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Link Between Opaque Cloud Properties and Atmospheric Dynamics in Observations and Simulations of Current Climate in the Tropics, and Impact on Future Predictions

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1 Link between opaque cloud properties
2 and atmospheric dynamics in
3 observations and simulations of current
4 climate in the Tropics, and impact on
5 future predictions

6

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17

18 **Key points:**

- 19
- We document how both models predict cloud properties in the present and in a future, warmer climate with weakened Walker/Hadley circulation
 - Both models show cloud properties evolve differently with vertical wind speeds smaller or larger than 20hPa/day
 - Cloud properties that suffer from biases in model simulations of current climate are affected by large changes in the future climate
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25

26 Abstract

27

28 Using spaceborne lidar observations and reanalyses (2008-2014), we relate the vertical wind
29 speed at 500 hPa (ω_{500}), indicator of atmospheric circulation, to properties of opaque clouds (altitude
30 and cover) and to the Cloud Radiative Effect (CRE) in the Tropics. We confront those observations
31 with simulations by IPSL-CM6 and CESM1 climate models using early 21st century emissions. Both
32 models overestimate the average opaque cloud cover. IPSL-CM6 puts high opaque clouds too high
33 (+2km), especially in ascendance. CESM1 overestimates the intermediate opaque cloud cover and
34 underestimates small and large opaque cloud covers. Both models agree that cloud properties
35 behave differently at wind speed above (strong subsidence) or below (weak subsidence and
36 ascendance) 20hPa/day. In future climate (2089-2095), variables affected by biases in current climate
37 are affected by notable changes: IPSL-CM6 puts high opaque clouds even higher (+2km) while
38 opaque cloud cover above 30% decreases and below 30% increases in CESM1. Both models predict
39 very little change in the average net CRE in the future. We find that predicted changes of cloud
40 properties can be regionally driven by dynamic or thermodynamic changes, depending on the
41 relationship between opaque cloud altitude and ω_{500} in the model. Overall, most changes are due to
42 thermodynamic changes in the relationship between cloud property and atmospheric dynamics.

43 Plain Language Summary

44
45 The largest uncertainty on climate predictions comes from our poor understanding of how
46 clouds will react to a warmer climate. A long-term record of cloud detections by active sensors, such
47 as lidars, will enable measuring the clouds vertical distribution, one of the properties most sensitive
48 to global warming. Here we investigate how two climate models predict the evolution of the vertical
49 distribution of clouds, in relation to the predicted evolution of large-scale air motions in the Tropics.
50 We discuss the changes predicted by the models in future climate conditions for cloud properties,
51 and how well they simulate them in current climate conditions, compared to current retrievals from
52 satellite sensors. We also find that when models generate upward or downward air motions, they
53 move opaque clouds higher or lower in very different ways. This explains why, even if both models
54 similarly predict that tropical atmospheric circulation will slow down in the future, they predict
55 different changes in cloud altitude.

56 **1 Introduction**

57

58 Climate models predict a weakening of the tropical atmospheric circulation (Kjellsson 2015),
59 more specifically a slowdown of Hadley and Walker circulations (Vecchi and Soden, 2006; Lu et al.,
60 2007; Birner, 2010; Davis and Rosenlof, 2012). The Hadley cells are maintained by convection, and
61 many studies predict that in a warming climate, convection will weaken due to changes in 1) the
62 atmospheric hydrological cycle (Held and Soden, 2006), 2) the mean advection of stratification, which
63 implies a cold/warm advection in the tropical troposphere in convective/subsidence regions (Ma et
64 al., 2012), or 3) the radiative cooling in the upper atmosphere (Bony et al., 2013). Chou et al. (2009)
65 showed that convection will weaken along the edges of convection regions due to advection of dry
66 air from subsidence regions towards convective regions: the “upped-ante” mechanism. Ma et al.
67 (2012) suggested that a warming of subsidence regions could strengthen the frequency of the
68 ascendance in regions today dominated by subsidence. Cloud formation and distribution in the
69 tropics, which are largely driven by vertical movements, will be impacted by these predicted changes
70 (e.g. Cess et al., 1989; Stephens, 2005; Zelinka and Hartmann, 2011; Su et al., 2014).

71 Many climate models predict that global warming will have a major impact on cloud properties
72 (e.g. Wetherald and Manabe, 1988; Ramanathan et al., 1989; Mitchell et al., 1989; Colman, 2003;
73 Ringer et al., 2006; Webb et al., 2006; Vial et al., 2013; Vaillant de Guélis et al., 2018; Zelinka et al.,
74 2020), including their geographic and vertical distribution. Climate feedbacks from clouds, which
75 amplify warming when positive (Hansen et al., 1984), are today the main source of uncertainty in
76 climate forecasts (e.g Vial et al., 2013; Webb et al., 2013; Caldwell et al., 2016; Ceppi et al., 2017,
77 Zelinka et al. 2020). Tropical clouds play a key role in the redistribution of solar energy (Cesana et al.,
78 2012; Dufresne and Bony, 2005; Lu et al, 2007; Kjellsson, 2014), and their evolution will likely affect
79 climate. Therefore, it is crucial to better understand how tropical clouds will evolve in a changing
80 climate.

81 Among cloud properties, the vertical distribution is sensitive to climate change (Hartmann and
82 Larson, 2012; O’Gorman and Singh, 2013; Chepfer et al., 2014; Vaillant de Guélis et al., 2018). Active
83 sensors integrated into satellites, such as CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization;
84 Winker et al., 2009), make it possible to obtain a detailed vertical distribution of clouds. CALIOP
85 measurements and calibration are more stable over time and more precise than passive remote
86 sensing satellite detectors (Winker et al., 2017; Chepfer et al., 2018). CALIOP observations can be
87 simulated in the atmospheric conditions predicted by climate models using lidar simulators (Chepfer
88 et al., 2008). Chepfer et al. (2018) showed that, assuming model predictions are correct, observations
89 from space lidars could monitor changes in the vertical distribution of tropical clouds in a way that
90 could provide information on how clouds will impact the future climate.

91 One of the main influences clouds have on the climate system is their Cloud Radiative Effect,
92 or CRE. A positive Top Of the Atmosphere (TOA) CRE means that clouds warm the climate system.
93 Conversely, a negative TOA CRE means clouds cool the climate system. Zelinka et al. (2012a)
94 quantified how cloud cover, altitude, and optical depth contribute to the cloud radiative response.
95 Zelinka et al. (2016) isolated the role of cloud cover and cloud altitude, separating high and low
96 clouds. In the infrared, or longwave (LW), clouds always have a warming effect ($CRE_{LW} > 0$) because
97 they absorb a part of the upwelling radiation emitted by the Earth and reemit a part of it downwards,
98 thus letting less energy escape to space. Opaque clouds provide the largest contribution to TOA
99 CRE_{LW} : when opaque cloud cover is large, CRE_{LW} is large (Vaillant de Guélis et al., 2017a). At global
100 scale, Vaillant de Guélis et al. (2017b) showed that opaque clouds contribute to 82% and thin clouds
101 to 18% of the mean observed LW CRE. Higher opaque clouds also lead to a stronger CRE_{LW} . In the
102 visible, or shortwave (SW), clouds almost always have a cooling effect ($CRE_{SW} < 0$) because they reflect
103 a part of the solar radiation back to space. The SW CRE is directly proportional to the cloud optical
104 depth (Yokohata et al., 2005; Taylor et al., 2007, Dupont et al. 2008), thus optically thin clouds
105 contribute less to the SW CRE than opaque clouds, supposing equivalent cloud covers as in
106 observations (Guzman et al., 2017). As the cover of opaque clouds increases, so will their albedo

107 effect, and the CRE_{SW} will get increasingly negative. Thus opaque clouds are the main contributors to
108 the CRE in the Tropics.

109 Understanding how models predict cloud vertical distribution will evolve in the future has
110 implications for how models predict the TOA CRE will evolve in the future (e.g. Bony et al., 2006;
111 Soden and Held 2006; Soden et al., 2008; Boucher et al., 2013). Many studies show that cloud
112 altitude change is the dominant contributor to the LW cloud feedback (e.g. Schneider, 1972; Cess,
113 1975; Hansen et al., 1984; Wetherald and Manabe, 1988; Cess et al., 1996; Hartmann and Larson,
114 2002; Zelinka et al., 2016). Vaillant de Guélis et al. (2018) showed that changes in altitude and cover
115 of opaque clouds are the main drivers of CRE change in the Tropics on short timescales. At this point,
116 however, it is still unclear how observing short-term, intra-decadal changes in cloud properties might
117 reveal the evolution of the CRE in future climate conditions, given the long-term, multi-decadal
118 changes in dynamical conditions of the tropics.

119 This paper has three goals. First, based on satellite observations and reanalyses (section 2),
120 we establish the relationship between atmospheric dynamic circulation, opaque cloud properties and
121 TOA CRE (section 3). Second, we compare this observed relationship with the one found in climate
122 model simulations of current climate conditions (section 4). Third, we investigate how model biases
123 in present climate conditions relate to their predictions in a warmer climate (section 5). All analyses
124 are ocean only, to help interpretation of our results in regard of recent studies using lidar-derived
125 opaque cloud properties (Vaillant de Guélis et al., 2017a, b, 2018; Höjgård-Olsen et al., 2020).

126

127 **2 Data**

128 In this study, we use cloud observations (section 2.1) from space lidar, vertical wind speed from
129 reanalysis, flux observations from space radiometer. On the modeling side (section 2.2), we use
130 climate simulations together with a lidar simulator in the present climate as well as in a warmer
131 climate.

132 **2.1 Observations**

133 **2.1.1 Cloud observations: CALIPSO-GOCCP Spaceborne Lidar Data**

134

135 We use 7 years of CALIPSO observations (2008-2014) from the GOCCP product (GCM-Oriented
136 CALIPSO Cloud Product, Chepfer et al., 2010, 2013). CALIPSO has been collecting data since 2006, but
137 in November 2007 the satellite tilt was changed from 0.3° to 3° off-nadir. This change in CALIPSO's
138 pointing direction can create discontinuities in retrieved cloud properties, in the Tropics and
139 elsewhere (Hu et al., 2007), so we only consider observations starting in 2008. GOCCP variables are
140 derived from CALIPSO level 1, vertical profiles measured every 330m at 30m-180m vertical
141 resolution. We used GOCCP V.3.1.2 (Chepfer et al., 2010) variables consistent with the COSP1.4 lidar
142 simulator outputs (section 2.2.2). From GOCCP data, we used 2 variables aggregated and averaged
143 over monthly periods on 2°x2° lat-lon grid cells and on a 480m regular vertical resolution grid, that
144 describe the properties of opaque clouds.

145 Opaque clouds are defined as clouds which totally attenuate the incoming lidar laser beam and
146 do not let any of it pass through as direct transmission. Their optical depth is typically larger than 3 in
147 the visible and an infrared (IR) emissivity close to 1; they are identified when the surface echo cannot
148 be found in full-resolution signal profiles from the space lidar (Guzman et al., 2017). In this study, we
149 use two lidar-derived properties of opaque clouds:

- 150 • The opaque cloud cover, named Copaque.

151 • The opaque cloud altitude, named Zopaque, which describes the altitude below which
152 the lidar is fully attenuated and is directly linked to the LW TOA radiative flux (Chepfer et
153 al., 2014; Vaillant de Guélis et al., 2017a; Guzman et al., 2017). The GOCCP Zopaque
154 calculation algorithm is based on detecting the altitude where the lidar signal is totally
155 attenuated. This attenuation is integrated over the entire column from the top, and can
156 be due to a single cloud layer or multiple cloud layers. In a given profile, the Zopaque can
157 be very low (e.g. 2 km) while thin high clouds can be present. When a situation combines
158 low level opaque clouds with optically thin high clouds, the lidar will penetrate the high
159 clouds and will get fully attenuated in the lower cloud. Compared to the situation with
160 low opaque clouds only, this would marginally rise the altitude of opacity. De Guélis et al.
161 (2017a) found that taking into account the optical depth of thinner clouds overlapping an
162 opaque cloud when calculating the cloud radiative effect only provides marginal
163 improvement.

164 Zopaque and Copaque have been used in several recent studies to understand interactions
165 between clouds and radiation (e.g. Vaillant de Guélis et al., 2017a and b, 2018; Morrisson et al.,
166 2018, 2019; Frey et al., 2018; Lacour et al., 2017, 2018; Chepfer et al., 2014, 2017, 2019).

167 **2.1.2 Vertical wind speed: ERA5 reanalysis**

168

169 To evaluate convection intensity, we use the vertical velocity at 500 hPa, ω_{500} . Averaged over a
170 month, it is a good indicator of the ascending/subsiding air motion (Bony et al., 2004). Ascending air
171 motion is identified by negative wind speeds at 500 hPa ($\omega_{500} < 0$) and subsidence air motions by
172 positive wind speeds at 500 hPa ($\omega_{500} > 0$). Here, we use 7 years (2008-2014) of ω_{500} from fifth-
173 generation reanalysis from ECMWF (European Centre for Medium-Range Weather Forecasts) ERA-5
174 (Hersbach et al., 2020).

175 These data are produced from the combination of a model of weather forecasts and
176 observations. These ERA5 reanalyses are provided hourly on a 0.28°x0.28° longitude-latitude mesh
177 and 137 vertical levels of varying pressure. We extracted the vertical velocity at 500 hPa and
178 averaged it on the GOCCP horizontal resolution: 2°x2° every month.

179 **2.1.3 Radiative flux: CERES Spaceborne Radiometer**

180

181 In the present study, we used 7 years (2008-2014) of TOA CRE from the Clouds and the Earth's
182 Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) top-of-atmosphere (TOA) data
183 product version 4.1 (Loeb et al., 2018; Kato et al., 2018). It is produced using 2 CERES instruments
184 from two satellite platforms (Aqua and Terra), that measure SW, LW and total fluxes at TOA. These
185 measurements are monthly averaged on a 1°x1° longitude-latitude grid.

186 **2.2 Simulations**

187 **2.2.1 General Circulation Models: CESM1 and IPSL-CM6**

188

189 In the present study we considered climate predictions from two general circulation models.

190 The first is the Community Earth System Model version 1 (CESM1), integrating the Community
191 Atmosphere Model version 5 (CAM5), developed by NCAR (National Center of Atmospheric
192 Research). CESM1-CAM5 participated in the fifth phase of the Coupled Model Intercomparison
193 Project (CMIP5, Taylor et al. 2012). We used CESM1 data on a grid with a spatial resolution of 1.25° x
194 0.94°, and 40 vertical levels. The second model is IPSL-CM6, the latest version of the IPSL (Institut
195 Pierre-Simon Laplace) climate model participated in the sixth phase of CMIP (Eyring et al., 2016).. We
196 used IPSL-CM6 data on a grid with a spatial resolution of 1.27 ° x2.5 °, and 79 pressure levels.

197 According to Table 1, both models have a rather large equilibrium climate sensitivity (ECS) but
198 ECS and cloud feedback values all fall in the range of CMIP6 multimodel means for both models. IPSL-
199 CM6 appears as the most sensitive, with the strongest LW cloud feedbacks.

	Equilibrium Climate Sensitivity (K)	Cloud Feedback Total (W/m ² /K)	Cloud Feedback SW (W/m ² /K)	Cloud Feedback LW (W/m ² /K)
CESM1-CAM5	4.1	+0.52	+0.42	+0.10
IPSL-CM6	4.6	+0.38	+0.13	+0.25
Multimodel mean interval CMIP6	2.6 to 4.8	+0.06 to +0.78	-0.39 to +0.59	+0.06 to 0.58

200

201 **Table 1: Climate sensibility (K) and Cloud feedback Total, SW and LW (W/m²/K) for CESM1 and IPSL-CM6. Adapted from**
 202 **Gettelman et al., 2019, Meehl et al. 2020, and Zelinka et al., 2020.**

203

204 For both models we considered 88 years of predictions, starting in 2008 as the observations and
 205 ending in 2095. Since CESM1 is a CMIP5 model and the historical period ends in 2005 for CMIP5
 206 (Taylor et al., 2011), historical runs do not exist for later years in CESM1. However, the cumulative
 207 CO₂ emissions observed during the 2008-2014 period are closest to the RCP8.5 scenario (Schalwm et
 208 al., 2020), and we used that scenario for CESM1 simulations over the 2008-2014 period. For the
 209 CMIP6 model IPSL-CM6, we used available historical runs for IPSL-CM6 over the period 2008-2014.
 210 For future climate conditions, both models were forced under the Representative Concentration
 211 Pathway (RCP) 8.5 scenario, the highest emissions and radiative forcing scenario of the
 212 Intergovernmental Panel on Climate Change exercise (Riahi et al., 2011). In the rest of the paper, we
 213 refer to the 2008-2014 period as current climate, and to the 2089-2095 period as future climate.

214 Out of predictions from those models, we use the vertical wind speed at 500 hPa (w_{500}) and
 215 the Cloud Radiative Effect (CRE) decomposed in 3 components: Net, LW and SW. The simulated CRE
 216 includes contributions of both opaque and non-opaque clouds.

217 **2.2.2 Lidar Simulator: COSP 1.4**

218

219 On each model was plugged the COSP1.4 (CFMIP Observation Simulator Package) lidar
 220 simulator (Bodas-Salcedo et al., 2011), which reproduces synthetic lidar observations that would be
 221 measured by existing spaceborne lidars flying over the atmosphere predicted by the model (Chepfer

222 et al., 2008). Here, from COSP outputs we use the monthly gridded opaque cloud cover (Copaque)
223 and altitude (Zopaque).

224 **3 Relationship between Opaque cloud and Vertical air velocity in** 225 **current observations**

226 The distribution of ascending and subsiding air motions, according to vertical wind speed
227 from reanalyses (Figure 1a), appears to drive the geographic patterns followed by the average
228 altitude (Figure 1b) and cover (Figure 1c) of opaque clouds derived from spaceborne lidar
229 observations (section 2.1). In ascending air motion ($\omega_{500} < 0$, red in Figure 1a), opaque clouds are high
230 and abundant, generally $Z_{opaque} > 3\text{km}$ (Figure 1b) and $Copaque > 40\%$ (Figure 1c). This is the case
231 over the InterTropical Convergence Zone (ITCZ), the mid-West Pacific Ocean and the warm pool, for
232 instance. In subsiding air motion ($\omega_{500} > 0$, blue in Figure 1a), opaque clouds are generally low and
233 few, with $Z_{opaque} < 3\text{km}$ (Figure 1b) and $Copaque < 40\%$ (Figure 1c). However, many opaque
234 ($Copaque > 60\%$) low altitude ($Z_{opaque} < 1\text{km}$) clouds are found in the edges of the West coast of
235 America (Mexico and Peru), of Africa (Angola/Namibia) and of Australia, corresponding to
236 stratocumulus regions. To better understand the relationship between the altitude and cover of
237 opaque clouds and vertical air motions, we focus on how opaque clouds and ω_{500} vary together.

238 Figure 2 shows how the opaque cloud altitude, Z_{opaque} , and the opaque cloud cover,
239 $Copaque$, relate to the vertical velocity at 500 hPa, ω_{500} . These figures suggest the existence of two
240 different regimes based on vertical velocity, linking cloud properties and dynamics in the Tropics. In
241 the right regime, related to strong subsidence ($\omega_{500} > 20$ hPa/d, 38% of points), Z_{opaque} is stable
242 between 0 and 2 km, whatever the vertical wind speed at 500hPa (Figure 2a). Meanwhile, the mean
243 $Copaque$ increases slightly with subsidence speed (+6% from +25 to +75 hPa/d); dispersion is large
244 for a given ω_{500} though. In the left regime, related to weak subsidence and convection ($\omega_{500} < 20$
245 hPa/d, 62% of points), as ascendance gets stronger, both cover and altitude of opaque clouds

246 increase (Figs. 2a and b): Copaque increases on average by +17% between 20 and -75 hPa/day.
247 Zopaque goes from an average of 1.5km at +20 hPa/day (subsiding air motion), to 3.8km at -25
248 hPa/day (weak ascending air motion), up to a 5km average at -75 hPa/day (deep ascending air
249 motion). The Zopaque altitude is by definition lower than the top of the opaque cloud (section 2.1),
250 so opaque clouds probably extend higher than 5km. Strong ascending motion (<-50 hPa/day)
251 represent less than 10% of points of the tropical belt (PDF Figure 2a).

252 These results are consistent with Vaillant de Guélis et al. (2017a), and show that spaceborne
253 lidar observations and reanalysis suggest there is a clear relationship between atmospheric dynamics
254 (ω_{500}) in the Tropics and opaque cloud properties (Zopaque and Copaque). In the next section, we
255 evaluate how the 2 models CESM1 and IPSL-CM6 simulate patterns of ω_{500} , Zopaque and Copaque.

256 **4 Relationship between Opaque cloud and Vertical air velocity in** 257 **simulations of current climate** 258

259 **4.1 Geographic patterns of opaque cloud properties and dynamic regimes** 260

261 Figs. 3a (CESM1) and b (IPSL-CM6) show that both models simulate geographic patterns of
262 ω_{500} similar to those from the reanalyses (black lines in Figs. 3a and 3b) in current climate conditions
263 (see also Figure S1 in Supplementary Information). Both models frequently simulate stronger
264 ascendance ($\omega_{500}<0$, red 6 in Figs. 3c and 3d) North of the ITCZ, West of the Warm Pool and East of
265 the South Pacific Convergence Zone, weaker ascendance ($\omega_{500}<0$, red 5) South of the ITCZ and across
266 the Warmpool, and stronger subsidence (blue 1) in the subsidence region of the South Equatorial
267 Pacific and in the North and South Atlantic. Both models tend to simulate ascendance instead of
268 subsidence at the southwest edges of subsidence-dominated areas (light salmon 4), for instance in
269 the South Pacific and West Indian Ocean. IPSL-CM6 simulates subsidence where ERA5 says
270 ascendance (cyan 3) between the subsidence zone of the Equatorial Pacific and the Warm pool.

271 CESM1 underestimates opaque cloud altitude on average almost everywhere by ≈ 0.5 km (Figure
272 3e) compared to observations (Figure 1b) and overestimates opaque cloud cover (+3.1 %, Figure 3g)
273 almost everywhere except in stratocumulus regions. In contrast with CESM1, IPSL-CM6
274 overestimates Zopaque (+1.48km on average, Figure 3f) and Copaque (+7.7%, Figure 3h) almost
275 everywhere except in the West part of the Equatorial Pacific (blue in the center of Figure 3f and h),
276 which is consistent with the fact that IPSL-CM6 simulates subsidence instead of ascendance and
277 increased subsidence in this region (cyan 3 and blue 1 in Figure 3d). Off the West coast of South
278 America, both models underestimate stratocumulus cover (dark blue in Figure 3g and h), a well-
279 known bias in climate models. Both models start to disagree further west, in the shallow cumulus
280 region: CESM1 underestimates their cover, while IPSL-CM6 overestimates it.

281 4.2 Distributions of opaque cloud properties vs. dynamic regimes

282

283 We now analyze how both models simulate the relationships between cloud properties and ω_{500}
284 in the current climate (Figure 4). The two regimes on each side on 20 hPa/d that were found in
285 observations also appear in model simulations. CESM1 (Figure 4, left column) underestimates
286 Zopaque (first row) in weak ascendance and subsidence (Figure 4a), and overestimates it in strong
287 ascendance ($\omega_{500} < -50$ hPa/d, Figure 4a) compared to observations (dotted black line with ± 2 std).
288 CESM1 (red line) put clouds at lower levels (below 1 km, PDF at right of the Figure 4a) than
289 observations (grey area). Significant underestimates occur between 2 and 5 km, which is contributed
290 from -50 to +25 hPa/day regimes, which are dominant (ω_{500} PDF, bottom left). IPSL-CM6 (right
291 column) overestimates Zopaque significantly: >2km on average in left regime, and the
292 overestimation is the largest near -25 hPa/d (Figure 4b) where most of ascending ω_{500} points are. The
293 PDF (Figure 4b, right side) shows that IPSL-CM6 simulates more high opaque clouds (8-10km) and
294 fewer very low opaque clouds (~ 1 km) compared to observations. The CESM1 overestimate of
295 Copaque (second row) increases with the ascendance speed (Figure 4c), while IPSL-CM6
296 overestimates Copaque for all ω_{500} (Figure 4d). In strong subsidence (right regime), only CESM1

297 overestimates the opaque cloud cover, but put too few thin clouds by half (Appendix, Figure S2). The
298 effect dominates the tropical distribution of thin clouds cover (Appendix, Figure S3), consistently with
299 the ‘too few, too bright’ problem (Nam et al., 2012). According to the PDF (right side of Figure 4c and
300 d), CESM1 overestimates medium Copaque (20-40%) significantly and underestimates small Copaque
301 (<20%), while IPSL-CM6 is mostly consistent with the PDF of observations (IPSL-CM6 overestimates a
302 little Copaque below 35% and underestimates it above 35% in the PDF, Figure 4d, right side). So,
303 CESM1 reproduces the relationship between Zopaque and ω_{500} better than IPSL-CM6, but IPSL-CM6
304 reproduces the global PDF of Copaque better than CESM1.

305 **4.3 Distributions of cloud radiative effects vs. dynamic regimes**

306

307 Using the same approach as Vaillant de Guélis et al., 2018, we found that opaque clouds
308 contribute 87% (IPSL-CM6) and 78% (CESM1) of the current climate CRE, hence here we interpret
309 CRE predictions through the properties of opaque clouds first. Both models overestimate the CRE_{LW}
310 where they overestimate Zopaque and Copaque: in strong ascendance ($\omega_{500} < -50$ hPa/d) for CESM1
311 (Figs. 4a 4c and 4e) and in ascendance for IPSL-CM6 (Figs. 4b, 4d and 4f). CESM1 underestimates the
312 CRE_{LW} (Figure 4e) where it underestimates Zopaque, in subsidence and weak ascendance. This is
313 consistent with higher opaque clouds producing a stronger greenhouse effect in the longwave. Both
314 models overestimate the CRE_{SW} in ascendance (Figs. 4g and 4h), mainly due to overestimated
315 Copaque at those regimes (Figs. 4c and 4d), CRE_{SW} not being sensitive to Zopaque. This is consistent
316 with more opaque clouds producing a stronger albedo effect in the shortwave. Both models
317 overestimate a lot the CRE_{net} compared to observations (dotted black lines in Figs. 4i and 4j), mostly
318 due to their overestimate of CRE_{SW} caused by overestimated Copaque. This happens in all dynamic
319 situations, and is especially notable in the left regime.

320 To sum up, Table 2 shows how model biases in CRE (evaluated against CERES measurements)
321 correlate with model biases in cloud properties (evaluated against CALIPSO retrievals). For both
322 models, biases in LW and SW CRE are strongly correlated with bias in Copaque. Biases in LW CRE are

323 also strongly correlated with bias on Zopaque. For both models, the bias in net CRE is correlated with
 324 the bias in Copaque, but not with the bias in Zopaque. Model bias on all CRE is linked to model bias
 325 on opaque cloud cover, while only model bias on LW CRE is linked to the bias on opaque cloud
 326 altitude (see Figure S4).

	Correlation between	Model Bias in LW CRE	Model bias in SW CRE	Model bias in total CRE
IPSL-CM6	Zopaque bias	0.59		-0.04
	Copaque bias	0.57	-0.71	-0.56
CESM1	Zopaque bias	0.76		-0.07
	Copaque bias	0.52	-0.69	-0.54

327

328 **Table 2: Correlation coefficient between model biases in CRE (evaluated against CERES measurements) vs model bias in**
 329 **cloud property (evaluated against CALIPSO retrievals) calculated based on 2°x2° monthly mean values. All correlation**
 330 **coefficients are statistically significant at 99% confidence level. See Figure S4 in supplementary material.**

331 CESM1 underestimates Zopaque (except in strong ascendance) and overestimates Copaque.
 332 Both effects lead to an underestimate of CRE_{LW}, an overestimate of CRE_{SW} and a CRE_{net} too negative
 333 compared to observations. The IPSL-CM6 CRE PDF is consistent with observations, but IPSL-CM6
 334 locates opaque clouds much higher (>2km) than observations in ascendance (-50 hPa/d to 0 hPa/d), a
 335 situation that the model overestimates compared to reanalyses (ω_{500} PDF below Figure 6j). Since the
 336 model is able to simulate a correct total CRE, the strong error in Zopaque must be compensated by
 337 less visible, symmetrical errors in at least one other cloud property (e.g. opacity, cover). IPSL-CM6
 338 overestimates the cover of opaque clouds (Figure 4d) and severely underestimates the cover of thin
 339 clouds (Figs. S2 and S3, Appendix). The relationships between cloud properties and CRE are shown in
 340 the Appendix for completeness (Figs. S5 and S6).

341 Let's see how CESM1 and IPSL-CM6 predict patterns of ω_{500} , Zopaque and Copaque in the
 342 future climate.

343 **5 Relationship between Opaque cloud and Vertical air velocity in** 344 **predictions of future climate**

345 **5.1 Changes in geographic patterns of opaque cloud properties and** 346 **dynamic regimes** 347

348 Figs. 5a (CESM1) and b (IPSL-CM6) show that geographic patterns of ω_{500} remain largely the
349 same in the future. Both CESM1 and IPSL-CM6 predictions appear dominated by a weakening of
350 upward motion in ascendance regions (red 5, Figure 5c and d) and a weakening of downward air
351 motion in subsidence regions (blue 2, Figure 5c and d), i.e. both models predict a weakening of the
352 Hadley/Walker circulation. CESM1 predicts that in a warmer climate opaque clouds will be lower (-
353 2km, Figure 5e) in the Warm Pool and in the ITCZ but higher in the ascendance zone of the
354 Southwest Pacific (+ 1km, Figure 5e) and in the subsidence zone of the East Equatorial Pacific (+2km,
355 Figure 5e), and that there will be fewer of them almost everywhere (Figure 5g), except in the
356 stratocumulus area (+20%, Figure 5g) at the west coast of South America. In a stark contrast, IPSL-
357 CM6 predicts opaque clouds will rise almost everywhere, with the strongest rise (+3 km) in the
358 subsidence region of the West Equatorial Pacific (Figure 5f). Exceptions are most of the North
359 Atlantic, and parts of Southeast Pacific, where IPSL-CM6 predicts lower opaque clouds. It also
360 predicts fewer opaque clouds in almost everywhere, with most notable exceptions in the center and
361 South Pacific (Figure 5h). In ascendance regimes only, CESM1 predicts a very small average rise in
362 Zopaque (+60m), while IPSL-CM6 predicts a much larger rise (+1.12km). This last value is consistent
363 with the +700m rise that would occur following the Fixed Anvil Temperature hypothesis (Hartmann
364 and Larson, 2002), considering an average +4°C increase in temperature between future and current
365 climate (RCP8.5), and a loss of 6°C per km in the tropical troposphere.

366 In summary, both models agree on the weakening of the Hadley/Walker circulation
367 dominating the predictions. Both models also agree on a strong rise of opaque clouds altitude in the

368 Equatorial Pacific subsidence region, and on a decrease of their altitude in the North Atlantic. They
369 disagree on opaque cloud altitude evolution almost everywhere else.

370 5.2 Changes in distributions of cloud properties vs. dynamic regimes

371

372 We now examine how relationships between ω_{500} and Zopaque/Copaque evolve in the future.

373 The two regimes that were found in observations and model simulations, on each side on 20 hPa/d

374 (Section 4), also appear in future predictions (Figure 6, dashed vertical line).

375 The distribution changes shown in Figure 6, when coupled with the predicted changes in ω_{500} ,

376 help explain the maps of changes in cloud properties discussed in the last section. The changes in

377 Zopaque in a given region can be explained by 1) a change in the Zopaque distribution for a given

378 ω_{500} , i.e. a vertical move on the joint Zopaque- ω_{500} distribution, 2) a change in the ω_{500} distribution in

379 the region, i.e. a horizontal move in the joint Zopaque- ω_{500} distribution, or 3) a combination of both.

380 For instance, were ω_{500} to remain constant over all the Tropics, CESM1 predicts that Zopaque would

381 rise in ascendance and would remain stable in subsidence (Figure 6a). However, CESM1's main

382 prediction is the weakening of the Hadley/Walker circulation, i.e. that positive and negative ω_{500} will

383 both mostly evolve towards zero. Since in regions dominated by strong subsidence (ω_{500}

384 $>20\text{hPa/day}$), Zopaque distributions are stable with ω_{500} (right regime in Figure 4a and 6a), any

385 Zopaque change will be driven by a change in its distribution (blue and red in the right regime of

386 Figure 6a), leading to a rise in Zopaque in most weakening subsidence areas (blue 2 in Figure 5a). In

387 such regions, the thermodynamic (joint Zopaque- ω_{500} distribution) changes have no effect on the

388 Zopaque, instead the dynamic (ω_{500}) changes drive the Zopaque change. By contrast, in regions

389 dominated by weak subsidence or ascendance ($\omega_{500} < 20\text{hPa/day}$), Zopaque distributions strongly

390 depend on the average ω_{500} : Zopaque are distributed at higher altitudes for more negative ω_{500} in

391 present and future simulations (left regime in Figure 4a and 6a). Hence, weakening ascendance

392 would lead to a decrease in Zopaque in the future if the joint Zopaque- ω_{500} distribution remained

393 constant. This relationship, however, does not remain constant: instead, it evolves towards higher

394 Zopaque for any $\omega_{500} < 0$ (Figure 6a). Thus, regions of predicted weakened ascendance (red 5 in Figure
395 5c) will see a decrease in Zopaque if ω_{500} changes (dynamic) are more important than changes in the
396 joint Zopaque- ω_{500} distribution (thermodynamic). This is the case over the Warm Pool or the South
397 Pacific Convergence Zone (Figure 5e). In such regions, the evolution of Zopaque is dominated by
398 dynamic changes, and not by thermodynamic changes. Regions of predicted weakened ascendance
399 could see an increase in Zopaque if changes in the joint Zopaque- ω_{500} distribution are more
400 important than changes in the ω_{500} in the region. Such regions appear rare in Figure 5e.

401 In contrast with CESM1, the IPSL-CM6 joint Zopaque- ω_{500} distributions in current and future
402 climate (Figure 4b and 6b) are rather stable with ω_{500} , except in the ± 15 hPa/day range, where it
403 fluctuates wildly. Hence, changes in predicted ω_{500} (dynamic changes) have little influence on the
404 predicted Zopaque, except in regions where ω_{500} get close to or through the ± 15 hPa/day range: for
405 instance, over the edges of the central pacific equatorial area ω_{500} gets close enough to zero to
406 trigger a strong rise in Zopaque. These changes in Zopaque are driven by dynamic changes. Regions
407 of predicted weakened ascendance (red 5 in Figure 5d), as long as the average ω_{500} remain out of the
408 ± 15 hPa/day range, are instead affected by the change in joint Zopaque- ω_{500} distribution (Figure 6b),
409 which predicts a general rise, observable for instance over the warm pool. Such changes are driven
410 by thermodynamic changes. Thus, in IPSL-CM6 predictions, both dynamic and thermodynamic
411 changes lead to increases in Zopaque.

412 Regarding the opaque cloud cover (Figs. 6c and d), both models predict a decrease of Copaque
413 in average (-2.4% for CESM1 and -2.1% for IPSL-CM6). But, CESM1 predicts Copaque will decrease in
414 all regimes, most in ascendance and less in subsidence (Figure 6c), while IPSL-CM6 predicts an
415 increase of Copaque in ascendance and a decrease in subsidence (Figure 6d). So, for increasingly
416 negative ω_{500} , CESM1 and IPSL-CM6 agree on the evolution of Zopaque (they both make it rise) but
417 on the evolution of Copaque (they both make it decrease).

418 In summary, CESM1 predicts no change in Zopaque while IPSL-CM6 predicts a rise of opaque
419 clouds for any fixed ω_{500} , but the general weakening of the vertical winds across the Tropics
420 sometimes takes priority over this rise and leads to a decrease in Zopaque. Zopaque changes in
421 CESM1 appear driven by dynamic changes everywhere. IPSL-CM6 changes of Zopaque appear mostly
422 driven by thermodynamic changes, except in regions of weak ascendance and subsidence where
423 dynamic changes dominate. What drives the Zopaque changes is thus dependent on the shape of the
424 joint Zopaque- ω_{500} distribution in the model.

425 **5.3 Changes in distributions of cloud radiative effect vs. dynamic regimes**

426

427 Since we find the future change of clear-sky upwelling TOA flux is 5-12% of the change of the
428 all-sky upwelling TOA flux in both models, we can suppose that the evolution of the CRE is mainly
429 related to changes in clouds. Following again the Vaillant de Guélis et al. (2018) approach shows that
430 opaque clouds still dominate the CRE in future climate conditions (87% for IPSL-CM6, 84% for
431 CESM1), so we can again interpret the CRE changes in light of opaque cloud property changes.

432 The future CRE_{LW} will decrease in all regimes according to CESM1 (Figure 6e). This is consistent
433 with its predicted decrease of Copaque (Figure 6c), but not with its predicted rise in Zopaque (Figure
434 6a). Thus the evolution of Copaque drives the evolution of the CRE_{LW} for CESM1. IPSL-CM6 predicts
435 an increase of CRE_{LW} in moderate ascendance ($-50 < \omega_{500} < 0$ hPa/d, Figure 6f), consistent with its
436 predicted increase of Zopaque and Copaque. IPSL-CM6 predicts a decrease of CRE_{LW} in subsidence,
437 consistent with the predicted decrease in Copaque (Zopaque does not change). This decrease
438 dominates the evolution of the CRE_{LW} PDF in IPSL-CM6 predictions (right side of Figure 6f).

439 The future CRE_{SW} will be weaker in all regimes according to CESM1 (Figure 6g), except in strong
440 ascendance. This weakening is consistent with the decrease CESM1 predicts for Copaque, the main
441 driver of CRE_{SW} . IPSL-CM6 predicts a stronger CRE_{SW} in ascendance (Figure 6h), consistent with the

442 increase predicted for Copaque (Figure 6d). The opposite is true in the right regime, where IPSL-CM6
443 predicts a weaker CRE_{SW} , linked to a decrease in Copaque.

444 The future CRE_{net} will change little overall according to the two models (Figs. 6i and 6j),
445 especially in the most frequent regimes (-25hPa/d to 25hPa/d) which stay constant. In moderate to
446 strong ascendance ($\omega_{500} < -25\text{hPa/d}$), the future CRE_{net} will be more strongly negative according to
447 both models. For CESM1, this is due to the decrease predicted for the CRE_{LW} , which in strong
448 ascendance is not compensated by a decrease in CRE_{SW} . As shown above, in this case Copaque
449 changes drive the evolution of the CRE_{LW} , hence the Copaque decrease predicted by CESM1 is
450 responsible for the CRE_{net} change in strong ascendance (Figure 6i). For IPSL-CM6, the change is due to
451 the stronger CRE_{SW} , driven by the increase predicted for Copaque. In moderate to strong subsidence
452 ($\omega_{500} > 25\text{hPa/d}$), both models predict a weakening of the future CRE_{net} , linked to a weaker CRE_{SW}
453 caused by a decrease Copaque. In the end, the small predicted CRE_{net} changes (in both subsidence
454 and ascendance) are due to Copaque changes in both models.

455 In summary, in the future, in ascendance, CESM1 raises Zopaque (increase of CRE_{LW} , more
456 warming) and decreases Copaque (decrease of CRE_{SW} , less cooling and decrease of CRE_{LW} , less
457 warming). Since CESM1 actually predicts a CRE_{net} more negative (more cooling), only the effect of
458 Copaque on the CRE_{LW} is consistent with this change, and Copaque changes drive the evolution of the
459 CRE_{net} in CESM1. In the current climate, CESM1 overestimates Copaque (Figure 4c). It is therefore
460 unclear whether the CRE_{net} changes predicted by CESM1 are reliable. In the future, IPSL-CM6 raises
461 Zopaque (increase of CRE_{LW} , more warming) and increases Copaque (increase of CRE_{SW} , more cooling
462 and increase of CRE_{LW} , more warming). Since IPSL-CM6 predicts a CRE_{net} slightly more negative (more
463 cooling), again the Copaque changes drives the evolution of the CRE_{net} through its impact on the
464 CRE_{SW} . In subsidence, there are no changes in the CRE_{net} for both models in the future.

465

466 6 Discussion of future changes and their origins

467

468 6.1 Overview of future changes in dynamic regimes

469

470 Figure 7 sums up how models simulate, in the current and future climate, opaque cloud
471 distribution and CRE. Looking first at cloud properties, in current climate compared to observations,
472 CESM1 underestimates Zopaque everywhere (most in subsidence) while IPSL-CM6 overestimates
473 Zopaque everywhere (most in ascendance, Figure 7a). Both models overestimate the cover of
474 opaque clouds (Figure 7b). In the future climate, CESM1 predicts an increase of Zopaque for $\omega_{500} < -5$
475 hPa/d and a decrease of Zopaque for $\omega_{500} > -5$ hPa/d, while IPSL-CM6 predicts an increase of Zopaque
476 everywhere (Figure 7a). For Copaque, CESM1 predicts a decrease everywhere in the future, while
477 IPSL-CM6 predicts a slight decrease for $\omega_{500} > -5$ hPa/d and an increase for $\omega_{500} < -5$ hPa/d (Figure 7b).

478 When considering the CRE_{LW} (Figure 7c), both models simulate it quite well in current climate
479 in ascendance ($\omega_{500} < -5$ hPa/d) compared to observations, but they underestimate it elsewhere. In
480 the future, both models predict a decrease of the CRE_{LW} everywhere, except in ascendance ($\omega_{500} < -5$
481 hPa/d) where IPSL-CM6 predicts an increase. Considering the CRE_{SW} (Figure 7d), in the current
482 climate, both models overestimate the CRE_{SW} everywhere compared to observations. In the future,
483 CESM1 predicts a weaker CRE_{SW} in all regimes, consistent with the predicted decrease in opaque
484 cloud cover (Figure 7b). IPSL-CM6 predicts that in the future CRE_{SW} will strengthen for $\omega_{500} < -5$ hPa/d
485 and will weaken elsewhere: consistent with more opaque clouds for $\omega_{500} < -5$ hPa/d, but not
486 consistent with more opaque clouds for $\omega_{500} > -5$ hPa/d. Considering the CRE_{net} (Figure 7e), both
487 models overestimate it a lot compared to observations. In the future, CESM1 predicts a stronger
488 CRE_{net} for $\omega_{500} < -5$ hPa/d but a weaker CRE_{net} elsewhere, while IPSL-CM6 predicts no change in
489 overall CRE_{net} in any regime.

490 For CESM1, the changes in Copaque in all regimes dominate the future evolution of the CRE_{LW} ,
491 of the CRE_{SW} , and of the CRE_{net} . For IPSL-CM6, there are only very little changes in Copaque or CRE_{net}

492 in any regime. Most noticeable is the increase in Zopaque , but this increase is only strong enough to
493 make the CRE_{LW} rise in ascendance ($\omega_{500} < -5$ hPa/d).

494 The radiative biases of each model in current climate compared to observations stay relevant
495 in the future, and the cloud property biases they come from become stronger. CESM1 simulates a
496 CRE_{net} too negative in current climate compared to observations (PDF CRE_{net} to the right of Figure 6i),
497 linked to an overestimation of Copaque (20-60%) and an underestimation of low Copaque (<20%).
498 This mechanism stays valid in future predictions, but with a decrease of Copaque which leads to a
499 decrease in the CRE_{LW} well compensated by the decrease of CRE_{SW} . IPSL-CM6 predicts in future
500 conditions a strengthening of the CRE_{SW} in moderate ascendance ($-50\text{hPa/d} < \omega_{500} < 0\text{hPa/d}$), a
501 situation that it overestimates in current climate compared to observations (Sect. 4.3). In these
502 conditions, it also predicts a strong rise (+2km) in the altitude of opaque clouds, which were already
503 too high in current climate compared to observations. Through an increase in CRE_{LW} , these changes
504 help compensate the strengthening of CRE_{SW} and bring the CRE_{net} close to the one IPSL-CM6
505 simulates in current climate conditions.

506 **6.2 Impact of dynamic vs. thermodynamic changes on cloud properties**

507
508 Finally, we try to evaluate, for each variable, if the simulated changes are due to changes in
509 the ω_{500} distribution alone (dynamic changes), or to changes in the relationship between the variable
510 and ω_{500} (thermodynamic changes). To do this, we consider the following. The Zopaque PDF is
511 equivalent to the product of the ω_{500} PDF and the joint Zopaque- ω_{500} distribution. Multiplying the
512 current ω_{500} PDF by the future joint Zopaque- ω_{500} distribution yields the future Zopaque PDF
513 attributable to the change in the joint Zopaque- ω_{500} distribution alone. Multiplying the future ω_{500}
514 PDF by the current joint Zopaque- ω_{500} distribution yields the future Zopaque attributable to the
515 change in the ω_{500} distribution alone (see Figure S7). Subtracting each of those PDFs to the PDF of
516 Zopaque in current climate quantifies the change to the Zopaque PDF due to the change in either the
517 ω_{500} distribution or the joint Zopaque- ω_{500} distribution. We applied this methodology to each cloud

518 property and radiative effect. The obtained numbers are reported in Table 3, which shows the total
 519 predicted change between PDFs of cloud property and radiative effect due (1) only to the change in
 520 the ω_{500} distribution, and (2) due only to the change in the relationship between ω_{500} and the
 521 considered variable. Table 3 suggests that overall, for most variables, the changes in the relationship
 522 between the dynamic conditions and the variable (thermodynamic changes) drive its change in the
 523 future climate, with the changes in ω_{500} (dynamic changes) being secondary. Exceptions are the
 524 opaque cloud cover, and SW and total CRE changes predicted by IPSL-CM6, which appear to be
 525 primarily driven by changes in the distribution of atmospheric dynamics. These are however the
 526 properties that change less between current and future climate conditions.

527

		Change in variable distribution	
		Due to change in ω_{500} only	Due to change in relationship only
CESM1	Zopaque	11%	24%
	Copaque	7%	25%
	CRE LW	11%	23%
	CRE SW	12%	21%
	CRE net	4%	6%
IPSL-CM6	Zopaque	11%	57%
	Copaque	15%	10%
	CRE LW	15%	27%
	CRE SW	14%	11%
	CRE net	10%	6%

528

529 **Table 3: Change in the distribution of cloud properties and CRE due to changes in the ω_{500} distribution only, and due to**
 530 **the changes in the relationship between the property and the ω_{500} only (see methodology and Figure S7 in the**
 531 **Supplementary Information). The bold values are the largest correlation coefficient for each variable.**

532

533 7 Summary and conclusions

534

535 This paper had three goals. To reach the first, we established the link between atmospheric
536 circulation, opaque cloud properties (altitude and cover) and Cloud Radiative Effect, in present day
537 climate based on 7 years of observation. Our second goal was to investigate the same link in present-
538 day simulations from 2 climate models. We found that compared to observations CESM1
539 overestimates medium (40%) opaque cloud covers, and underestimates large (60-80%) and small (0-
540 20%) opaque cloud covers. CESM1 also overestimates low opaque cloud altitude (<1 km). IPSL-CM6
541 overestimates opaque cloud cover (+7.7 % on average, PDF shifted to high values) and overestimates
542 high opaque cloud altitude in the present climate. In both models, CRE_{LW} is driven by both Zopaque
543 and Copaque while CRE_{SW} is only driven by Copaque, in agreement with Guzman et al. (2017) and
544 Vaillant de Guélis et al. (2017b). The relationship between opaque cloud properties and atmospheric
545 dynamics is well simulated in CESM1 in current climate compared to IPSL-CM6 simulations, but the
546 distribution of medium Copaque (20-50%) is extremely different compared to observations. Most
547 notably, IPSL-CM6 overestimates the amount of weak ascendance and, in this condition, significantly
548 overestimates the Zopaque (+2km). This overestimation of Zopaque helps IPSL-CM6 balance other
549 errors to get its predicted CRE_{net} close to observations. For CESM1, it is the Copaque \sim 40% and the
550 CRE_{SW} that are overestimated, which lead to an overestimate of the CRE_{net} , especially in the left
551 regime (ascendance and weak subsidence). Even though the climate sensitivity and cloud feedback
552 amplitude are quite similar for both models and fall within the CMIP6 spread, each model simulates
553 cloud properties in a very different way.

554 To reach our third goal, we examined how climate models simulate the evolution of cloud
555 properties and atmospheric dynamics in the Tropics during the next century, according to the RCP8.5
556 scenario. Both models in future climate predict weaker ascendance and weaker subsidence motions
557 in regions dominated by ascendance and subsidence in current climate, respectively, consistent with
558 many previous studies (e.g. Vecchi and Soden, 2006; Su et al., 2014). CESM1 in the future predicts

559 more medium opaque clouds (40%) but less extreme values (0-20% and 60-80%). It also predicts that
560 the PDF of Zopaque shift down a little in the future. IPSL-CM6, in the future, predicts a slight
561 decrease in average (-2.1%, Figure 5h) but significantly higher (+1.84km) opaque clouds almost
562 everywhere in the Tropics. The PDF of high Zopaque shifted by +2 km while the PDF of Copaque
563 remains stable in the future. Both models predict very little change in the mean net CRE in the future
564 on average. Small but noticeable changes in the net CRE (in relatively strong ascendance or
565 subsidence) can be explained by predicted changes in Copaque for both models, with changes in
566 cloud altitude having little influence. Even the very strong rise in Zopaque predicted by IPSL-CM6 in a
567 regime it generates too frequently ($-50\text{hPa/d} < \omega_{500} < -25\text{hPa/day}$) has no significant impact on the
568 evolution of the CRE_{net} . IPSL-CM6 strongly overestimates Zopaque in current climate compared to
569 observations in the same regime.

570 Our results show that even though the dynamic distribution (i.e. the ω_{500}) is the main influence
571 on model biases in ascendance in current climate conditions, changes in thermodynamic effects (e.g.
572 the temperature) are instead responsible for most of predicted changes in cloud properties and CRE.
573 This is true overall in both models for the altitude of attenuation of opaque clouds, and thus for their
574 vertical distribution. These conclusions change depending on the model and the location: in CESM1,
575 changes in the altitude of attenuation appear driven by changes in dynamic conditions in regions
576 dominated by ascendance and weak subsidence, and driven by changes in thermodynamic conditions
577 in regions dominated by strong subsidence. These results agree well with those from Xu and Cheng,
578 2016 who showed that, in weak subsidence, dynamic changes have a strong impact on cloud
579 feedback while thermodynamic changes have a strong impact on cloud feedback in moderate-to-
580 strong subsidence and strong convection. We find the opposite true in IPSL-CM6, due to the strong
581 differences in the shape of the joint Zopaque- ω_{500} distribution in both models.

582 In the end, we find that the variables affected by model biases in current climate conditions
583 change significantly in future climate condition, in a way that affect the CRE and cloud feedbacks. Our

584 results suggest that the representation in each model of opaque cloud properties in the current
585 climate, including its relationship with atmospheric dynamics, has a strong impact on the model
586 cloud feedback predictions. In the future, we hope to be able to leverage GCM simulations with high
587 temporal resolution to investigate the impact that short-timescales processes can have on the
588 relationship between cloud properties and their possible feedbacks.

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590
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597

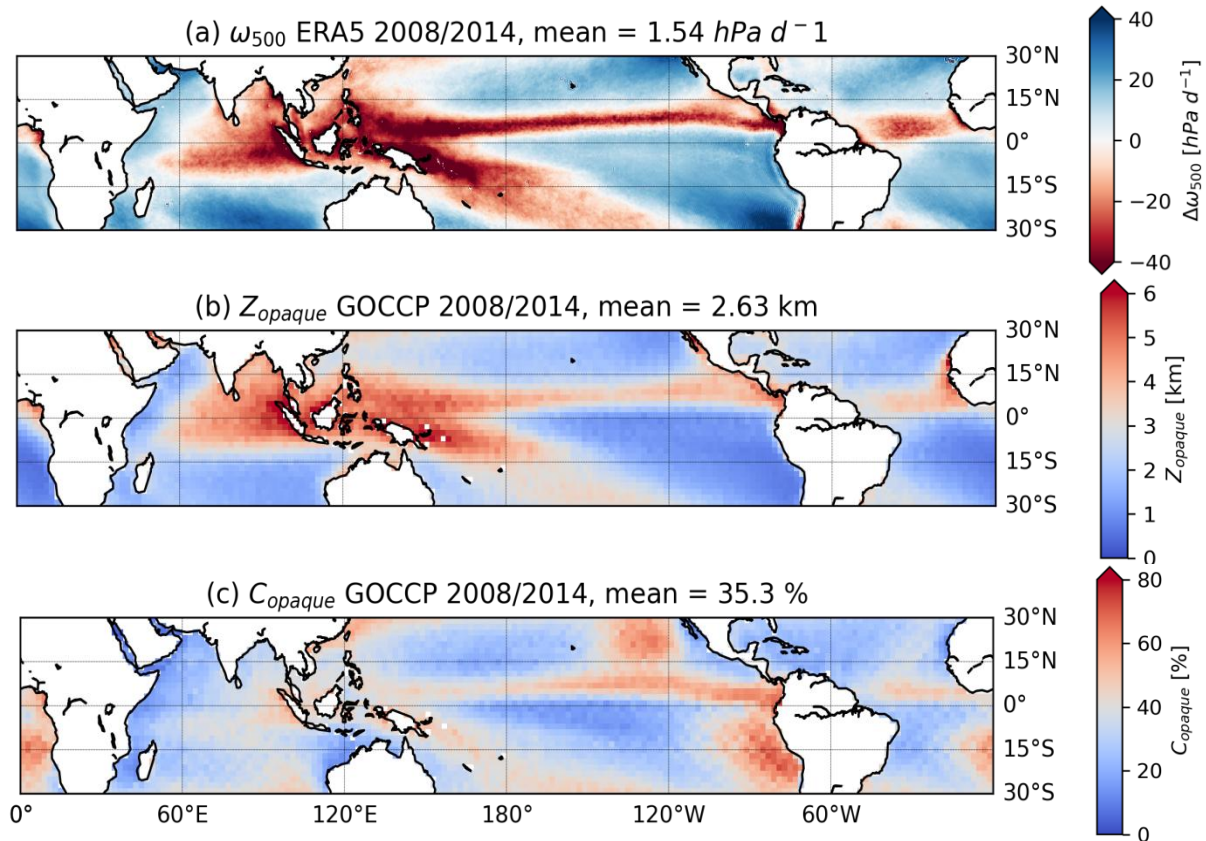
598 **Data availability**

599
600 CALIPSO-GOCCP observations data are available on [https://climserv.ipsl.polytechnique.fr/cfmip-](https://climserv.ipsl.polytechnique.fr/cfmip-obs/Calipso_goccp.html)
601 [obs/Calipso_goccp.html](https://climserv.ipsl.polytechnique.fr/cfmip-obs/Calipso_goccp.html) . ERA5 reanalyses data are available on
602 [https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form)
603 [means?tab=form](https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels-monthly-means?tab=form). All data that we use in this paper are available here:
604 <https://doi.org/10.14768/e91cc5fa-bcde-435c-b40f-65c93daae7d2>

605

606 Figures

607

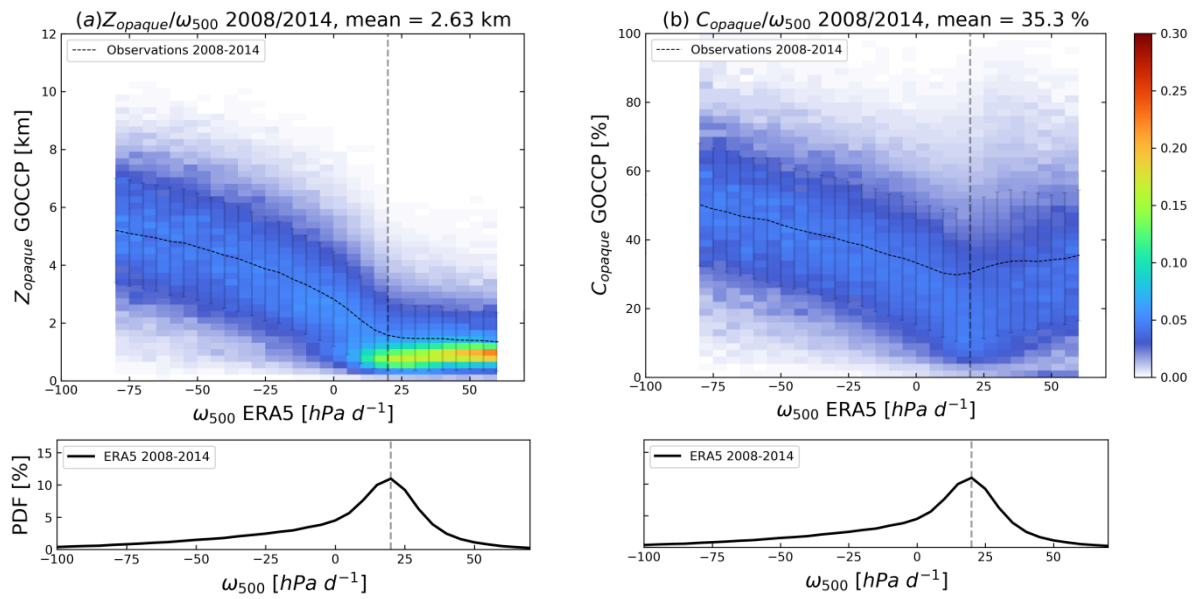


608

609 **Figure 1: Maps of (a) vertical velocity at the 500 hPa level (ω_{500}) according to ERA5 reanalysis, (b) Z_{opaque} and (c)**
610 **C_{opaque} according to CALIPSO GOCCP observations. Red represents ascending regions ($\omega_{500}<0$), high Z_{opaque}**
611 **($Z_{opaque}>3\text{km}$) and large C_{opaque} ($C_{opaque}>40\%$). Blue represents descending regions ($\omega_{500}>0$), low Z_{opaque}**
612 **($Z_{opaque}<3\text{km}$) and small C_{opaque} ($C_{opaque}<40\%$). Tropics [30°S-30°N] multi-annual mean averaged over the 2008-**
613 **2014 period.**

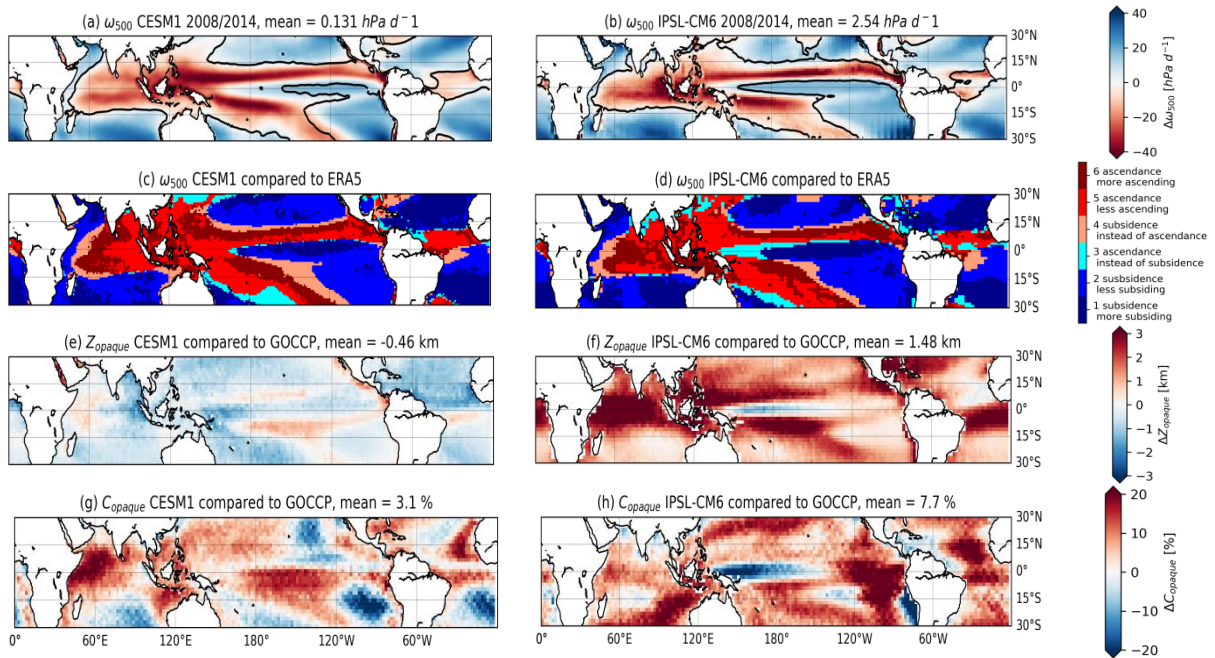
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616

617 **Figure 2: Normalized histogram showing the distribution of (a) Z_{opaque} [km] and the vertical velocity at 500 hPa, ω_{500}**
618 **[hPa/d], and (b) C_{opaque} [%] and ω_{500} [hPa/d] considering values from all year monthly mean values over a $2^{\circ} \times 2^{\circ}$ grid**
619 **[$30^{\circ}S-30^{\circ}N$], ocean only, for the 2008-2014 period combined with the probability distribution of monthly ω_{500} [hPa/d]**
620 **over the 2008-2014 period. Z_{opaque} and C_{opaque} come from CALIPSO GOCCP observations, ω_{500} from ERA5 reanalysis.**
621 **The dotted vertical line represents $\omega_{500} = +20$ hPa/d. The dotted black curve represents the distribution over the 2008-**
622 **2014 period according to GOCCP observations. To normalize, we divide Z_{opaque} (C_{opaque}) occurrences along the y-axis**
623 **by the total number of occurrences in each ω_{500} bin. Hence, the sum of the normalized occurrences of Z_{opaque}**
624 **(C_{opaque}) for a given ω_{500} is 1. ω_{500} ranges containing less than 2000 absolute occurrences are masked (white).**



625

626

Figure 3: Maps of (a and b) vertical velocity at 500 hPa (ω_{500}) from climate models in current climate. Maps of

627

differences between models and observations (c and d) vertical velocity at 500 hPa (ω_{500}), (e) and (f) opaque cloud

628

altitude (Z_{opaque}) and (g) and (h) opaque cloud cover (C_{opaque}). Left column refers to the CESM1 model and the right

629

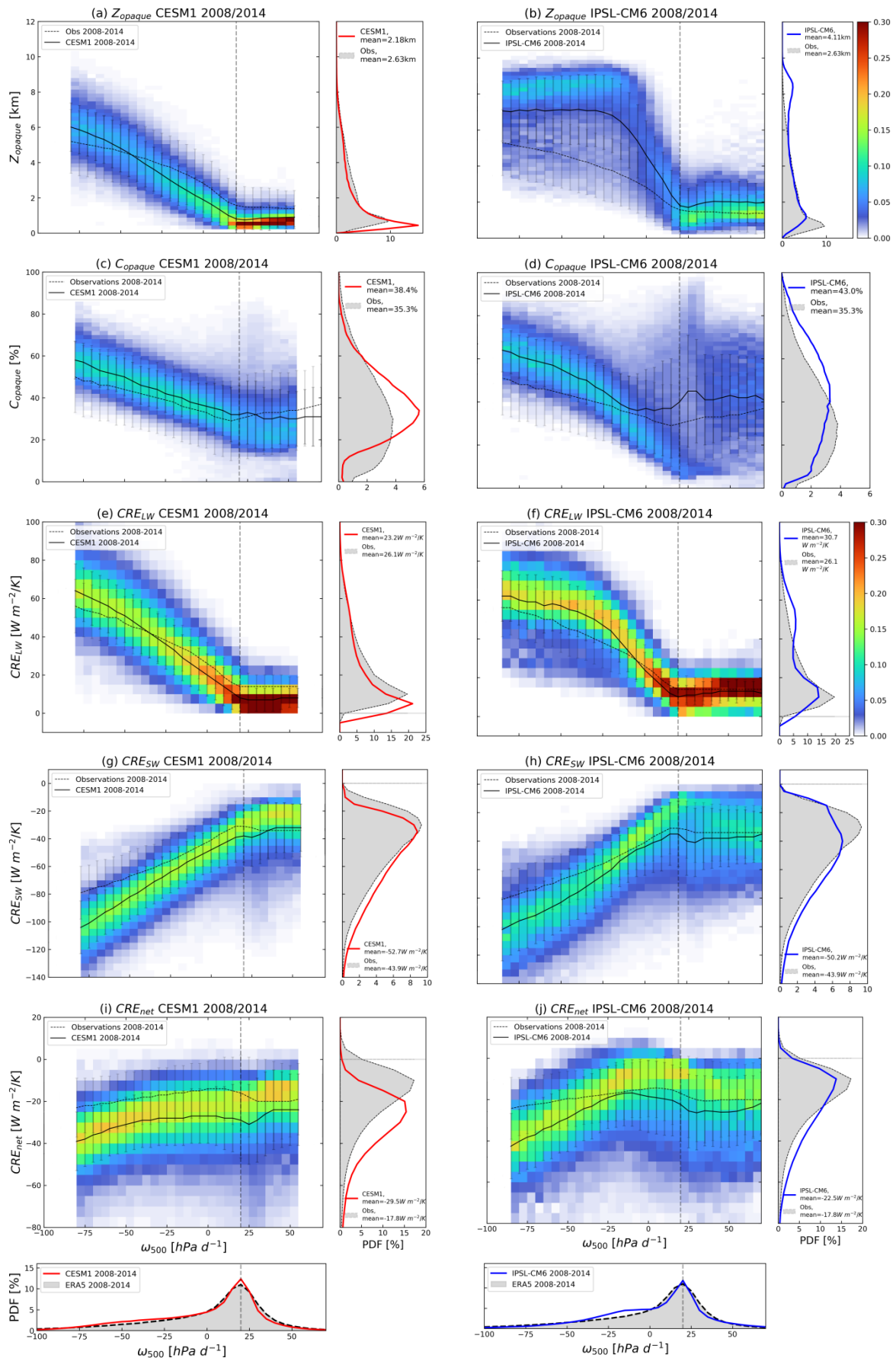
column to the IPSL-CM6 model. Observations of C_{opaque} and Z_{opaque} are from CALIPSO-GOCCP, and ω_{500} from ERA-5

630

reanalyses. Black lines in a and b show the $\omega_{500} = 0$ hPa/d isocontour in ERA5 reanalyses. All data averaged over the

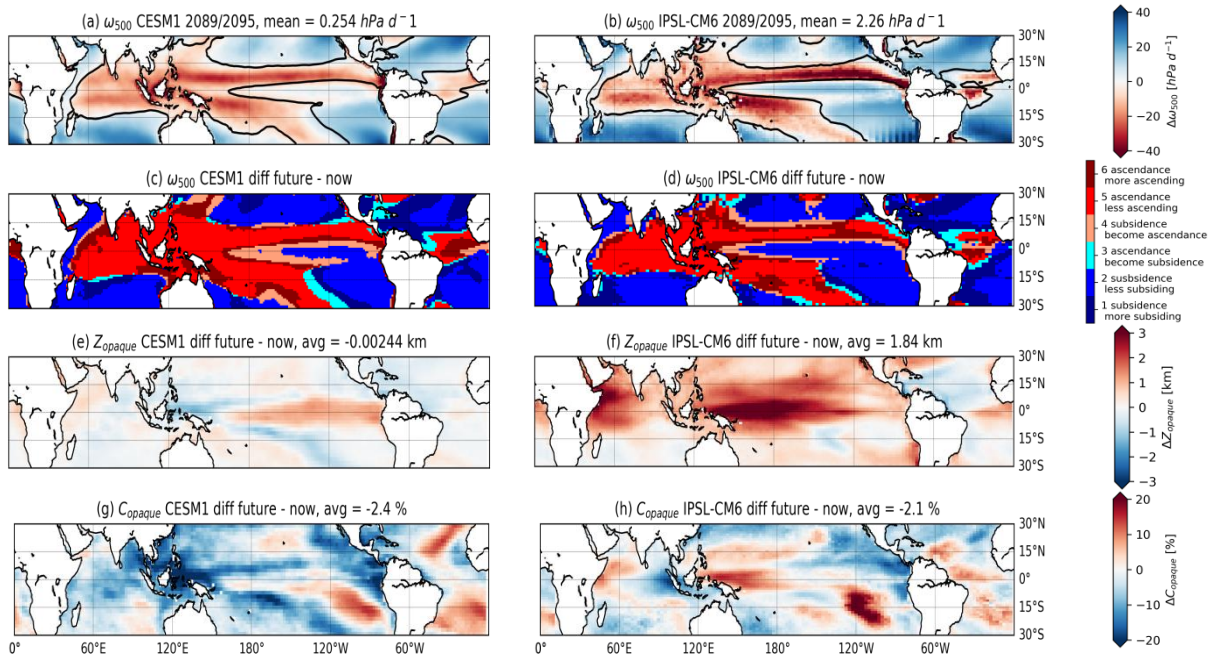
631

2008-2014 period.



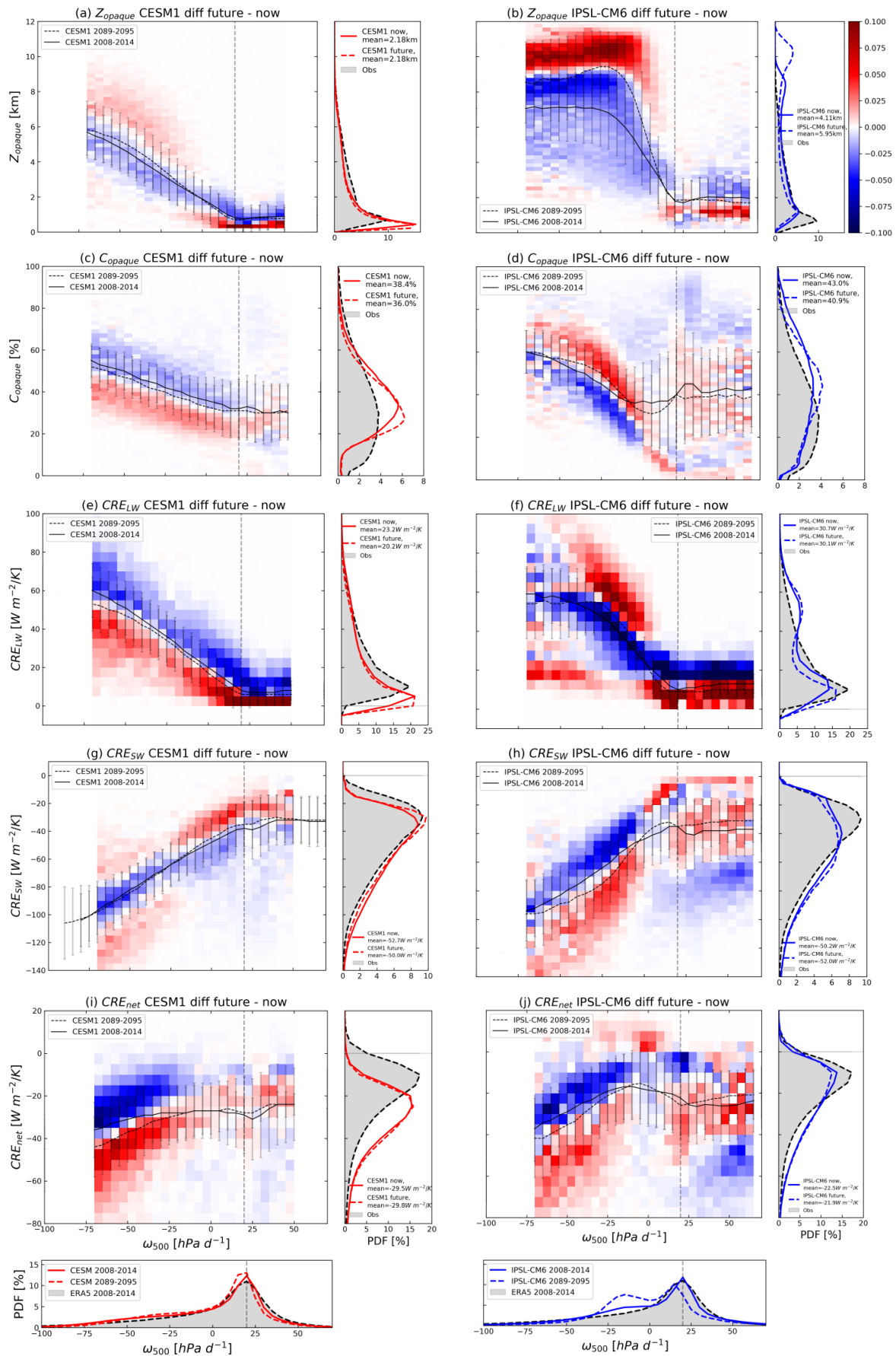
632 Figure 4: Normalized histogram showing the distribution of (a and b) Zopaque [km], (c and d) Copaque [%], (e and f)
633 CRE_{LW} [$W/m^2/K$], (g and h) CRE_{SW} [$W/m^2/K$] and (i and j) CRE_{net} [$W/m^2/K$] and the PDF of the vertical velocity at 500 hPa,
634 ω_{500} [hPa/d] in the Tropics [30°N-30°S], ocean only. The CESM1 model is in left column (red curves) and the IPSL-CM6
635 model in the right column (blue curves). ω_{500} ranges containing less than 2000 absolute occurrences for CESM1 and less
636 than 1000 absolute occurrences for IPSL-CM6 are masked (white). The dotted black curve represents, for each variable,
637 the distribution over the 2008-2014 period according to GOCCP observations and CERES observations and the black curve
638 represents the distribution over the 2008-2014 period according to CESM1 and IPSL-CM6 simulations. The error bars
639 show the ± 2 standard deviation of the 7-years means. PDF of monthly (a and b) Zopaque, (c and d) Copaque, (e and f)
640 CRE_{LW} , (g and h) CRE_{SW} and (i and j) CRE_{net} to the right of each normalized histogram. PDFs of monthly ω_{500} under
641 normalized histograms of CRE_{net} . The grey shadows represent the distribution over the 2008-2014 periods according to
642 GOCCP observations (cloud properties), CERES observations (CRE) and ERA5 reanalysis (ω_{500}).

643

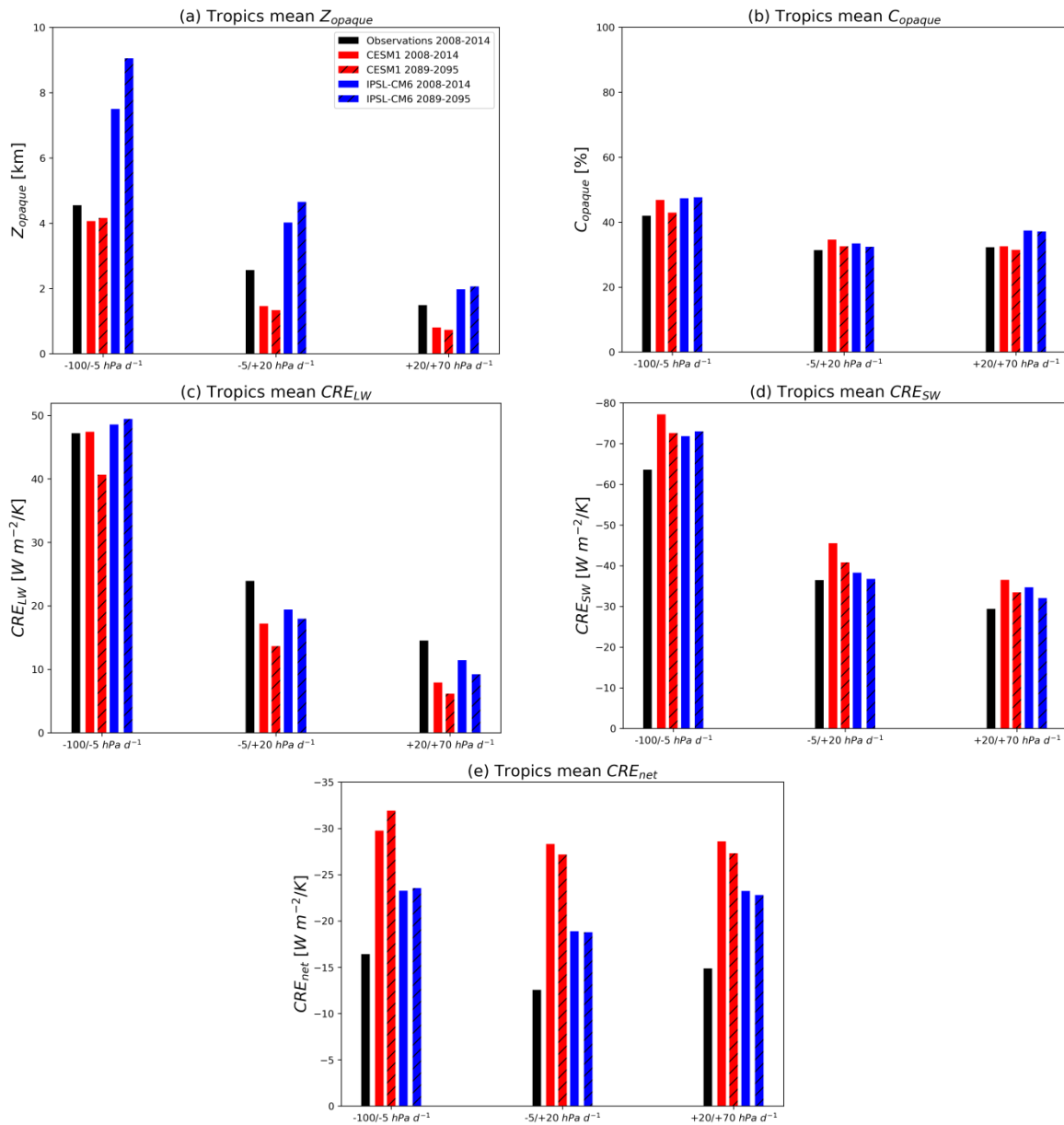


645

646 **Figure 5: Maps of (a and b) vertical velocity at 500 hPa (ω_{500}) from climate models in future climate. Black lines in a and b**
 647 **show the $\omega_{500} = 0$ hPa/d isocontour in present climate conditions. Maps of differences between future (2089-2095) and**
 648 **current (2008-2014) climate previsions of (c, d) vertical velocity at 500 hPa (ω_{500}), (e, f) opaque cloud altitude (Z_{opaque})**
 649 **and (g, h) opaque cloud cover (C_{opaque}) in CESM1 (left column) and IPSL-CM6 (right column). Current climate is the**
 650 **reference.**



652 Figure 6: Differences between future and current normalized histograms of (a and b) Zopaque [m], (c and d)
653 Copaque [%], (e and f) CRE_{LW} [$W/m^2/K$], (g and h) CRE_{SW} [$W/m^2/K$] and (i and j) CRE_{net} [$W/m^2/K$] and the PDF of the
654 vertical velocity at 500 hPa, ω_{500} [hPa/d] in the Tropics [30°N-30°S], ocean only. The CESM model [2089-2095 / 2008-
655 2014] is in left column (red curves) and the IPSL model [2089-2095 / 2008-2014] in the right column (blue curves). ω_{500}
656 ranges containing less than 5000 absolute occurrences for CESM1 and less than 2000 absolute occurrences for IPSL-CM6
657 are masked (white). PDFs of monthly (a and b) Zopaque [hPa/d], (c and d) Copaque, (e and f) CRE_{LW} , (g and h) CRE_{SW} and
658 (i and j) CRE_{net} to the right of each normalized histogram. The last row shows PDFs of monthly ω_{500} . Grey shadows
659 represent the distributions of cloud properties according to GOCCP observations, of CRE according to and CERES
660 observations (panels a-j) and the ω_{500} distribution from ERA5 reanalysis (w_{500} distribution, bottom) over the 2008-2014
661 period. Full curves represent the 2008-2014 period and dotted curves represent the 2089-2095 period.



663

664 **Figure 7: Mean values of (a) Zopaque, (b) Copaque, (c) CRE_{LW}, (d) CRE_{SW} and (e) CRE_{net} over $\omega_{500} = +20/+70$**

665 **hPa/d (right of each plot), $\omega_{500} = -5/+20$ hPa/d (center of each plot) and $\omega_{500} = -100/-5$ hPa/d (left of each plot) in the**

666 **Tropics [30°S-30°N], ocean only. Observations (black) of Zopaque and Copaque are from CALIPSO-GOCCP (2008-2014)**

667 **and observations of CREs are from CERES-EBAF (2008-2014). Simulations are from CESM (red) and IPSL-CM6 (blue)**

668 **averaged over the 2008-2014 period (no pattern) and over the 2089-2095 period (dashed pattern).**

669

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