), while the mean shortwave (SW) cloud feedback is
78 essentially zero ($0.02 \text{ W m}^{-2} \text{ K}^{-1}$).

79 Of all the climate feedback processes, cloud feedback exhibits the largest amount of inter-model
80 spread, originating primarily from the SW effect^{3, 6, 26, 32}. The important contribution of clouds to the
81 spread in total feedback parameter and equilibrium climate sensitivity (ECS) stands out in Fig. 1. The
82 net cloud feedback is strongly correlated with the total feedback parameter ($r=0.80$) and ECS
83 ($r=0.73$).

84 **Box 2: Cloud-radiative effect and cloud feedback**

85 The radiative impact of clouds is measured as the *cloud-radiative effect* (CRE), the difference
86 between clear-sky and all-sky radiative flux at the top of atmosphere. Clouds reflect solar radiation
87 (negative SW CRE, global-mean effect of -45 W m^{-2}) and reduce outgoing terrestrial radiation
88 (positive LW CRE, 27 W m^{-2}), with an overall cooling effect estimated at -18 W m^{-2} (numbers from
89 Henderson et al.³³). CRE is proportional to cloud fraction, but is also determined by cloud altitude
90 and optical depth. The magnitude of SW CRE increases with cloud optical depth, and to a much
91 lesser extent with cloud altitude. By contrast, the LW CRE depends primarily on cloud altitude, which
92 determines the difference in emission temperature between clear and cloudy skies, but also
93 increases with optical depth.

94 As the cloud properties change with warming, so does their radiative effect. The resulting radiative
95 flux response at the top of atmosphere, normalized by the global-mean surface temperature
96 increase, is known as *cloud feedback*. This is not strictly equal to the change in CRE with warming,
97 because the CRE also responds to changes in clear-sky radiation – for example due to changes in
98 surface albedo or water vapor³⁴. The CRE response thus underestimates cloud feedback by about 0.3
99 W m^{-2} on average^{34, 35}. Cloud feedback is therefore the component of CRE change that is due to
100 changing cloud properties only.

101 Various methods exist to diagnose cloud feedback from standard GCM output. The values presented
102 in this paper are either based on CRE changes corrected for non-cloud effects³⁰, or estimated directly
103 from changes in cloud properties, for those GCMs providing appropriate cloud output³¹. The most
104 accurate procedure involves running the GCM radiation code offline – replacing instantaneous cloud
105 fields from a control climatology with those from a perturbed climatology, while keeping other fields
106 unchanged – to obtain the radiative perturbation due to changes in clouds^{36, 37}. This method is
107 computationally expensive and technically challenging, however.

108 *Rapid Adjustments*

109 The cloud-radiative changes that accompany CO₂-induced global warming partly result from a rapid
110 adjustment of clouds to CO₂ forcing and land-surface warming^{38, 39}. Because it is unrelated to the
111 global-mean surface temperature increase, this rapid adjustment is treated as a forcing rather than a
112 feedback in the current feedback analysis framework⁴⁰. An important implication is that clouds cause
113 uncertainty in both forcing and feedback. For a quadrupling of CO₂ concentration, the estimated
114 global-mean radiative adjustment due to clouds ranges between 0.3 and 1.1 W m⁻², depending on
115 the analysis method and GCM set, and has been ascribed mainly to SW effects^{6, 41, 42}. Accounting for
116 this adjustment reduces the net and SW component of the cloud feedback. We refer the reader to
117 Andrews et al.⁴³ and Kamae et al.⁴⁴ for a thorough discussion of rapid cloud adjustments in GCMs.
118 Hereafter we focus solely on changes in cloud properties that are mediated by increases in global-
119 mean temperature.

120 *Decomposition by cloud type*

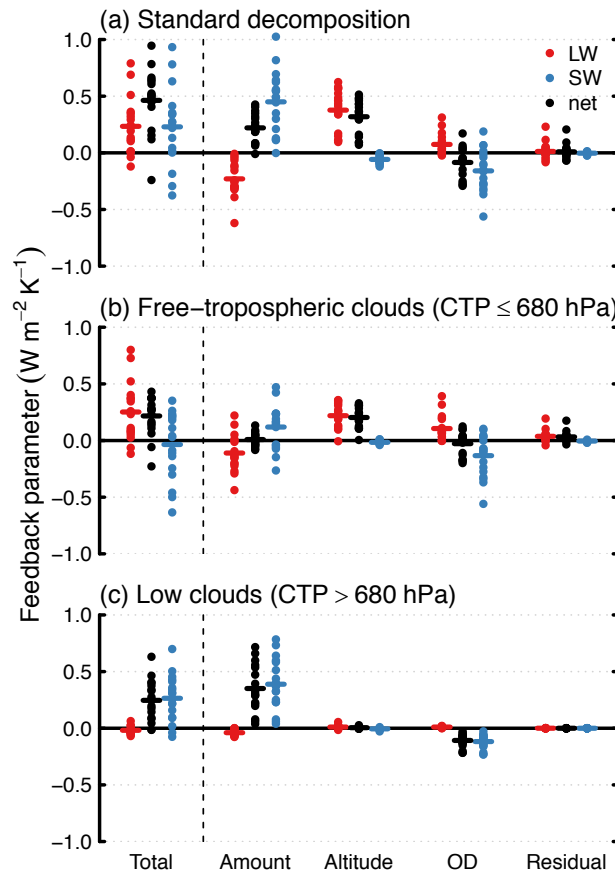
121 For models providing output that simulates measurements taken by satellites, the total cloud
122 feedback can be decomposed into contributions from three relevant cloud properties: cloud
123 altitude, amount, and optical depth (plus a small residual)⁴⁵. The multi-model-mean net cloud
124 feedback can then be understood as the sum of positive contributions from cloud altitude and
125 amount changes, and a negative contribution from optical depth changes (Fig. 2a). The various cloud
126 properties have distinctly different effects on LW and SW radiation. Increasing cloud altitude
127 explains most of the positive LW feedback, with minimal effect on SW. By contrast, cloud amount
128 and optical depth changes have opposing effects on SW and LW radiation, with the SW term
129 dominating. (Note that 11 of the 18 feedback values in Fig. 2 include the positive effect of rapid
130 adjustments, yielding a more positive multi-model mean SW feedback compared with Fig. 1.)

131 The cloud property decomposition in Fig. 2a can be refined by separately considering *low* (cloud top
132 pressure > 680 hPa) and *free-tropospheric* clouds (cloud top pressure ≤ 680 hPa), as this more
133 effectively isolates the factors contributing to the net cloud feedback²⁶. This vertical decomposition
134 reveals that the multi-model mean LW feedback is entirely due to rising free-tropospheric clouds
135 (Fig. 2b). For such clouds, amount and optical depth changes do not contribute to the net feedback
136 because their SW and LW effects cancel nearly perfectly. Meanwhile, the SW cloud feedback can be
137 ascribed to low cloud amount and optical depth changes (Fig. 2c). Thus, the results in Fig. 2b,c
138 highlight the three main contributions to the net cloud feedback in current GCMs: rising free-
139 tropospheric clouds (a positive LW effect), decreasing low cloud amount (a positive SW effect), and
140 increasing low cloud optical depth (a weak negative SW effect), yielding a net positive feedback in
141 the multi-model mean. It is noteworthy that all CMIP5 models agree on the sign of these
142 contributions.

143 **Spatial distribution of cloud feedback**

144 The contributions to LW and SW cloud feedback are far from being spatially homogeneous,
145 reflecting the distribution of cloud regimes (Fig. 3). Although the net cloud feedback is generally
146 positive, negative values occur over the Southern Ocean poleward of about 50° S, and to a lesser
147 extent over the Arctic and small parts of the tropical oceans. The most positive values are found in
148 regions of large-scale subsidence, such as regions of low SST in the equatorial Pacific and the

149 subtropical oceans. Weak to moderate subsidence regimes cover most of the tropical oceans, and
 150 are associated with shallow marine clouds such as stratocumulus and trade cumulus. In most GCMs
 151 such clouds decrease in amount^{17, 46}, strongly contributing to the positive low cloud amount
 152 feedback seen in Fig. 2c. This explains the importance of shallow marine clouds for the overall
 153 positive cloud feedback, and their dominant contribution to inter-model spread in net cloud
 154 feedback¹⁷.



155

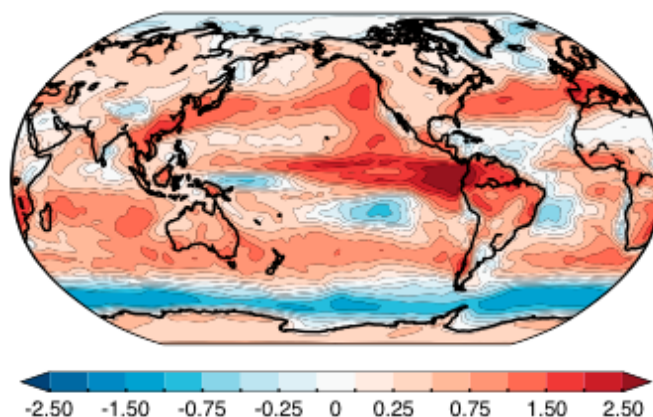
156 Fig. 2. Global mean LW (red), SW (blue), and net (black) cloud feedbacks decomposed into amount, altitude,
 157 optical depth (OD) and residual components for (a) all clouds, (b) free-tropospheric clouds only, and (c) low
 158 clouds only, defined by cloud top pressure (CTP). Multi-model mean feedbacks are shown as horizontal lines.
 159 Results are based on an analysis of 11 CMIP3 and 7 CMIP5 models²⁶; the CMIP3 values do not account for rapid
 160 adjustments. Model names and total feedback values are listed in Table S2. Redrawn with permission from
 161 Zelinka et al.²⁶

162

163 Taking a zonal-mean perspective highlights the meridional dependence of cloud property changes
 164 and their contributions to cloud feedback (Fig. 4). Free-tropospheric cloud tops robustly rise globally,
 165 producing a positive cloud altitude LW feedback at all latitudes that peaks in regions of high
 166 climatological free-tropospheric cloud cover (blue curve). The positive cloud amount feedback
 167 (orange curve), dominated by the SW effect of low clouds (cf. Fig. 2), also occurs over most of the
 168 globe with the exception of the high southern latitudes; by contrast, the effect of optical depth
 169 changes is near zero everywhere except at high southern latitudes, where it is strongly negative
 170 (green curve). This yields a complex meridional pattern of net cloud feedback (black curve in Fig. 4).

171 The patterns of cloud amount and optical depth changes suggest the existence of distinct physical
172 processes in different latitude ranges and climate regimes, as discussed in the next section.

173



174 Fig. 3. Spatial distribution of the multi-model mean net cloud feedback (in $W m^{-2}$ per K surface warming) in a
175 set of 11 CMIP3 and 7 CMIP5 models subjected to an abrupt increase in CO_2 (Table S2). Redrawn with
176 permission from Zelinka et al.²⁶

177

178 The results in Fig. 4 allow us to further refine the conclusions drawn from Fig. 2. In the multi-model
179 mean, the cloud feedback in current GCMs mainly results from

- 180 • *globally* rising free-tropospheric clouds,
- 181 • decreasing low cloud amount at *low to middle latitudes*, and
- 182 • increasing low cloud optical depth at *middle to high latitudes*.

183 **Summary**

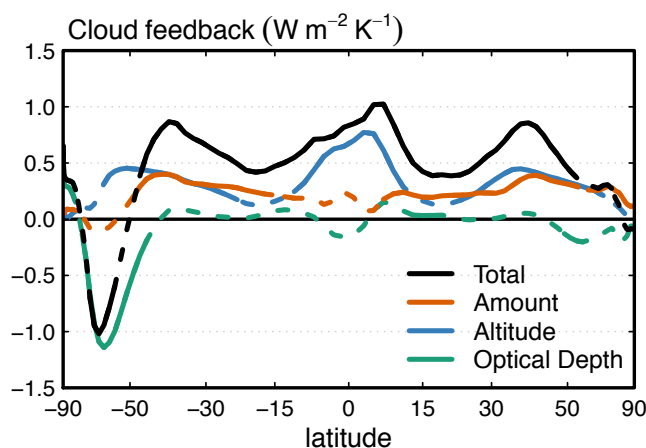
184 Cloud feedback is the main contributor to inter-model spread in climate sensitivity, ranging from
185 near zero to strongly positive (-0.13 to $1.24 W m^{-2} K^{-1}$) in current climate models. It is a combination
186 of three effects present in nearly all GCMs: rising free-tropospheric clouds (a LW heating effect);
187 decreasing low cloud amount in tropics to midlatitudes (a SW heating effect); and increasing low
188 cloud optical depth at high latitudes (a SW cooling effect). Low cloud amount in tropical subsidence
189 regions dominates the inter-model spread in cloud feedback.

190

191 **INTERPRETING CLOUD PROPERTY CHANGES IN GLOBAL CLIMATE MODELS**

192 Having diagnosed the radiatively-relevant cloud responses in GCM, we assess our understanding of
193 the physical mechanisms involved in these cloud changes, and discuss their representation in GCMs.
194 We consider in turn each of the three main effects identified in the previous section, and address
195 the following questions:

- 196 • What physical mechanisms are involved in the cloud response? To what extent are these
197 mechanisms supported by theory, high-resolution modeling, and observations?
- 198 • How well do GCMs represent these mechanisms, and what parameterizations does this
199 depend on?
- 200 • What explains the inter-model spread in cloud responses?



201
202 Fig. 4. Zonal-, annual-, and multi-model-mean net cloud feedbacks in a set of 11 CMIP3 and 7 CMIP5 models
203 (Table S2), plotted against the sine of latitude, and partitioned into components due to the change in cloud
204 amount, altitude, and optical depth. Curves are solid where 75% or more of the models agree on the sign of
205 the feedback, dashed otherwise. Redrawn with permission from Zelinka et al.²⁶

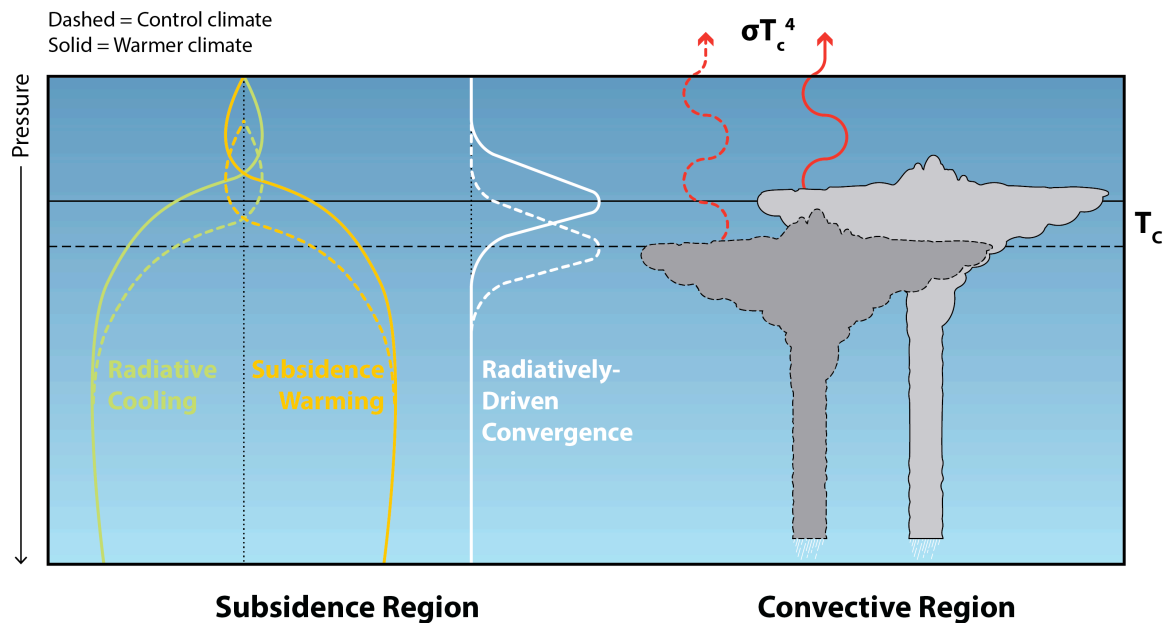
207 Cloud altitude

208 Physical mechanisms

209 Owing to the decrease of temperature with altitude in the troposphere, higher cloud tops are colder
210 and thus emit less thermal infrared radiation to space. Therefore, an increase in the altitude of cloud
211 tops imparts a heating to the climate system by reducing outgoing LW radiation. Fundamentally, the
212 rise of upper-level cloud tops is firmly grounded in basic theory (the deepening of the well-mixed
213 troposphere as the planet warms), and is supported by cloud-resolving modeling experiments and by
214 observations of both interannual cloud variability and multi-decadal cloud trends. The combination
215 of theoretical and observational evidence, along with the fact that all GCMs simulate rising free-
216 tropospheric cloud tops as the planet warms, make the positive cloud altitude feedback one of the
217 most fundamental cloud feedbacks.

218 The tropical free troposphere is approximately in radiative-convective equilibrium, where latent
219 heating in convective updrafts balances radiative cooling, which is itself primarily due to thermal
220 emission by water vapor⁴⁷. Because radiative cooling by the water vapor rotation and vibration
221 bands falls off rapidly with decreasing water vapor mixing ratio in the tropical upper troposphere⁴⁸,
222 so too must convective mass flux. Hence, mass detrainment from tropical deep convection and its
223 attendant anvil cloud coverage both peak near the altitude where emission from water vapor drops
224 off rapidly with pressure, which we refer to as the altitude of peak radiatively-driven convergence.
225 Because radiative cooling by water vapor is closely tied to water vapor concentration and the latter

226 is fundamentally controlled by temperature through the Clausius-Clapeyron equation, the dramatic
 227 decrease in water vapor concentration in the upper troposphere occurs primarily due to the
 228 decrease of temperature with decreasing pressure. This implies that the level that marks the peak
 229 coverage of anvil cloud tops is set by temperature. As isotherms rise with global warming, so too
 230 must tropical anvil cloud tops, leading to a positive cloud altitude feedback. This “fixed anvil
 231 temperature” (FAT) hypothesis⁴⁹, illustrated schematically in Fig. 5, provides a physical basis for
 232 earlier suggestions that fixed cloud top temperature is a more realistic response to warming than
 233 fixed cloud altitude^{50, 51}.



234

235 Fig. 5. Schematic of the relationship between clear-sky radiative cooling, subsidence warming, radiatively-
 236 driven convergence, and altitude of anvil clouds in the tropics in a control and warm climate, as articulated in
 237 the FAT hypothesis. Upon warming, radiative cooling by water vapor increases in the upper troposphere,
 238 which must be balanced by enhanced subsidence in clear-sky regions. This implies that the level of peak
 239 radiatively-driven convergence and the attendant anvil cloud coverage must shift upward. T_c denotes the anvil
 240 cloud top temperature isotherm.

241

242 In practice, tropical high clouds rise slightly less than the isotherms in response to modeled global
 243 warming, leading to a slight warming of their emission temperature – albeit a much weaker warming
 244 than occurs at a fixed pressure level (roughly six times smaller)⁵². This is related to an increase in
 245 upper tropospheric static stability with warming that was not originally anticipated in the FAT
 246 hypothesis. The proportionately higher anvil temperature (PHAT) hypothesis⁵² allows for increases in
 247 static stability that cause the level of peak radiatively-driven convergence to shift to slightly warmer
 248 temperatures. The upward shift of this level closely tracks the upward shift of anvil clouds under
 249 global warming, and captures their slight warming. The aforementioned upper-tropospheric static
 250 stability increase has been described as a fundamental consequence of the first law of
 251 thermodynamics, which results in static stability having an inverse-pressure dependence²¹, although
 252 the radiative effect of ozone has also been shown to play a role⁵³.

253 Cloud-resolving (horizontal grid spacing ≤ 15 km) model simulations of tropical radiative-convective
254 equilibrium support the theoretical expectation that the distribution of free-tropospheric clouds
255 shifts upward with surface warming nearly in lockstep with the isotherms, making their emission
256 temperature increase only slightly⁵³⁻⁵⁶. This response is also seen in global cloud-resolving models⁵⁷⁻
257 ⁵⁹. This is important for confirming that the response seen in GCMs^{21, 52} and mesoscale models⁴⁹ is
258 not an artifact of parameterized convection. Furthermore, observed interannual relationships
259 between cloud top altitude and surface temperature are also in close agreement with theoretical
260 expectations⁶⁰⁻⁶⁵. Recent analyses of satellite cloud retrievals showed that both tropical and extra-
261 tropical high clouds have shifted upward over the period 1983-2009^{66, 67}.

262 Although FAT was proposed as a mechanism for *tropical* cloud altitude feedback, it is possible that
263 radiative cooling by water vapor also controls the vertical extent of *extratropical* motions, and
264 thereby the strength of extratropical cloud altitude feedback (Thompson et al., submitted
265 manuscript). In any case, the extratropical free tropospheric cloud altitude feedback in GCMs is at
266 least as large as its counterpart in the tropics²⁶, despite having received much less attention in the
267 literature.

268 **Box 3: FAT and the cloud altitude feedback**

269 Cloud tops rising as the surface warms produces a positive feedback: by rising so as to remain at
270 nearly constant temperature, their emission to space does not increase in concert with emission
271 from the clear-sky regions, inhibiting the radiative cooling of the planet under global warming.

272 The fact that cloud top temperature remains roughly fixed makes the interpretation of the feedback
273 potentially confusing: how can high clouds warm the planet if their emission temperature remains
274 nearly unchanged? It is important to recall that feedbacks due to variable X are defined as the
275 change in radiation due to the temperature-mediated change in X *holding all else fixed*⁶⁸. In the case
276 where X is cloud top altitude, the feedback quantifies the change in radiation due *solely* to the
277 change in cloud top altitude, holding the temperature structure of the atmosphere fixed at its
278 unperturbed state. Thus, increased cloud top altitude causes a LW heating effect because – in the
279 radiation calculation – the emission temperature of the cloud top actually decreases by the product
280 of the mean-state lapse rate and the change in the cloud top altitude.

281 An important point to avoid losing in the details is that as long as the free tropospheric cloud tops
282 rise under global warming, the altitude feedback is positive. The extent to which cloud top
283 temperatures change affects only the magnitude of the feedback, not its sign.

284

285 *Representation in global climate models and causes of inter-model spread*

286 Given its solid foundation in well-established physics (radiative-convective equilibrium, Clausius-
287 Clapeyron relation), it is unsurprising that all GCMs simulate a nearly isothermal rise in the tops of
288 free tropospheric clouds with warming, in excellent agreement with PHAT. The multi-model mean
289 net free-tropospheric cloud altitude feedback is $0.20 \text{ W m}^{-2} \text{ K}^{-1}$, with an inter-model standard
290 deviation of $0.09 \text{ W m}^{-2} \text{ K}^{-1}$ (Fig. 1b). Although the spread in this feedback is roughly half as large as
291 that in the low cloud amount feedback, it is still substantial and remains poorly understood. Since

292 the altitude feedback is defined as the radiative impact of rising cloud tops while holding everything
293 else fixed (Box 3), the magnitude of this feedback at any given location should be related to (1) the
294 change in free-tropospheric cloud top altitude, (2) the decrease in emitted LW radiation per unit
295 increase of cloud top altitude, and (3) the free-tropospheric cloud fraction. These are discussed in
296 turn below.

297 Based on the discussion above, one would expect the magnitude of the upward shift of free-
298 tropospheric cloud tops (term 1) to be related to the upward shift of the level of radiatively-driven
299 convergence. Both of these are dependent on the magnitude of upper tropospheric warming^{69, 70},
300 which varies appreciably across models^{71, 72} for reasons that remain unclear.

301 The decrease in emitted LW radiation per unit increase in cloud top altitude depends on the mean-
302 state temperature and humidity profile of the atmosphere, and on cloud LW opacity. To the extent
303 that inter-model differences in atmospheric thermodynamic structure are small, inter-model
304 variance in term 2 would arise primarily from differences in the mean state cloud opacity, which
305 determines whether an upward shift is accompanied by a large decrease in LW flux (for thick clouds)
306 or a small decrease in LW flux (for thin clouds). Overall, the dependence of LW fluxes on cloud
307 optical thickness is small, however, because clouds of intermediate to high optical depth are
308 completely opaque to infrared radiation. Therefore, we do not expect cloud optical depth biases to
309 dominate the spread in cloud altitude feedback.

310 Finally, the mean-state free-tropospheric cloud fraction (term 3) is likely to exhibit substantial inter-
311 model spread. A four-fold difference in the simulated high (cloud top pressure ≤ 440 hPa) cloud
312 fraction was found among an earlier generation of models⁷³, though this spread has decreased in
313 CMIP5 models¹². Furthermore, climate models systematically underestimate the relative frequency
314 of occurrence of tropical anvil and extratropical cirrus regimes^{74, 75}. Taken alone, such biases would
315 lead to models systematically underestimating the cloud altitude feedback.

316 **Low cloud amount**

317 *Physical mechanisms*

318 The low cloud amount feedback in GCMs is dominated by the response of tropical, warm, liquid
319 clouds located below about 3 km to surface warming. Several types of clouds fulfill the definition of
320 “low”, differing in their radiative effects and in the physical mechanisms underlying their formation,
321 maintenance and response to climate change. So far, most insights into low cloud feedback
322 mechanisms have been gained from high-resolution models – particularly large-eddy simulations
323 (LES) that can explicitly represent the turbulent and convective processes critical for boundary-layer
324 clouds on scales smaller than one kilometer⁷⁶. The low cloud amount feedback in GCMs is
325 determined by the response of the most prevalent boundary-layer cloud types at low latitudes:
326 stratus, stratocumulus, and cumulus clouds.

327 Although they cover a relatively small fraction of Earth, *stratus and stratocumulus* (StCu) have a
328 large SW CRE, so that even small changes in their coverage may have significant regional and global
329 impacts. StCu cloud coverage is strongly controlled by atmospheric stability and surface fluxes⁷⁷:
330 observations suggest a strong relationship between inversion strength at the top of the planetary
331 boundary layer (PBL) and cloud amount^{78, 79}. A stronger inversion results in weaker mixing with the

332 dry free troposphere, shallowing the PBL and increasing cloudiness. Since inversion strength will
333 increase with global warming owing to the stabilization of the free-tropospheric temperature
334 profile⁸⁰, one might expect low cloud amount to increase, implying a negative feedback⁸¹.

335 However, LES experiments suggest that StCu clouds are sensitive to other factors than inversion
336 strength, as summarized by Bretherton¹⁵. Over subsiding regions, (1) increasing atmospheric
337 emissivity owing to water vapor feedback will cause more downward LW radiation, decreasing
338 cloud-top entrainment and thinning the cloud layer (less cloud and hence a positive radiative
339 feedback); (2) the slowdown of the general circulation will weaken subsidence, raising cloud tops
340 and thickening the cloud layer (a negative dynamical feedback); (3) a larger vertical gradient of
341 specific humidity will dry the PBL more efficiently, reducing cloudiness (a positive thermodynamic
342 feedback). Evidence for these physical mechanisms is usually also found in GCMs⁸²⁻⁸⁴ or when
343 analyzing observed natural variability⁸⁵⁻⁸⁷. The real-world StCu feedback will most likely result from
344 the relative importance of these antagonistic processes. LES models forced with an idealized climate
345 change suggest a reduction of StCu clouds with warming⁷⁶.

346 *Shallow cumuli* (ShCu) usually denote clouds with tops around 2-3 km localized over weak
347 subsidence regions and higher surface temperature. Despite their more modest SW CRE, ShCu are of
348 major importance to global-mean cloud feedback in GCMs because of their widespread presence
349 across the tropics¹⁷. Yet mechanisms of ShCu feedback in LES are less robust than for StCu. Usually,
350 LES reduce clouds with warming, with large sensitivity to precipitation (mostly related to
351 microphysical assumptions). This reduction has been explained by a stronger penetrative
352 entrainment that deepens and dries the PBL more efficiently^{13, 88} (closely related to the
353 thermodynamic feedback seen for StCu), although the strength of this positive feedback may
354 depend on the choice of prescribed or interactive sea surface temperatures (SSTs)^{89, 90} and
355 microphysics parameterization¹⁴. Other feedbacks seen for StCu may act on ShCu but with different
356 relative importance¹⁴. Although LES results suggest a positive ShCu feedback¹⁴, a global model that
357 explicitly resolves the crudest form of convection shows the opposite response⁹¹. Hence further
358 work with a hierarchy of model configurations (LES, global cloud-resolving model, GCMs) combined
359 with observational analyses will be needed to validate the ShCu feedback.

360 Recent observational studies of the low cloud response to changes in meteorological conditions
361 broadly support the StCu and ShCu feedback mechanisms identified in LES experiments^{84, 87, 92}. These
362 studies show that low clouds in both models and observations are mostly sensitive to changes in SST
363 and inversion strength. Although these two effects would tend to cancel each other, observations
364 and GCM simulations constrained by observations suggest that SST-mediated low cloud reduction
365 with warming dominates, increasing the likelihood of a positive low cloud feedback and high climate
366 sensitivity^{87, 93-95}. Nevertheless, recent ground-based observations of co-variations of ShCu with
367 meteorological conditions suggest that a majority of GCMs are unlikely to represent the temporal
368 dynamics of the cloudy boundary-layer^{96, 97}. This may reduce our confidence in GCM-based
369 constraints of ShCu feedback with warming.

370 *Representation in global climate models and sources of inter-model spread*

371 Cloud dynamics depend heavily on small-scale processes such as local turbulent eddies, non-local
372 convective plumes, microphysics, and radiation. Since the typical horizontal grid size of GCMs is
373 around 50 km, such processes are not explicitly simulated and need to be parameterized as a

374 function of the large-scale environment. GCMs usually represent cloud-related processes through
375 distinct parameterizations, with separate assumptions for subgrid variability, despite a goal for
376 unification^{98, 99}. Physical assumptions used in PBL parameterizations often relate cloud formation to
377 buoyancy production, stability, and wind shear. Low cloud amount feedbacks are constrained by
378 how these cloud processes are represented in GCMs and how they respond to climate change
379 perturbations. Since parameterizations are usually crude, it is not evident that the mechanisms of
380 low cloud amount feedback in GCMs are realistic.

381 All CMIP5 models simulate a positive low cloud amount feedback, but with considerable spread (Fig
382 2c); this feedback is by far the largest contributor to inter-model variance in net cloud feedback^{5, 17,}
383 ²⁶. Spread in low cloud amount feedback can be traced back to differences in parameterizations used
384 in atmospheric GCMs^{92, 100-102}, and changes in these parameterizations within individual GCMs also
385 have clear impacts on the intensity (and sign) of the response¹⁰²⁻¹⁰⁴. Identifying the low cloud
386 amount feedback mechanisms in GCMs is a difficult task, however, because the low cloud response
387 is sensitive to the competing effects of a variety of unresolved processes. Considering that these
388 processes are parameterized in diverse and complex ways, it appears unlikely that a single
389 mechanism can account for the spread of low cloud amount feedback seen in GCMs.

390 It has been proposed that convective processes play a key role in driving inter-model spread in low
391 cloud amount feedback¹⁰⁵⁻¹¹⁰. As the climate warms, convective moisture fluxes strengthen due to
392 the robust increase of the vertical gradient of specific humidity controlled by the Clausius-Clapeyron
393 relationship⁸². Increasing convective moisture fluxes between the PBL and the free troposphere lead
394 to a relatively drier PBL with decreased cloud amount, suggesting a positive feedback, but the
395 degree to which convective moisture mixing increases seems to strongly depend on model-specific
396 parameterizations¹⁰⁹. GCMs with stronger present-day convective mixing (and therefore more
397 positive low cloud amount feedback) have been argued to compare better with observations¹⁰⁹,
398 implying that convective overturning strength could provide an observational constraint on GCM
399 behavior. However, running GCMs with convection schemes switched off does not narrow the
400 spread of cloud feedback¹¹¹, suggesting that non-convective processes may play an important role
401 too^{92, 104}.

402 We believe that inter-model spread in low cloud amount feedback does not depend on the
403 representation of convection (deep and shallow) alone, but rather on the interplay between various
404 parameterized processes – particularly convection and turbulence. It has been argued that the
405 relative importance of parameterized convective drying and turbulent moistening of the PBL
406 accounts for a large fraction of the inter-model differences in both the mean state, and global
407 warming response of low clouds⁴⁶. In GCMs that attribute a large weight to convective drying in the
408 present-day climate, the strengthening of moisture transport with warming causes enhanced PBL
409 ventilation, efficiently reducing low cloud amount¹⁰⁹. Conversely if convective drying is less active,
410 turbulence moistening induces low cloud shallowing rather than a change in cloud amount^{46, 110}. In
411 some models, additional parameterization-dependent mechanisms may contribute to the low cloud
412 feedback, such as cloud amount increases by enhancement of surface turbulence^{83, 112} or by changes
413 in cloud lifetime¹¹³.

414 **Low cloud optical depth**

415 *Physical mechanisms*

416 The primary control on cloud optical depth is the vertically-integrated liquid water content, termed
417 liquid water path (LWP). If other microphysical parameters are held constant, cloud optical depth
418 scales with LWP within the cloud¹¹⁴. Cloud optical depth is also affected by cloud particle size and
419 cloud ice content, but the ice effect is smaller since ice crystals are typically several times larger than
420 liquid droplets, and therefore less efficient at scattering sunlight per unit mass¹¹⁵. Consistent with
421 this, the cloud optical depth change maps well onto the LWP response in global warming
422 experiments, both quantities increasing at middle to high latitudes in nearly all GCMs^{18, 19, 45, 116, 117}.
423 Understanding the negative cloud optical depth feedback therefore requires explaining why LWP
424 increases with warming, and why it does so mostly at high latitudes.

425 Two plausible mechanisms may contribute to LWP increases with warming, and both predict a
426 preferential increase at higher latitudes and lower temperatures. The first mechanism is based upon
427 the assumption that the liquid water content within a cloud is determined by the amount of
428 condensation in saturated rising parcels that follow a moist adiabat Γ_m , from the cloud base to the
429 cloud top¹¹⁸⁻¹²⁰. This is often referred to as the "adiabatic" cloud water content. Under this
430 assumption, it may be shown that the change in LWP with temperature is a function of the
431 temperature derivative of the moist adiabat slope, $\partial\Gamma_m/\partial T$. This predicts that the adiabatic cloud
432 water content always increases with temperature, and increases more strongly at lower
433 temperatures in a relative sense¹¹⁸.

434 A second mechanism involves phase changes in mixed-phase clouds. Liquid water is commonly
435 found in clouds at temperatures substantially below freezing, down to about -38°C where
436 homogeneous freezing occurs^{115, 121}. Clouds between -38°C and 0°C containing both liquid water and
437 ice are termed mixed-phase. As the atmosphere warms, the occurrence of liquid water should
438 increase relative to ice; for a fixed total cloud water path, this would lead to an optically thicker
439 cloud owing to the smaller effective radius of droplets^{19, 115, 121}. In addition, a higher fraction of liquid
440 water is expected to decrease the overall precipitation efficiency, yielding an increase in total cloud
441 water and a further optical thickening of the cloud^{19, 115, 119, 121}. Reduced precipitation efficiency may
442 also increase cloud lifetime, and hence cloud amount^{121, 122}. Because the phase change mechanism
443 can only operate below freezing, its occurrence in low clouds is restricted to middle and high
444 latitudes.

445 Satellite and in-situ observations of high-latitude clouds support increases in cloud LWP and optical
446 depth with temperature^{18, 19, 120}, and suggest a negative cloud optical depth feedback²⁰, although this
447 result is sensitive to the analysis method¹²³. The positive LWP sensitivity to temperature is generally
448 restricted to mixed-phase regions and is typically larger than that expected from moist adiabatic
449 increases in water content alone^{18, 19}. This lends observational support for the importance of phase
450 change processes. While the moist adiabatic mechanism should still contribute to LWP increases
451 with warming, LES modeling of warm boundary-layer clouds (in which phase change processes play
452 no role) suggests that optical depth changes are small relative to the effects of drying and deepening
453 of the boundary layer with warming¹³.

454 *Representation in global climate models*

455 The low cloud optical depth feedback predicted by GCMs can only be trusted to the extent that the
456 driving mechanisms are understood and correctly represented. We therefore ask, how reliably are
457 these physical mechanisms represented in GCMs? The first mechanism involves the *source* of cloud
458 water from condensation in saturated updrafts. It results from basic, well-understood
459 thermodynamics that do not directly rely on physical parameterizations, and should be correctly
460 implemented in all models. As such, it constitutes a simple and powerful constraint on the cloud
461 water content response to warming, to the point that some early studies proposed the *global* cloud
462 feedback might be negative as a result¹²⁴⁻¹²⁶. Considering this mechanism in isolation ignores
463 important competing factors that affect the cloud water budget, however, such as the entrainment
464 of dry air into the convective updrafts, phase change processes, or precipitation efficiency. The
465 competition between these various factors may explain why no simple, robust LWP increase with
466 temperature is seen in all regions across the world in GCMs.

467 The second mechanism is primarily related to the liquid water *sink* through conversion to ice and
468 precipitation by ice-phase microphysical processes. The representation of cloud microphysics in
469 state-of-the-art GCMs is mainly *prognostic*, meaning that rates of change between the different
470 phases – vapor, liquid, ice, and precipitation – are computed. Rather than being a direct function of
471 temperature (as in a *diagnostic* scheme), the relative amounts of liquid and ice thus depend on the
472 efficiencies of the source and sink terms. In GCMs, cloud water production in mixed-phase clouds
473 occurs mainly in liquid form; subsequent glaciation may occur through a variety of microphysical
474 processes, particularly the Wegener-Bergeron-Findeisen¹²⁷ mechanism (see Storelvmo et al.¹²⁸ for a
475 description and a review). Ice-phase microphysics are therefore mainly a sink of cloud liquid water.
476 Upon warming, this sink should become suppressed, resulting in a larger reservoir of cloud liquid
477 water¹⁹.

478 In GCMs, the optical depth feedback is likely dominated by microphysical phase change processes.
479 Several lines of evidence support this idea. As in observations, low cloud optical depth increases with
480 warming almost exclusively at high latitudes, and the increase in cloud water content is typically
481 restricted to temperatures below freezing^{117, 129, 130} – a finding that cannot be satisfactorily explained
482 by the adiabatic water content mechanism. Imposing a temperature increase only in the ice-phase
483 microphysics explains roughly 80% of the total LWP response to warming in two contemporary
484 GCMs run in aquaplanet configuration¹⁹. Furthermore, changes in the efficiency of phase conversion
485 processes have dramatic impacts on the cloud water climatology and sensitivity to warming in
486 GCMs¹³¹⁻¹³³.

487 *Causes of inter-model spread*

488 Although GCMs agree on the sign of the cloud optical depth response in mixed-phase clouds, the
489 magnitude of the change remains highly uncertain. This is in large part because the efficiency of
490 phase change processes varies widely between models, impacting the mean state and the sensitivity
491 to warming¹¹⁶.

492 GCMs separately simulate microphysical processes for cloud water resulting from large-scale
493 (resolved) vertical motions, and convective (unresolved, parameterized) motions. In convection
494 schemes, microphysical phase conversions are crudely represented, usually as simple, model-

495 dependent analytic functions of temperature. While the representation of microphysical processes is
496 much more refined in large-scale microphysics schemes, ice-phase processes remain diversely
497 represented due to limitations in our understanding, particularly with regard to ice formation
498 processes^{134, 135}. In models explicitly representing aerosol-cloud interactions, an additional
499 uncertainty results from poorly constrained ice nuclei concentrations¹²². For mixed-phase clouds,
500 perturbing the parameterizations of phase transitions can significantly affect the ratio of liquid water
501 to ice, the overall cloud water budget, and cloud-radiative properties^{19, 133}. Owing to these
502 uncertainties, the simple constraint that the liquid water fraction must increase with warming is
503 strong but merely qualitative in GCMs.

504 It is believed that mixed-phase clouds may become glaciated too readily in most GCMs^{121, 128}.
505 Satellite retrievals suggest models underestimate the supercooled liquid fraction in cold clouds^{132, 136-}
506 ¹³⁸; this may be because models assume too much spatial overlap between ice and supercooled
507 clouds, overestimating the liquid-to-ice conversion efficiency¹²⁸. An expected consequence is that
508 liquid water and cloud optical depth increase too dramatically with warming in GCMs, since there is
509 too much climatological cloud ice in a fractional sense. Comparisons with observations appear to
510 support that idea^{18, 20}. Such microphysical biases could have powerful implications for the optical
511 depth feedback, as models with excessive cloud ice may overestimate the phase change effect^{130, 133,}
512 ^{139, 140}. In summary, the current understanding is that the negative cloud optical depth feedback is
513 likely too strong in most GCMs. Further work with observational data is needed to constrain GCMs
514 and confirm the existence of a negative optical depth feedback in the real world.

515 **Other possible cloud feedback mechanisms: tropical and extratropical dynamics**

516 While the mechanisms discussed above are mainly linked to the climate system's thermodynamic
517 response to CO₂ forcing, dynamical changes could have equally important implications for clouds
518 and radiation. This poses a particular challenge: not only are the cloud responses to a given
519 dynamical forcing uncertain¹⁴¹, but the future dynamical response is also much more poorly
520 constrained than the thermodynamic one¹⁴². Below we discuss two possible effects of changes in
521 atmospheric circulation, one involving the degree of aggregation of tropical convection, and another
522 based on extratropical circulation shifts with warming. We assess the relevance of these proposed
523 feedback processes in GCMs and in the real world.

524 *Convective aggregation and the "iris effect"*

525 Tropical convective clouds both reduce outgoing LW radiation and reflect solar radiation. These
526 effects tend to offset each other, and over the broad expanse of warm waters in the western Pacific
527 and Indian Ocean areas these two effects very nearly cancel, so that net cloud radiative effect is
528 about zero¹⁴³⁻¹⁴⁵. The net neutrality of tropical cloud radiative effects results from a cancellation
529 between positive effects of thin anvil clouds and negative effects of the thicker rainy areas of the
530 cloud¹⁴⁶. That convective clouds tend to rise in a warmed climate has been discussed above, but it is
531 also possible that the optical depth or area coverage of convective clouds could change in a warmed
532 climate. For high clouds with no net effect on the radiation balance, a change in area coverage
533 without change in the average radiative properties of the clouds would have little effect on the
534 energy balance (unless the high clouds are masking bright low clouds). Because the individual LW
535 and SW effects of tropical convective clouds are large, a small change in the balance of these effects
536 could also provide a large feedback.

537 So far more attention has been directed at oceanic boundary layer clouds, whose net CRE is large,
538 since their substantial SW effect is not balanced by their relatively small LW effect. But since the SW
539 effect of tropical convective clouds is as large as that of boundary-layer clouds in stratocumulus
540 regimes, a substantial feedback could occur if the relative area coverage of thin anvils versus rainy
541 cores with higher albedos changes in a way to disrupt the net radiative neutrality of convective
542 clouds. Relatively little has been done on this problem, since global climate models do not resolve or
543 explicitly parameterize the physics of convective complexes and their associated meso- and
544 microscale processes.

545 It has been proposed that tropical anvil cloud area should decrease in a warmed climate, possibly
546 causing a negative LW feedback, but the theoretical and observational basis for this hypothesis
547 remains controversial¹⁴⁷⁻¹⁵¹. The response of tropical high cloud amount to warming in GCMs is very
548 sensitive to the particular parameterizations of convection and cloud microphysics that are
549 employed^{107, 152}, as might be expected.

550 One basic physical argument for changing the area of tropical high clouds with warming involves
551 simple energy balance and the dependence of saturation vapor pressure on temperature³⁵. The
552 basic energy balance of the atmosphere is radiative cooling balanced by latent heating. Convection
553 must bring enough latent heat upward to balance radiative losses. Radiative losses increase rather
554 slowly with surface temperature (~1.5% per K), whereas the latent energy in the atmosphere
555 increases by ~7% per K warming^{35, 153}. If one assumes that latent heating is proportional to saturation
556 vapor pressure times convective mass flux, it follows that convective mass flux must decrease as the
557 planet warms³⁵. If the cloud area decreases with the mass flux, then the high cloud area should
558 decrease with warming. Some support for this mechanism is found in global cloud-resolving model
559 experiments⁵⁷.

560 Another mechanism is the tendency of tropical deep convection to aggregate in part of the domain,
561 leaving another part of the domain with little high cloud and low relative humidity. This is observed
562 to happen in radiative-convective equilibrium models in which the mesoscale dynamics of
563 convective clouds is resolved¹⁵⁴⁻¹⁵⁶, although the relevance of this mechanism to realistic models and
564 the real world remains unclear. The presence of convection moistens the free troposphere, and the
565 radiative and microphysical effects of this encourage convection to form where it has already
566 influenced the environment. Away from the convection, the air is dry and radiative cooling supports
567 subsidence that suppresses convection. It has been argued that since self-aggregation occurs at high
568 temperatures, global warming may lead to a greater concentration of convection that may reduce
569 the convective area and lead to a cloud feedback²¹. Since tropical convection is also organized by the
570 large-scale circulations of the tropics, and the physics of tropical anvil clouds are not well-
571 represented in global models, these ideas remain a topic of active research. Basic thermodynamics
572 make the static stability a function of pressure, which may affect the fractional coverage of high
573 clouds in the tropics^{21, 52}.

574 *Shifts in midlatitude circulation with global warming*

575 Atmospheric circulation is a key control on cloud structure and radiative properties¹⁵⁷. Because
576 current GCMs predict systematic shifts of subtropical and extratropical circulation toward higher
577 latitudes as the planet warms¹⁵⁸, it has been suggested that midlatitude clouds will shift toward
578 regions of reduced insolation, causing an overall positive SW feedback^{3, 159}.

579 Although this poleward shift of storm-track clouds counts among the robust positive cloud feedback
580 mechanisms identified in the fifth IPCC assessment report (Fig. 7.11 in Boucher et al.³), the picture is
581 much less clear in analyses of cloud-radiative responses to storm track shifts in GCM experiments.
582 While some GCMs produce a clear cloud-radiative SW dipole in response to storm track shifts¹⁶⁰,
583 others simulate no clear zonal- or global-mean SW response^{24, 161-163}. In the context of observed
584 variability, the GCMs with no significant cloud-radiative response to a storm-track shift are clearly
585 more consistent with observations^{22, 24}. The lack of an observed SW cloud feedback to storm track
586 shifts results from free-tropospheric and boundary-layer clouds responding to storm track variability
587 in opposite ways. As the storms shift poleward, enhanced subsidence in the midlatitudes causes
588 free-tropospheric drying and cloud amount decreases, resulting in the expected shift of free-
589 tropospheric cloudiness. Meanwhile, however, lower-tropospheric stability increases, favoring
590 enhanced boundary-layer cloudiness and maintaining the SW CRE nearly unchanged²⁴. The ability of
591 GCMs to reproduce this behavior has been linked to their shallow convection schemes¹⁶³ and to
592 their representation of the effect of stability on boundary-layer cloud²⁴. If unforced variability
593 provides a good analog for the cloud response to forced dynamical changes – thought to be
594 approximately true in GCMs¹⁶³ – then the above results suggest little SW radiative impact from
595 future jet and storm track shifts.

596 Since LW radiation is much more sensitive to the response of free-tropospheric clouds than to low
597 cloud changes, storm-track shifts do cause coherent LW cloud-radiative anomalies²³. These
598 anomalies are small in the context of global warming-driven cloud feedback, however²³, so that
599 future shifts in midlatitude circulation appear unlikely to be a major contribution to global-mean LW
600 cloud feedback. Given the strong seasonality of LW and SW cloud-radiative anomalies, it remains
601 possible that extratropical circulation shifts have non-negligible radiative impacts on seasonal time
602 scales^{164, 165}. It is also possible that clouds and radiation respond more strongly to other aspects of
603 atmospheric circulation than the midlatitude jets and storm tracks; it has been recently proposed
604 that midlatitude cloud changes are more strongly tied to Hadley cell shifts than to the jet¹⁶⁵. Further
605 observational and modeling work is needed to confirm these relationships and assess their relevance
606 to cloud feedback.

607

608 **CONCLUDING REMARKS**

609 *Possible pathways to an improved representation of cloud feedback in GCMs*

610 Recent progress on the problem of cloud feedback has enabled unprecedented advances in process-
611 level understanding of cloud responses to CO₂ forcing. The main cloud property changes responsible
612 for radiative feedback in GCMs – rising high clouds, decreasing tropical low cloud amount, increasing
613 low cloud optical depth – are supported to varying degree by theoretical reasoning, high-resolution
614 modeling, and observations.

615 Much of the recent gains in understanding of radiatively-important tropical low cloud changes have
616 been accomplished through the use of limited-area, high-resolution LES models, able to explicitly
617 represent the critical boundary layer processes unresolved by GCMs. Because limited-area models
618 must be forced with prescribed climate change conditions, however, such models are unable to
619 represent the important feedbacks of clouds onto the large-scale climate. To fully understand how

620 cloud feedback affects climate sensitivity, atmospheric and oceanic circulation, and regional climate,
621 we must rely on global models.

622 Accurately representing clouds and their radiative effects in global models remains a formidable
623 challenge, however, and GCM spread in cloud feedback has not decreased substantially in recent
624 decades. Uncertainties in the global warming response of clouds are linked to the difficulty in
625 representing the complex interactions among the various physical processes at play – radiation,
626 microphysics, convective and turbulent fluxes, dynamics – through traditional GCM
627 parameterizations. Owing to sometimes unphysical interactions between individual
628 parameterizations, cloud feedback mechanisms may differ between GCMs^{46, 110}, and these
629 mechanisms may also be distinct from those acting in the real world.

630 One approach to circumvent the shortcomings of traditional GCM parameterizations involves
631 embedding a cloud-resolving model in each GCM grid box over part of the horizontal domain¹⁶⁶⁻¹⁶⁸.
632 Such “superparameterized” GCMs can thus explicitly simulate some of the convective motions and
633 subgrid variability that traditional parameterizations fail to represent accurately, while remaining
634 computationally affordable relative to global cloud-resolving models. However, superparameterized
635 GCMs remain unable to resolve the boundary-layer processes controlling radiatively-important low
636 clouds – and similarly to global cloud resolving models, they report disappointingly large spread in
637 their cloud feedback estimates¹⁵.

638 A recent further development, made possible by steady increases in computing power, involves the
639 use of LES rather than cloud-resolving models as a substitute for GCM parameterizations^{16, 169}. First
640 results suggest encouraging improvements in the representation of boundary-layer clouds (C.
641 Bretherton, pers. comm.). Superparameterization with LES combines aspects of the model hierarchy
642 into a single model, making it possible to represent both the small-scale processes and their impact
643 on the large scales. Analyses of superparameterized model experiments could also be used to design
644 more realistic parameterizations to improve boundary-layer characteristics, cloud variability, and
645 thus cloud feedback in traditional GCMs. An important caveat, however, is that current LES
646 superparameterizations are relatively coarse and may not represent processes such as entrainment
647 well, so that further increases in computing power may be necessary to fully exploit the possibilities
648 of LES superparameterization.

649 Irrespective of future increases in spatial resolution, GCMs will continue requiring parameterization
650 of the important microphysical processes of liquid droplet and ice crystal formation. As discussed in
651 this review, microphysical processes constitute a major source of uncertainty in future cloud
652 responses, particularly with regard to mixed-phase cloud radiative properties¹⁹ and precipitation
653 efficiency in convective clouds¹⁰⁷. The treatment of cloud-aerosol interactions also remains deficient
654 in current parameterizations¹⁷⁰. Improving the parameterization of microphysical processes must
655 therefore remain a priority for future work; this will involve a combined use of laboratory
656 experiments¹⁷¹, and satellite and in-situ observations of cloud phase^{119, 138}.

657 Although the main focus of this paper has been on the representation of clouds in GCMs,
658 observational analyses will remain crucial to advance our understanding of cloud feedback, in
659 conjunction with process-resolving modeling and global modeling. On the one hand, reliable
660 observations of clouds and their environment at both local and global scales are indispensable to
661 test and improve process-resolving models and GCM parameterizations. On the other hand, models

662 can provide process-based understanding of the relationship between clouds and the large-scale
663 environment, which can be exploited to identify observational constraints on cloud feedback.

664 *Current limits of understanding*

665 We conclude this review by highlighting two problems which we regard as key limitations in our
666 understanding of how cloud feedback impacts the climate system's response to external forcing. The
667 first problem relates to the relevance of cloud feedback to future atmospheric circulation changes,
668 which control climate change impacts at regional scales¹⁴². The circulation response is driven by
669 changes in diabatic heating, to which the radiative effects of clouds are an important contribution.
670 Hence cloud feedbacks must affect the dynamical response to warming, but the dynamical
671 implications of cloud feedback are just beginning to be quantified and understood. Recent work has
672 shown that cloud feedbacks have large impacts on the forced dynamical response to warming and
673 particularly the shift of the jets and storm tracks^{22, 161, 172, 173}. Thus the cloud response to warming
674 appears as one of the key uncertainties for future circulation changes. Substantial research efforts
675 are currently underway to improve our understanding of cloud-circulation interactions at various
676 scales and their implications for climate sensitivity, a problem identified as one of the current "grand
677 challenges" of climate science¹⁷³⁻¹⁷⁵.

678 Our second point concerns the problem of time dependence of cloud feedback. The traditional
679 feedback analysis framework is based on the simplifying assumption that feedback processes scale
680 with global-mean surface temperature, independent of the spatial pattern of warming. However,
681 recent research shows that the global feedback parameter does depend upon the pattern of surface
682 warming, which itself changes over time in CO₂-forced experiments^{7, 176-178}. In particular, most CMIP5
683 models subjected to an abrupt quadrupling of CO₂ concentrations indicate that the SW cloud
684 feedback parameter *increases* after about two decades, and this is a direct consequence of changes
685 in the SST warming pattern¹⁷⁹. Since future patterns of SST increase are uncertain in GCMs, and may
686 differ from those observed in the historical record, this introduces an additional uncertainty in the
687 magnitude of global-mean cloud feedback and our ability to constrain it using observations^{180, 181}.
688 Therefore, further work is necessary to understand what determines the spatial patterns of SST
689 increase, and how these patterns influence cloud properties at regional and global scales.

690

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702 climate modeling groups (listed in the Supporting Information) for producing and making available

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704 and Intercomparison provides coordinating support and led development of software infrastructure
705 in partnership with the Global Organization for Earth System Science Portals.

706

707 FURTHER READING

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