

Cloud feedback mechanisms and their representation in global climate models

Article

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Cloud feedback mechanisms and their representation in global climate models

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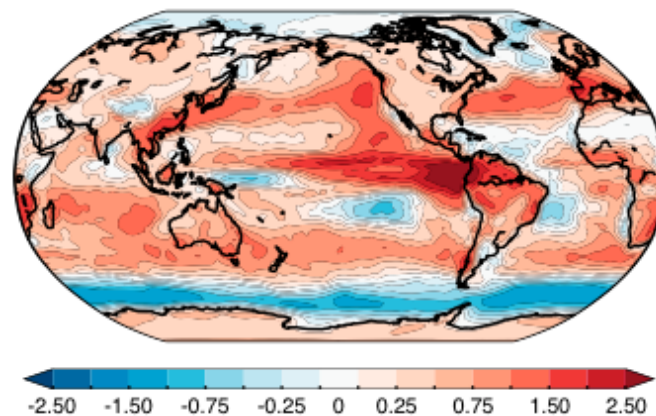
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Abstract

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.

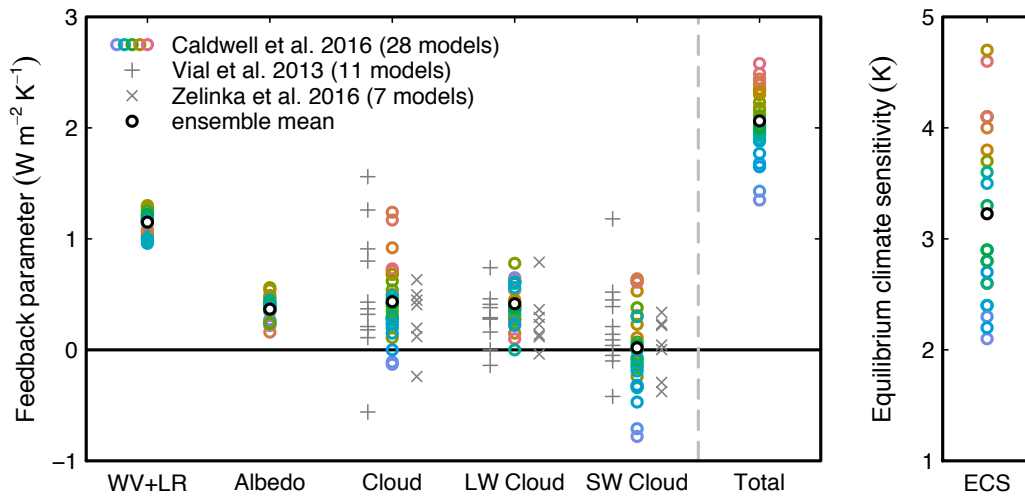
31 DIAGNOSING CLOUD FEEDBACK IN GLOBAL CLIMATE MODELS

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*

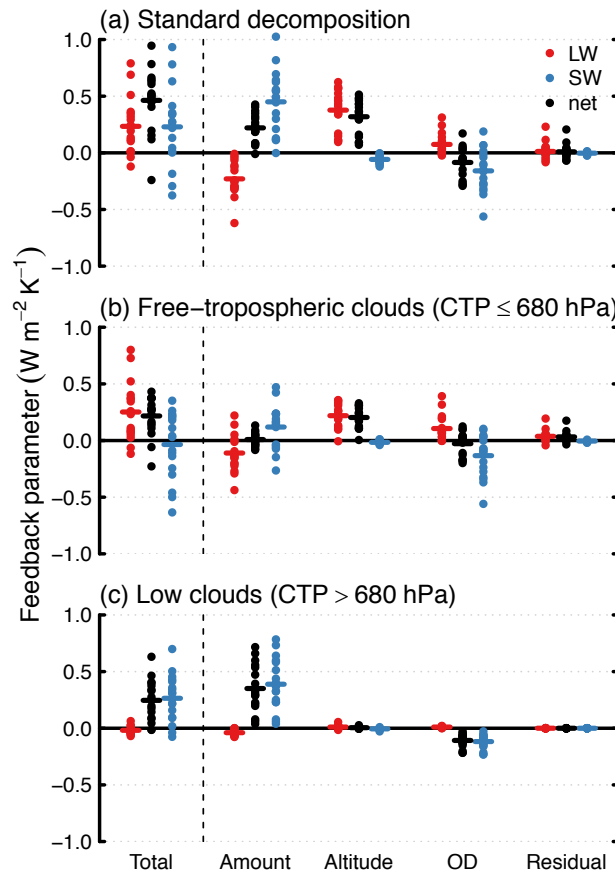
121 For models providing output that simulates measurements taken by satellites, the total cloud
122 feedback can be decomposed into contributions from three relevant cloud properties: cloud
123 altitude, amount, and optical depth (plus a small residual)⁴⁵. The multi-model-mean net cloud
124 feedback 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

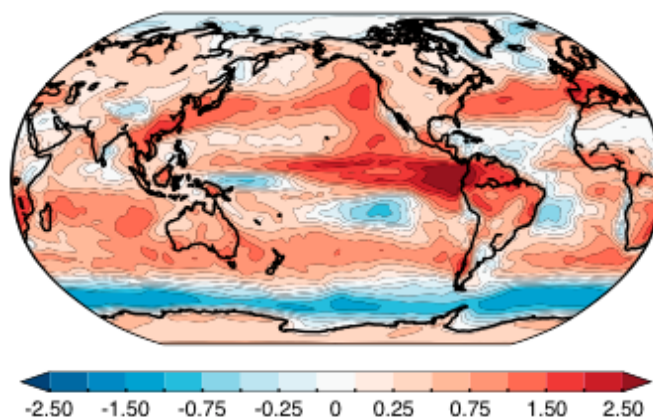
156 Fig. 2. Global mean LW (red), SW (blue), and net (black) cloud feedbacks decomposed into amount, altitude,
 157 optical depth (OD) and residual components for (a) all clouds, (b) free-tropospheric clouds only, and (c) low
 158 clouds only, defined by cloud top pressure (CTP). Multi-model mean feedbacks 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**

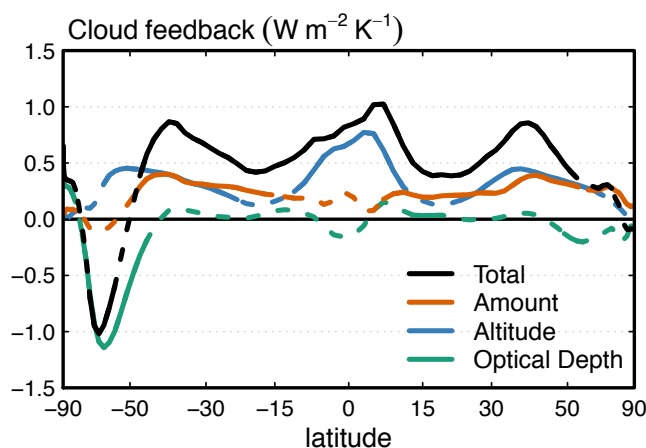
184 Cloud feedback is the main contributor to inter-model spread in climate sensitivity, ranging from
185 near zero to strongly positive (-0.13 to $1.24 W m^{-2} K^{-1}$) in current climate models. It is a combination
186 of three effects present in nearly all GCMs: rising free-tropospheric clouds (a 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

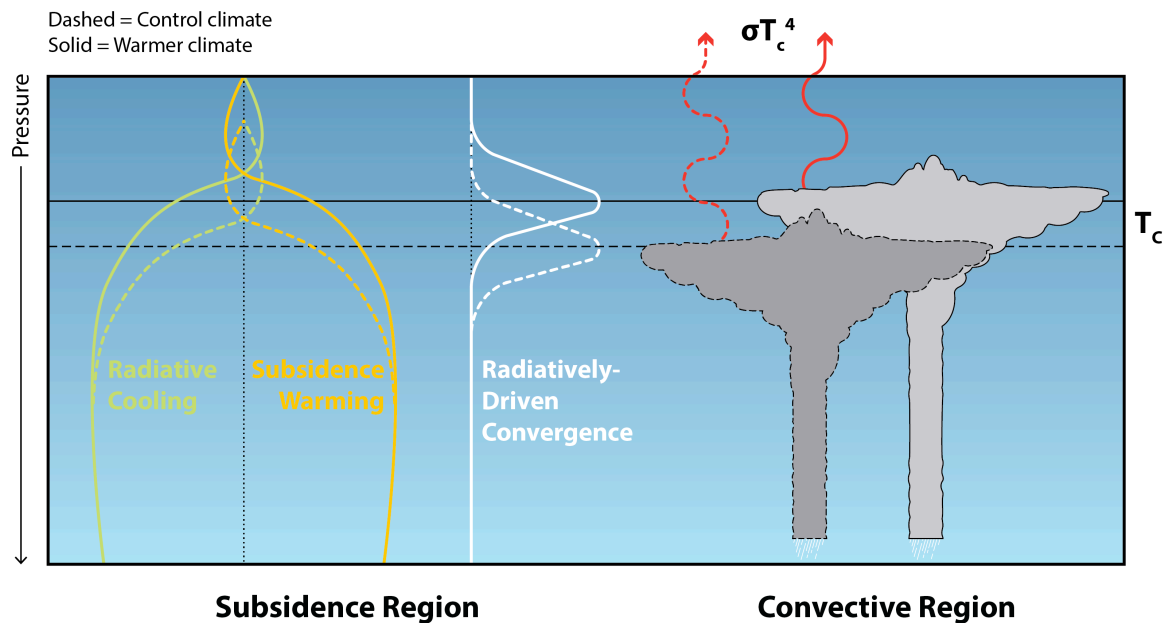
207 Cloud altitude

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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706

707 FURTHER READING

708 A very useful review of cloud feedbacks in high-resolution models: Bretherton CS. Insights into low-
709 latitude cloud feedbacks from high-resolution models. *Philosophical transactions. Series A,*
710 *Mathematical, physical, and engineering sciences* 2015, 373:3354-3360

711 A discussion of cloud phase changes in high-latitude clouds: Storelvmo T, Tan I, Korolev AV. Cloud
712 Phase Changes Induced by CO₂ Warming – a Powerful yet Poorly Constrained Cloud-Climate
713 Feedback. *Current Climate Change Reports* 2015, 1:288-296

714 A review on interactions between dynamics and clouds in the extratropics, including a discussion of
715 the roles of storm-track shifts in future cloud feedbacks: Ceppi P, Hartmann DL. Connections
716 Between Clouds, Radiation, and Midlatitude Dynamics: a Review. *Current Climate Change Reports*
717 2015, 1:94-102

718

719 REFERENCES

- 720 1. Manabe S, Wetherald RT. Thermal Equilibrium of the Atmosphere with a Given Distribution
721 of Relative Humidity. *Journal of the Atmospheric Sciences* 1967, 24:241-259.
- 722 2. Schneider SH. Cloudiness as a Global Climatic Feedback Mechanism: The Effects on the
723 Radiation Balance and Surface Temperature of Variations in Cloudiness. *Journal of the*
724 *Atmospheric Sciences* 1972, 29:1413-1422.
- 725 3. Boucher O, Randall D, Artaxo P, Bretherton C, Feingold G, Forster P, Kerminen V-M, Kondo Y,
726 Liao H, Lohmann U, et al. Clouds and Aerosols. In: Stocker TF, Qin D, G.-K P, Tignor M, Allen
727 SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, eds. *Climate Change 2013: The Physical*
728 *Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the*
729 *Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, NY,
730 USA: Cambridge University Press; 2013, 571-657.
- 731 4. Taylor KE, Stouffer RJ, Meehl GA. An Overview of CMIP5 and the Experiment Design. *Bulletin*
732 *of the American Meteorological Society* 2012, 93:485-498.
- 733 5. Caldwell PM, Zelinka MD, Taylor KE, Marvel K. Quantifying the Sources of Intermodel Spread
734 in Equilibrium Climate Sensitivity. *Journal of Climate* 2016, 29:513-524.
- 735 6. Vial J, Dufresne J-L, Bony S. On the interpretation of inter-model spread in CMIP5 climate
736 sensitivity estimates. *Climate Dynamics* 2013, 41:3339-3362.
- 737 7. Stevens B, Sherwood SC, Bony S, Webb MJ. Prospects for narrowing bounds on Earth's
738 equilibrium climate sensitivity. *Earth's Future* 2016, 4:512-522.
- 739 8. Arakawa A. Modelling clouds and cloud processes for use in climate models. In: *GARP*
740 *Publication Series No. 16*: WMO; 1975, 183–197.
- 741 9. Charney JG, Arakawa A, Baker DJ, Bolin B, Dickinson RE, Goody RM, Leith CE, Stommel HM,
742 Wunsch CI. Carbon Dioxide and Climate: A Scientific Assessment. *Report of an Ad Hoc Study*
743 *Group on Carbon Dioxide and Climate* 1979.
- 744 10. Mitchell JFB. The “Greenhouse” effect and climate change. *Reviews of Geophysics* 1989,
745 27:115-115.

- 746 11. Cess RD, Potter GL, Blanchet JP, Boer GJ, Del Genio AD, Déqué M, Dymnikov V, Galin V,
747 Gates WL, Ghan SJ, et al. Intercomparison and interpretation of climate feedback processes
748 in 19 atmospheric general circulation models. *Journal of Geophysical Research* 1990,
749 95:16601.
- 750 12. Klein SA, Zhang Y, Zelinka MD, Pincus R, Boyle J, Gleckler PJ. Are climate model simulations
751 of clouds improving? An evaluation using the ISCCP simulator. *Journal of Geophysical
752 Research-Atmospheres* 2013, 118:1329-1342.
- 753 13. Rieck M, Nuijens L, Stevens B. Marine Boundary Layer Cloud Feedbacks in a Constant
754 Relative Humidity Atmosphere. *Journal of the Atmospheric Sciences* 2012, 69:2538-2550.
- 755 14. Bretherton CS, Blossey PN, Jones CR. Mechanisms of marine low cloud sensitivity to
756 idealized climate perturbations: A single-LES exploration extending the CGILS cases. *Journal
757 of Advances in Modeling Earth Systems* 2013, 5:316-337.
- 758 15. Bretherton CS. Insights into low-latitude cloud feedbacks from high-resolution models.
759 *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences* 2015,
760 373:3354-3360.
- 761 16. Schneider T, Teixeira J, Bretherton CS, Brient F, Pressel KG, Schär C, Siebesma AP. Climate
762 goals and computing the future of clouds. *Nature Climate Change* 2017, 7:3-5.
- 763 17. Bony S, Dufresne J-L. Marine boundary layer clouds at the heart of tropical cloud feedback
764 uncertainties in climate models. *Geophysical Research Letters* 2005, 32:L20806.
- 765 18. Gordon ND, Klein SA. Low-cloud optical depth feedback in climate models. *Journal of
766 Geophysical Research: Atmospheres* 2014, 119:6052-6065.
- 767 19. Ceppi P, Hartmann DL, Webb MJ. Mechanisms of the negative shortwave cloud feedback in
768 high latitudes. *Journal of Climate* 2016, 29:139-157.
- 769 20. Ceppi P, McCoy DT, Hartmann DL. Observational evidence for a negative shortwave cloud
770 feedback in middle to high latitudes. *Geophysical Research Letters* 2016, 43:1331-1339.
- 771 21. Bony S, Stevens B, Coppin D, Becker T, Reed KA, Voigt A, Medeiros B. Thermodynamic
772 control of anvil cloud amount. *Proceedings of the National Academy of Sciences* 2016.
- 773 22. Grise KM, Polvani LM. Southern Hemisphere Cloud-Dynamics Biases in CMIP5 Models and
774 Their Implications for Climate Projections. *Journal of Climate* 2014, 27:6074-6092.
- 775 23. Ceppi P, Hartmann DL. Connections Between Clouds, Radiation, and Midlatitude Dynamics: a
776 Review. *Current Climate Change Reports* 2015, 1:94-102.
- 777 24. Grise KM, Medeiros B. Understanding the varied influence of mid-latitude jet position on
778 clouds and cloud-radiative effects in observations and global climate models. *Journal of
779 Climate* 2016:JCLI-D-16-0295.0291.
- 780 25. Klein SA, Hall A. Emergent Constraints for Cloud Feedbacks. *Current Climate Change Reports*
781 2015, 1:276-287.
- 782 26. Zelinka MD, Zhou C, Klein SA. Insights from a Refined Decomposition of Cloud Feedbacks.
783 *Geophysical Research Letters* 2016, 43:9259-9269.
- 784 27. Andrews T, Gregory JM, Webb MJ, Taylor KE. Forcing, feedbacks and climate sensitivity in
785 CMIP5 coupled atmosphere-ocean climate models. *Geophysical Research Letters* 2012,
786 39:n/a-n/a.
- 787 28. Forster PM, Andrews T, Good P, Gregory JM, Jackson LS, Zelinka M. Evaluating adjusted
788 forcing and model spread for historical and future scenarios in the CMIP5 generation of
789 climate models. *Journal of Geophysical Research: Atmospheres* 2013, 118:1139-1150.
- 790 29. Flato G, Marotzke J, Abiodun B, Braconnot P, Chou SC, Collins W, Cox P, Drriouech F, Emori S,
791 Eyring V, et al. Evaluation of Climate Models. *Climate Change 2013: The Physical Science
792 Basis. Contribution of Working Group I to the Fifth Assessment Report of the
793 Intergovernmental Panel on Climate Change* 2013, Pages 741-866.
- 794 30. Soden BJ, Held IM, Colman R, Shell KM, Kiehl JT, Shields CA. Quantifying Climate Feedbacks
795 Using Radiative Kernels. *Journal of Climate* 2008, 21:3504-3520.

- 796 31. Zelinka MD, Klein SA, Hartmann DL. Computing and Partitioning Cloud Feedbacks Using
797 Cloud Property Histograms. Part I: Cloud Radiative Kernels. *Journal of Climate* 2012,
798 25:3715-3735.
- 799 32. Tomassini L, Geoffroy O, Dufresne J-L, Idelkadi A, Cagnazzo C, Block K, Mauritsen T, Giorgetta
800 M, Quaas J. The respective roles of surface temperature driven feedbacks and tropospheric
801 adjustment to CO₂ in CMIP5 transient climate simulations. *Climate Dynamics* 2013, 41:3103-
802 3126.
- 803 33. Henderson DS, L'Ecuyer T, Stephens G, Partain P, Sekiguchi M. A Multisensor Perspective on
804 the Radiative Impacts of Clouds and Aerosols. *Journal of Applied Meteorology and
805 Climatology* 2013, 52:853-871.
- 806 34. Soden BJ, Broccoli AJ, Hemler RS. On the Use of Cloud Forcing to Estimate Cloud Feedback.
807 *Journal of Climate* 2004, 17:3661-3665.
- 808 35. Held IM, Soden BJ. Robust Responses of the Hydrological Cycle to Global Warming. *Journal
809 of Climate* 2006, 19:5686-5699.
- 810 36. Colman R. A comparison of climate feedbacks in general circulation models. *Climate
811 Dynamics* 2003, 20:865-873.
- 812 37. Colman RA, McAvaney BJ. A study of general circulation model climate feedbacks
813 determined from perturbed sea surface temperature experiments. *Journal of Geophysical
814 Research* 1997, 102:19383.
- 815 38. Andrews T, Forster PM. CO₂ forcing induces semi-direct effects with consequences for
816 climate feedback interpretations. *Geophysical Research Letters* 2008, 35:L04802.
- 817 39. Gregory J, Webb M. Tropospheric Adjustment Induces a Cloud Component in CO₂ Forcing.
818 *Journal of Climate* 2008, 21:58-71.
- 819 40. Sherwood SC, Bony S, Boucher O, Bretherton C, Forster PM, Gregory JM, Stevens B.
820 Adjustments in the Forcing-Feedback Framework for Understanding Climate Change. *Bulletin
821 of the American Meteorological Society* 2015, 96:217-228.
- 822 41. Chung E-S, Soden BJ. An Assessment of Direct Radiative Forcing, Radiative Adjustments, and
823 Radiative Feedbacks in Coupled Ocean-Atmosphere Models. *Journal of Climate* 2015,
824 28:4152-4170.
- 825 42. Zelinka MD, Klein SA, Taylor KE, Andrews T, Webb MJ, Gregory JM, Forster PM.
826 Contributions of Different Cloud Types to Feedbacks and Rapid Adjustments in CMIP5.
827 *Journal of Climate* 2013, 26:5007-5027.
- 828 43. Andrews T, Gregory JM, Forster PM, Webb MJ. Cloud Adjustment and its Role in CO₂
829 Radiative Forcing and Climate Sensitivity: A Review. *Surveys in Geophysics* 2012, 33:619-635.
- 830 44. Kamae Y, Watanabe M, Ogura T, Yoshimori M, Shiogama H. Rapid Adjustments of Cloud and
831 Hydrological Cycle to Increasing CO₂: a Review. *Current Climate Change Reports* 2015, 1:103-
832 113.
- 833 45. Zelinka MD, Klein SA, Hartmann DL. Computing and Partitioning Cloud Feedbacks Using
834 Cloud Property Histograms. Part II: Attribution to Changes in Cloud Amount, Altitude, and
835 Optical Depth. *Journal of Climate* 2012, 25:3736-3754.
- 836 46. Brient F, Schneider T, Tan Z, Bony S, Qu X, Hall A. Shallowness of tropical low clouds as a
837 predictor of climate models' response to warming. *Climate Dynamics* 2016, 47:433-449.
- 838 47. Manabe S, Strickler RF. Thermal Equilibrium of the Atmosphere with a Convective
839 Adjustment. *Journal of the Atmospheric Sciences* 1964, 21:361-385.
- 840 48. Clough SA, Iacono MJ, Moncet JL. Line-by-line calculations of atmospheric fluxes and cooling
841 rates: Application to water vapor. *Journal of Geophysical Research-Atmospheres* 1992,
842 97:15761-15785.
- 843 49. Hartmann DL, Larson K. An important constraint on tropical cloud-climate feedback.
844 *Geophysical Research Letters* 2002, 29:1951.

- 845 50. Cess RD. Radiative transfer due to atmospheric water vapor: Global considerations of the
846 earth's energy balance. *Journal of Quantitative Spectroscopy and Radiative Transfer* 1974,
847 14:861-871.
- 848 51. Ramanathan V, Coakley JA. Climate modeling through radiative-convective models. *Reviews*
849 *of Geophysics* 1978, 16:465-489.
- 850 52. Zelinka MD, Hartmann DL. Why is longwave cloud feedback positive? *Journal of Geophysical*
851 *Research* 2010, 115:D16117.
- 852 53. Harrop BE, Hartmann DL. Testing the Role of Radiation in Determining Tropical Cloud-Top
853 Temperature. *Journal of Climate* 2012, 25:5731-5747.
- 854 54. Tompkins AM, Craig GC. Sensitivity of tropical convection to sea surface temperature in the
855 absence of large-scale flow. *J. Climate* 1999, 12:462-476.
- 856 55. Kuang Z, Hartmann DL. Testing the Fixed Anvil Temperature Hypothesis in a Cloud-Resolving
857 Model. *Journal of Climate* 2007, 20:2051-2057.
- 858 56. Khairoutdinov M, Emanuel K. Rotating radiative-convective equilibrium simulated by a
859 cloud-resolving model. *Journal of Advances in Modeling Earth Systems* 2013, 5:816-825.
- 860 57. Satoh M, Iga S-i, Tomita H, Tsushima Y, Noda AT. Response of Upper Clouds in Global
861 Warming Experiments Obtained Using a Global Nonhydrostatic Model with Explicit Cloud
862 Processes. *Journal of Climate* 2012, 25:2178-2191.
- 863 58. Tsushima Y, Iga S-i, Tomita H, Satoh M, Noda AT, Webb MJ. High cloud increase in a
864 perturbed SST experiment with a global nonhydrostatic model including explicit convective
865 processes. *Journal of Advances in Modeling Earth Systems* 2014, 6:571-585.
- 866 59. Bretherton CS, Blossey PN, Stan C. Cloud feedbacks on greenhouse warming in the
867 superparameterized climate model SP-CCSM4. *Journal of Advances in Modeling Earth*
868 *Systems* 2014, 6:1185-1204.
- 869 60. Li Y, Yang P, North GR, Dessler A. Test of the Fixed Anvil Temperature Hypothesis. *Journal of*
870 *the Atmospheric Sciences* 2012, 69:2317-2328.
- 871 61. Zelinka MD, Hartmann DL. The observed sensitivity of high clouds to mean surface
872 temperature anomalies in the tropics. *Journal of Geophysical Research-Atmospheres* 2011,
873 116.
- 874 62. Eitzen ZA, Xu KM, Wong T. Cloud and Radiative Characteristics of Tropical Deep Convective
875 Systems in Extended Cloud Objects from CERES Observations. *J. Climate* 2009, 22:5983-
876 6000.
- 877 63. Xu KM, Wong T, Wielicki BA, Parker L, Eitzen ZA. Statistical Analyses of Satellite Cloud Object
878 Data from CERES. Part I: Methodology and Preliminary Results of the 1998 El Niño/2000 La
879 Niña. *J. Climate* 2005, 18:2497-2514.
- 880 64. Xu KM, Wong T, Wielicki BA, Parker L, Lin B, Eitzen ZA, Branson M. Statistical Analyses of
881 Satellite Cloud Object Data from CERES. Part II: Tropical Convective Cloud Objects during
882 1998 El Nino and Evidence for Supporting the Fixed Anvil Temperature Hypothesis. *J. Climate*
883 2007, 20:819-842.
- 884 65. Kubar TL, Hartmann DL, Wood R. Radiative and Convective Driving of Tropical High Clouds. *J.*
885 *Climate* 2007, 20:5510-5526.
- 886 66. Norris JR, Allen RJ, Evan AT, Zelinka MD, O'Dell CW, Klein SA. Evidence for climate change in
887 the satellite cloud record. *Nature* 2016, 536:72-75.
- 888 67. Marvel K, Zelinka M, Klein SA, Bonfils C, Caldwell P, Doutriaux C, Santer BD, Taylor KE.
889 External Influences on Modeled and Observed Cloud Trends. *Journal of Climate* 2015,
890 28:4820-4840.
- 891 68. Wetherald RT, Manabe S. Cloud Feedback Processes in a General Circulation Model. *Journal*
892 *of the Atmospheric Sciences* 1988, 45:1397-1416.
- 893 69. Santer BD, Sausen R, Wigley TML, Boyle JS, AchutaRao K, Doutriaux C, Hansen JE, Meehl GA,
894 Roeckner E, Ruedy R, et al. Behavior of tropopause height and atmospheric temperature in

895 models, reanalyses, and observations: Decadal changes. *Journal of Geophysical Research-*
896 *Atmospheres* 2003, 108.

897 70. Santer BD, Wehner MF, Wigley TML, Sausen R, Meehl GA, Taylor KE, Ammann C, Arblaster J,
898 Washington WM, Boyle JS, et al. Contributions of anthropogenic and natural forcing to
899 recent tropopause height changes. *Science* 2003, 301:479-483.

900 71. Fu Q, Manabe S, Johanson CM. On the warming in the tropical upper troposphere: Models
901 versus observations. *Geophysical Research Letters* 2011, 38.

902 72. Mitchell DM, Thorne PW, Stott PA, Gray LJ. Revisiting the controversial issue of tropical
903 tropospheric temperature trends. *Geophysical Research Letters* 2013, 40:2801-2806.

904 73. Zhang MH, Lin WY, Klein SA, Bacmeister JT, Bony S, Cederwall RT, Del Genio AD, Hack JJ,
905 Loeb NG, Lohmann U, et al. Comparing clouds and their seasonal variations in 10
906 atmospheric general circulation models with satellite measurements. *Journal of Geophysical*
907 *Research-Atmospheres* 2005, 110.

908 74. Williams K, Webb M. A quantitative performance assessment of cloud regimes in climate
909 models. *Climate Dyn.* 2009, 33:141-157.

910 75. Tsushima Y, Ringer MA, Webb MJ, Williams KD. Quantitative evaluation of the seasonal
911 variations in climate model cloud regimes. *Climate Dynamics* 2013, 41:2679-2696.

912 76. Blossey PN, Bretherton CS, Zhang M, Cheng A, Endo S, Heus T, Liu Y, Lock AP, de Roode SR,
913 Xu K-M. Marine low cloud sensitivity to an idealized climate change: The CGILS LES
914 intercomparison. *Journal of Advances in Modeling Earth Systems* 2013, 5:234-258.

915 77. Bretherton CS, Wyant MC. Moisture Transport, Lower-Tropospheric Stability, and
916 Decoupling of Cloud-Topped Boundary Layers. *Journal of the Atmospheric Sciences* 1997,
917 54:148-167.

918 78. Klein SA, Hartmann DL. The Seasonal Cycle of Low Stratiform Clouds. *Journal of Climate*
919 1993, 6:1587-1606.

920 79. Wood R, Bretherton CS. On the Relationship between Stratiform Low Cloud Cover and
921 Lower-Tropospheric Stability. *Journal of Climate* 2006, 19:6425-6432.

922 80. Qu X, Hall A, Klein SA, Caldwell PM. The strength of the tropical inversion and its response to
923 climate change in 18 CMIP5 models. *Climate Dynamics* 2015, 45:375-396.

924 81. Miller RL. Tropical Thermostats and Low Cloud Cover. *Journal of Climate* 1997, 10:409-440.

925 82. Brient F, Bony S. Interpretation of the positive low-cloud feedback predicted by a climate
926 model under global warming. *Climate Dynamics* 2013, 40:2415-2431.

927 83. Zhang M, Bretherton CS, Blossey PN, Austin PH, Bacmeister JT, Bony S, Brient F, Cheedela SK,
928 Cheng A, Del Genio AD, et al. CGILS: Results from the first phase of an international project
929 to understand the physical mechanisms of low cloud feedbacks in single column models.
930 *Journal of Advances in Modeling Earth Systems* 2013, 5:826-842.

931 84. Myers TA, Norris JR. On the Relationships between Subtropical Clouds and Meteorology in
932 Observations and CMIP3 and CMIP5 Models. *Journal of Climate* 2015, 28:2945-2967.

933 85. Albrecht BA, Jensen MP, Syrett WJ. Marine boundary layer structure and fractional
934 cloudiness. *Journal of Geophysical Research* 1995, 100:14209-14209.

935 86. Myers TA, Norris JR. Observational Evidence That Enhanced Subsidence Reduces Subtropical
936 Marine Boundary Layer Cloudiness. *Journal of Climate* 2013, 26:7507-7524.

937 87. Qu X, Hall A, Klein SA, DeAngelis AM. Positive tropical marine low-cloud cover feedback
938 inferred from cloud-controlling factors. *Geophysical Research Letters* 2015, 42:7767-7775.

939 88. Vogel R, Nuijens L, Stevens B. The role of precipitation and spatial organization in the
940 response of trade-wind clouds to warming. *Journal of Advances in Modeling Earth Systems*
941 2016, 8:843-862.

942 89. Tan Z, Schneider T, Teixeira J, Pressel KG. Large-eddy simulation of subtropical cloud-topped
943 boundary layers: 1. A forcing framework with closed surface energy balance. *Journal of*
944 *Advances in Modeling Earth Systems* 2016, 8:1565-1585.

- 945 90. Tan Z, Schneider T, Teixeira J, Pressel KG. Large-eddy simulation of subtropical cloud-topped
946 boundary layers: 2. Cloud response to climate change. *Journal of Advances in Modeling Earth*
947 *Systems* 2017.
- 948 91. Wyant MC, Bretherton CS, Blossey PN. Subtropical Low Cloud Response to a Warmer Climate
949 in a Superparameterized Climate Model. Part I: Regime Sorting and Physical Mechanisms.
950 *Journal of Advances in Modeling Earth Systems* 2009, 1:n/a-n/a.
- 951 92. Qu X, Hall A, Klein SA, Caldwell PM. On the spread of changes in marine low cloud cover in
952 climate model simulations of the 21st century. *Climate Dynamics* 2014, 42:2603-2626.
- 953 93. Brient F, Schneider T. Constraints on climate sensitivity from space-based measurements of
954 low-cloud reflection. *Journal of Climate* 2016.
- 955 94. Myers TA, Norris JR. Reducing the uncertainty in subtropical cloud feedback. *Geophysical*
956 *Research Letters* 2016, 43:2144-2148.
- 957 95. McCoy DT, Eastman R, Hartmann DL, Wood R. The change in low cloud cover in a warmed
958 climate inferred from AIRS, MODIS and ECMWF-Interim reanalysis. *Journal of Climate*
959 2017:JCLI-D-15-0734.0731.
- 960 96. Nuijens L, Medeiros B, Sandu I, Ahlgrimm M. Observed and modeled patterns of covariability
961 between low-level cloudiness and the structure of the trade-wind layer. *Journal of Advances*
962 *in Modeling Earth Systems* 2015, 7:1741-1764.
- 963 97. Nuijens L, Medeiros B, Sandu I, Ahlgrimm M. The behavior of trade-wind cloudiness in
964 observations and models: The major cloud components and their variability. *Journal of*
965 *Advances in Modeling Earth Systems* 2015, 7:600-616.
- 966 98. Siebesma AP, Soares PMM, Teixeira J. A Combined Eddy-Diffusivity Mass-Flux Approach for
967 the Convective Boundary Layer. *Journal of the Atmospheric Sciences* 2007, 64:1230-1248.
- 968 99. Larson VE, Schanen DP, Wang M, Ovchinnikov M, Ghan S. PDF Parameterization of Boundary
969 Layer Clouds in Models with Horizontal Grid Spacings from 2 to 16 km. *Monthly Weather*
970 *Review* 2012, 140:285-306.
- 971 100. Medeiros B, Stevens B, Bony S. Using aquaplanets to understand the robust responses of
972 comprehensive climate models to forcing. *Climate Dynamics* 2015.
- 973 101. Neggers RAJ. Attributing the behavior of low-level clouds in large-scale models to sub-grid
974 scale parameterizations. *Journal of Advances in Modeling Earth Systems* 2015, 7:2029-2043.
- 975 102. Geoffroy O, Sherwood S, Fuchs D. On the role of the stratiform cloud scheme in the
976 intermodel spread of cloud feedback. *Journal of Advances in Modeling Earth Systems* 2017.
- 977 103. Watanabe M, Shiogama H, Yokohata T, Kamae Y, Yoshimori M, Ogura T, Annan JD,
978 Hargreaves JC, Emori S, Kimoto M. Using a Multiphysics Ensemble for Exploring Diversity in
979 Cloud-Shortwave Feedback in GCMs. *Journal of Climate* 2012, 25:5416-5431.
- 980 104. Kamae Y, Shiogama H, Watanabe M, Ogura T, Yokohata T, Kimoto M. Lower-Tropospheric
981 Mixing as a Constraint on Cloud Feedback in a Multiparameter Multiphysics Ensemble.
982 *Journal of Climate* 2016, 29:6259-6275.
- 983 105. Gettelman A, Kay JE, Shell KM. The Evolution of Climate Sensitivity and Climate Feedbacks in
984 the Community Atmosphere Model. *Journal of Climate* 2012, 25:1453-1469.
- 985 106. Zhao M. An Investigation of the Connections among Convection, Clouds, and Climate
986 Sensitivity in a Global Climate Model. *Journal of Climate* 2014, 27:1845-1862.
- 987 107. Zhao M, Golaz JC, Held IM, Ramaswamy V, Lin SJ, Ming Y, Ginoux P, Wyman B, Donner LJ,
988 Paynter D, et al. Uncertainty in Model Climate Sensitivity Traced to Representations of
989 Cumulus Precipitation Microphysics. *Journal of Climate* 2016, 29:543-560.
- 990 108. Tomassini L, Voigt A, Stevens B. On the connection between tropical circulation, convective
991 mixing, and climate sensitivity. *Quarterly Journal of the Royal Meteorological Society* 2015,
992 141:1404-1416.
- 993 109. Sherwood SC, Bony S, Dufresne J-L. Spread in model climate sensitivity traced to
994 atmospheric convective mixing. *Nature* 2014, 505:37-42.

- 995 110. Vial J, Bony S, Dufresne J-L, Roehrig R. Coupling between lower-tropospheric convective
996 mixing and low-level clouds: Physical mechanisms and dependence on convection scheme.
997 *Journal of Advances in Modeling Earth Systems* 2016.
- 998 111. Webb MJ, Lock AP, Bretherton CS, Bony S, Cole JNS, Idelkadi A, Kang SM, Koshiro T, Kawai H,
999 Ogura T, et al. The impact of parametrized convection on cloud feedback. *Philosophical
1000 transactions. Series A, Mathematical, physical, and engineering sciences* 2015, 373.
- 1001 112. Kawai H. Examples of Mechanisms for Negative Cloud Feedback of Stratocumulus and
1002 Stratus in Cloud Parameterizations. *SOLA* 2012, 8:150-154.
- 1003 113. Zhang M, Bretherton C. Mechanisms of Low Cloud–Climate Feedback in Idealized Single-
1004 Column Simulations with the Community Atmospheric Model, Version 3 (CAM3). *Journal of
1005 Climate* 2008, 21:4859-4878.
- 1006 114. Stephens GL. Radiation Profiles in Extended Water Clouds. II: Parameterization Schemes.
1007 *Journal of the Atmospheric Sciences* 1978, 35:2123-2132.
- 1008 115. Pruppacher HR, Klett JD. *Microphysics of Clouds and Precipitation*. 2010, 18:954.
- 1009 116. McCoy DT, Hartmann DL, Zelinka MD, Ceppi P, Grosvenor DP. Mixed-phase cloud physics
1010 and Southern Ocean cloud feedback in climate models. *Journal of Geophysical Research:
1011 Atmospheres* 2015, 120:9539-9554.
- 1012 117. Tsushima Y, Emori S, Ogura T, Kimoto M, Webb MJ, Williams KD, Ringer MA, Soden BJ, Li B,
1013 Andronova N. Importance of the mixed-phase cloud distribution in the control climate for
1014 assessing the response of clouds to carbon dioxide increase: a multi-model study. *Climate
1015 Dynamics* 2006, 27:113-126.
- 1016 118. Betts AK, Harshvardhan. Thermodynamic constraint on the cloud liquid water feedback in
1017 climate models. *Journal of Geophysical Research* 1987, 92:8483.
- 1018 119. Klein SA, McCoy RB, Morrison H, Ackerman AS, Avramov A, Boer Gd, Chen M, Cole JNS, Del
1019 Genio AD, Falk M, et al. Intercomparison of model simulations of mixed-phase clouds
1020 observed during the ARM Mixed-Phase Arctic Cloud Experiment. I: single-layer cloud.
1021 *Quarterly Journal of the Royal Meteorological Society* 2009, 135:979-1002.
- 1022 120. Tselioudis G, Rossow WB, Rind D. Global Patterns of Cloud Optical Thickness Variation with
1023 Temperature. *Journal of Climate* 1992, 5:1484-1495.
- 1024 121. Storelvmo T, Tan I, Korolev AV. Cloud Phase Changes Induced by CO₂ Warming – a Powerful
1025 yet Poorly Constrained Cloud-Climate Feedback. *Current Climate Change Reports* 2015,
1026 1:288-296.
- 1027 122. DeMott PJ, Prenni AJ, Liu X, Kreidenweis SM, Petters MD, Twohy CH, Richardson MS,
1028 Eidhammer T, Rogers DC. Predicting global atmospheric ice nuclei distributions and their
1029 impacts on climate. *Proceedings of the National Academy of Sciences* 2010, 107:11217-
1030 11222.
- 1031 123. Terai CR, Klein SA, Zelinka MD. Constraining the low-cloud optical depth feedback at middle
1032 and high latitudes using satellite observations. *Journal of Geophysical Research:
1033 Atmospheres* 2016, 121:9696-9716.
- 1034 124. Somerville RCJ, Remer LA. Cloud optical thickness feedbacks in the CO₂ climate problem.
1035 *Journal of Geophysical Research* 1984, 89:9668.
- 1036 125. Paltridge GW. Cloud-radiation feedback to climate. *Quarterly Journal of the Royal
1037 Meteorological Society* 1980, 106:895-899.
- 1038 126. Mitchell JFB, Senior CA, Ingram WJ. CO₂ and climate: a missing feedback? *Nature* 1989,
1039 341:132-134.
- 1040 127. Findeisen W. Die kolloidmeteorologischen Vorgänge bei Niederschlagsbildung.
1041 *Meteorologische Zeitschrift* 1938, 55:121-133.
- 1042 128. Storelvmo T, Tan I. The Wegener-Bergeron-Findeisen process – Its discovery and vital
1043 importance for weather and climate. *Meteorologische Zeitschrift* 2015.
- 1044 129. Senior CA, Mitchell JFB. Carbon Dioxide and Climate. The Impact of Cloud Parameterization.
1045 *Journal of Climate* 1993, 6:393-418.

- 1046 130. Choi Y-S, Ho C-H, Park C-E, Storelvmo T, Tan I. Influence of cloud phase composition on
1047 climate feedbacks. *Journal of Geophysical Research: Atmospheres* 2014, 119:3687-3700.
- 1048 131. Li Z-X, Le Treut H. Cloud-radiation feedbacks in a general circulation model and their
1049 dependence on cloud modelling assumptions. *Climate Dynamics* 1992, 7:133-139.
- 1050 132. Kay JE, Bourdages L, Miller NB, Morrison A, Yettella V, Chepfer H, Eaton B. Evaluating and
1051 improving cloud phase in the Community Atmosphere Model version 5 using spaceborne
1052 lidar observations. *Journal of Geophysical Research: Atmospheres* 2016, 121:4162-4176.
- 1053 133. Tan I, Storelvmo T, Zelinka MD. Observational constraints on mixed-phase clouds imply
1054 higher climate sensitivity. *Science* 2016, 352:224-227.
- 1055 134. DeMott PJ, Möhler O, Stetzer O, Vali G, Levin Z, Petters MD, Murakami M, Leisner T, Bundke
1056 U, Klein H, et al. Resurgence in Ice Nuclei Measurement Research. *Bulletin of the American
1057 Meteorological Society* 2011, 92:1623-1635.
- 1058 135. Gettelman A, Liu X, Barahona D, Lohmann U, Chen C. Climate impacts of ice nucleation.
1059 *Journal of Geophysical Research: Atmospheres* 2012, 117:n/a-n/a.
- 1060 136. Hu Y, Rodier S, Xu K-m, Sun W, Huang J, Lin B, Zhai P, Josset D. Occurrence, liquid water
1061 content, and fraction of supercooled water clouds from combined CALIOP/IIR/MODIS
1062 measurements. *Journal of Geophysical Research* 2010, 115:D00H34.
- 1063 137. Komurcu M, Storelvmo T, Tan I, Lohmann U, Yun Y, Penner JE, Wang Y, Liu X, Takemura T.
1064 Intercomparison of the cloud water phase among global climate models. *Journal of
1065 Geophysical Research: Atmospheres* 2014, 119:3372-3400.
- 1066 138. Cesana G, Waliser DE, Jiang X, Li J-LF. Multi-model evaluation of cloud phase transition using
1067 satellite and reanalysis data. *Journal of Geophysical Research: Atmospheres* 2015, 120.
- 1068 139. McCoy DT, Tan I, Hartmann DL, Zelinka MD, Storelvmo T. On the relationships among cloud
1069 cover, mixed-phase partitioning, and planetary albedo in GCMs. *Journal of Advances in
1070 Modeling Earth Systems* 2016, 8:1-19.
- 1071 140. Bodas-Salcedo A, Andrews T, Karmalkar AV, Ringer MA. Cloud liquid water path and
1072 radiative feedbacks over the Southern Ocean. *Geophysical Research Letters* 2016.
- 1073 141. Bony S, Dufresne J-L, Le Treut H, Morcrette J-J, Senior C. On dynamic and thermodynamic
1074 components of cloud changes. *Climate Dynamics* 2004, 22:71-86.
- 1075 142. Shepherd TG. Atmospheric circulation as a source of uncertainty in climate change
1076 projections. *Nature Geoscience* 2014, 7:703-708.
- 1077 143. Hartmann DL, Short DA. On the Use of Earth Radiation Budget Statistics for Studies of Clouds
1078 and Climate. *Journal of the Atmospheric Sciences* 1980, 37:1233-1250.
- 1079 144. Ramanathan V, Cess RD, Harrison EF, Minnis P, Barkstrom BR, Ahmad E, Hartmann D. Cloud-
1080 Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment. *Science*
1081 1989, 243.
- 1082 145. Harrison EF, Minnis P, Barkstrom BR, Ramanathan V, Cess RD, Gibson GG. Seasonal variation
1083 of cloud radiative forcing derived from the Earth Radiation Budget Experiment. *Journal of
1084 Geophysical Research* 1990, 95:18687-18687.
- 1085 146. Hartmann DL, Moy LA, Fu Q. Tropical Convection and the Energy Balance at the Top of the
1086 Atmosphere. *Journal of Climate* 2001, 14:4495-4511.
- 1087 147. Lindzen RS, Chou M-D, Hou AY. Does the Earth Have an Adaptive Infrared Iris? *Bulletin of the
1088 American Meteorological Society* 2001, 82:417-432.
- 1089 148. Hartmann DL, Michelsen ML. No Evidence for Iris. *Bulletin of the American Meteorological
1090 Society* 2002, 83:249-254.
- 1091 149. Fu Q, Baker M, Hartmann DL. Tropical cirrus and water vapor: an effective Earth infrared iris
1092 feedback? *Atmospheric Chemistry and Physics* 2002, 2:31-37.
- 1093 150. Chambers LH, Lin B, Young DF. Examination of New CERES Data for Evidence of Tropical Iris
1094 Feedback. *Journal of Climate* 2002, 15:3719-3726.
- 1095 151. Lin B, Wielicki BA, Chambers LH, Hu Y, Xu K-M. The Iris Hypothesis: A Negative or Positive
1096 Cloud Feedback? *Journal of Climate* 2002, 15:3-7.

- 1097 152. Mauritsen T, Stevens B. Missing iris effect as a possible cause of muted hydrological change
1098 and high climate sensitivity in models. *Nature Geoscience* 2015, 8:346-351.
- 1099 153. Mitchell JFB, Wilson CA, Cunningham WM. On CO2 climate sensitivity and model dependence
1100 of results. *Quarterly Journal of the Royal Meteorological Society* 1987, 113:293-322.
- 1101 154. Su H, Bretherton CS, Chen SS. Self-Aggregation and Large-Scale Control of Tropical Deep
1102 Convection: A Modeling Study. *Journal of the Atmospheric Sciences* 2000, 57:1797-1816.
- 1103 155. Bretherton CS, Blossey PN, Khairoutdinov M. An Energy-Balance Analysis of Deep Convective
1104 Self-Aggregation above Uniform SST. *Journal of the Atmospheric Sciences* 2005, 62:4273-
1105 4292.
- 1106 156. Wing AA, Emanuel KA. Physical mechanisms controlling self-aggregation of convection in
1107 idealized numerical modeling simulations. *Journal of Advances in Modeling Earth Systems*
1108 2014, 6:59-74.
- 1109 157. Bony S, Colman R, Kattsov VM, Allan RP, Bretherton CS, Dufresne J-L, Hall A, Hallegatte S,
1110 Holland MM, Ingram W, et al. How Well Do We Understand and Evaluate Climate Change
1111 Feedback Processes? *Journal of Climate* 2006, 19:3445-3482.
- 1112 158. Barnes EA, Polvani L. Response of the midlatitude jets and of their variability to increased
1113 greenhouse gases in the CMIP5 models. *Journal of Climate* 2013, 26:7117-7135.
- 1114 159. Bender FA-M, Ramanathan V, Tselioudis G. Changes in extratropical storm track cloudiness
1115 1983–2008: observational support for a poleward shift. *Climate Dynamics* 2012, 38:2037-
1116 2053.
- 1117 160. Grise KM, Polvani LM, Tselioudis G, Wu Y, Zelinka MD. The ozone hole indirect effect: Cloud-
1118 radiative anomalies accompanying the poleward shift of the eddy-driven jet in the Southern
1119 Hemisphere. *Geophysical Research Letters* 2013, 40:3688-3692.
- 1120 161. Ceppi P, Zelinka MD, Hartmann DL. The response of the Southern Hemispheric eddy-driven
1121 jet to future changes in shortwave radiation in CMIP5. *Geophysical Research Letters* 2014,
1122 41:3244-3250.
- 1123 162. Kay JE, Medeiros B, Hwang YT, Gettelman A, Perket J, Flanner MG. Processes controlling
1124 Southern Ocean Shortwave Climate Feedbacks in CESM. *Geophysical Research Letters* 2014,
1125 41:616-622.
- 1126 163. Wall CJ, Hartmann DL. On the influence of poleward jet shift on shortwave cloud feedback in
1127 global climate models. *Journal of Advances in Modeling Earth Systems* 2015, 7:2044-2059.
- 1128 164. Li Y, Thompson DWJ, Huang Y, Zhang M. Observed linkages between the northern annular
1129 mode/North Atlantic Oscillation, cloud incidence, and cloud radiative forcing. *Geophysical*
1130 *Research Letters* 2014, 41:1681-1688.
- 1131 165. Tselioudis G, Lipat BR, Konsta D, Grise KM, Polvani LM. Midlatitude cloud shifts, their
1132 primary link to the Hadley cell, and their diverse radiative effects. *Geophysical Research*
1133 *Letters* 2016, 43:4594-4601.
- 1134 166. Randall D, Khairoutdinov M, Arakawa A, Grabowski W. Breaking the Cloud Parameterization
1135 Deadlock. *Bulletin of the American Meteorological Society* 2003, 84:1547-1564.
- 1136 167. Grabowski WW, Smolarkiewicz PK. CRCP: a Cloud Resolving Convection Parameterization for
1137 modeling the tropical convecting atmosphere. *Physica D: Nonlinear Phenomena* 1999,
1138 133:171-178.
- 1139 168. Khairoutdinov MF, Randall DA. A cloud resolving model as a cloud parameterization in the
1140 NCAR Community Climate System Model: Preliminary results. *Geophysical Research Letters*
1141 2001, 28:3617-3620.
- 1142 169. Grabowski WW. Towards Global Large Eddy Simulation: Super-Parameterization Revisited.
1143 *Journal of the Meteorological Society of Japan* 2016, 94:327-344.
- 1144 170. Gettelman A, Sherwood SC. Processes Responsible for Cloud Feedback. *Current Climate*
1145 *Change Reports* 2016:1-11.
- 1146 171. Herbert RJ, Murray BJ, Dobbie SJ, Koop T. Sensitivity of liquid clouds to homogenous freezing
1147 parameterizations. *Geophysical Research Letters* 2015, 42:1599-1605.

- 1148 172. Ceppi P, Hartmann DL. Clouds and the atmospheric circulation response to warming. *Journal*
1149 *of Climate* 2016, 29:783-799.
- 1150 173. Shaw TA, Baldwin M, Barnes EA, Caballero R, Garfinkel CI, Hwang YT, Li C, O'Gorman PA,
1151 Rivière G, Simpson IR, et al. Storm track processes and the opposing influences of climate
1152 change. *Nature Geoscience* 2016, 9:656-664.
- 1153 174. Bony S, Stevens B, Frierson DMW, Jakob C, Kageyama M, Pincus R, Shepherd TG, Sherwood
1154 SC, Siebesma AP, Sobel AH, et al. Clouds, circulation and climate sensitivity. *Nature*
1155 *Geoscience* 2015, 8:261-268.
- 1156 175. Webb MJ, Andrews T, Bodas-Salcedo A, Bony S, Bretherton CS, Chadwick R, Chepfer H,
1157 Douville H, Good P, Kay JE, et al. The Cloud Feedback Model Intercomparison Project
1158 (CFMIP) contribution to CMIP6. *Geoscientific Model Development* 2017, 10:359-384.
- 1159 176. Winton M, Takahashi K, Held IM. Importance of Ocean Heat Uptake Efficacy to Transient
1160 Climate Change. *Journal of Climate* 2010, 23:2333-2344.
- 1161 177. Armour KC, Bitz CM, Roe GH. Time-Varying Climate Sensitivity from Regional Feedbacks.
1162 *Journal of Climate* 2013, 26:4518-4534.
- 1163 178. Rose BEJ, Armour KC, Battisti DS, Feldl N, Koll DDB. The dependence of transient climate
1164 sensitivity and radiative feedbacks on the spatial pattern of ocean heat uptake. *Geophysical*
1165 *Research Letters* 2014, 41:1071-1078.
- 1166 179. Andrews T, Gregory JM, Webb MJ. The Dependence of Radiative Forcing and Feedback on
1167 Evolving Patterns of Surface Temperature Change in Climate Models. *Journal of Climate*
1168 2015, 28:1630-1648.
- 1169 180. Gregory JM, Andrews T. Variation in climate sensitivity and feedback parameters during the
1170 historical period. *Geophysical Research Letters* 2016, 43:3911-3920.
- 1171 181. Zhou C, Zelinka MD, Klein SA. Impact of decadal cloud variations on the Earth's energy
1172 budget. *Nature Geoscience* 2016, 9:871-874.

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