Evolution over two decades of the tropical clouds in a subsidence area and their relation to large-scale environment

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2 **relations to large-scale environment**

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18 **Abstract**

19   The interannual variability of cloud properties in a tropical subsidence area (South

20 Atlantic Ocean) is examined using 23 years of ISCCP cloud fractions and optical depths,

21 complemented with ISCCP/Meteosat visible reflectance and a four-years comparison with

22 CALIPSO-GOCCP products. The mean seasonal cloud properties are examined in the area, as

23 their interannual evolution. Circulation regimes (characterized with the SST and w_{500} from

24 NCEP and ERA-Interim) that dominate summer and winter are also examined, and

25 atmospheric situations are classified in five circulation regimes: ascending air masses, and

26 moderate or strong subsidence with warm or cold SSTs. We examine the mean cloud cover,

27 optical depth, and reflectance in each regime and their evolution in time over 23 years.

28 Observational results (mean values and interannual variability) are compared with simulations

29 from the IPSL and CNRM climate models (part of the CMIP5 experiment), using simulators

30 to ensure that differences can be attributed to model defects.

31   It results that regime occurrence strongly depends on the dataset (NCEP or ERA-

32 Interim), as do their evolution in time along 23 years. The observed cloud cover is stable in

33 time and weakly regime-dependent, whereas the cloud optical depth and reflectance are

34 clearly regime-dependent. Some cloud properties trends actually do exist only in some

35 particular regimes. Compared to observations, models underestimate cloud cover and

36 overestimate cloud optical depth and reflectance. Climate models poorly reproduce regime

37 occurrence and their evolution in time, as well as variations in cloud properties associated

38 with regime change. It means that errors in the simulation of clouds from climate models are

39 firstly due to errors in the simulation of the dynamic and thermodynamic environmental

40 conditions.

1. Introduction

Cloud response to anthropogenic forcing remains one of the main uncertainties for model-based estimates of climate prediction evolution [*Soden et al.* 2006; *Webb et al.* 2006; *Ringer et al.* 2006]. In the Tropics, the response of low level tropical clouds (below 440 hPa) to anthropogenic forcing is highly variable from one climate model to another, suggesting that low-level clouds contribute significantly to tropical climate cloud feedback uncertainties [*Bony and Dufresne* 2005]. *Bony et al.* [2004] showed that tropical low-clouds have a moderate sensitivity to temperature, but their statistical weight is so important that they could have a large influence on the tropical radiation budget. As a consequence, it is necessary to study low-level clouds in a context of global warming.

Tropical low clouds and their relations to dynamic and thermodynamic variables have been widely studied in the past: in the Pacific Ocean [*Clement et al.* 2009. *Klein et al.* 1995. *Norris* 1998; *Norris and Klein* 2000; *Lau and Crane* 1995; *Kubar et al.* 2010], in the Atlantic Ocean [*Zhang et al.* 2009; *Mauger and Norris* 2010; *Oreopoulos and Davis* 1993], and in all tropical oceans [*Williams et al.* 2003; *Yuan et al.* 2008; *Klein and Hartman* 1993; *Sandu et al.* 2010; *Rozendal and Rossow* 2003; *Medeiros and Stevens* 2009; *Bony et al.* 2004]. Only a few papers are dedicated to the interannual variability of low-clouds: *Clement et al.* [2009] used fifty years of low cloud observations in the Pacific Ocean and showed for example a positive trend of the total cloud fraction at the end of the 90's, associated with similar trends in the thermodynamical variables; *Oreopoulos and Davies* [1993] used cloud satellite observations in two tropical oceanic locations to study the effect of temperature variations on the cloud albedo, in particular its monthly variation during five years.

The current paper aims at characterizing the interannual variability of south-Atlantic tropical clouds located in the 0°/30°S – 30°W/8°E square (Fig. 1a), under predominance of subsidence air motion. We have chosen a larger region than the "Namibian" square used in

66 the KH93, RR03 and Zh09 studies (Tab. 1) because this area is a location of maximum stratus

67 (KH93), and the goal of the current study is to examine all types of clouds associated with

68 subsidence conditions. The high precipitation isolines in Fig. 1a show that the region under

69 study is exposed to the ITCZ (Inter-Tropical Convergence Zone) in the northern edge in DJF

70 (December – January – February), but not in JJA (June – July – August). Most of the time,

71 this region is exposed to the descending air masses of the Hadley cell; in JJA its southern

72 edge could be influenced by the subtropical anticyclone [*Venegas et al.* 1996]. This region

73 contains both opaque stratocumulus clouds along the African coast, and shallow cumulus

74 clouds westwards (Tab. 1, 3rd line). Like previous studies (RR03, Zh09 for the Atlantic

75 Ocean; *Klein et al.* 1995; *Norris* 1998; *Norris and Klein* 2000 for equivalent subsidence

76 locations in the Pacific Ocean), we analyze DJF and JJA independently because those are

77 opposite seasons in terms of ITCZ influence.

78   The first objective of this paper is to analyze (i) the evolution of montlhy mean cloud

79 radiative properties over two decades in a region of subsidence, and (ii) the evolution of the

80 concommittent dynamic and thermodynamic atmospheric properties. We try to determine if

81 there is a robust relationship between these environmental variables (from reanalysis) and the

82 observed cloud radiative properties (seasonal averaging and spatial resolution of 2.5° x 2.5°),

83 and if this relationship is stable over two decades. It would suggest that we could know cloud

84 radiative properties when dynamic and thermodynamic conditions are known. Moreover, our

85 confidence in model-based predictions of future climate, depends on the ability of models to

86 simulate realisticly the current climate. The second objective of this paper is to evaluate the

87 ability of two climate models to reproduce the evolution over two decades of (i) the observed

88 cloud properties, (ii) the concommittent dynamic and thermodynamic atmospheric conditions,

89 and (iii) the relationship between these environmental conditions and cloud radiative

90 properties.

91   Cloud properties are first characterized using satellite observations (Sect. 2). Then, we

92   focus (Sect. 3) on the characterization of dynamical and thermodynamical regimes and their

93   evolution with time. Sect. 4 describes the cloud properties associated with each regime and

94   their interannual variability. In each section, the main results (i.e. interannual trends) are

95   compared with simulations from the IPSL (Institut Pierre Simon Laplace 4, Hourdin et al.

96   2012) and CNRM (Centre National de Recherches Météorologiques, Voldoire et al. 2011)

97   climate models. Discussion and conclusion are drawn in Sect. 5.

98

99   **2. Cloud satellite observations**

100   <u>2.1. Satellite data</u>

101   Most papers studying tropical clouds (Tab. 1) are based on satellite observations.

102   Many of those use ISCCP (International Satellite Cloud Climatology Project, *Rossow et al.*

103   1991a and b; 1993; 1996; 2004) Cloud Fraction (CF), e.g: *Clement et al.* [2009], *Klein and*

104   *Hartman* [1993], *Rozendal and Rossow* [2003], *Williams et al.* [2003], *Medeiros and Stevens*

105   [2009], *Zhang et al.* [2009], *Lau and Crane* [1995], *Oreopoulos and Davies* [1993]. A few

106   papers study tropical low clouds with A-Train observations that give more detailed

107   information on cloud properties: *Sandu et al.* [2010] used cloud types and cloud fraction from

108   MODIS (Moderate Resolution Imaging Spectroradiometer), associated with collocated

109   observations of water vapor and precipitation; *Mauger and Norris* [2010] used both MODIS

110   and CERES (Clouds and the Earth's Radiant Energy System) to study the influence of

111   previous meteorological conditions on sub-tropical cloud properties; *Kubar et al.* [2010] used

112   the more complex observations from CALIPSO (Cloud Aerosol Lidar and Infrared

113   Pathfinder) and CloudSat along a tropical cross-section during one year.

114   Here, we use three datasets to characterize clouds: cloud fractions and optical depths

115   from ISCCP D2 products [*Rossow et al.* 1991 and 1996; *Rossow and Schiffer* 1991], cloud

116   fractions from CALIPSO-GOCCP (CALIPSO – GCM Oriented CALIPSO Cloud Product,

117   *Chepfer et al.* 2010), and visible reflectance from ISCCP/Meteosat DX products [*Desormeaux*

118   et al. 1993].

119

120   *a) ISCCP cloud fraction and optical depth*

121   The ISCCP analyzes satellite radiance measurements to retrieve cloud fraction and

122   optical depth. The same algorithms are applied to several spaceborne instruments, such as

123   GOES (Geostationary Operational Environmental Satellite) instruments and Meteosat, or

124   polar orbiters, in order to get long-term information on clouds at global scale. We used the

125   cloud fraction for low-level clouds ($CF_{low/ISCCP}$, cloud top pressure P_{top} between ground and

126   680 hPa), mid-level clouds ($CF_{mid/ISCCP}$, P_{top} between 680 hPa and 440 hPa), and high-level

127   clouds ($CF_{high/ISCCP}$, P_{top} under 440 hPa) as well as the total cloud fraction CF_{ISCCP} (sum of CF

128   at the three pressure levels) and optical depth τ, results of the D2 data. Because cloud fraction

129   retrieval is based on passive remote-sensing measurements, there is no overlap between

130    $CF_{low/ISCCP}$, $CF_{mid/ISCCP}$ and $CF_{high/ISCCP}$, hence CF_{ISCCP} never exceeds 100%.

131   We analyzed 23 years (1984 to 2006) of monthly-mean data averaged seasonally (in

132   DJF and JJA) and spatially at a horizontal resolution of 2.5° x 2.5°. These observations are

133   averaged over the diurnal cycle, unlike the observations used hereafter.

134

135   *b) CALIPSO-GOCCP cloud fraction and vertical profile*

136   The CALIPSO satellite, launched in 2006, holds the lidar CALIOP (Cloud-Aerosol

137   Lidar with Orthogonal Polarization), which allows the characterization of the cloud vertical

138   structure. The CALIPSO-GOCCP [*Chepfer et al.* 2010] was initially designed to evaluate

139   cloudiness in Global Circulation Models. It is derived from CALIPSO Level 1 NASA

140   (National Aeronautics and Space Administration) products [*Winker et al.* 2009] and contains

141 four types of files, including seasonal cloud fraction maps at three levels of altitude (low-,

142 mid-, and high-level defined consistently with ISCCP). As this retrieval is based on active

143 remote sensing, there can be an overlap between the low-level cloud fraction ($CF_{low/GOCCP}$),

144 the mid-level one ($CF_{mid/GOCCP}$), and the high-level one ($CF_{high/GOCCP}$); and the sum of the

145 three can be larger than 100%. Nevertheless, the total cloud fraction CF_{GOCCP} detects if there

146 is a cloud in the column (it does not correspond to the sum of the low, mid and high cloud

147 fraction) and cannot exceed 100%. We also used vertical profiles of cloud fraction

148 ($CF_{GOCCP3D}$) at 40 equidistant levels (480m) from the ground to 20 km of altitude.

149   We analyzed four years (2007 to 2010) of CALIPSO-GOCCP seasonal mean (DJF and

150 JJA) cloud fractions. Initially, the CALIPSO-GOCCP cloud detection is done at the full

151 CALIOP Level 1 horizontal resolution (330 m along track and 75 m across track) to allow the

152 detection of small-size fractionated boundary layer clouds; cloud occurrences are then

153 statistically summarized over 2.5° x 2.5° grid box consistently with ISCCP cloud fraction.

154 The CALIPSO-GOCCP cloud fraction reported here are collected in day-time (1330 LST, A-

155 train orbit). In the current study, this product helps to understand the vertical distribution of

156 clouds from one season to another, and from one regime to another, but is not used to draw

157 any trend.

158

159 *c) ISCCP/ Meteosat visible reflectance*

160   To consolidate our analysis, and avoid making it dependent of the inversion

161 algorithms, we also use Meteosat Level 1 reflectance measurements (visible, wavelength near

162 0.6 μm) from ISCCP/Meteosat DX files. Reflectance can be seen as a proxy of cloud fraction

163 combined to cloud optical depth: a radiative signature of the cloud scene.

164   Since we focus on a given geographical zone, the satellite viewing direction is

165 constant; moreover the analysis is not impacted by the change of instruments as shown by

166   clear sky evolution in Appendix A. We use reflectance observed at a constant time 1200 UTC

167   (3-hours time slot, as close as possible to the CALIPSO overpass time), seasonally averaged

168   (DJF and JJA) during 23 years. The horizontal resolution is 0.5° x 0.5°, and the reflectance

169   uncertainty is 0.004. Since the satellite azimuthal relative angle changes with the season, DJF

170   and JJA reflectance cannot be compared in a quantitative way. Nevertheless, as the angles are

171   the same every year at the same date and same location, the same seasons can be compared

172   over different years, in order to study the interannual variability (Appendix A). Typically,

173   stratus (St) are associated with higher reflectance than stratocumulus (Sc), cumulus (Cu)

174   being the less reflective.

175

176   2.2. Cloud properties observed by satellite in the region under study: main patterns

177

178   *a) Spatial distribution*

179   Reflectance value is high in three regions (Fig. 1i-j): northeast, southwest and mid-

180   east, all with low standard deviations suggesting homogeneity of cloud solar reflectivity over

181   years. This is consistent with previous studies that found a lot of stratus in this area, even if

182   the area of maximum reflectance is not completely contained in the Namibian square studied

183   previously (KH93, RR03, Zh09).

184   The mid-east region is characterized by important cloud fractions (about 0.8) observed

185   by both GOCCP (Fig. 1b-c) and ISCCP (Fig. 1e-f) with low standard deviations (not shown),

186   and large optical thickness ($\tau \sim 8$, Fig. 1g) with important standard deviations (not shown).

187   This suggests that low clouds are present most of the time in this region but their cloud optical

188   thickness is highly variable (probably due to transitions between different types of low

189   clouds). This region corresponds with the "Namibian" area studied in KH93 who show that

190   stratus clouds are more frequent in JJA than in DJF (0.67 versus 0.6): opposite result is found

191   for CF_{ISCCP} (Fig. e versus Fig. 1f) probably due to the large amount of clouds at higher levels

192   (Fig. 1d).

193   The southwest region shows large cloud fraction (about 0.8) in ISCCP and GOCCP

194   with smaller values of optical thickness ($\tau \sim 4$, Fig. 1i-j). Examining maps for low-/mid-/high-

195   cloud fractions from ISCCP and GOCCP (not shown) indicates that this southwest region is

196   mostly characterized by a mix of mid- and high-clouds.

197

198   *b) Mean cloud properties*

199   When averaged in time over 23 years and spatially over the entire area under study,

200   cloud covers (Tab. 2) show that ISCCP detects almost only low-clouds (about 40%) whereas

201   GOCCP detects some mid- and high-clouds (up to 20%). In complement, the mean vertical

202   profile (Fig. 1d) shows that high-clouds are often present in this area ($CF_{GOCCP3D} \sim 20\%$),

203   with a maxima around 12 km of altitude, and these high clouds are not optically thin enough

204   to mask the important presence of low clouds.

205   The two seasons exhibit similar cloud covers, but the small seasonal variation (less

206   than 10% difference) is different in ISCCP and CALIPSO-GOCCP. The ISCCP cloud

207   fraction CF_{ISCCP} and optical depth τ are slightly higher in DJF than in JJA (Tab. 2). This is

208   still the case when considering each year individually (not shown). The seasonal variation

209   from GOCCP is opposite to ISCCP: the mean cloud cover is slightly higher in JJA than in

210   DJF (Tab. 2, Fig. 1b-c-e-f). The discrepancy between ISCCP and GOCCP occurs only in JJA

211   in which GOCCP observes more clouds than ISCCP at all levels of altitudes. The important

212   result is that the difference between the cloud covers from the two datasets is less than 10%

213   for all levels of altitude: both datasets will be used together for the rest of the interpretation.

214   The detailed cloud vertical distribution (Fig. 1d) changes with season: JJA shows less

215   high clouds and more low clouds ($CF_{GOCCP3D} \sim 0.25$) than DJF. The low cloud variation can

216 be due in part to the high cloud masking low clouds in DJF. These seasonal differences in the

217 vertical cloud distribution confirm that the cloud types are different during each season in the

218 area under study, and that the two seasons need to be analyzed independently in the rest of

219 this paper (even when split into regime).

220   The results of climate models simulations obtained by the IPSL and CNRM models in

221 the same region and period are given in Tab. 2. Those results have been obtained with the

222 ISCCP [*Webb and Klein* 2006], CALIPSO [*Chepfer et al.* 2008] and reflectance simulators

223 [*Konsta et al.*, under review] included in COSP (CFMIP Observations Satellites Package,

224 *Bodas et al.* 2011). This way, "Climate Model+Simulator" (CMS) outputs are kept consistent

225 with satellite observations. In this region and on average over 23 years, both CMS

226 underestimate by a factor of two the cloud cover whatever the season (Tab. 2), and

227 overestimate significantly the reflectance (up to + 0.1 in JJA), confirming that 1) climate

228 models do not produce enough clouds in the tropics (particularly at low levels), and 2) when

229 models do create clouds, they are optically too thick. This result is consistent with the "too

230 few, too bright" low-level tropical cloud problem identified in CMIP5 models (i.e. Nam et al.

231 2012).

232

233   2.3. Interannual variability of cloud properties (1984-2006)

234   The interannual variability of cloud fraction CF_{ISCCP}, optical depth τ and reflectance

235 *ref* is large over 23 years (Fig. 2) in both DJF and JJA. The trend of each variable, i.e. the

236 value of the linear regression slope multiplied by the number of years is given in each subtitle

237 in Fig. 2 (it is outlined within a rectangle when it is superior to the value of the standard

238 deviation). In DJF, the cloud optical depth τ and reflectance *ref* have increased in 23 years,

239 despite almost no change in the cloud cover CF_{ISCCP}. In JJA, the cloud optical depth has

240 increased of +1.2 in 23 years and reflectance remains almost stable. Anomalies can be

241   isolated: for example, reflectance is enhanced by +0.3 in DJF 1997 and JJA 1985, there is a

242   strong deficit of *ref* and τ in DJF 1988. Year 1997 corresponds with an El Niño event: the

243   important anomalies of cloud properties for this year are consistent with *Belon et al.* [2010]

244   results: in the tropics, the fraction of interannual variability of low-cloud cover that is related

245   to SST variability is driven by El Niño index.

246   This important variability in observations is well reproduced by CNRM model,

247   whereas it is smoother with IPSL model (Fig. 2d-e-f). The two models give very different

248   results: they do not show the same years of maximum and minimum for example. For one

249   single model, DJF and JJA are in phase (increase or decrease the same years, maximum and

250   minimum the same years…) whereas it is not the case in observations.

251

252   **3. Characterization of the atmospheric circulation in the region under study**

253   At first order, the cloud occurrences and optical depth depend on the atmospheric

254   circulation of the air masses; as a consequence, any change in the atmospheric circulation will

255   affect cloud properties. In order to understand if the observed interannual variability of the

256   cloud properties (and its anomalies) is mainly due to variations of atmospheric circulation or

257   to the change in cloud physical processes we will separate the cloud population in

258   atmospheric circulation regimes, based on the analysis of dynamic and thermodynamic

259   variables: in the following, it will be only called "regime".

260

261   <u>3.1. Definition of the regimes used in this study.</u>

262   Various dynamic and thermodynamic variables are used in the literature to

263   characterize the atmospheric environment in the Tropics. *Bony et al.* [2004] showed that

264   clouds, and in particular low clouds, are sensitive to both large-scale circulation and

265   thermodynamic structure of the atmosphere. *Klein et al.* [1995] also concluded that the low-

266   level cloud fraction is better correlated to temperatures 24 to 28 hours previously, than to

267   simultaneous ones, and that this cloud fraction is linked to atmospheric circulation at the

268   interannual scale. The Sea Surface Temperature (SST), the Lower Tropospheric Stability

269   (LTS) and the vertical velocity of air at 500 hPa (w_{500}) are also frequently used to characterize

270   the dynamic and thermodynamic state of the atmosphere. Wi03 showed that the clouds

271   response depends more on changes in both w_{500} and SST than on changes in SST alone.

272   *Medeiros and Stevens* [2009] suggested that w_{500} alone is not good to separate low clouds, but

273   is useful with LTS: w_{500} identifies subsidence and LTS separates cloud types in these

274   subsidence motions. More generally, several approaches have been followed, using only w_{500}

275   as in *Bony et al.* [2004], only LTS as in *Wyant et al.* [2009], or a combination of both as in

276   *Medeiros and Stevens* [2009]. In this study, we privileged the two w_{500} variable for the large-

277   scale dynamics, and SST variable for the thermodynamics in the following, the combination

278   of these two variables will be called "environmental variables".

279   Figures 3 shows the distribution of SSTs and w_{500} over the region, as simulated by

280   NCEP (National Centers for Environmental Prediction, Fig.3a-b) and ERA-Interim (ECMWF

281   Re-Analyses, Fig 3.c-d) reanalyses, and IPSL (Fig. 3g-h) and CNRM (Fig. 3i-j) climate

282   models. The seasonal variation of SST and w_{500} is roughly consistent with the position of the

283   Hadley cell in the four models: the SST is colder in JJA than in DJF, and air masses

284   ascending more ($w_{500} < 0$) in DJF than JJA. Reanalyses show higher variability than climate

285   models, suggesting than the latter reproduce the mean values for the SST (but not for w_{500}),

286   whereas the real variability is poor for models. In JJA for example, strong subsidence is too

287   frequent and weak subsidence is missing for CNRM model, and strong subsidence never

288   appears for IPSL model.

289   The PDF (Probability Density Function) of w_{500} and SST from NCEP (not shown)

290   have been examined and values are split following sections of the curves. It leads the

291   separations of the dataset in five regimes (white lines in Fig.3) that are studied independently

292   hereafter: an ascending regime ("As") associated with deep convection, strong subsidence

293   with cold ("SSu-cold") or warm ("SSu-warm") SSTs (associated with Stratocumulus), and

294   weak subsidence with cold ("WSu-cold") or warm ("WSu-warm") SSTs associated with

295   trade-wind cumulus). Weak and strong subsidence are separated at 30 hPa/day, and warm and

296   cold SSTs are separated at 298,5 K (respectively 296,5 K) in DJF (respectively JJA).

297

298   3.2. Interannual variability of regime distribution (1984-2010)

299   The occurrence of each regime evolves in time over 27 years (1984 to 2010, in order

300   to get both ISCCP years and GOCCP years). Figure 4 presents the interannual evolution of

301   their occurrence as an anomaly. The interannual trends (calculated as in Sect. 2.3) that are

302   statistically significant (underlined by a rectangle in the subtitle of each subplot in Fig.4),

303   represent about half (11 out of the 20) of the values reported here. A single regime in one

304   season exhibits a consistent interannual trend statistically robust in both datasets (NCEP and

305   ERA-Interim): the occurrence of the As regime decreases by 12-15% in 27 years in DJF. For

306   all other regimes, the trends obtained with the two reanalyses are inconsistent and/or not

307   statistically representative. Moreover, based in NCEP reanalyzes, the As regime is dominant

308   in DJF from 1984 to 1990 whereas SSu-cold dominates 1998 to 2010 (not shown).

309   Similarly to the reanalyses, climate models (Fig. 4f and g) do not suggest a significant

310   change in regime occurrence with time, except for the WSu-warm regime in DJF (only for

311   CNRM model). Nevertheless, this regime becomes more frequent with time in DJF for

312   CNRM model, which is in contradiction with the trend produced by ERA-Interim and NCEP

313   reanalyses. Moreover, trends that are significant in the reanalyses are not significant in the

314   models.

315   This suggests that both climate models are far of reproducing the occurrence of

316   regimes given by the reanalyses, but they are even more far away of reproducing their

317   evolution in time. In particular, the models predict that ascending branch of the Hadley cell

318   (As regime) is more frequent, which is not the case in the reanalyses.

319

320   **4. Analysis of cloud properties for each regime**

321   4.1. Characterization of cloud properties in regimes

322   To assess how robust is the mean cloud properties dependence on the regime, results

323   obtained with the different satellite datasets (ISCCP, CALIPSO-GOCCP) and reanalyses

324   datasets (NCEP and ERA-Interim) are reported in Fig. 5.

325   Observations (blue and green) are consistent for both datasets: the mean cloud fraction

326   varies slightly (between 0.4 and 0.6) when the regime changes, whereas the mean optical

327   depth (between 3 and 6) and the mean reflectance (between 0.15 and 0.25) are significantly

328   regime dependent, and seasonally dependent. In DJF, the larger optical depth and reflectance

329   are associated with strong subsidence regime (stratocumulus), which optical depth decreases

330   significantly in winter. In JJA, the cloud cover is about the same for all regimes, but larger

331   optical depths (and reflectance) are encountered in deep convection (As regime). These results

332   show that regimes do not drive significantly the mean cloud cover in the region, but do drive

333   the mean cloud optical depth and reflectance, and significantly the vertical structure (Fig. 6).

334   In particular, for the subsidence regime, the SST impacts more the vertical structure than w_{500},

335   consistently with Wi03 results, in particular in winter (JJA). However, a regime (as defined in

336   this study) does not by itself completely determine the cloud optical depth and reflectance: for

337   a given regime the mean optical depth and reflectance also depend on the season. This

338   seasonal dependency can be explained by the change in the cloud vertical distribution as

339   shown in Fig. 6.

340   Compared to the observations, CMS underestimate the cloud cover (Fig. 5a and d) by

341   a factor of two (or more) in all regimes and seasons, except in the As regime that is better

342   described by one CMS (CNRM). Differences between observations and CMS cloud cover can

343   be more than a factor of three for some regimes: SSu-cold and -warm (but they are not

344   significant in term of population, Fig.3) and WSu-cold in DJF, and SSu-warm in JJA (i.e.

345   41% of the population for CNRM model, Fig. 3h). It confirms that the boundary layer cloud

346   scheme, that drives the amount of cloud forms in subsidence conditions, remains a

347   challenging task for those two climate models.

348   The IPSL model errors on the reflectance (overestimate, Fig. 5c-f) and on the cloud

349   cover (underestimate, Fig. 5a-c) likely compensate to produce correct shortwave fluxes at the

350   top of the atmosphere (in both seasons) as already mentioned in previous section. Figure 5

351   shows that this error compensation applies to all regimes that are significant in term of

352   population.

353

354   4.2. Interannual variability of cloud properties using regime classification

355   Figure 7 shows the trends of observed cloud variables (blue and green bars) over 23

356   years in each regime. It means for example that *ref* has an increase of +0.03 in 23 years for

357   the As regime in DJF (based on NCEP reanalyses). The cloud fraction is stable in time in all

358   regimes (contrary to Clement et al. 2009), except in the warm strong subsidence regime where

359   it decreases (Fig. 7a) consistently with the reflectance (Fig. 7c). In the other four regimes,

360   cloud optical depth (Fig. 7b) and reflectance (Fig. 7c) have increased very slightly in summer

361   (DJF) over 23 years (about +0.5 for τ and about +0.035 for *ref*, in 23 years). A more

362   important increase of cloud optical depth occurs in winter (JJA) in all regimes (about +1.5),

363   but it is not associated with change in the reflectance that remains stable in time.

364   A trend is robust if it is observed in both sets of reanalyses, hence the final results are:

365   (1) a decrease of cloud fraction for the SSu-warm regime in DJF, (2) an increase of optical

366   depth for weak subsidence in DJF and for all regimes (except ascent) in JJA, and (3) an

367   increase of reflectance in the ascent regime in DJF.

368   In most of the cases, the IPSL CMS does not show any robust trend in the cloud cover

369   and reflectance. When it shows some trends (vertical arrows in Fig. 7), those are sometimes in

370   contradiction with the observations: in the WSu-warm regime, the modelled *CF* and *ref* in

371   JJA increase in time along the last 23 years (Fig. 7c) which is not consistent with the

372   observations. This increase of *ref* suggests that the clouds of this specific regime reflect more

373   solar light now than 23 years ago. But the observations disagree with this modelled

374   reflectance trend.

375

376   **5. Conclusion**

377   We have examined cloud properties in a tropical subsidence area (south Atlantic

378   Ocean) using 23 years of ISCCP cloud fractions and optical depths, complemented with 23

379   years of visible reflectance from ISCCP/Meteosat, and cloud vertical profiles from

380   CALIPSO-GOCCP collected during four years. We first studied the mean cloud properties

381   (cloud cover, optical depth, and reflectance) in DJF and JJA. The region under study contains

382   about 40% of low-level clouds and 20% of high-clouds (around 12 km). The difference

383   between ISCCP and GOCCP cloud cover is less than 10%, but the small seasonal variation is

384   not consistent between the two dataset. Then we looked at the interannual variability of cloud

385   properties over 23 years using ISCCP: cloud cover is stable in time and cloud optical depth

386   exhibits a positive trend (+0.55 in DJF and +1.2 in JJA).

387   We compared the observational results with output from climate models (IPSL and

388   CNRM models within CMIP5), coupled with COSP to ensure that differences can be

389 attributed to model defects. Models underestimate cloud cover by a factor of two, and

390 overestimate reflectance (+0.1). The CNRM model produces a stable cloud cover in time, in

391 agreement with observations, whereas the IPSL model shows a significant and unrealistic

392 positive cloud cover trend over the years.

393   As the cloud formation and properties are primarily driven by atmospheric dynamic

394 and thermodynamic variables, we examined the regimes (characterized with the SST and w_{500}

395 from NCEP and ERA-Interim) that dominate DJF and JJA. We classified atmospheric

396 situations in five categories: ascending air masses, moderate subsidence with warm / cold

397 SSTs, strong subsidence with warm / cold SSTs. The occurrence of each regime in the region

398 depends significantly on the dataset used (NCEP or ERA-Interim). The evolution in time of

399 the occurrence of each regime along the 23 years is different and inconsistent in both datasets,

400 except for the "ascending air" regime: its occurrence decreases significantly in time (of more

401 than 10%) according to both datasets. The occurrence of all regimes is poorly reproduced by

402 both climate models (CNRM and IPSL). Moreover, both report an increase in occurrence of

403 the "ascending air" regime contrarily to the observations.

404   We examined the relationship between environmental variables and the observed

405 cloud properties (seasonal averaging and spatial resolution of 2.5° x 2.5°). Observations

406 indicate that the cloud cover (0.4 to 0.6) is slightly regime dependent whereas the optical

407 depth (4 to 6) and the reflectance (0.15 to 0.25) are more significantly regime dependent.

408 Differences between modeled and observed cloud cover and reflectance are not regime

409 dependent.

410   We study the evolution of the relationship between the environmental variables and

411 cloud radiative properties over two decades. The observations exhibit two robust trends over

412 23 years in specific regimes. The optical depth increases only in weak subsidence conditions

413 in DJF (+0.6), and for weak and strong subsidence regimes in JJA (+1). The reflectance

414   increases only for the ascent regime in DJF (+0.03). This later trend is reproduced by IPSL

415   model with a smaller amplitude (+0.01). Trends detected in cloud properties before the

416   regime separation are now explained in some regime, particularly in DJF: the decrease of

417   cloud fraction over 23 years is explained by only one regime (strong subsidence with warm

418   SSTs), as for the optical depth increase which is detected only for weak subsidence, whereas

419   the reflectance increase is not detected in the subsidence (only in ascent).

420   In summary, this study suggests that the main difficulty to built reliable relationships

421   between environmental variables and clouds comes from the significant uncertainties in these

422   environmental variables produced by the different reanalyses and by climate models. It limits

423   the ability to detect robust regime-dependent trend in the observations, and it may be the first-

424   order limitation for models to reproduce observed clouds.

425   Future work will consist in extending this study to the entire tropical belt including all

426   CMIP5 models and the same two sets of reanalyses. It will aim at determining if, at this scale,

427   some of the regimes (and related trends) are better reproduced than others and in these cases if

428   the link between cloud properties and environmental variable (and related trends) is better

429   predicted by models.

430

431

Appendix A

There are two well-known problems for the retrieval of cloud fraction using satellite passive remote sensing, in particular from the ISCCP program: the variations of the satellite angles, and the calibration of satellites when the instruments are changed. In this Annex we investigate if these problems affect the dataset used in our study.

Figure A1.a shows an example of the satellite viewing angle θ_v for the complete area of study, for one day of the database. The values of this angle are between a few degrees and approximately 40°, depending on the location. Figure A1.b shows the percentage of days when θ_v is lower or smaller than its median value by more than 2°, for each pixel during the time period of the study. This percentage is always lower than 4%, and Fig. A1.c shows that the concerned θ_v do not deviate from the median by more than 3°. This shows that, during the 23 years of the study, the variations of θ_v are so small that they should not be a problem for our study of reflectance trends.

Figure A2.a is the same as Fig. A1.a but for the satellite relative azimuthal angle ϕ. The values of this angle are between 0° and 180°, depending on location and time. Figure A2.b is approximately the same as Fig. A1.b but for each pixel, the percentage is calculated every year for the same day, so from 23 values, in order to remove the natural variations of ϕ and only consider the variations due to technical problems. Another difference is that the percentage is calculated when ϕ is lower or smaller than its median value by more than 5°. This percentage is about 4% or 8% (one or two cases on twenty three) and Fig. A2.c shows that the concerning ϕ can be different from the median value by 50°. Figure A3 shows the value of the solar angle for the area under study, in January (Fig. A3a) and in July (Fig. A3b). Using extreme values of these three angles (Fig. A1-A3), the correspondence between reflectance and optical depth values has been calculated. The calculation is done using a doubling/adding radiative transfer code [*De Haan et al.* 1987], assuming the atmosphere is

457 plane parallel infinite. The atmosphere contains a cloud composed of liquid water spherical

458 particles of 6-µm radius (Mie Theory). Six values of cloud optical depth (τ_{calc} = 0, 1, 5, 10,

459 50, 100) are considered and four different geometries (two extremes of January, and two

460 extremes of July). Figure A4 is an illustration of this calculation (using a linear interpolation),

461 and it shows that for one given optical depth, the reflectance variability is very small from one

462 geometry to another (less than 0.1).

463 Figure A5 shows the variation in time of the clear sky reflectance for the complete

464 time period by selecting, for each day, the smallest reflectance in the area. The figure shows

465 that instrument changes are not associated with any gap in clear sky reflectance values. It

466 follows that instrument changes are not either a problem for the current study that focuses on

467 reflectance.

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575   **List of Tables**

576   **Table 1:** Review of previous studies concerning tropical low clouds and their relations

577   to dynamic and thermodynamic variables, when the area of study includes part of total of the

578   location of the following paper, called A. *SON is for September to November, MAM is for

579   March to May, MJJAS is for May to September, NDJFM is for November to March; **Cloud

580   Top Pressure; ***Sc for Stratocumulus, Cu for Cumulus.

581   **Table 2**: Mean values (0° - 30°S, 30°W – 8°E) of the entire database for ISCCP (1984

582   – 2006) and CALIPSO-GOCCP (2007 – 2010). Equivalent simulated values from the IPSL

583   and CNRM models have been added when available.

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Reference	Important results in the A area	Location
Klein and Hartman 1993 [KH93]	- SON* is season of maximum stratus & maximum LTS - A is an area of maximum stratus - interannual variability in stratus are related to changes in LTS	Area contained in A
Rozendal and Rossow 2003 [RR03]	- CF_{low}(MJJAS*) > CF_{low}(NDJFM*) - notable differences between the low cloud areas in Pacific and the low cloud areas in Atlantic (CF, τ, CTP**…) - more the subsidence is important, more the cloud top is low	Area contained in A
Sandu et al. 2010 [Sa10]	- transition of decrease CF associated with strong increase of SST & decrease of LTS, & free troposphere gradual humidification - Sc to Cu*** transition is stable from one Ocean to another, but Sc CF is higher in South Hemisphere Oceans	All Atlantic Ocean
Williams et al. 2003 [Wi03]	- cloud response depends more on w_{500} & SST changes than on SST changes only - low clouds: many with medium τ, CF more important for strong subsidence and cold SSTs	All tropical oceans
Medeiros and Stevens 2009 [MS09]	- CF_{low} increase as LTS increase but is independent of w_{500} - the peak of CF_{low} is about 30%, very large and very low values of CF_{low} are rare - in A: a few shallow-Cu at high level, a lot of Sc at low level	All tropical oceans
Zhang et al. 2009 [Zh09]	- CF_{low} increases linearly as a function of LTS - CF_{low} & LTS: both are maximum in SON* and minimum in MAM*	Area contained in A
Oreopoulos and Davies 1993 [OD93]	- SST has negative correlation with Albedo and CF, also for interannual variations	Area contained in A
Bony et al. 2004 [Bo04]	- low clouds have moderate sensitivity to temperature change but have an important statistical weight, so a large influence on the tropical Radiative budget - cloud Radiative forcing is high for ascendance and small for subsidence	All tropical oceans

588

589 *Table 1: Review of previous studies concerning tropical low clouds and their relations to*

590 *dynamic and thermodynamic variables, when the area of study includes part of total of the*

591 *location of the following paper, called A. *SON is for September to November, MAM is for*

592 *March to May, MJJAS is for May to September, NDJFM is for November to March; **Cloud*

593 *Top Pressure; ***Sc for Stratocumulus, Cu for Cumulus.*

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	CF_{ISCCP}		τ_{ISCCP}		CF_{GOCCP}		ref	
	DJF	JJA	DJF	JJA	DJF	JJA	DJF	JJA
Low – obs	0.46	0.39	_	_	0.39	0.47	_	_
Mid – obs	0.05	0.07	_	_	0.13	0.11	_	_
High – obs	0.01	0.03	_	_	0.20	0.16	_	_
Tot – obs	0.52	0.49	4.21	3.97	0.52	0.56	0.18	0.15
Tot – mod IPSL	0.18	0.17	_	_	0.21	0.20	0.2	0.3
Tot – mod CNRM	0.22	0.21	_	_	0.26	0.26	_	_

596

597 *Table 2: Mean values (0° - 30°S, 30°W – 8°E) of the entire database for ISCCP (1984 – 2006)*

598 *and CALIPSO-GOCCP (2007 – 2010). Equivalent simulated values from the IPSL and*

599 *CNRM models have been added when available.*

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627 both NCEP and ERA-Interim reanalysis, and the significant ones are in rectangles. Vertical

628 lines are the same as in Fig. 2. f-g. Equivalent trends (the value of the linear regression slope

629 of the curve, multiplied by the number of years) values over 27 years for DJF (f.) and JJA (g.)

630 calculated from NCEP, ERA-Interim, IPSL model, CNRM model. Significant trends are

631 indicated by an arrow.

632 **Figure** 5: Mean values of cloud properties for the five dynamical regimes. Three first

633 lines are *CF*, *τ*, and *ref* in DJF, three last lines the same in JJA. Blue bars are based on NCEP

634 reanalyses, green ones on ERA-Interim reanalyses. Same results from models (IPSL and

635 CNRM) have been added (not colour bars).

636 **Figure 6**: mean vertical profile of $CF_{GOCCP3D}$ (2007 − 2010). The complete database

637 are represented by the black dotted lines, it is then separated onto the five regimes. a) in DJF;

638 b) in JJA. X axis is in logarithmic scale.

639 **Figure 7**: Same as Fig. 5 but for trend values (over 23 years) instead of mean values.

640 A "trend" is the value of the linear regression slope of the curve, multiplied by the number of

641 years. CF_{GOCCP} values are not drawn as there are too few years for trend estimation. Black

642 arrows are added when the trend is superior to the variability (i.e. the standard deviation).

643 Same results from models (IPSL and CNRM) have been added (not colour bars).

644 **Figure A.1**: Satellite viewing angle θ_v (a) example of values in January, (b)

645 percentage of values that are more than 2° lower or larger than the median value for the entire

646 time period, (c) mean value of the difference between θ_v and its median when the percentage

647 of (b) is non-zero.

648 **Figure A.2**: Satellite azimuthal relative angle ϕ (a) example of values in January, (b)

649 percentage of values that are more than 5° lower or larger than the median value for the entire

650 time period, (c) mean value of the difference between ϕ and its median when the percentage

651 of (b) is non-zero.

652   **Figure A.3**: (a) Solar zenithal angle at 1200 UTC on January 15th; (b) same as (a) but

653   on July 15th.

654   **Figure A.4**: Simulation of the reflectance as a function of the optical thickness, for

655   four representation of the satellite geometry: solar zenithal angle of 20°/angle of viewing

656   direction with nadir of 15°/relative viewing azimuth angle of 50° (characteristic of January,

657   red plane line), 32°/15°/50° (characteristic of January, blue plane line); 22°/42°/130°

658   (characteristic of July, red dashed line); 50°/42°/130° (characteristic of July, red dashed line).

659   **Figure A.5**: Time evolution of the clear sky reflectance, during the complete period

660   (in blue). Satellite changes are indicated by vertical red lines.

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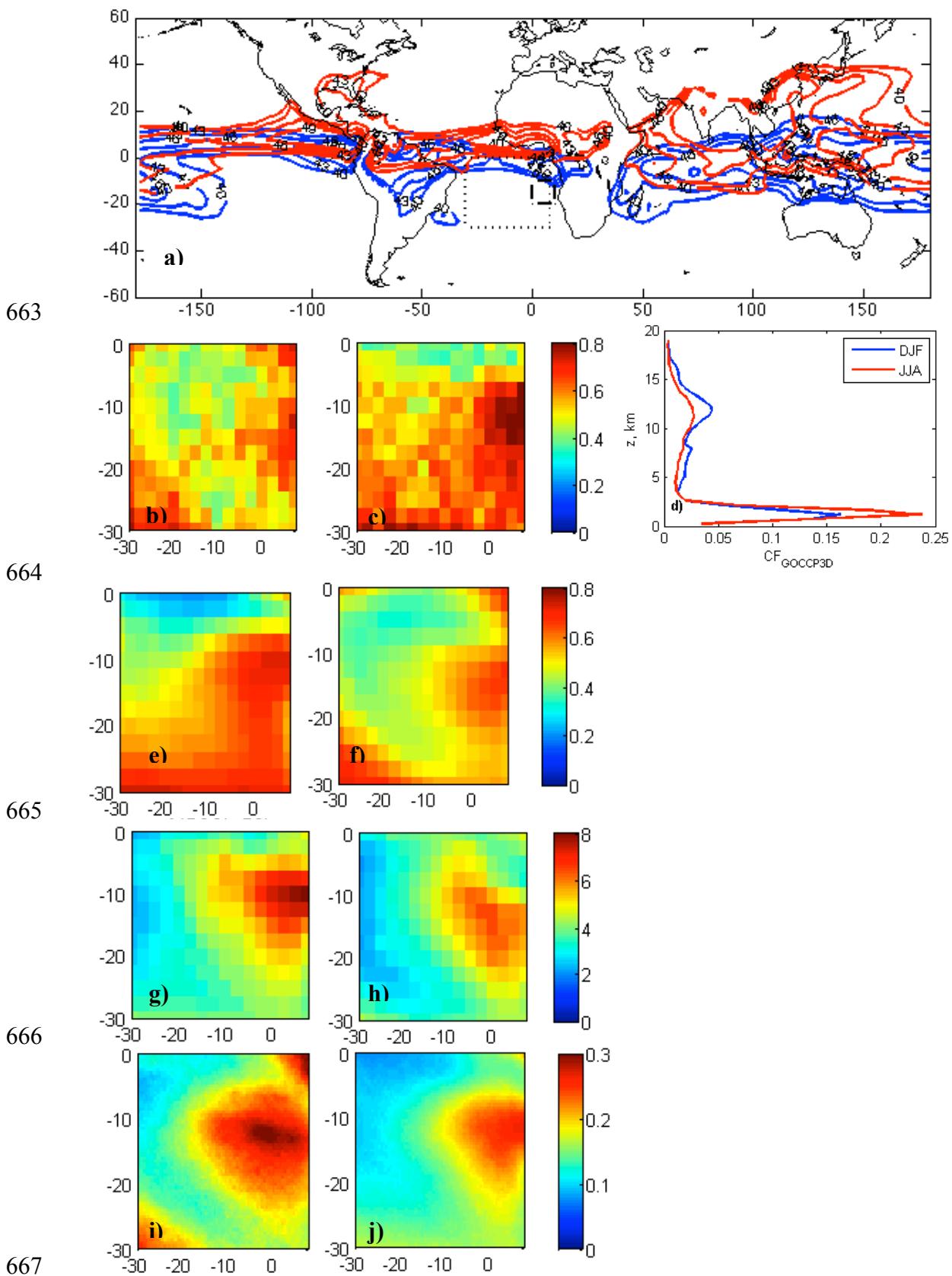
668 *Figure 1: Area under study. a) Isolines of NCEP precipitable water for entire atmosphere*
669 *(1984 – 2006), every 3 kg/m², only larger than 35 kg/m² highlighting ITCZ area. Red is July,*
670 *blue is January. Dotted square is the area of current study, dashed one is the area of KH93*
671 *study; b-c) Mean CF_{GOCCP} (2007 – 2010) (DJF-JJA); d) $CF_{GOCCP3D}$ mean vertical profile*
672 *(2007 – 2010); e-f) same as b-c) for CF_{ISCCP} (1984 – 2006); g-h) for τ; i-j), for ref.*

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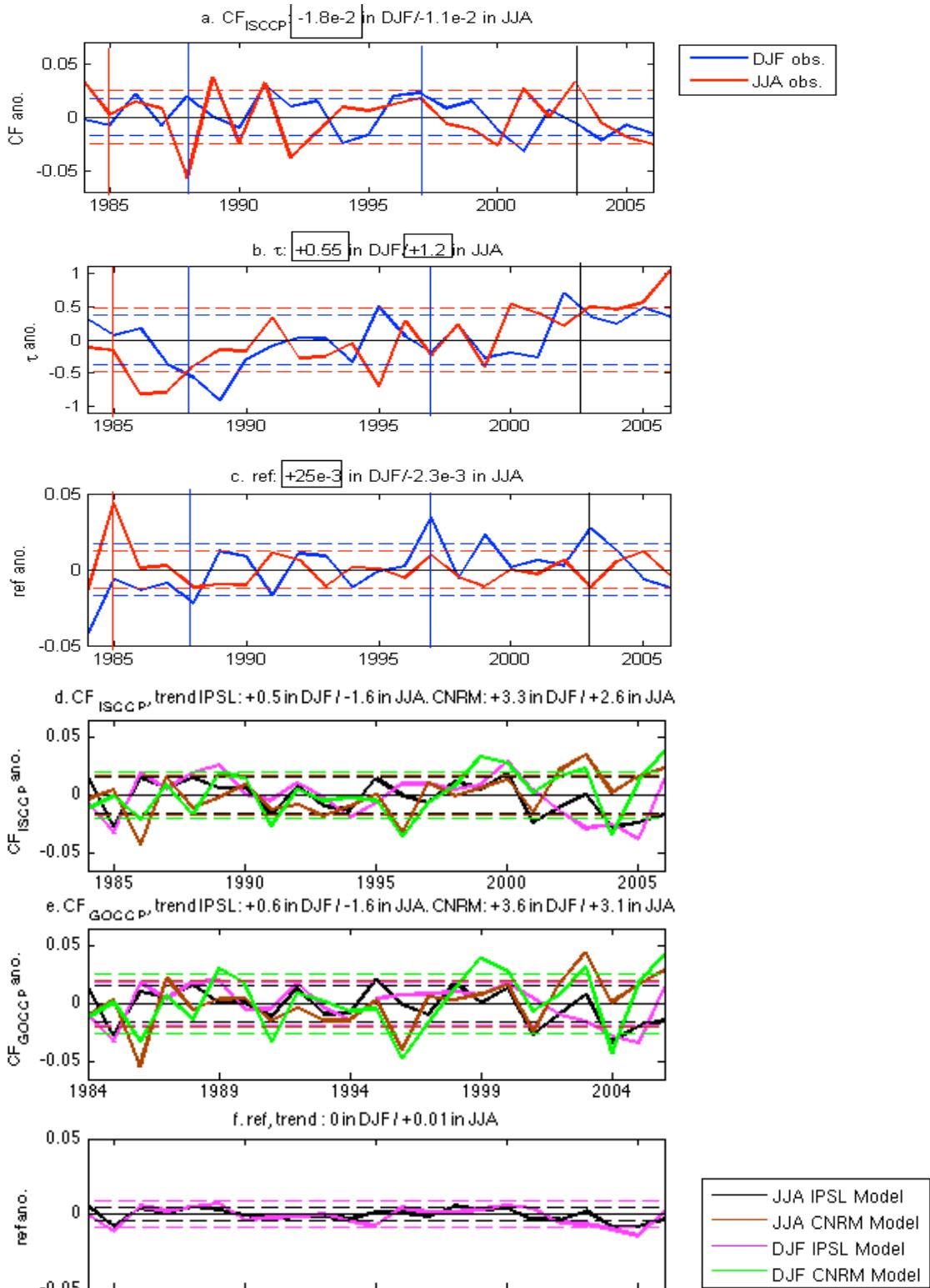
678 *Figure 2: Evolution of the mean cloud properties anomaly from 1984 to 2006. a) CF_{ISCCP}; b)*
679 *τ; c) ref; d) CF_{ISCCP} from models; e) CF_{GOCCP} from models; e) ref from models. Blue for DJF*
680 *observed, red for JJA observed, black for JJA IPSL model, brown for JJA CNRM model,*
681 *magenta for DJF IPSL model, green for DJF CNRM model. Horizontal dashed lines*
682 *correspond to the values of standard deviations. Numbers in the titles are values of trends in*
683 *23 years, and the significant ones (i.e. superior to the variability – standard deviation) are in*
684 *rectangles. Blue vertical lines indicate particular years in DJF, red ones the same in JJA, and*
685 *black ones particular years in both DJF and JJA.*

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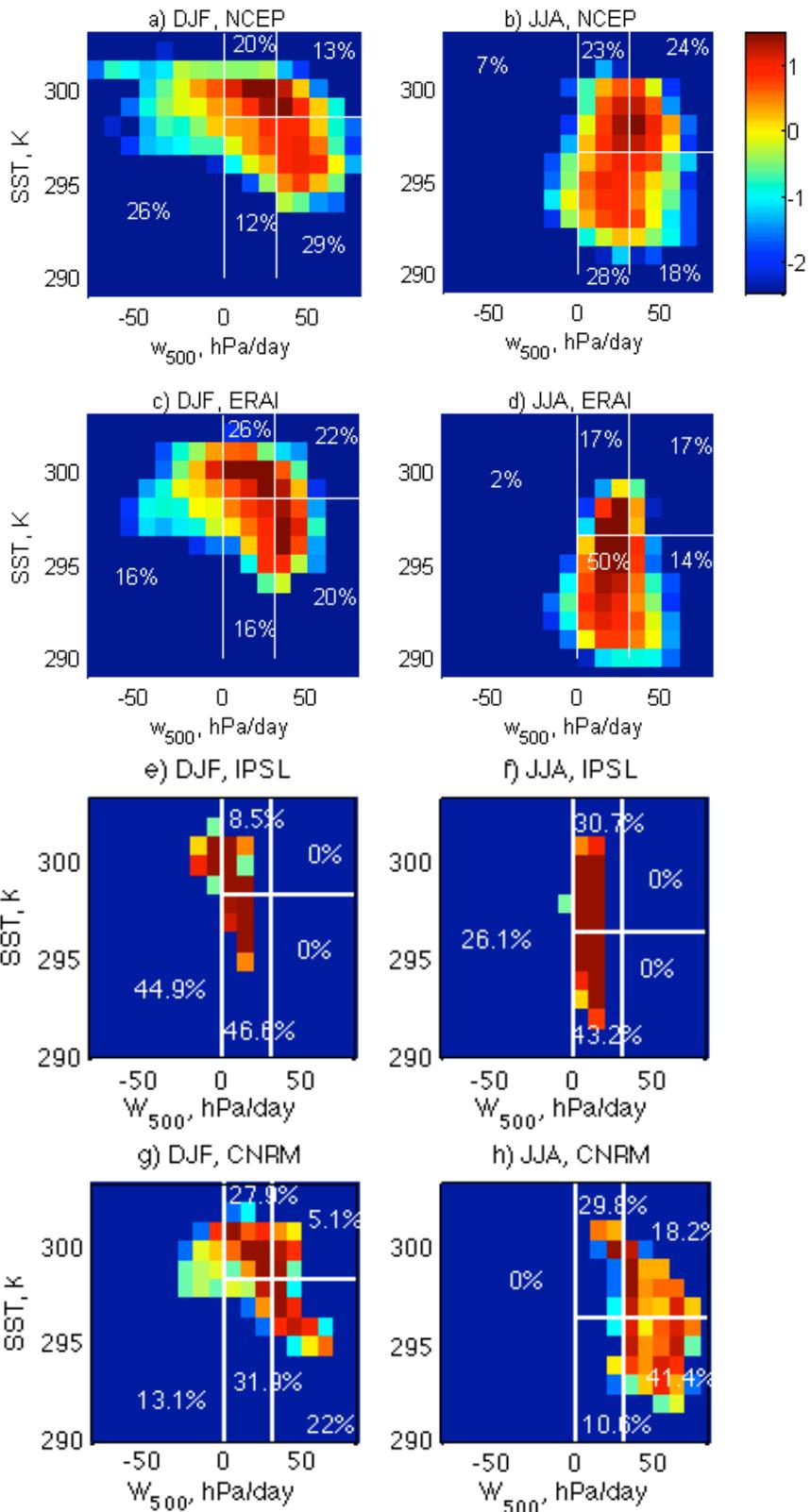
Figure 3: Log of percentage of occurrence of SST values (by classes of 1 K) versus w_{500} values (by classes of 10 hPa/day) from 1984 to 2010. a) NCEP in DJF; (b) NCEP in JJA; (c) ERA-Interim in DJF; d) ERA-Interim in JJA; e) IPSL model in DJF; f) IPSL model in JJA; g) CNRM model in DJF; h) CNRM model in JJA. (white horizontal and vertical lines indicate the limits of the five dynamical regimes and the number in white are the percentage of pixels of each regime).

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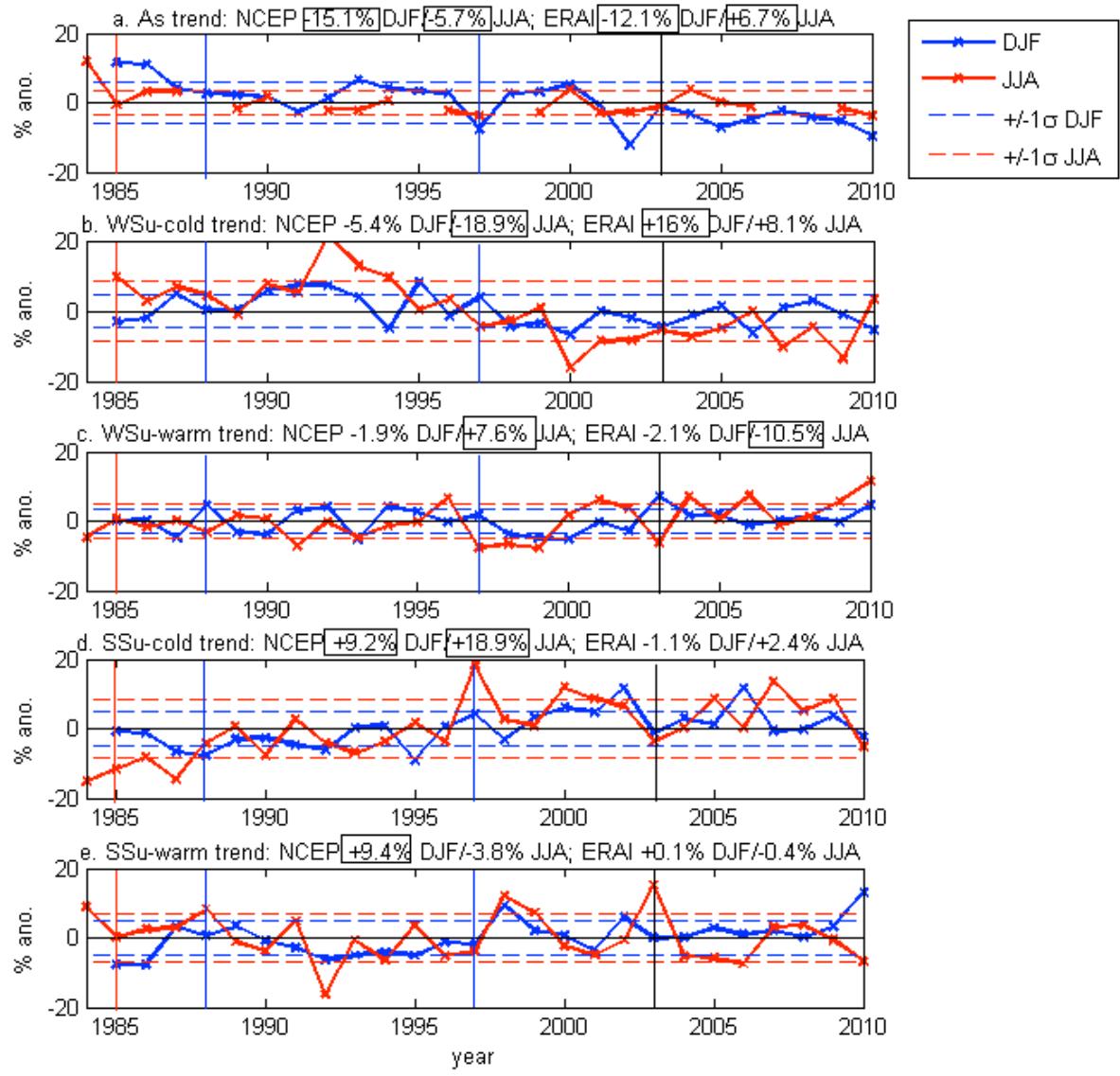
Figure 4: a-e. Anomaly of the percentage of pixels of each dynamical regime from 1984 to 2010 (DJF in blue, JJA in red) defined by NCEP w_{500} and SST values. a) As, b) WSu-cold, c) WSu-warm, d) SSu-cold, e) SSu-warm. The horizontal dashed lines correspond to the values of standard deviations. Values of the trends in 27 years are indicated in the titles for both NCEP and ERA-Interim reanalysis, and the significant ones are in rectangles. Vertical lines are the same as in Fig. 2. f-g. Equivalent trends (the value of the linear regression slope of the curve, multiplied by the number of years) values over 27 years for DJF (f.) and JJA (g.) calculated from NCEP, ERA-Interim, IPSL model, CNRM model. Significant trends are indicated by an arrow.

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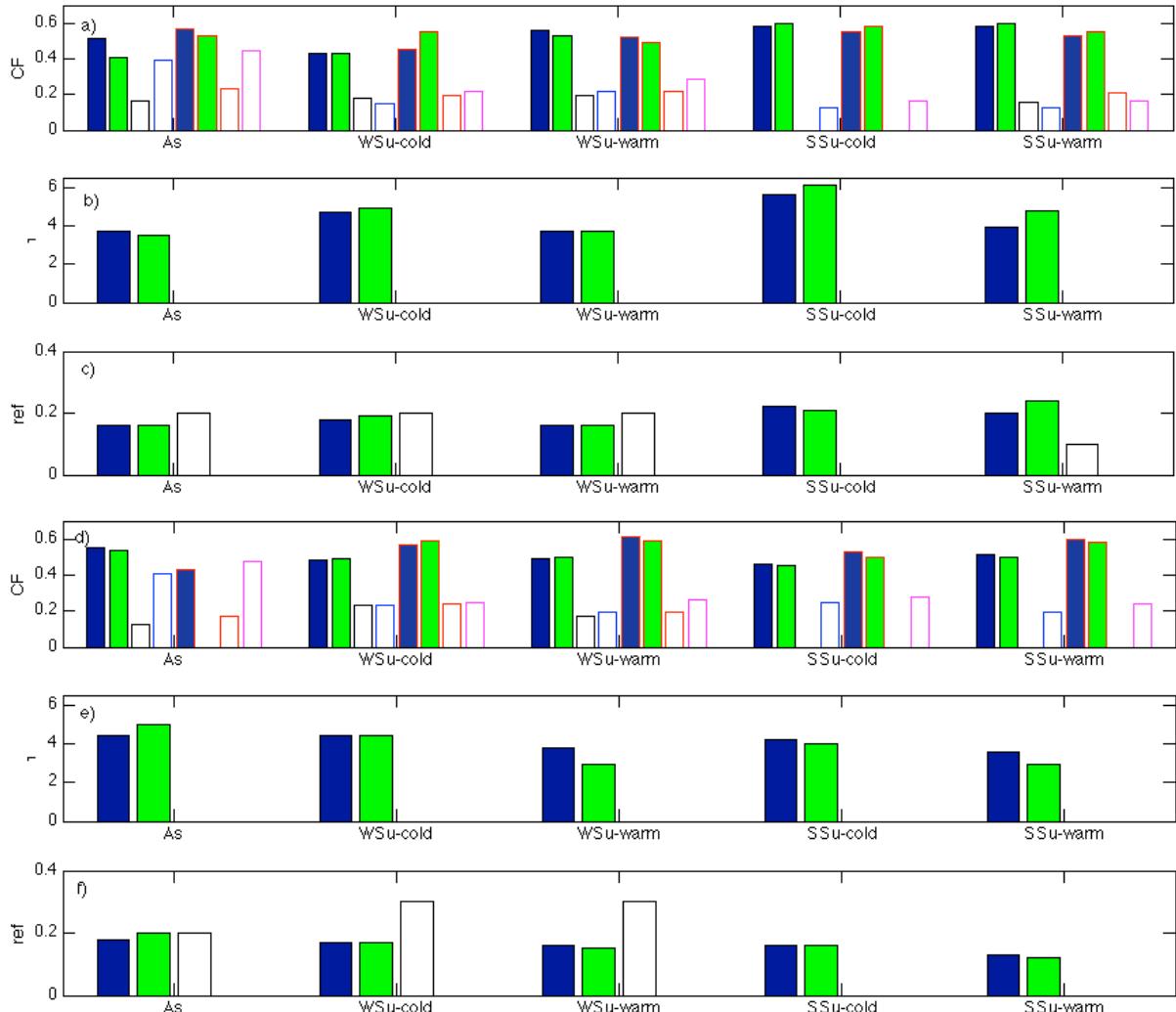
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714 *are CF, τ, and ref in DJF, three last lines the same in JJA. Blue bars are based on NCEP*
715 *reanalyses, green ones on ERA-Interim reanalyses. Same results from models (IPSL and*
716 *CNRM) have been added (not colour bars).*
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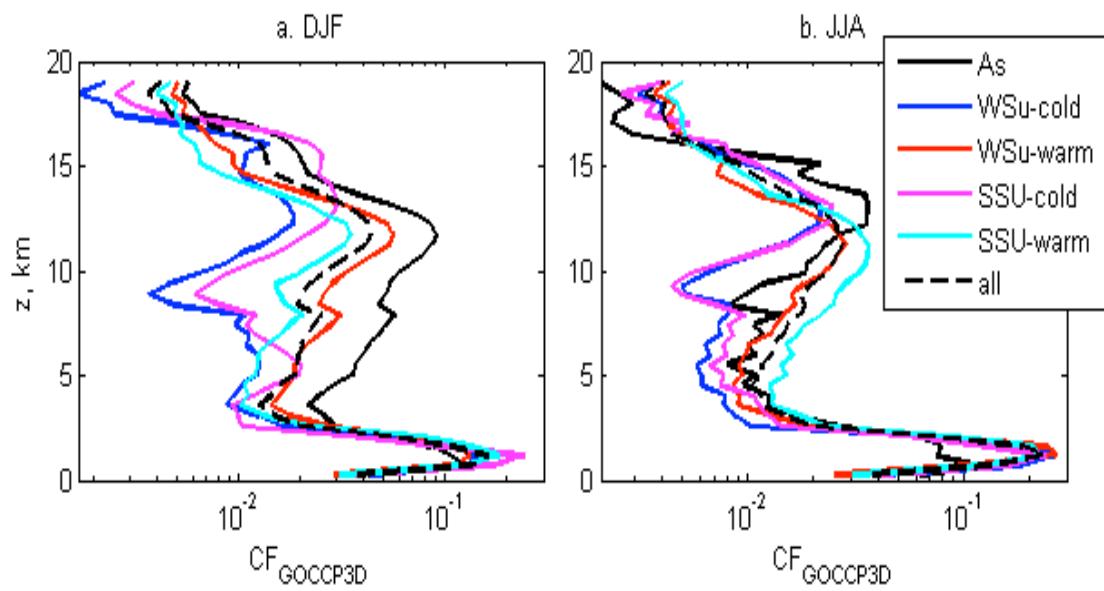
718
719 *Figure 6: mean vertical profile of $CF_{GOCCP3D}$ (2007 – 2010). The complete database are*
720 *represented by the black dotted lines, it is then separated onto the five regimes. a) in DJF; b)*
721 *in JJA. X axis is in logarithmic scale.*
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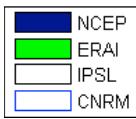
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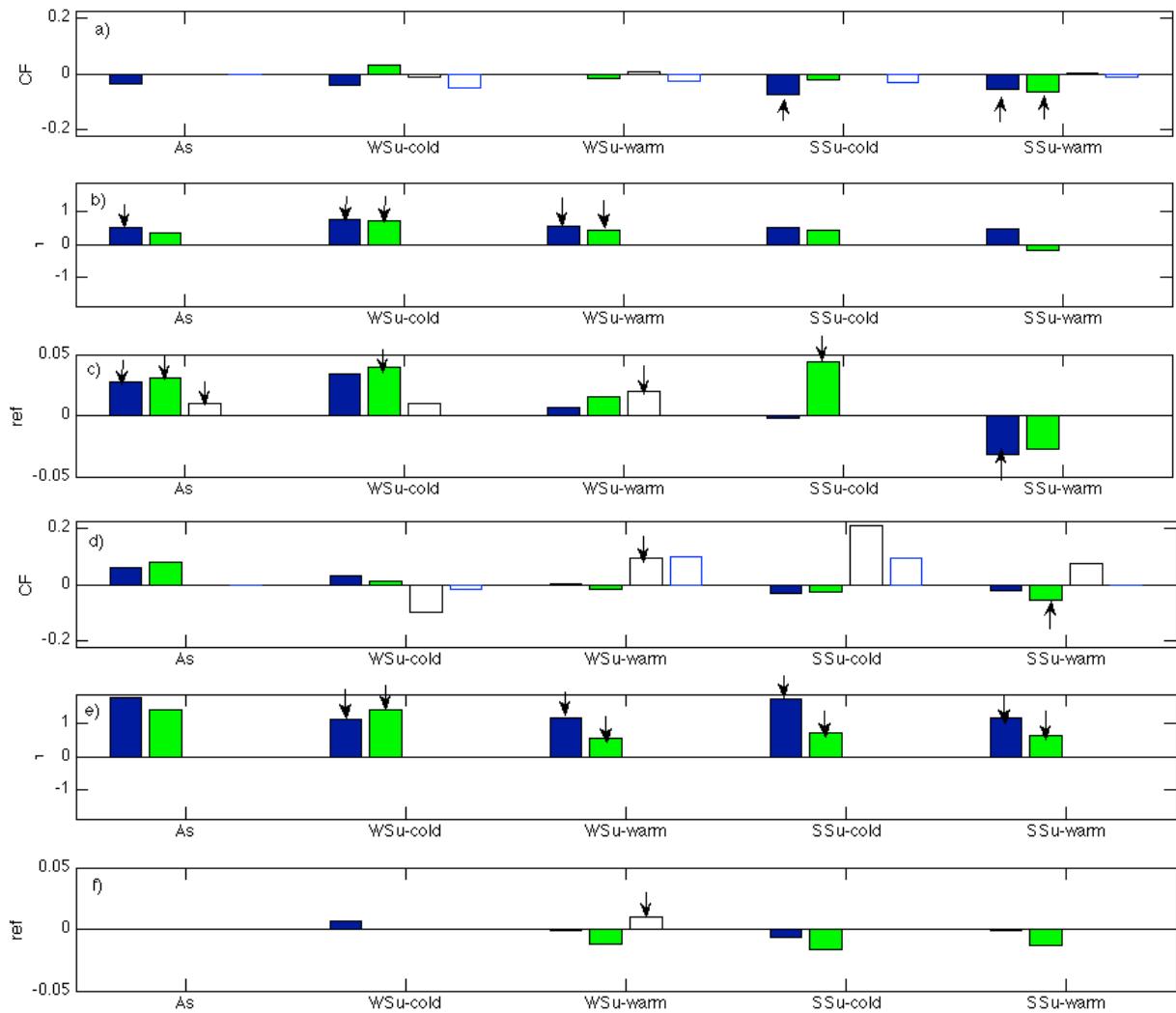
725

726
727 Figure 7: Same as Fig. 5 but for trend values (over 23 years) instead of mean values. A
728 "trend" is the value of the linear regression slope of the curve, multiplied by the number of
729 years. CF_{GOCCP} values are not drawn as there are too few years for trend estimation. Black
730 arrows are added when the trend is superior to the variability (i.e. the standard deviation).
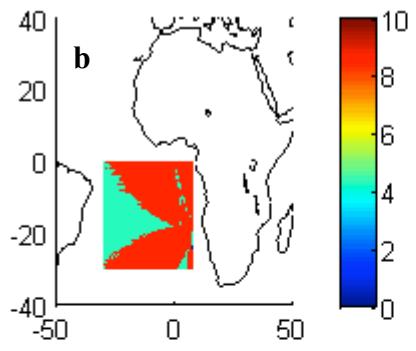731 Same results from models (IPSL and CNRM) have been added (not colour bars).
732
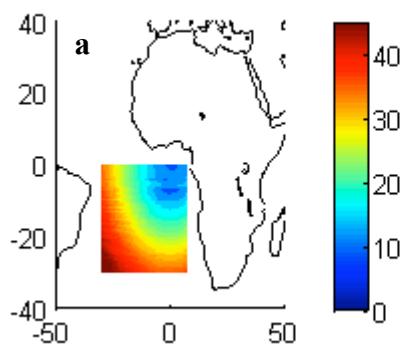
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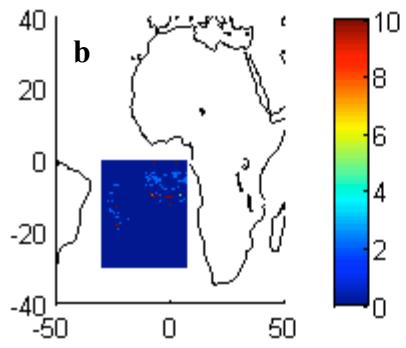
734
735 *Figure A.1: Satellite viewing angle θ_v (a) example of values in January, (b) percentage of*
736 *values that are more than 2° lower or larger than the median value for the entire time period,*
737 *(c) mean value of the difference between θ_v and its median when the percentage of (b) is non-*
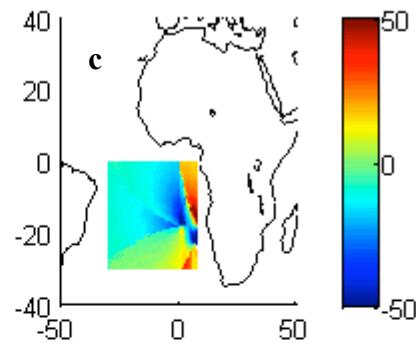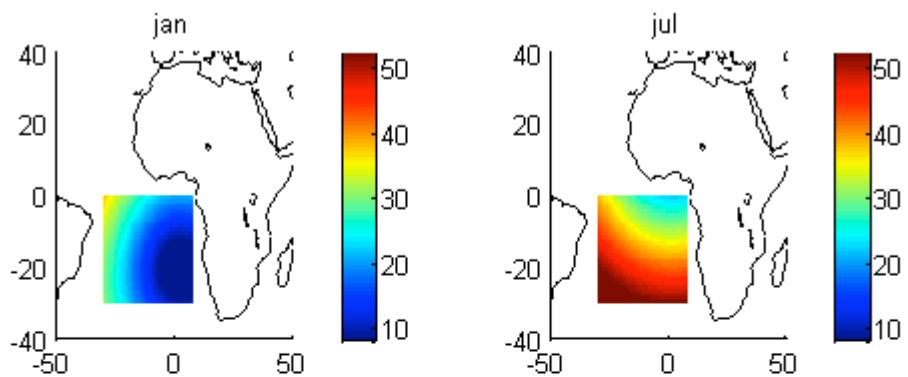738 *zero.*
739

740

741
742 *Figure A.2: Satellite azimuthal relative angle ϕ (a) example of values in January, (b)*
743 *percentage of values that are more than 5° lower or larger than the median value for the*
744 *entire time period, (c) mean value of the difference between ϕ and its median when the*
745 *percentage of (b) is non-zero.*
746

747
748   *Figure A.3: (a) Solar zenithal angle at 1200 UTC on January 15ᵗʰ; (b) same as (a) but on July*

749   *15ᵗʰ.*

750
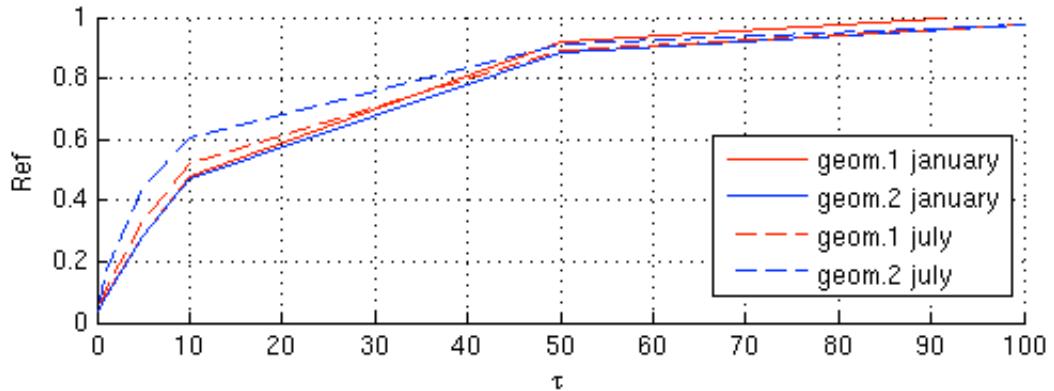
751
752 *Figure A.4: Simulation of the reflectance as a function of the optical thickness, for four*
753 *representation of the satellite geometry: solar zenithal angle of 20°/angle of viewing direction*
754 *with nadir of 15°/relative viewing azimuth angle of 50° (characteristic of January, red plane*
755 *line), 32°/15°/50° (characteristic of January, blue plane line); 22°/42°/130° (characteristic of*
756 *July, red dashed line); 50°/42°/130° (characteristic of July, red dashed line).*
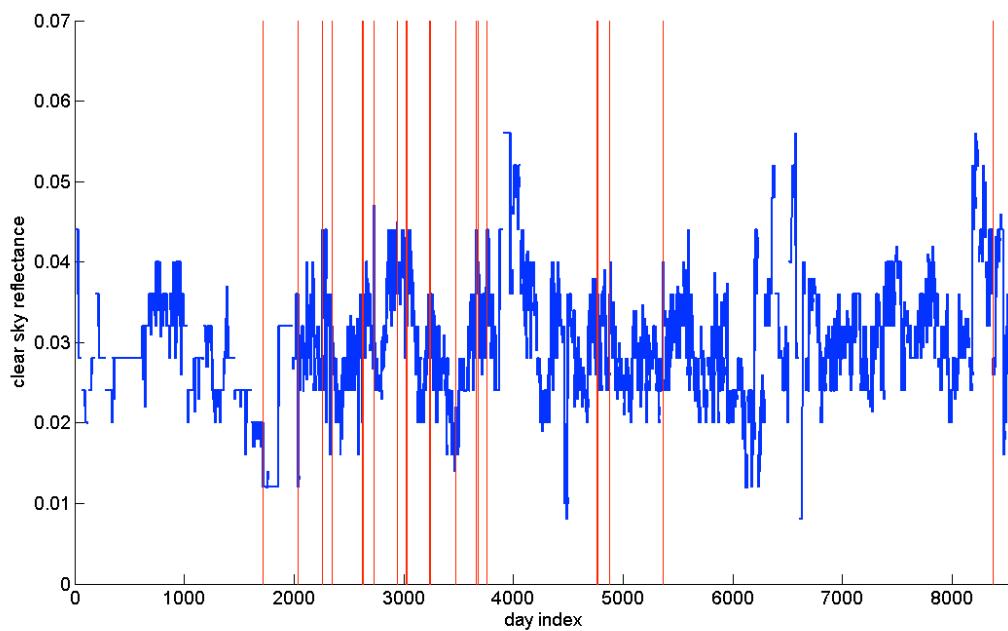
757
758 *Figure A.5: Time evolution of the clear sky reflectance, during the complete period (in blue).*
759 *Satellite changes are indicated by vertical red lines.*
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