

1 Response to Editor

2  
3 **OPTIONS:**

4 (C) You make the changes I recommend below (or argue convincingly against them) and I then  
5 accept the paper on the basis that I am confident that Referee 2's concerns have been  
6 addressed. The changes I have marked with \* are those that I regard as essential.

7  
8 Many thanks for your helpful and detailed comments.

9 We have revised the manuscript according to option (C) following your recommendation.

10  
11 We revised the SVD analysis in Fig. 6 of the previous version to objectively show the existence  
12 of different modes of variability in meridional circulation and their relationship with Hadley  
13 cells. Based on this result, we rewrote the section 3.2 'Ascending branch in Hadley circulation'.  
14 We have also added several references to ITCZ and tropical expansion studies with potential  
15 mechanisms in the Introduction. We hope this can clarify your questions.

16  
17 (4) You have also included a completely new section 3.5 on the 'Stepwise seasonal transition'.  
18 This is an interesting topic, but this material has not been considered by either of the referees.  
19 So if you want to include this material then I think the only way forward is to treat this version  
20 of your paper as a new submission and start the refereeing process again.

21  
22 Section 3.5 'Stepwise seasonal transition' was removed.

23  
24 Because there are many comments on the same subjects– i) ITCZ, ii) Ascending branch, and iii)  
25 Changes from 1999, we have responded to them as a group.

26  
27 **i) ITCZ**

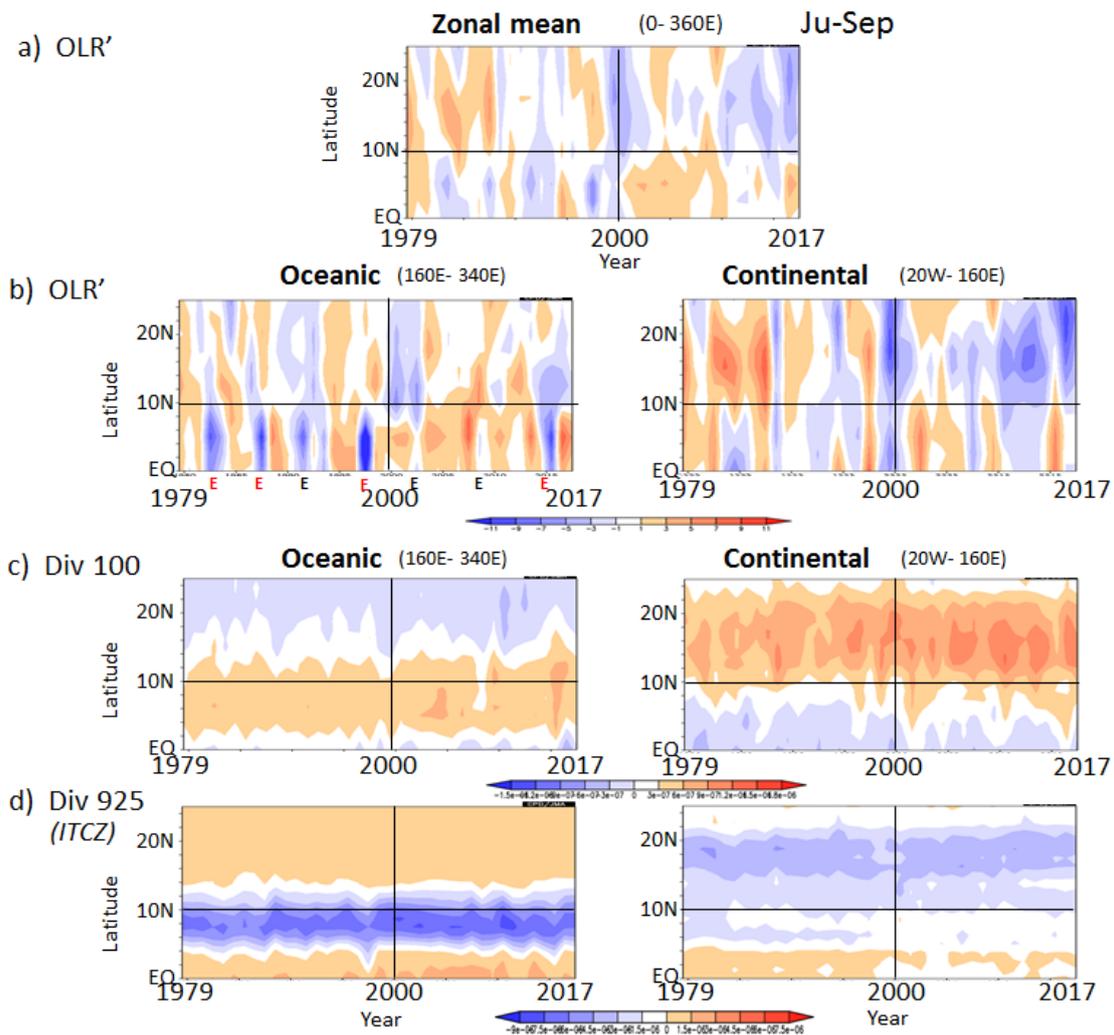
28 (1) You have spent some time in your responses arguing that what the referee identifies as  
29 work on 'change in ITCZ locations' is only of tangential relevance to your work. (You have also  
30 very briefly mentioned this point in the revised paper at the end of Section 4 — and — minor  
31 point — your citation is incorrect.) Your line is basically that the ICTZ is all to do with the  
32 'shallow branch' in your Figure 1 and that what you are discussing is to do with the 'deep  
33 branch'.

34 But then looking through the paper there are many cases where you discuss quantities such as  
35 OLR, omega at 300hPa, SST — so I'm not convinced that you can separate the ICTZ from what  
36 you are discussing. You might argue that the ICTZ is a primarily oceanic feature whereas you  
37 are emphasising changes over land, i.e. that changes in convection over land in summer can  
38 somehow be considered to be independent of changes in convection over the ocean, but to  
39 me this seems highly speculative.

40  
41 -Change in location of ITCZ

42 We have assumed that the shift in the ITCZ is not particularly relevant for the present study  
43 because clear changes in the location of the ITCZ were not observed during the study period, as

44 illustrated in Fig. R 1 below. Anomalous negative OLR in the zonal mean field appear to have  
 45 shifted northward around 1999 (Fig. R1 a) because convective activity north of 10° N  
 46 strengthened over the continental sector, while that over the oceanic sector south of 10° N didn't  
 47 increase (Fig. R1 b). Enhanced convective activity over the continental sector occurred in  
 48 association with an increase in upper-level divergence at around 15° N without a latitudinal shift  
 49 (Fig. R1 c). The ITCZ depicted in the 925hPa divergence field (Fig. R1 d) shows practically no  
 50 change in intensity or the latitude of maximum divergence in both sectors. This suggests that the  
 51 phenomenon we are studying here (Fig. R1 b,c) is not directly related to the meridional shift of  
 52 the ITCZ on this time scale.  
 53



54  
 55 Fig. R1 (a) Latitude-time sections of anomalous zonal mean OLR. (b) Same as (a), except for  
 56 (left) oceanic (160° E-340° E) sector, and (right) continental (20° W - 160° E) sector. (c) Same  
 57 as (b), except for horizontal divergence at 100 hPa. (d) Same as (c), except for divergence at 925  
 58 hPa.

59

60 \*p12 l1-3: 'A poleward shift in the convective zone occurred because of enhanced convective  
 61 activity in the deep ascending branch of the Hadley circulation over the continental sector.'

62 The first sentence is unclear — are you suggesting that the shift occurred as a result of  
63 enhanced convective activity in the deep ascending branch ...', i.e. there are two separate  
64 phenomena here and one causes the other. To me it seems to be very difficult to separate the  
65 shift on the one hand and the enhanced convective activity on the other — aren't they  
66 different aspects of a single phenomenon. If you want to claim that there is cause and effect  
67 then you need to be much clearer on how to separate the two things. Once again, you need to  
68 be very clear about what exactly you mean by the 'deep ascending branch of the Hadley  
69 circulation over the continental sector' — Fig 1 is helpful here but it is not enough — it needs  
70 to be reinforced by clear text. Also is your separation of the tropical circulation into (i) shallow  
71 branch of HC and (ii) deep branch of HC, or is the second part 'the deep branch of the HC over  
72 the continental sector'? If one uses Fig 1a as a basis of the separation then it is not at all clear  
73 what part can be assigned to the continental sector and what to the oceanic sector.

74

75 As stated in the above, a poleward shift in the convective zone appears in zonal mean field due  
76 to enhanced convective activity over the continental sector. According to the comment, the  
77 sentence was modified as follows. (p11| 27)

78

79 'In the present study, a poleward shift in the convective zone corresponds to enhanced  
80 convective activity in the deep ascending branch in the summertime Hadley circulation, located  
81 at a higher latitude (around 15° N) than the main ascending branch over the ocean (around 7.5°  
82 N)'

83

84 \*p12 l2: 'This phenomenon studied here is different from the shift of the ITCZ over the oceanic  
85 sector due to perturbations in the atmospheric energy balance such as discussed by Schneider  
86 et al. (2017).' — again this is not at all obvious and I see the only way forward without you  
87 doing more detailed work on this is to be clear that the study reported in this paper is based  
88 on the hypothesis that changes in the 'deep branch of the HC over the continental sector' or  
89 whatever can be considered as independent of the shift in the ITCZ studied by many other  
90 authors — Schneider (2017) being an example and Byrne et al (2018) being another — which  
91 you see as primarily relevant to the oceanic sector. You must remind the reader explicitly of  
92 this hypothesis here, at the end of the paper

93

94 According to the comments, the following sentences are added in the text. (p11| 27)

95

96 'In the present study, a poleward shift in the convective zone corresponds to enhanced  
97 convective activity in the deep ascending branch in the summertime Hadley circulation, located  
98 at a higher latitude (around 15° N) than the main ascending branch over the ocean (around 7.5°  
99 N). For the purposes of this paper we assume that the changes that we discuss are independent  
100 from those associated with tropical expansion. This paper is based on the hypothesis that recent  
101 increase in the convective activity in deep branch of the Hadley circulation over the continental  
102 sector can be considered as independent of the shift in the ITCZ studied by many other authors  
103 such as Schneider (2017) and Byrne et al. (2018) which are primarily relevant to the oceanic

104 sector. It should also be noted that the expansion rates of the tropics should be much smaller  
105 than those reported in past studies (Staten et al., 2018).'

106

107 Staten P.W., Lu J., Grise K.M., Davis S.M, and Birner T.: Re-examining tropical expansion, Nature climate change,  
108 8, 768-775, DOI:10.1038/s41558-018-0246-2, 2018.

109

110 (2) The same applies to a lesser extent to 'Hadley Cell widening' or 'tropical expansion'. You  
111 assert in Section 1 that this is, again, distinct from what you are discussing. But your argument  
112 is that the 'expansion' is 'due to changes in the positions of jet streams and storm tracks'. The  
113 expansion might be manifested by those changes, but I don't believe that anyone has clearly  
114 ruled out that the changes in say, tropical convection, are not part of the cause.

115

116 Hu and Fu (2007) demonstrated a widening of the tropics in boreal summer by using OLR data.  
117 A northward shift is observed in the northern edge of the tropics around 42° N, but the latitude  
118 of the ascending branch remains unchanged at ~7.5° N. This is an example of case where the  
119 expansion of the tropics is not necessarily associated with the shift in the ascending branch of  
120 the HC.

121

122 Hu, Y., and Fu, Q.: Observed poleward expansion of the Hadley circulation since 1979, Atmos. Chem. Phys. 7,  
123 5229–5236, 2007.

124

125 We also have added the following sentence for better explanation (p3 | 5).

126 'Among the studies on tropical expansion those on the role of the tropical SST (Allen et al.,  
127 2018; Amaya et al., 2018) may be relevant to the present study. However, as will be shown later,  
128 a decadal ocean variability such as PDO may not be a fundamental factor which produces recent  
129 decadal trend in boreal summer. '

130

131 \*p2 | 31: See comment (2) above. This paragraph is at one level OK — you say that you are  
132 looking at different quantities to those being considered by those interested in tropical  
133 expansion — but I recommend that you an additional comment (which could be in your final  
134 section) along the lines of 'For the purposes of this paper we assume that the changes that we  
135 discuss are independent from those associated with tropical expansion' — i.e. an explicit  
136 statement that your arguments for a role for the stratosphere should not be interpreted as  
137 applying to tropical expansion (because if they did you would have to give more detail on the  
138 various mechanisms that have been proposed for that).

139

140 According to the comment, the following sentence was added. (p. 3| 8)

141 'For the purposes of this paper we assume that the changes that we discuss are independent  
142 from those associated with tropical expansion.'

143

144 ii) Ascending branch

145 (3) You have included a new section 3.1 'Deep branch of the Hadley circulation' primarily, it  
146 seems to me, to counter Referee 2's recommendation that there is more discussion of the  
147 relation between your work and other previous work on shifts in the ITCZ/broadening of the  
148 tropics. But while this section puts on record that there is considerable variation in the

149 properties of the tropospheric circulation with height, and that, for example, there is no single  
150 pattern of geographical variation for all physical quantities, it doesn't convincingly make the case,  
151 to me, that what you are describing can be regarded as completely independent of, say, the  
152 shift in the ITCZ and therefore that all previous discussion can be ignored.

153

154 -> Concerning to the shift of the ITCZ, please see the response for "change in ITCZ" in the  
155 above.

156

157 To be specific — you are essentially looking at Fig 1a and, pretty arbitrarily in my view,  
158 deciding that it can be decomposed into two parts, one composed of streamlines that reach  
159 above 100hPa and the other of streamlines that do not, that can be regarded as separate  
160 entities. This seems particularly difficult to justify for the narrow upwelling part of the  
161 circulation.

162

163 We revised the SVD analysis in Fig. 6 of the previous version to objectively extract the different  
164 modes of variability. A new SVD analysis (Fig. R2 and R3, shown in the manuscript as Figures  
165 3 and 4) clearly indicates that two modes of variability have different vertical structures: SVD 2  
166 represents the variability associated with the deep ascending branch of the HC extending into  
167 the stratosphere, while SVD 1 and 3 are those related with changes in the ascending branch of  
168 Hadley cells confined within the troposphere (Fig. R2). Correlation maps with the time  
169 coefficients (Fig. R3) show that SVD 1 and 3 are ENSO-related year-to-year variations over the  
170 Pacific Ocean that modulate the Pacific ITCZ. SVD2 showing increasing trend, however,  
171 associated with the variability of deep convection over the African-Asian sector. This clearly  
172 shows the contrasting vertical structure of ascending branch of Hadley cell over the continent  
173 and the ocean. A more detailed description is added in section 3.2 of the new revised manuscript.

174

175 We do not intend to ignore previous works on the shift in the ITCZ, but the focus of the present  
176 study is different: this study focuses on the vertical structure and strengthening of the upwelling  
177 in the TTL rather than a shift in the tropical convergence zone at the surface. Because the deep  
178 ascending branch of the Hadley cell is located near the northern edge of the main upwelling  
179 region, enhanced convective activity in the deep ascending branch of the Hadley cell manifests  
180 as a poleward shift in convective activity.

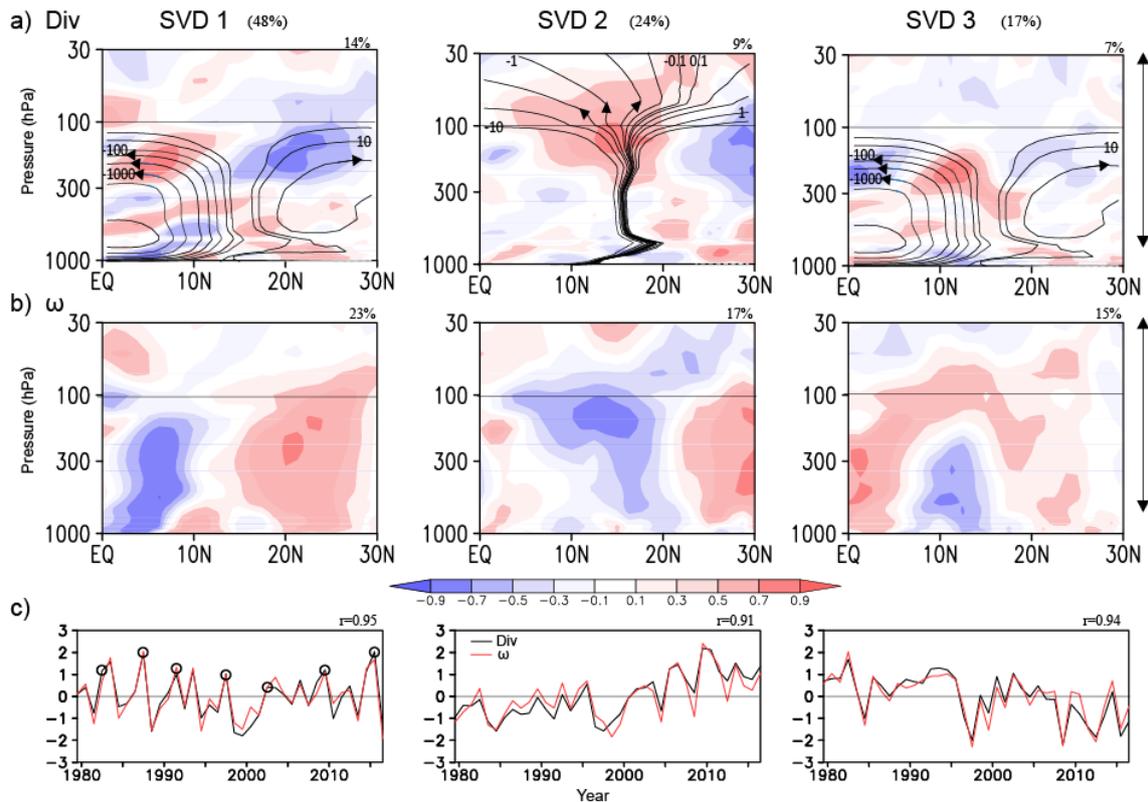
181

182 We also added references of ITCZ studies and presented potential mechanisms in Introduction.

183

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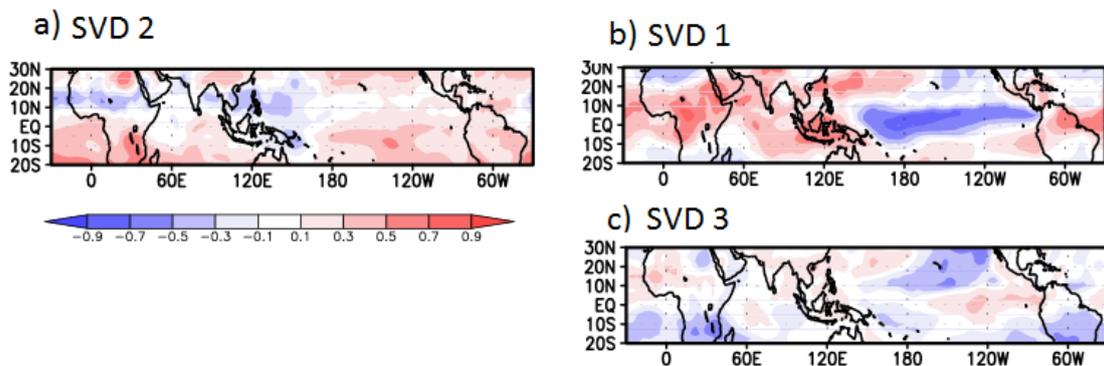
194

Fig. R2: Singular value decomposition (SVD) analysis of the zonal-mean anomalous horizontal divergence and anomalous pressure vertical velocity in the tropics ( $30^{\circ}$  S– $30^{\circ}$  N) during JAS from 1979 to 2016: From left to right, SVD 1, SVD 2 and SVD 3. (a) Heterogeneous correlation map of horizontal divergence. (b) same as (a), except for pressure vertical velocity map. (c) Time coefficients. Arrows indicate the levels used in the SVD calculations. Stream lines in (b) indicate mass stream function of the climatological residual mean meridional circulation (Stream lines are plotted with logarithmic scaling:  $\pm 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100 \dots \times 10^{10} \text{ kg s}^{-1}$ ). Open circles in (c) indicate El Niño event.

195

196

### Correlation with OLR



197

198

199

Fig. R3: Correlation coefficient between OLR at each grid, and time series of (a) SVD 2, (b) SVD 1, and (c) SVD 3.

200

201

202 \*p1 l15:

203 'deep ascending branch' — I don't believe this is a standard term, so you need to define it  
204 carefully. See comments above, particularly(C), and further detailed comments below.  
205 Amongst the various problems I see with this term a relatively minor one is that the terms  
206 'shallow' and 'deep' are very likely to be confused with the shallow and deep branches of the  
207 Brewer-Dobson circulation. (These terms seem to have become widely used.)

208

209 To avoid confusion with 'shallow and deep branch' of B-D circulation, only 'deep ascending  
210 branch of HC' is used in the revised version.

211

212 To define the 'deep ascending branch', we added the following sentences (p 4|30). 'It should be  
213 noted that the climatological mean stream lines around 15°N are connected to the stratosphere  
214 by crossing the tropopause (100 hPa) in boreal summer (see e.g., Fig 3 of Seviour et al., 2012).  
215 In the present study, we call this part of the ascending branch of the Hadley circulation that  
216 penetrates the lower stratosphere as the 'deep ascending branch.'

217

218 \*p4 l28:

219 'Because the upwelling of the deep branch is driven by convective activity' — unless you are  
220 defining the 'deep branch' in this way — in which I can't see how you can identify the deep  
221 branch from any of the information in Fig 1 (since none of this information tells you what  
222 drives what) — this statement is pure speculation. I think that the only acceptable way to  
223 proceed is for you to define carefully what you mean by 'deep branch' — by certain features  
224 appearing in observational fields, rather than being caused by something — and then to say  
225 that your working hypothesis is that the deep branch can be considered independently of  
226 other aspects of the tropical tropospheric circulation (such as the ITCZ over oceans).

227

228 According to the suggestion the following phrase is included in the text. (p7 |20)

229 'The present analysis suggests that the variability of deep ascending zone represented by SVD 2  
230 is an linearly independent mode from that related to the oceanic ITCZ, represented by SVD 1  
231 and 3. However, the climate system is highly nonlinear. Therefore, changes in the deep  
232 ascending branch of the Hadley circulation such as those represented in SVD2, could modulate  
233 the ITCZ over the oceanic sector through induced changes in cross-equatorial winds as  
234 suggested in Fig. 2.

235

236 \*p4 l31:

237 Please refer to explicit Figure/sub-Figure numbers e.g. Fig 1b, rather than 'left panel' etc. One  
238 reason for that is that you are making the quite strong and at first sight surprising statement  
239 that  $\theta_e$  at 925hPa is part of the 'deep branch' rather than the 'shallow branch'. You  
240 should note this explicitly in the text as a further aspect of your working hypothesis.

241

242 That sentence was included to point out that large moist static energy near the surface is a  
243 necessary condition for producing strong convective instability. However, because Fig. 1 was

244 based on previously non-submitted material both the Figure and its associated discussion were  
 245 removed from the current revised version according to the option (C).

246

247 \*p6 l25: ‘corresponding to the deep ascending branch of ...’ — change to ‘corresponding to  
 248 what we have identified as the deep ascending branch of’ — to make it absolutely clear that  
 249 this statement depends on your working hypothesis. The same applies to p6 l16 — ‘which  
 250 according to our hypothesis correspond to the locations ...’

251

252 (p8| 3)

253 Modified as suggested: ‘which according to our hypothesis correspond to the location of the  
 254 deep ascending branch in summertime Hadley circulation ’

255

256 p6 l16

257 The same applies to p6 l16 — ‘which according to our hypothesis correspond to the locations  
 258 ...’

259

260 According to the suggestion, the sentence was modified as follows. (p7| 26)

261 ‘According to our hypothesis the former corresponds to the variability in oceanic ITCZ  
 262 constituting the main ascending branch of the Hadley cells, and the latter is related to the deep  
 263 ascending branches of the Hadley circulation connected to the stratosphere.’

264

265

### 266 **iii) Changes from 1999 to present**

267

268 \*p1 l13:

269 Large changes in tropical circulation, in particular those related to the summer monsoon and  
 270 cooling of the sea surface in the equatorial eastern Pacific, were noted from the mid-to-late  
 271 1990s.’—needs clarification — change to —‘Large changes in tropical circulation from the mid-  
 272 to-late 1990s to the present, in particular changes related to the summer monsoon and cooling  
 273 of the sea surface in the equatorial eastern Pacific, are noted.’

274

275 Changed as indicated. (p1|13)

276 ‘Large changes in tropical circulation from the mid-to-late 1990s to the present, in particular  
 277 changes related to the summer monsoon and cooling of the sea surface in the equatorial eastern  
 278 Pacific, are noted.’

279

280 \*p1 l13 bis:

281 [The above comment:, and several other of my comments, are based on the my interpretation  
 282 that the ‘recent trends’ you are describing are represented by a change from the mid-late  
 283 1990s to the present. But this is never completely clear — and if I have misinterpreted what  
 284 you mean that is by itself good reason for you to clarify what you mean by terms like ‘trend’  
 285 and ‘anomaly’ whenever you use them.]

286

287 In the Introduction, the terms “trend” and “anomaly” have been used with their most general  
 288 meaning, that is, “*trend*” as prevailing tendency or direction of changes (or developments) and  
 289 “*anomaly*” as a deviation from the “normal” or expected behavior. At this point (i.e., in the  
 290 Introduction) we feel it is unnecessary to define a specific time frame for the trends or  
 291 anomalies as we are formulating the problem we want to address in light of previous studies.  
 292 Following your remark, we have clarified these terms specifically in our study by adding the  
 293 following sentences in Section 2: (p4|14)

294

295 'The exact starting dates of the recent decadal change is difficult to determine on the one hand  
 296 due to the interannual variability (such as the El Niño events), and variable dependent  
 297 characteristics of change. For example, while some variables show a stepwise transition, others  
 298 show a more gradual change. In the present study, we define the recent decadal change as the  
 299 1999-2016 mean anomalies from the 30-year (1981-2010) mean unless otherwise specified. By  
 300 selecting the year 1999 as the starting year, we excluded the extremely large 1997/98 El Niño  
 301 event from the recent period.'

302

303 \*p1 l26:

304 'Large changes in tropical circulation occurred from the mid-to-late 1990s.' — needs  
 305 clarification — change to — 'Large changes in tropical circulation occurred from the mid-to-  
 306 late 1990s to the present.'

307

308 (p1 | 27) Changed as suggested.

309

310 \*p5 l9:

311 I see now that this is where you define what you mean by terms such as trend and anomaly —  
 312 i.e. you are looking specifically at the difference between the 1999-2016 mean and the 1981-  
 313 2010 mean. You need to make this absolutely clear much earlier in the paper — e.g. even in  
 314 the first line of the paper when you talk about changes 'from the mid to late 1990s'. Then here  
 315 you should confirm that you will be using the term 'anomaly' or 'anomalous ...' to mean  
 316 precisely this difference.

317

318 We have now put it explicitly at an earlier point, in Section 2 (p4| 14) as mentioned above.

319

320 \*p2 l16:

321 'the anomalous tropical circulation of the 1990s' — this comes back to the question of what  
 322 you mean by 'trends' or 'anomalous circulation'. The phrase you use here sounds as if you  
 323 mean an anomaly that was present in the 1990s, but has since disappeared — but I don't  
 324 believe that you mean that. Please clarify.

325

326 The sentence was modified as follows.(p2 | 19)

327 'the anomalous tropical circulation from the mid-to-late 1990s did not terminate with the hiatus  
 328 around 2013, but still persists today'

329

330 p11 l4: I still find this use of ‘changes from the middle to the end of the 1990s’ unnecessarily  
 331 mysterious. It sounds as though you mean change from 1995 to 2000, but surely you don’t. In  
 332 practice you must, given the quantities that you have been showing, mean the difference  
 333 between 1999-2016 relative to 1981-2010 (or surely equivalently — difference between 1999-  
 334 2016 on the one hand and 1981-1998 on the other). It would be much better if you could find  
 335 a clear simple term for this — and use it consistently.

336

337 We have rewritten the introductory sentences of Section 4 (p11| 6) in order to avoid confusion:  
 338 ‘the observed 1999-2016 decadal SST cooling’

339

#### 340 **Others**

341 p1 l27: Personally I find it a bit weird to describe a ‘slowdown, or hiatus, of global warming’ as  
 342 a ‘large change in tropical circulation’.

343

344 We could consider the change in tropical circulation as one aspect of the phenomenon related to  
 345 the hiatus.

346

347 The sentence has been rewritten as (p 1| 28): ‘Such a decrease in the tropical east Pacific sea  
 348 surface temperature (SST) has been associated with a slowdown, or hiatus, of global warming’

349

350 p2 l3: My reading of Evan and Camargo (2011) is that they are very careful NOT to say that  
 351 there is a long-term systematic change over the period that they consider. (They use terms like  
 352 ‘interannual variation’.) The Wang et al (2012) paper is a brief Comment on another paper, and  
 353 is disputed by the authors of that paper.

354

355 The references were removed.

356

357 p2 l6: ‘Indeed, recent numerical model studies show that cooling of the tropopause impacts  
 358 the intensity of tropical storms as well as SSTs’

359 — change to (at least according to my interpretation) — ‘Indeed, recent numerical model  
 360 studies show that cooling of the tropopause, as well as SSTs, impacts the intensity of tropical  
 361 storms’

362

363 (p 2| 8) Changed as suggested.

364

365 \*p2 l28: ‘In this paper, we show that the fundamental cause of the recent decadal trend in the  
 366 tropics from the mid-to-late 1990s is not the PDO, but rather a strengthening of the deep  
 367 ascending branch of the summertime Hadley circulation extending into the stratosphere.’ —  
 368 this statement is MUCH too strong. You surely don’t show that this is true — you suggest that  
 369 it is true and provide some circumstantial evident to support your suggestion.

370

371 Modified as indicated (p2| 31): ‘In this paper, we suggest that ....’

372

373 p4 l1: Include a very brief description (perhaps just a few words) of the criteria being used for  
374 an 'overshooting cloud'.

375

376 The following sentence was added for a description of the overshooting cloud (p4 | 4).

377 "In the case of extreme deep convection, strong updraft further penetrates beyond the level of  
378 neutral buoyancy and overshoots into the tropical tropopause layer (TTL)....."

379

380 \*p4 l9-14: This is new material that has not been considered by the referees and should be  
381 removed if you want to follow routes (B) or (C) above.

382

383 Related Figures and text were removed.

384

385 \*p5 l19: 'Thus, the primary cause ...' — you can only use 'Thus' if the following statement  
386 follows logically from the preceding statement. I don't see how your statement about the  
387 cause of cold tongues etc can possibly follow logically from the previous sentence — I guess  
388 that it is something that has been proposed/demonstrated by Xie and others. So 'Thus' should  
389 be removed.

390

391 Removed.

392

393 \*p5 l21: 'Therefore, changes in the zonal-mean meridional circulation ... can affect eastern  
394 Pacific SSTs.' — again I don't follow the logic at all — and I think that it is this sort of statement  
395 that troubled referee 2. The simplest change would be to remove this sentence, or you could  
396 say 'We suggest in this paper that ...'. Anything else needs much clearer supporting argument.

397

398 Modified (p5| 11) as 'We suggest in this paper that changes in the meridional circulation can  
399 similarly affect equatorial eastern Pacific SSTs by modulating the cross-equatorial winds, as  
400 depicted in Figure 2.'

401

402 p5 l30: I'm not very clear about the logic here either, but neither of the referees seemed  
403 particularly worried about this.

404

405 According to the comment, the sentence was modified as follows. (p5| 20)

406 'This suggests that SST cooling west of South America is not driven solely by the PDO, but is  
407 related to a stronger cross-equatorial winds that we hypothesize is connected to an enhanced  
408 convective activity over African-Asian sector.'

409

410 \*p6 l1: 'The impact of the recent decadal variation ...' — this makes it sound as though what  
411 you are showing is caused by decadal variation — but, at the level of the discussion in this  
412 paper, this is simply an aspect of decadal variation. So please modify appropriately.

413

414 Modified as follows. (p5| 23)

415 'The atmospheric circulation and SST changes associated with the convective activity are  
416 depicted in Fig. 2'.

417

418 \*p8 l8-20: There seems to be confusion between Fig 7 and Fig 8 in this paragraph.

419

420 Corrected

421

422 \*p9 l19: 'Results of the above analyses are summarised in Fig 10(left).' — change to make it  
423 very clear that you are advancing a hypothesis. It certainly isn't the case that the results you  
424 present lead inevitably to the mechanism depicted in Fig 10. E.g. you could say 'On the basis of  
425 the results presented in the previous sections we suggest the mechanism depicted in Fig 10.'  
426 Then you need to include a sentence or two explaining the mechanism that Fig 10 is supposed  
427 to depict — the Fig alone is not enough.

428

429 We added the following sentences in Section 3.4 (p 10| 11).

430 (a) Cooling in the lower stratosphere adds to the global warming in the troposphere. (b)  
431 Decrease of the lower stratospheric temperature produced favourable conditions for the  
432 development of extreme deep convection. Stratospheric cooling effect is felt by convections  
433 reaching the TTL, primarily over the continental sector. (c) Enhancement of extreme deep  
434 convection off-equatorial region produces stronger cross-equatorial flow near the surface. (d)  
435 Strengthening of surface winds cools the ocean by increased evaporation.

436

437 p9 l32: 'This time evolution tentatively suggests a causality among the variables' — that's fine,  
438 but I recommend including a sentence spelling out what causality you are inferring (to make  
439 sure the reader is clear about that).

440

441 To clarify, the following sentence was added. (p10|33)

442 'That is, change in Pacific SST occurred following a change in cross-equatorial winds, increased  
443 upwelling in the TTL, and stratospheric cooling in early summer '

444

445 \*p10 l4-32: As noted previously, this section (and Figs 11-13) should to be removed unless you  
446 want to go straight to option A. (But note that on l6 you have referred to Fig 10, but surely you  
447 mean Fig 11.)

448

449 Stepwise transition section 3.5 and Figs 11-13 were removed.

450

451 \*p11 l11: 'Nevertheless, time lags introduced in selection of variables from summer to autumn  
452 demonstrate that the processes are related, ...' — you say 'are related', but earlier you have  
453 said that these time correlations suggested a causal relationship and you should use the term  
454 'causal' again here (if you mean it). But 'demonstrate' is too strong — you should be clear that  
455 you (i.e. the authors) are suggesting a causal relationship on the basis of these correlations,  
456 but also that you accept that (much) more evidence is needed to demonstrate this conclusively.

457

458 The word 'demonstrate' was changed to 'suggest'.

459

460 Others comments:

461 I can't find any reference in the text to Fig 5a. If it is not mentioned in the text (i.e. it is not part  
462 of the arguments made in the paper then it doesn't seem necessary to include it).

463

464 It is indicated in 3 lines before together with Fig. 4b as 'Figs 4a and 5a', but for the clarity it is  
465 added at the end of the sentence as ' ..... located in the NH near 5° N–10° N throughout the  
466 year (Fig 6a)'. (p8| 1)

467

468 Many of the Figures are very small. Of course if reading a paper online the Figures can be  
469 magnified, but it should be easy to read text and Figures together. I recommend that most of  
470 the Figures are enlarged so that the entire Figure (i.e. all the panels as displayed) fill most of  
471 the width of the page.

472

473 Figures magnified.

474

475 -----

476 Texts had been removed in new revised version.

477

478 \*p7 l13: 'In addition to changes in the troposphere, Abalos et al (2015) identified ...' — this  
479 makes it sound as if Abalos et al identified changes in the troposphere.

480

481 \*p7 l14: 'Because the upwelling in the deep ascending ..., it is expected ... may exist.' — make it  
482 clear that it is you that expect this — there are almost certainly many other people who do  
483 NOT expect it — i.e. it would be better if this sentence was re-written along the lines of 'we  
484 suggest that'.

485

486 p7 l31: 'These results suggest a stronger connection ...' — why 'stronger' — stronger than  
487 what? More importantly you should add an explicit qualifier that causality cannot be deduced  
488 from this analysis alone — you have used 'connection between' which is good, but the explicit  
489 qualifier is needed too.

490

491 \*p7 l32: 'This is consistent with results from ...' — this is too strong a statement. Both of these  
492 papers (which are certainly interesting) were about variations on SSW-type timescales, not on  
493 interannual variability. Also the Eguchi et al study is very preliminary in the sense that only one  
494 simulation is carried out when really an ensemble is needed and the Kodera et al study is  
495 largely (but not exclusively) about changes in the TTL rather than through the depth of the  
496 troposphere. So the sentence needs to be moderated appropriately.

# Implication of tropical lower stratospheric cooling in recent trends in tropical circulation and deep convective activity

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**Abstract.** Large changes in tropical circulation from the mid-to-late 1990s to the present, in particular changes related to the summer monsoon and cooling of the sea surface in the equatorial eastern Pacific, are noted. The cause of such recent decadal variations in the tropics was studied using a meteorological reanalysis dataset. Cooling of the equatorial southeastern Pacific Ocean occurred in association with enhanced cross-equatorial southerlies, which resulted from a strengthening of the deep ascending branch of the boreal summer Hadley circulation over the continental sector connected to stratospheric circulation. From boreal summer to winter, the anomalous convective activity centre moves southward following the seasonal march to the equatorial Indian Ocean–Maritime Continent region, which strengthens the surface easterlies over the equatorial central Pacific. Accordingly, ocean surface cooling extends over the equatorial central Pacific. We suggest that the fundamental cause of the recent decadal change in the tropical troposphere and the ocean is a poleward shift of convective activity that resulted from a strengthening of extreme deep convection penetrating into the tropical tropopause layer, particularly over the African and Asian continents and adjacent oceans. We conjecture that the increase in extreme deep convection is produced by a combination of land surface warming due to increased CO<sub>2</sub> and a reduction of static stability in the tropical tropopause layer due to tropical stratospheric cooling.

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## 1 Introduction

Large changes in tropical circulation occurred from the mid-to-late 1990s to the present, in particular changes related to the summer monsoon and cooling of the sea surface in the equatorial eastern Pacific, are noted. Such a decrease in the tropical

east Pacific sea surface temperature (SST) has been associated with a slowdown, or hiatus, of global warming (Kosaka and Xie, 2013; England et al., 2014; Trenberth et al., 2014; Watanabe et al., 2014). Changes were also found in the advancement of the onset of the Asian summer monsoon (Kajikawa et al., 2012; Gautam and Regmi, 2013; Xiang and Wang, 2013; Yun et al., 2014) and an increase in precipitation over the Sahel in West Africa (Fontaine et al., 2011; Brandt et al., 2014; Maidment et al., 2015; Diawara et al., 2016). An increase in precipitation in southern Africa was also observed during austral summer (Vizy and Cook, 2016). In addition to these large-scale circulation changes, variations occurred in mesoscale phenomena such as an increase in Mesoscale Convective Systems (MCSs) over the Sahel (Taylor et al., 2017). A relationship between tropopause layer cooling and tropical cyclone activity in the Atlantic has also been suggested (Emanuel et al., 2013). **Indeed, recent numerical model studies show that cooling of the tropopause, as well as SSTs, impacts the intensity of tropical storms** (Ramsay, 2013; Wang et al., 2014). In this respect, the recent cooling of the tropical tropopause and lower stratosphere from around 2000 (Randel et al., 2006; Randel and Jensen, 2013) should be investigated together with tropical tropospheric change.

The importance of the Pacific Decadal Oscillation (PDO) to decadal changes in global temperature and precipitation has been noted previously (Meehl et al., 2013; Dong and Dai, 2015; Trenberth, 2015). The most recent hiatus in global warming ended around 2013 followed by a strong warming due to an El Niño event in 2015 (Hu and Fedorov, 2017; Liu and Zhou, 2017; Urabe et al., 2017; Xie and Kosaka, 2017). However, the El Niño of 2015/16 differed from the large 1997/98 El Niño, which involved less warming in the eastern Pacific (Paek et al., 2017), conforming to a trend of increasing intensity of central Pacific-type El Niños (Kao and Yu, 2009; Johnson, 2013). In this sense, **the anomalous tropical circulation from the mid-to-late 1990s did not terminate with the hiatus around 2013, but still persists today.** Similarly, the northward shift of the convective zone in boreal summer continues, as shown below.

Multidecadal variations in the atmosphere–ocean coupled mode, such as the Atlantic Multidecadal Oscillation, have also been proposed as a cause of recent changes in tropics (Wang et al., 2013; Kamae et al., 2017). Kamae et al. (2017) studied the impact of SSTs in various oceanic basins on recent trends in monsoon precipitation using a coupled ocean model. They were able to reproduce the recent increasing trend in monsoon rainfall in the Northern Hemisphere (NH), except for the Asian monsoon, with changes in Atlantic SST. Atlantic SSTs, however, have practically no effect on the African or Australian monsoons in the Southern Hemisphere (SH). Another difference from observations is that the simulated increase in rainfall occurs mainly over the oceans and at low latitudes between the equator and 15°N rather than the observed increase over continents between around 10°N and 20°N (see fig. 3 of Kamae et al., 2017). Thus, it is difficult to attribute recent global trends to a regional mode of decadal oceanic variation alone. **In this paper, we suggest** that the fundamental cause of the recent decadal trend in the tropics from **around 1999 is** not the PDO, but rather a strengthening of the deep ascending branch of the summertime Hadley circulation extending into the stratosphere.

One of the components of the recent tropical circulation change is an expansion of the tropics (e.g., Davis and Rosenlof, 2012; Lucas et al., 2013; Hu et al., 2018; Byrne et al., 2018). Tropical expansion has been linked to changes in the descending branch of the Hadley cell in the subtropics (Kang and Polvani, 2011), but other potential mechanisms include changes in SST and in the vertical temperature structure of the troposphere, an overall increase in tropopause height, the internal variability of the climate system, and possibly stratospheric climate change (Seidel et al., 2007). Among the studies on tropical expansion those on the role of the tropical SST (Allen et al., 2018; Amaya et al., 2018) may be relevant to the present study. However, as will be shown later, a decadal ocean variability such as PDO may not be a fundamental factor which produces recent decadal trend in boreal summer. For the purposes of this paper we assume that the changes that we discuss are not directly related to those associated with tropical expansion.

Global climate change involves diverse aspects from the stratosphere to the ocean, from the polar region to the tropics, and from monsoons to severe storms. Each of these elements should be investigated independently in great detail, as well as their relationships to each other and their roles in global climate change. Without the latter, we will be unable to see the ‘big picture.’ Stratospheric variation has generally been treated as a problem separate from recent surface climate change. The goal of this study is to provide a framework for assembling these diverse pieces of the climate-change puzzle by investigating the connection between the atmosphere and ocean in the tropics.

The remainder of this paper is organized as follows. The data used in this study are presented in section 2, and the results of our analysis are given in section 3. A summary and discussion of the causes of recent climate changes in tropics are presented in section 4.

## 2 Data

We use meteorological reanalysis data produced by the Japan Meteorological Agency (JMA), JRA55 (Kobayashi et al., 2015). A large discontinuity was found at the end of the 1990s in a previous reanalysis product, JRA25, when the TIROS Operational Vertical Sounder (TOVS) onboard the National Oceanic and Atmospheric Administration (NOAA) satellite was switched to Advanced TOVS (ATOVS; Li et al., 2000). This discontinuity has largely been removed in the JRA55 reanalysis (Kobayashi et al., 2015).

Outgoing longwave radiation (OLR) data provided by NOAA are widely used in analyses of convective activity in the tropics. In the present study, we use monthly mean OLR data ( $1^\circ \times 1^\circ$  latitude–longitude resolution) derived from the High-Resolution Infrared Radiation Sounder (HIRS) (Lee et al., 2007), available at <ftp://eclipse.ncdc.noaa.gov/cdr/hirs-olr/monthly/>. An analysis of the precipitation is performed using Global Precipitation Climatology Project (GPCP) monthly

mean data version 2.3 (Adler et al., 2003). Monthly mean gridded SST data from COBE with  $1^\circ \times 1^\circ$  grid cells compiled by the JMA (Ishii et al., 2005) are used for the study of ocean surface change.

In the case of extreme deep convection, strong updraft further penetrates beyond the level of neutral buoyancy and overshoots into the tropical tropopause layer (TTL). Such tropical overshooting clouds (COV) were identified using the diagnostics developed by Hong et al. (2005), which are based on brightness temperature differences measured by three high-frequency channels of the Advanced Microwave Sensing Unit (AMSU) module B or the Microwave Humidity Sensor (MHS). Data are from NOAA and MetOp satellites with periods of 2007–2013 for MetOp-A and 2014–2017 for MetOp-B. Their equatorial crossing times are nearly identical (see fig. 1 of Funatsu et al., 2016). The original data calculated on a  $0.25^\circ \times 0.25^\circ$  grid were resampled to a coarse one of  $2.25^\circ \times 2.25^\circ$  grid for plotting. The number density of COV is defined as the total number of COV detected in each  $2.25^\circ \times 2.25^\circ$  bin divided by the MetOp–MHS total pixel number to remove sampling bias, with units of parts-per-thousand.

The climatology is defined here as the 30-year mean from 1981 to 2010. The exact starting dates of the recent decadal change is difficult to determine on the one hand due to the interannual variability (such as the El Niño events), and variable dependent characteristics of change. For example, while some variables show a stepwise transition, others show a more gradual change. In the present study, we define the recent decadal change as the 1999–2016 mean anomalies from the 30-year (1981–2010) mean unless otherwise specified. By selecting the year 1999 as the starting year, we excluded the extremely large 1997/98 El Niño event from the recent period.

Seven El Niño events after 1979 are identified by the JMA based on 6-monthly mean SSTs in the Niño 3 sector ( $5^\circ \text{S}–5^\circ \text{N}$ ,  $150^\circ \text{W}–90^\circ \text{W}$ ; available at <http://ds.data.jma.go.jp/gmd/tcc/tcc/products/elnino/ensoevents.html>). In this study, we define the NH cold seasons of 1982/83, 1986/87, 1991/92, 1997/98, 2002/03, 2009/10, and 2015/16 as El Niño winters. The choice of the year 1999 was made to exclude the extremely large 1997/98 El Niño event from the recent period.

## 3 Results

### 3.1 Recent decadal change

The recent change of tropical convective activity is identified from the July–September 1999–2016 mean anomalous OLR relative to the 30-year climatology (1981–2010) (Fig. 1a). Increase in convective activity occurs over the African and Asian summer monsoon regions. Deep convective activity reaching the TTL in boreal summer is located primarily over the continents and their adjacent ocean north of  $10^\circ \text{N}$  (see e.g., Fig 2 in Liu and Zipser, 2005). It should be noted that the climatological mean stream lines around  $15^\circ \text{N}$  are connected to the stratosphere by crossing the tropopause (100 hPa) in boreal summer (see e.g., Fig 3 of Seviour et al., 2012). In the present study, we call this part of the ascending branch of the

Hadley circulation that penetrates the lower stratosphere as the 'deep ascending branch. Because the latitudinal location of extreme deep convective zone is higher than the that of oceanic ITCZ, enhancement of convective activity of this continental sector appears as a poleward shift in convective activity in the zonal mean field (Fig. 1b): whereas the climatological OLR peaks around 10°N, the anomalous OLR of the recent period has a maximum around 15°N.

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There is a close relationship between the location of the seasonally varying tropical convective active zone and cold tongues in the oceans. Convective activity shifts northward during boreal summer. Accordingly, cross-equatorial winds west of the American and African continents increase, which leads to a decrease in SSTs along coastal regions during boreal summer as a part of a seasonal cycle. The primary cause of cold tongues in tropical SSTs is the shape of the continents, the air–sea interaction, and the location of the rising branch of the Hadley circulation, as described by Xie and Philander (1994) and Xie (2004). We suggest in this paper that changes in the meridional circulation can similarly affect equatorial eastern Pacific SSTs by modulating the cross-equatorial winds, as depicted in Figure 2.

In order to investigate whether the northward shift in the convective zone is driven by the PDO, anomalous OLR during the two periods of neutral and negative phases of the PDO is shown in Fig. 1c and d with anomalous SSTs during those periods (Fig. 1e and f). A characteristic horseshoe pattern in northern Pacific SST is evident during the negative phase of the PDO. Anomalous OLR indicates that convective activity is enhanced along 15° N–20° N irrespective of the phase of the PDO, except for the sector under the direct influence of the PDO in the eastern Pacific, where cooling is greater during the negative phase. However, even during the neutral phase of the PDO, negative anomalies in SST exist in the tropics west of South America. This suggests that SST cooling west of South America is not driven solely by the PDO, but is related to a stronger cross-equatorial winds that we hypothesize is connected to an enhanced convective activity over African-Asian sector.

The atmospheric circulation and SST changes associated with the convective activity are depicted in Fig. 2. The spatial structure of the recent decadal trend varies with the season. The top panels show the 1999–2016 mean anomalous OLR during (a) JAS and (b) OND. Because the response of SST follows the atmospheric circulation, anomalous SSTs during the following month (i.e., August, September and October (ASO) and November, December and January (NDJ)) are displayed in Fig. 2c and d, respectively. During JAS, the anomalous cross-equatorial flow west of South America intensifies following a poleward shift in convectively active regions. The cross-equatorial flow changes from westward to eastward when it crosses the equator, following the change in sign of the Coriolis force. This results in a strengthening of the climatological easterlies in the SH and enhances anomalous convergence near New Guinea. In contrast, easterlies are weakened in the NH, which explains the warming (cooling) north (south) of the equator. Such a meridional seesaw of anomalous SSTs and cross-equatorial flow suggests an important role for wind–evaporation–SST (WES) feedback (Xie and Philander, 1994) in recent trends. The centre of anomalous negative OLR moves to the equatorial eastern Indian Ocean from boreal summer to autumn,

which results in a strengthening of anomalous easterlies over the equatorial central Pacific and a westward extension of low SSTs over the equator.

### 3.2 Ascending branch of the Hadley circulation

The Hadley circulation is usually represented by a pair of thermally direct cells, symmetric about the equator, with rising motion over the equatorial belt and sinking motion over the subtropics, with noticeable seasonal variability (e.g., Dima and Wallace, 2003). The mean meridional circulation driven by extreme deep convection further penetrates up to the tropical tropopause (Liu and Zipser, 2005). Here we first investigate the different modes of variability in mean meridional circulation and their relationship with Hadley cells during the boreal summer, focusing on the vertical structure including the lower stratosphere.

Because large detrainment occurs from deep convective clouds near the cloud top, a combination of the vertical velocity and horizontal divergence may indicate large scale circulation related with deep convective activity. Therefore, a singular value decomposition (SVD) analysis (Kuroda, 1998) was conducted using the normalized covariance matrix between zonal-mean pressure vertical velocity ( $\omega$ ) and horizontal air divergence for July-August-September (JAS) 1979-2016. The value at each grid point was weighted by the vertical-layer thickness and the cosine of the latitude in the meridional direction. The SVD calculations were performed from 700 to 30 hPa levels, but to obtain a general view of the entire troposphere the heterogeneous correlation was extended down to 1000 hPa. Results for the 3 SVD leading modes are presented in Fig. 3.

Figure 3a shows that the centers of actions in the divergence field are located in the upper troposphere around 200 hPa for SVD 1 and 3, whereas in the case of SVD 2 it is located around the tropopause at 100 hPa. Accordingly, the vertical velocity fields of SVD 1 and 3 are confined within the troposphere, but that of SVD 2 is extended from the TTL to the lower stratosphere. It is also noticeable that SVD 1 and 3 show similar structure of a meridional seesaw in divergence and vertical velocity fields, except that the horizontal scale of SVD 3 is about a half of the SVD 1.

The mass stream function of the climatological residual mean meridional circulation (Kobayashi and Iwasaki, 2016) was examined (Fig. 3a) in order to investigate the correspondence between the climatological Hadley circulation. For convenience, stream lines related to the closed cells in the troposphere, and those extending to the stratosphere (i.e., deep ascending branch) are displayed separately. The results suggest that SVD 1 and 3 represent changes in the strength and meridional shift of the rising branch of Hadley cells. For SVD 2, however, the picture is different: negative values of vertical velocity field in SVD 2 are located along the climatological stream lines connected to the stratosphere, suggesting a strengthening of vertical velocity around the climatological deep ascending branch of the Hadley cell. The different nature of SVD 2 from that of SVD 1 and 3 is also apparent in their time coefficients: an increasing trend is prominent for SVD 2, while for SVD 1 and 3 there is large year-to-year variation. In addition, the amplitude of the interannual variation in the time

series of SVD 1 and 3 show a decadal change. In the case of SVD 1, negative values became smaller from the beginning of the 2000's, whereas in the case of SVD 3 negative values become larger from the end of the 1990's. This almost simultaneous change in the amplitude and a similarity in spatial structure suggest the possibility that a decadal variation of the spatial structure of the same phenomenon is represented by two SVD modes.

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Correlation coefficients between the time coefficients of the divergence component of each SVD mode and the OLR, divergence at 925 hPa, and surface (2m) air temperature are shown in Fig. 4. (For easier comparison correlation with SVD 1 time coefficients are displayed above those of SVD 3.) SVD 2 has quite different characteristics compared to SVD 1 and 3: reinforced negative OLR (that is, of convective activity) does not coincide with the region of higher surface temperature as in SVD 1 and 3. Surface temperature does not change, or even decrease in some part over the African-Asian continental sector. It is also noted that enhanced convective zone over the continental sector shows little relationship with the convergence near surface. SVD 1 is easily identified as ENSO related phenomenon with large amplitude in the surface temperature and OLR over the equatorial eastern Pacific. This is in agreement with results from the times series shown in Fig. 3c for SVD 1, which shows that peaks in the time series coincide with the occurrence of the El Niño (dots). Surface temperature and divergence maps of SVD 3 show a meridional seesaw in the tropical northeastern Pacific. Such pattern suggests that SVD 3 is related with the Pacific Meridional mode (PMM) (Chiang and Vimont, 2004) or the Central Pacific ENSO (Stuecker, 2018). The above results support the rationale that the decadal evolution of ENSO-related variation is represented by two SVD modes 1 and 3.

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The present analysis suggests that the variability of deep ascending zone represented by SVD 2 is a linearly independent mode from that related to the oceanic ITCZ, represented by SVD 1 and 3. However, the climate system is highly nonlinear. Therefore, changes in the deep ascending branch of the Hadley circulation such as those represented in SVD2, could modulate the ITCZ over the oceanic sector through induced changes in cross-equatorial winds as suggested in Fig. 2.

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### 3.3 Variations over continents and oceans

In the analysis above, two different features of decadal variability are evident, over oceanic and continental sectors. According to our hypothesis the former corresponds to the variability in oceanic ITCZ constituting the main ascending branch of the Hadley cells, and the latter is related to the deep ascending branches of the Hadley circulation connected to the stratosphere. Here we examine variations over the African continental (10°W–40°E) and Pacific Ocean (170°W–120°W) sectors to reveal the most prominent characteristics in each region. The climatological annual cycle in zonal-mean pressure vertical velocity at 300 hPa for each region are depicted in Figs 5a and 6a. A region of enhanced convective activity migrates north and south over the African continent following the seasonal variation of solar heating (Fig. 5a). It should be noted that the evolution of the convective zone includes a jump during the summer monsoon season (Hagos and Cook, 2007). Over the

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Pacific Ocean, the convective zone shows only a small latitudinal displacement and is located in the NH near 5° N–10° N throughout the year (Fig. 6a). Latitude–time cross-sections of the 3-monthly mean anomalous (departures from the 1981–2010 climatology) 300-hPa vertical velocities are shown for February 1979 to November 2016 over the African sector in Fig. 5b. The vertical velocity increases from the mid-1990s in both hemispheres around 10°–20° in latitude, which according to our hypothesis correspond to the location of the deep ascending branch in summertime Hadley circulation. Accordingly, the annual mean precipitation over Africa has increased during the recent period (1999–2016) in both hemispheres over the Sahel and Namibia (Fig. 5c).

Over the Pacific Ocean sector (Fig. 6b), strong upward motion appears over the equator when El Niño events occur. This has been identified as an effect of the ENSO on the ITCZ (Waliser and Gautier, 1993). The anomalous region of upward motion, however, tends to remain north of the equator after 1999. Accordingly, the annual mean anomalous precipitation during the recent period shows a large increase near 5° N–10° N, the mean position of the ITCZ over the ocean, but decreases over the equator and the SH (Fig. 6c). This manifests as a narrowing and intensification of the ITCZ in recent decades, with little change in its latitudinal position (Lucas et al., 2013; Wodzicki and Rapp, 2016). The change over the ocean sector is related to the varying strength of the cross-equatorial winds (Fig. 6d). After 1999, although SSTs increased over the equator during El Niño events, anomalous northward winds remained strong and convective activity tended to remain in the NH.

Figure 6e shows the longitude–time section of the anomalous OLR over the equatorial SH (0°–10° S). The effects of cooling of the eastern equatorial Pacific in the SH can also be seen in structural changes in El Niño/Southern Oscillation (ENSO) phenomena after 1999. Convective activity greatly increases over the Pacific during El Niño events before 1999. However, after 1999, Pacific convective activity is suppressed and an increase in convective activity during El Niño is apparent only over the central Pacific. In contrast, convective activity west of 160° E over the Maritime Continent generally increases after 1999. Such changes are likely related to a decadal change in anomalous zonal winds over the tropical SH (10° S–5° N; Fig. 6f), which in turn is connected to increased cross-equatorial southerlies through Coriolis-force effects. Latitude–time sections of 3-monthly anomalous SSTs in the Niño 3.4 sector (Fig. 6g) indicate little change in latitudinal structure, thus changes in spatial structure related to the ENSO around 1999 supports our interpretation of the relationship between SVD 1 and 3 in the above.

We next take a closer look into tropospheric vertical velocity variations. The tropospheric zonal-mean vertical velocity has a relatively weak connection with the horizontal distribution of OLR possibly because regional-scale variations dominate in the lower troposphere due to surface topography. Therefore, meridional sections of standardized mean JAS 1999–2016 anomalous pressure vertical velocity were calculated for several sectors instead of zonal means (Fig. 7). The top panel in Fig. 7a shows the anomalous zonal-mean field (shaded), which is comparable to that extracted by SVD 2 in Fig. 3b, along with contours indicating the 30-yr climatology for reference. The middle panels are the same as the top panel, but divided into

two parts: (b) an African–Asian continental sector (30° W–130° E) and (c) a Pacific–Atlantic oceanic sector (130° E–330° E). A strengthening of upward velocity in the TTL and lower stratosphere occurs in the continental sector, together with a northward shift in the troposphere, whereas in the oceanic sector a strengthening in vertical velocity occurs around 5° N–10° N without a latitudinal shift. If we limit the continental sector to the African continent (20° W–20° E) to exclude the influence of the Indian Ocean, the above-mentioned continental characteristics become even clearer (Fig. 7d). Over the oceanic sector, an increase in vertical velocity occurs around 7.5° N (Fig. 7f), but in the western Pacific sector (130° E–170° E) the upward velocity develops primarily south of the equator (10° S–0°; Fig. 7e). We also note that the climatological vertical velocity in the western Pacific sector is essentially confined to the lower troposphere over the equatorial SH (10° S–0°). This observation can be attributed to the fact that convergence occurs over the warm ocean east of New Guinea (Fig. 2c). This result indicates that despite a variety of profiles among the sectors, the zonal-mean vertical field in the TTL primarily follows variations over the African–Asian continental sector.

### 3.4 Stratosphere-troposphere coupling

Continuity in a zonally averaged field does not necessarily mean actual continuity at each location, as is evident from the above analysis. To investigate continuity within the deep ascending branch of the Hadley circulation from the upper troposphere to the stratosphere in more detail, longitude–height sections of the normalized anomalous pressure vertical velocities averaged over latitudes of 10°–20° in the summer hemisphere are displayed in the top panels of Fig. 8a and b. The bottom panels show the distributions of climatological (2007–2017) COV occurrence frequency in the same latitudinal zone. If a normal distribution is assumed, absolute values of 17-year mean standardized anomalies that are larger than 0.5 are statistically different from 0 at the 95% confidence level. An increasing trend in upwelling occurs over the continental sector, particularly where COVs are frequent. These characteristics are commonly seen in both summer hemispheres. The contrast between the continental and oceanic sectors is clearer in the SH (Fig. 8b) where the distribution of land is simpler. Because COV occurs in deep convective clouds penetrating into the TTL beyond the level of neutral buoyancy, such increased vertical velocity in the TTL over the region of frequent COV seems reasonable. It should also be noted that a connection between COV and vertical velocity in the tropical lower stratosphere on a daily scale has been identified in a previous study by Kodera et al. (2015).

To investigate stratosphere-related variations in the troposphere, the JAS mean pressure vertical velocity ( $\omega$ ) at 30 hPa averaged over the tropical SH (0°–25° S) is chosen as the index of stratospheric mean meridional circulation ( $I_\omega$ ; Fig. 9a). The correlation coefficient between  $I_\omega$  and zonal-mean  $\omega$  at each grid point (Fig. 9b) shows a correlation pattern similar to the SVD 2 in Fig. 1. To highlight the relationship between the interannual variation and climatology, the stream function from Fig. 3 is displayed as contours in Fig. 9b and c. It is clearly seen that the variation in stratospheric upwelling (Brewer–Dobson circulation) is connected to the upwelling of the deep ascending branch of the Hadley circulation, similar to that in climatology.

The correlation between  $I_{\omega}$  and zonal-mean temperature at each grid point from 90° S to 90° N is shown in Fig. 9c. Tropical upwelling is not only related to cooling in the tropics and the summer hemisphere, but to warming in the downwelling region around the winter polar stratosphere. This suggests the dynamic nature of recent tropical stratospheric cooling. Stratospheric upwelling is also connected with convective activity along 15° N–20° N (Fig. 9d), as discussed above. Correlation coefficients between  $I_{\omega}$  and 925-hPa zonal and meridional winds at each grid point are shown as arrows in Fig. 9e. An increase in cross-equatorial winds in the eastern Pacific and Atlantic is observed. The impact of near-surface wind variations on SST can be seen in the lagged correlation with SST in Fig. 9e. Cooling in the equatorial eastern Pacific is largest with a time lag of 5 months (i.e., during December, January, and February, DJF), consistent with the development of La Niña-like SSTs during boreal autumn (Fig. 2).

On the basis of the results presented in the previous sections we suggest the mechanism depicted in Fig 10. (a) Cooling in the lower stratosphere adds to the global warming in the troposphere. (b) Decrease of the lower stratospheric temperature produced favourable conditions for the development of extreme deep convection. Stratospheric cooling effect is felt by convections reaching the TTL, primarily over the continental sector. (c) Enhancement of extreme deep convection off-equatorial region produces stronger cross-equatorial flow near the surface. (d) Strengthening of surface winds cools the ocean by increased evaporation.

Accordingly, we selected four variables that can be considered fundamental to the recent tropical trends: (a) tropical lower-stratospheric temperatures in early summer (temperature at 70 hPa averaged over 20°S–20°N from 16 July to 16 August); (b) pressure vertical velocity at the bottom of the TTL (150 hPa) in August; (c) August–October mean southward winds south of the equator (10° S–0°) in the western hemisphere (180° W–0°); and (d) time tendency of SST from early summer (May–July) to late autumn (October–December) in the tropical Pacific west of the South American continent (15° S–5° S, 100° W–80° W). Time series of these four variables (a–d) are displayed in Fig 10 (right). When all four variables are negative (red dots), we define this as a negative event. Similarly, when all variables are positive (black dots), it is defined as a positive event. All six positive events occurred within the first 14 years, whereas all seven negative events occurred during the last 13 years. A chi-squared test was conducted to examine whether such distributions of events can occur by chance, by dividing the whole 39 years into three equal 13-year periods. The result ( $\chi^2 = 23$ ) indicates that the probability of such distributions occurring by chance is less than 0.1%. Therefore, there is a statistically significant trend towards negative events in recent decades.

However, the key question here is whether there is a causal relationship among the variables. We introduced a seasonal variation in the selection of the variable from the period of stratospheric cooling at the end of July and to the cooling of the ocean from summer to autumn: That is, change in Pacific SST occurred following a change in cross-equatorial winds,

increased upwelling in the TTL, and stratospheric cooling in early summer. This time evolution tentatively suggests a causality among the variables.

#### 4. Summary and discussion

Convective activity around the deep ascending branch of the boreal summer Hadley circulation (Fig. 3, SVD 2) shows an increasing trend over the continental sector (Fig. 4). In contrast, over the oceanic sector the decadal change manifested as changes in the spatial structure of the ENSO related phenomenon (Fig. 4, SVD 1). It is suggested that the observed 1999-2016 decadal SST cooling in the eastern Pacific is related to an increase in cross-equatorial winds, and easterlies in the tropical SH, which are themselves related to a strengthening of convective activity around the climatological deep ascending branch of the Hadley circulation during boreal summer over the African–Asian sector (Fig. 2). In addition, a correlation analysis (Fig. 9) indicates that these variations in convective activity and SST are related to vertical velocity near the tropopause. The relationship between convective activity and cooling of the tropical eastern Pacific can be explained through changes in cross-equatorial winds involved in a wind–evaporation–SST (WES) feedback (Xie, 2004). Accordingly, a combination of these two processes can be used as a working hypothesis for the recent tropical changes, as shown in Fig. 10.

It is difficult to demonstrate statistically a causal relationship among variables having large trends, such as (a) lower stratospheric temperature, (b) upwelling in the TTL, (c) cross-equatorial near-surface winds, and (d) time tendency of SST from boreal summer to autumn. Nevertheless, time lags introduced in selected variables from summer to autumn suggest that the above processes are related, as shown schematically in the left panel of Fig 10.

Although their period of observation may be too short (10 years of Atmospheric Infrared Sounder data), Aumann and Ruzmaikin (2013) reported that tropical deep convection over land shows an increasing trend, whereas that over oceans shows a decreasing trend. Furthermore, Taylor et al. (2017) showed that intense mesoscale convective systems in which cloud-top temperatures were lower than  $-70^{\circ}\text{C}$  largely increased over the Sahel since 1982. A temperature of  $-70^{\circ}\text{C}$  corresponds to the air temperature at  $\sim 150$  hPa. This means that extreme deep convection penetrating into the TTL largely increased over the African continent, consistent with the analysis presented here.

In the present study, a poleward shift in the convective zone corresponds to enhanced convective activity in the deep ascending branch in the summertime Hadley circulation, located at a higher latitude (around  $15^{\circ}$  N) than the main ascending branch over the ocean (around  $7.5^{\circ}$  N). For the purposes of this paper we assume that the changes that we discuss are independent from those associated with tropical expansion. This paper is based on the hypothesis that recent increase in the convective activity in deep branch of the Hadley circulation over the continental sector can be considered as independent of the shift in the ITCZ studied by many other authors such as Schneider (2017) and Byrne et al. (2018) which are primarily

relevant to the oceanic sector. It should also be noted that the expansion rates of the tropics should be much smaller than those reported in past studies (Staten et al., 2018).

5 The increasing trend in Earth's surface temperature is generally attributed to an increase in greenhouse gases, such as CO<sub>2</sub> (IPCC, 2013). Such a change in radiative forcing may explain the global characteristics of recent changes. The effect of increased CO<sub>2</sub> can be divided into a direct radiative effect and an indirect effect through changes in SST. Model experiments have shown that the direct radiative effect of CO<sub>2</sub> increases tropical upward motion, particularly over the Sahelian sector, whereas it suppresses upwelling over the oceanic sector in the Pacific (see fig. 8 of Gaetani et al., 2016). An increase in CO<sub>2</sub> raises the Earth's surface temperature, but decreases stratospheric temperatures. Note, however, that recent cooling in the lower stratosphere–tropopause region is also due to a dynamic effect (Abalos et al., 2015). Further investigation is needed to determine whether the stratosphere is merely passively responding or playing an active role in tropospheric circulation change. Here we emphasized that stratospheric change should be considered together with tropospheric change.

## 5 Data availability

15 Datasets used in this paper are all publicly available. Meteorological reanalysis datasets created by JMA (JRA55) are available from <http://search.diasjp.net/en/dataset/JRA55>. The COBE monthly mean SST dataset can be obtained from the JMA website (<http://ds.data.jma.go.jp/tcc/tcc/products/elnino/cobesst/cobe-sst.html>). Monthly mean HIRS OLR data can be obtained from NOAA by FTP (<ftp://eclipse.ncdc.noaa.gov/cdr/hirs-olr/monthly/>). The GPCP monthly mean precipitation dataset can be obtained from the NOAA website (<https://www.esrl.noaa.gov/psd/data/gridded/data.gpcp>). The AMSU/MHS data are available at NOAA's Comprehensive Large Array Data Stewardship System. In this work, AMSU/MHS raw data were obtained with support from the INSU-CNES French Mixed Service Unit ICARE/climserv/AERIS and accessed with the help of ESPRI/IPSL.

## Acknowledgements

25 The authors wish to express their thanks to Leonhard Pfister for valuable discussions and comments. This work was supported in part by Grants-in-Aid for Scientific Research (25340010, 26281016, and 16H01184) from the Japan Society for the Promotion of Science. Preliminary analysis of this study were made using Interactive Tool for Analysis of Climate System, ITACS, provided by the Japan Meteorological Agency.

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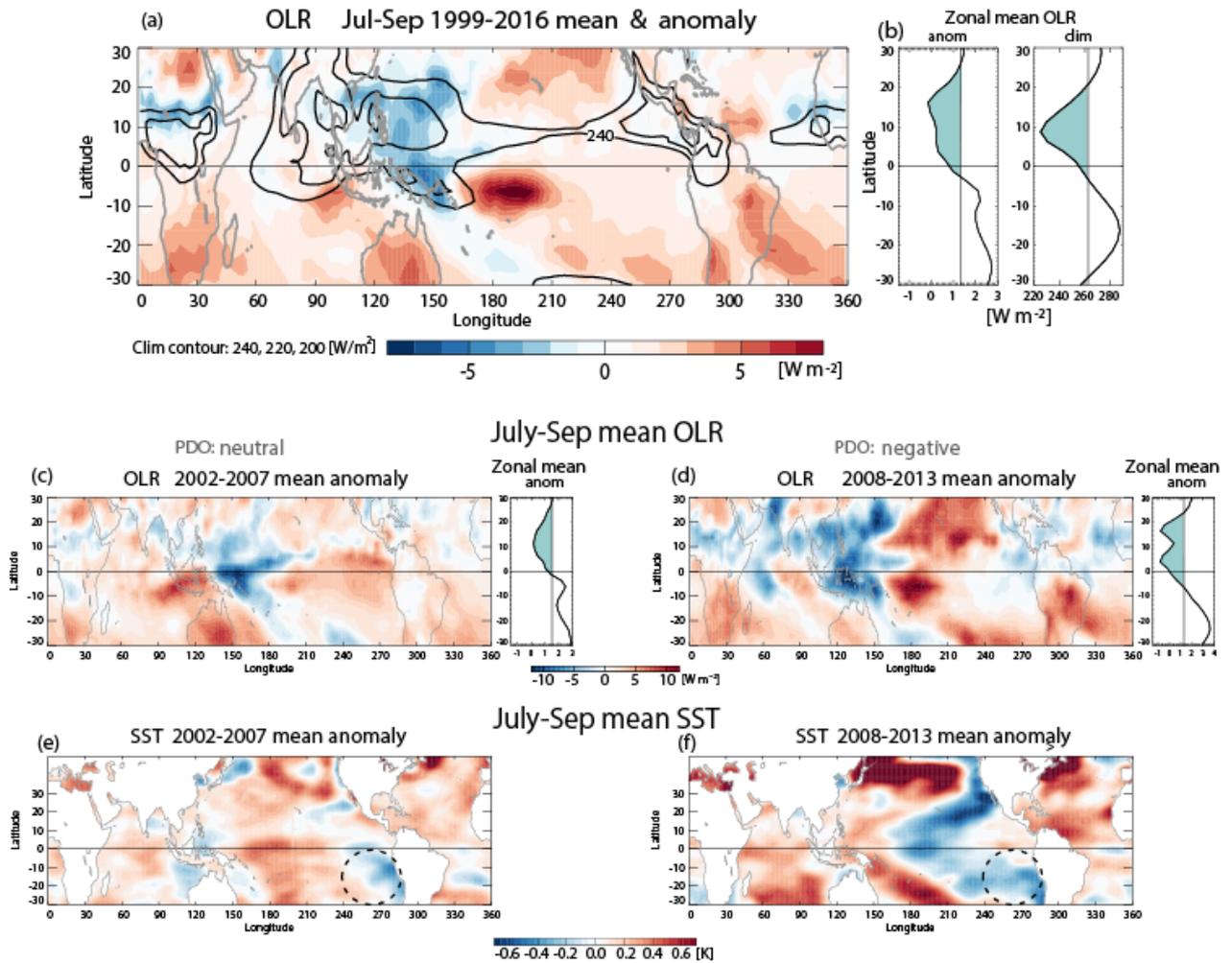
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Figures



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Figure 1: (a) Climatological (1981–2010) July–September mean OLR (contours: 240, 220, and 200  $\text{W m}^{-2}$ ) and anomalous July–September OLR (departures from climatology) during 1999–2016 (colour shading); (b) zonal-mean profiles of (a): anomalies from climatology (left) and climatology (right); (c) anomalous OLR as in (a) and (b, left) but for 2002–2007; (d) anomalous OLR as in (a) and (b, left) but for 2008–2013; and anomalous July–September SST (departures from climatology) for (e) 2002–2007 and (f) 2008–2013.

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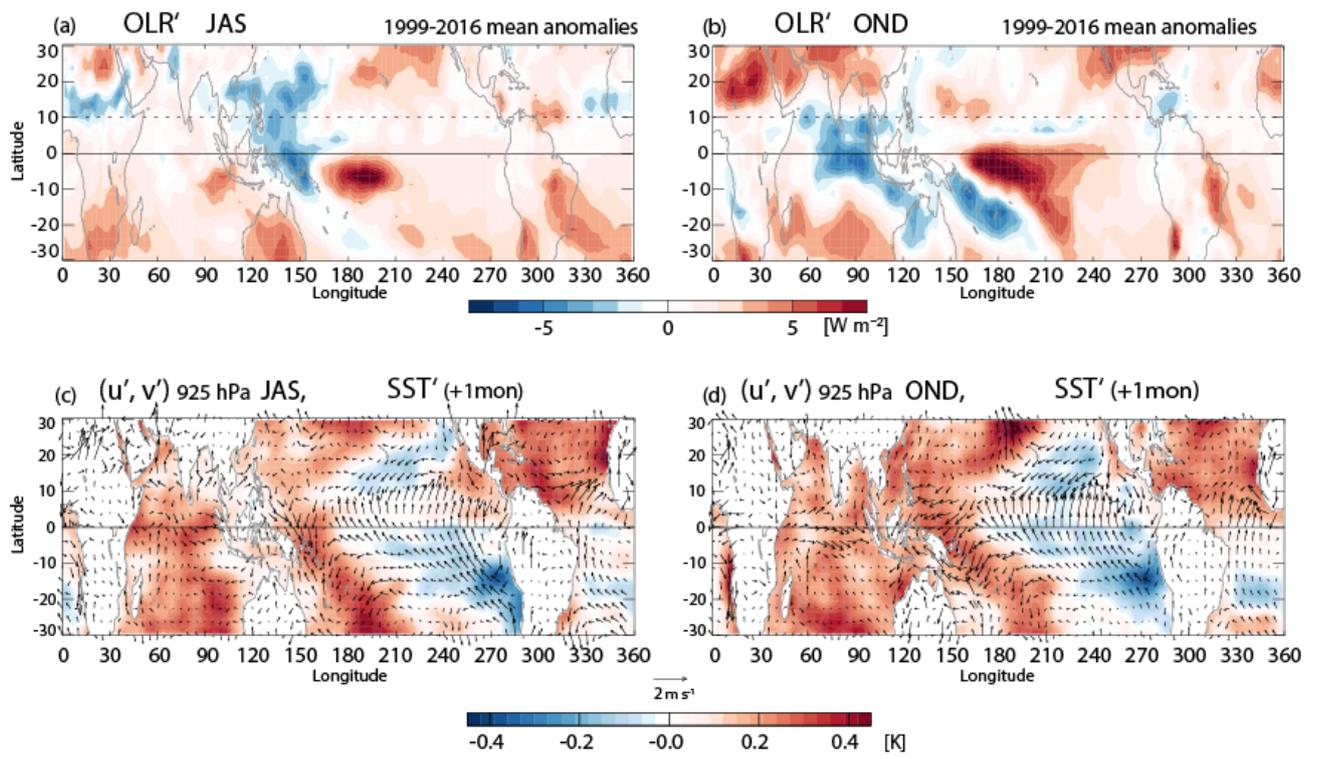
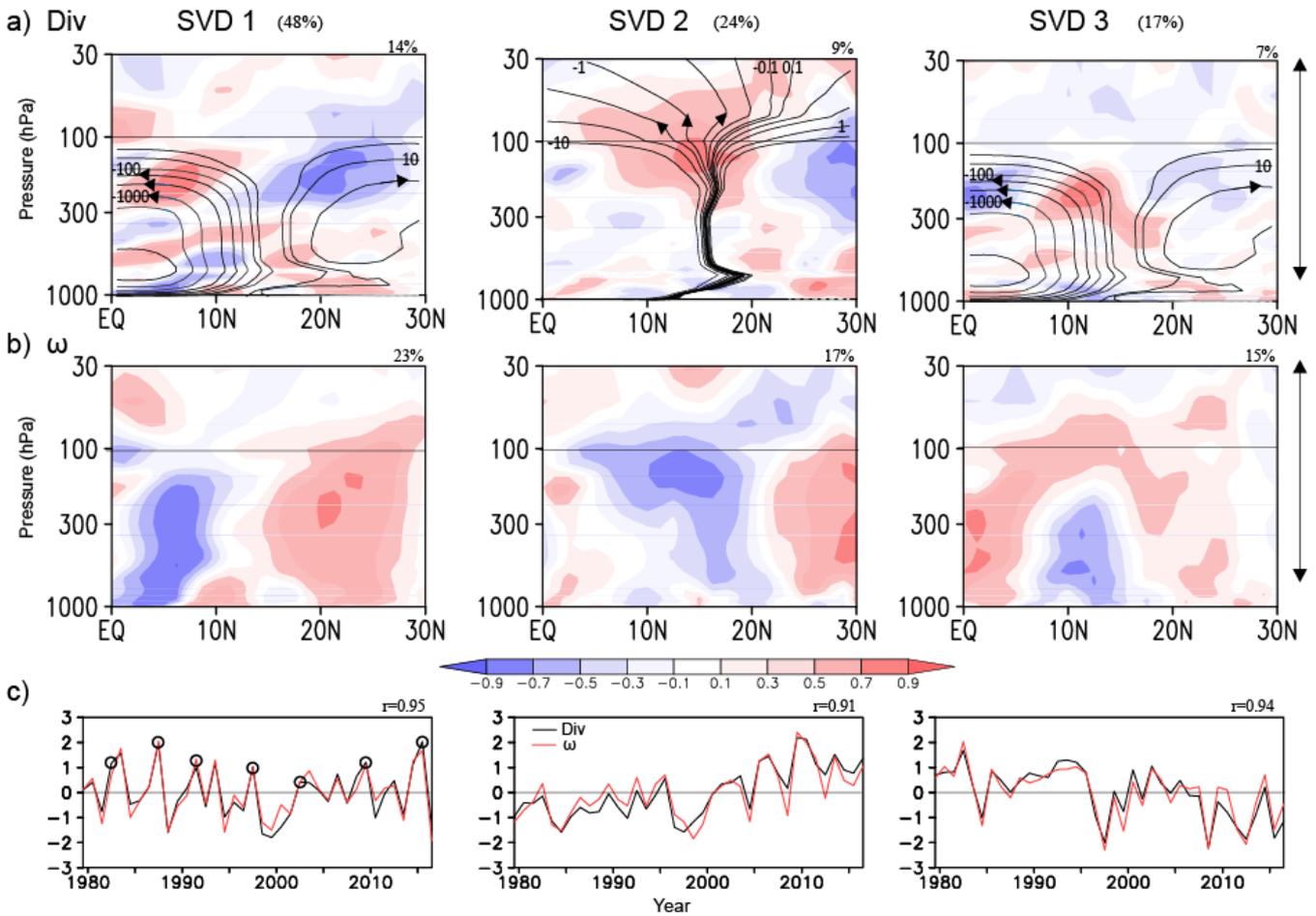


Figure 2: (a) JAS and (b) OND mean anomalous OLR for 1999–2016; (c) JAS and (d) OND mean anomalous horizontal winds at 925 hPa (arrows) for 1999–2016 superimposed on anomalous SSTs (colour shading) with a one-month lag (i.e., ASO and NDJ, respectively).

5



5 **Figure 3: Singular value decomposition analysis of the zonal-mean anomalous horizontal divergence and anomalous pressure vertical velocity in the tropics (30°S–30°N) during JAS from 1979 to 2016: From left to right, SVD 1, SVD 2 and SVD 3. (a) Heterogeneous correlation map of horizontal divergence. (b) same as (a), except for pressure vertical velocity map. (c) Time coefficients (black: divergence, red: vertical velocity). Arrows indicate the levels used in the SVD calculations. Stream lines in (a) indicate mass stream function of the climatological residual mean meridional circulation (Stream lines are plotted with logarithmic scaling:  $\pm 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100 \dots \times 10^{10} \text{ kg s}^{-1}$ ). Open circles in (c) indicate El Niño event.**

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Correlation with SVD Div. time coeff.

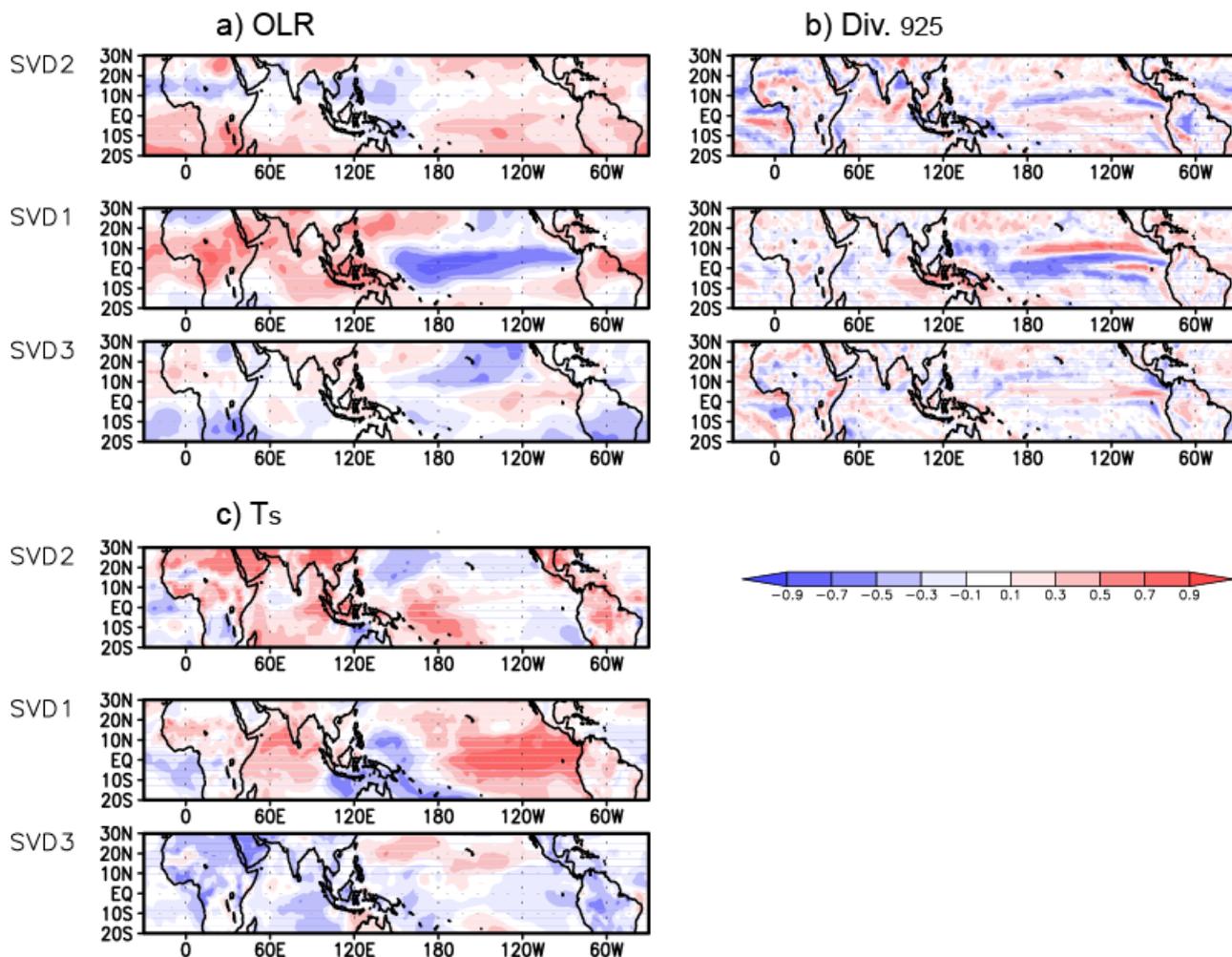
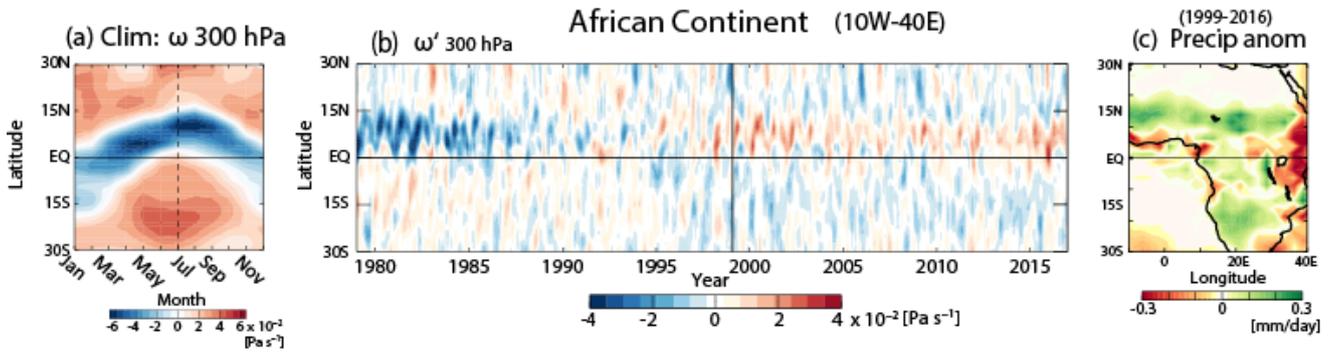
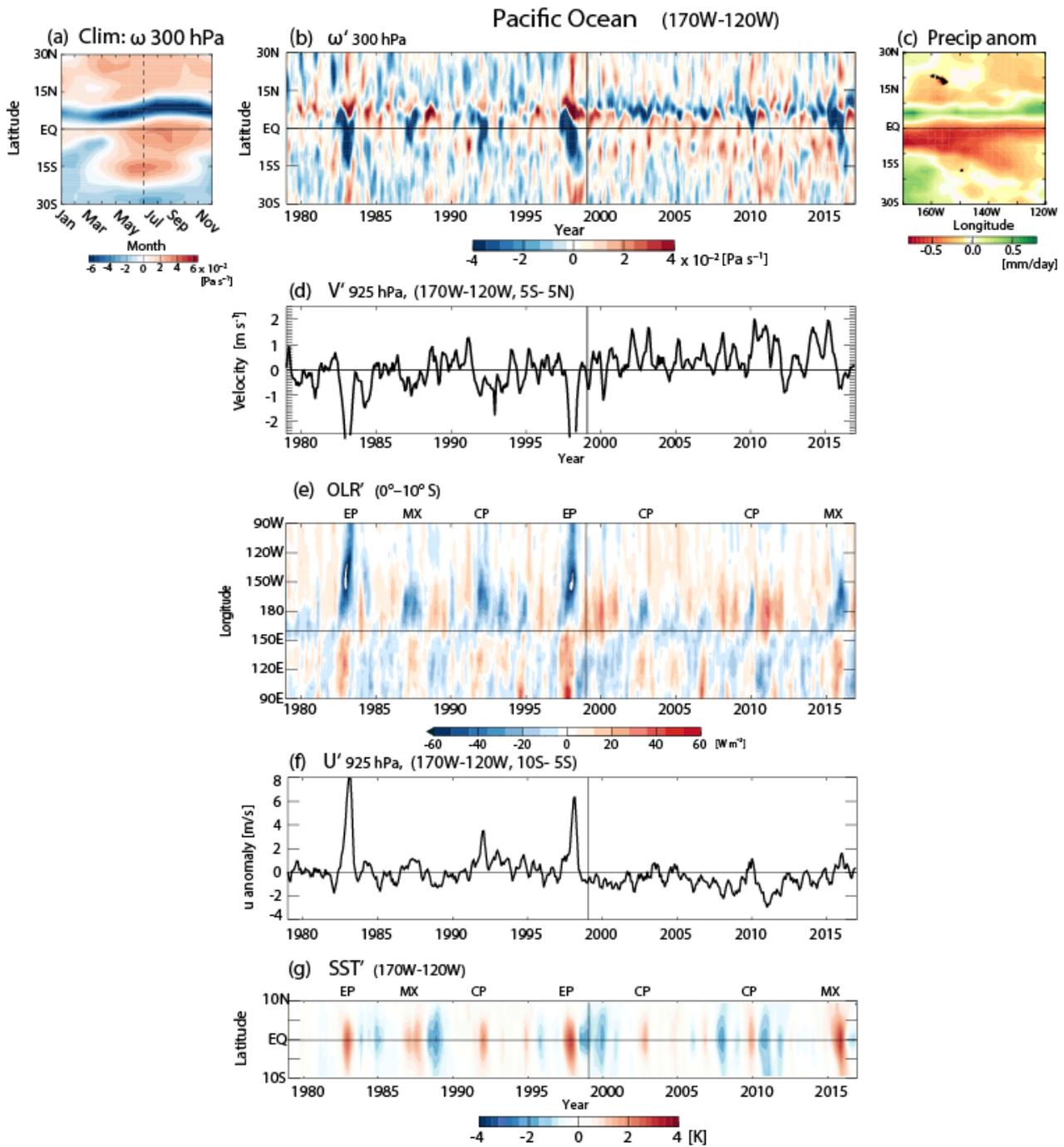


Figure 4: Correlation coefficient between time series of divergence component of each SVD mode and (a) OLR, (b) horizontal divergence at 925 hPa, and (c) surface temperature, at each grid. Each panel in Fig. a, b, and c shows correlation map of SVD 2, SVD 1, and SVD 3, from top to bottom.

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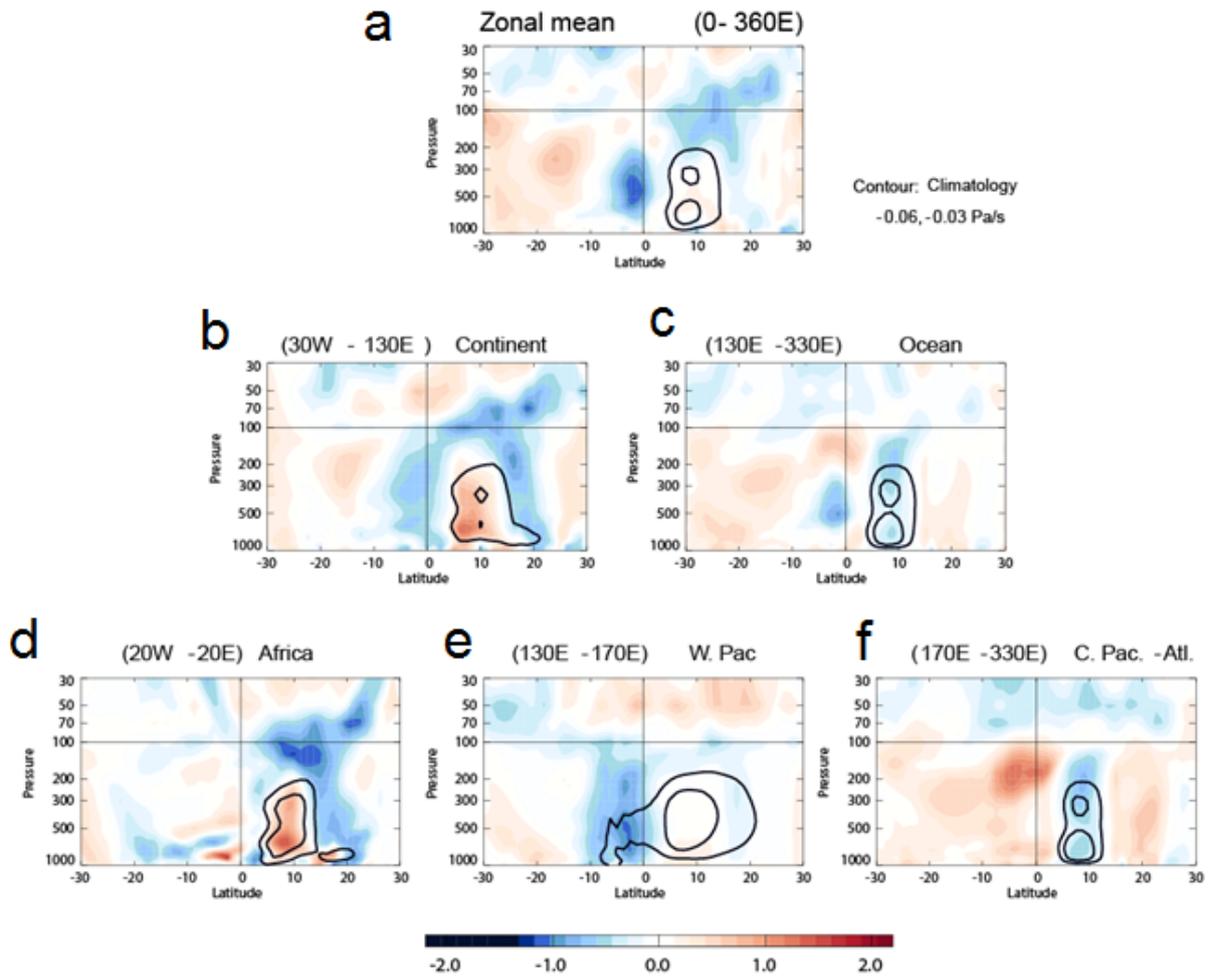


5 Figure 5: (a) Latitude–time section of the climatological zonal-mean pressure vertical velocity at 300 hPa averaged over the African sector (10°W–40°E); (b) latitude–time section of monthly mean anomalous pressure vertical velocity from February 1979 to November 2016; and (c) latitude–longitude map of annual mean anomalous precipitation during 1999–2016 over the African sector. A three-month running mean is applied in (b).



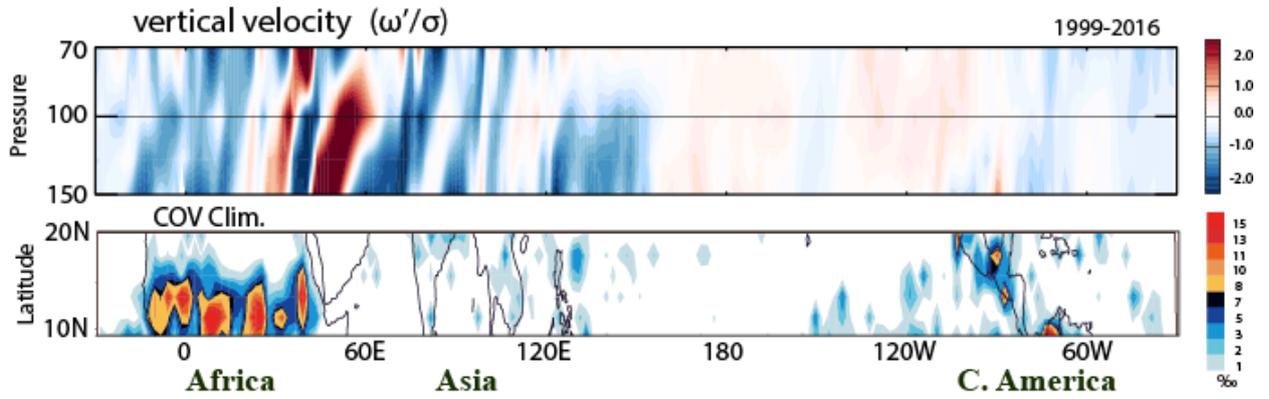
5 Figure 6: (a–c) Same as Fig. 5 but for the eastern Pacific Niño-3.4 (170°W–120°W) sector; (d) monthly mean anomalous meridional wind component around the Equator (5°S–5°N) over the Niño 3.4 sector; (e) similar to (a), but for the time–longitude section of OLR around the Equator (5°S–5°N) over the Indian Ocean–Pacific sector; (f) same as (d), but for the zonal wind component in the tropical SH (10°S–5°S); and (g) monthly mean anomalous SST over the Niño 3.4 sector. Eastern Pacific (EP), central Pacific (CP), and mixed-type (MX) El Niño events are indicated (Paek et al., 2017).

Standardized JAS 1999-2016 mean  $\omega$



5 **Figure 7:** (a) Standardized anomalous pressure vertical velocity (departures from 1981–2010 climatology)—the climatological JAS mean, zonal-mean pressure vertical velocity is indicated by contours ( $-0.06$  and  $-0.03 \text{ Pa s}^{-1}$ ). (middle panels) Same as (a), but for (b) the African–Asian continental sector ( $30^{\circ}\text{W}$ – $130^{\circ}\text{E}$ ) and (c) the Pacific–Atlantic oceanic sector ( $130^{\circ}\text{E}$ – $330^{\circ}\text{E}$ ). (bottom panels) same as (a), but for (d) the African continental sector ( $20^{\circ}\text{W}$ – $20^{\circ}\text{E}$ ), (e) the Western Pacific sector ( $130^{\circ}\text{E}$ – $170^{\circ}\text{E}$ ), and (f) the Central Pacific–Atlantic sector ( $170^{\circ}\text{E}$ – $330^{\circ}\text{E}$ ).

(a) Jul-Sep (10N-20N)



(b) Dec-Feb (10S-20S)

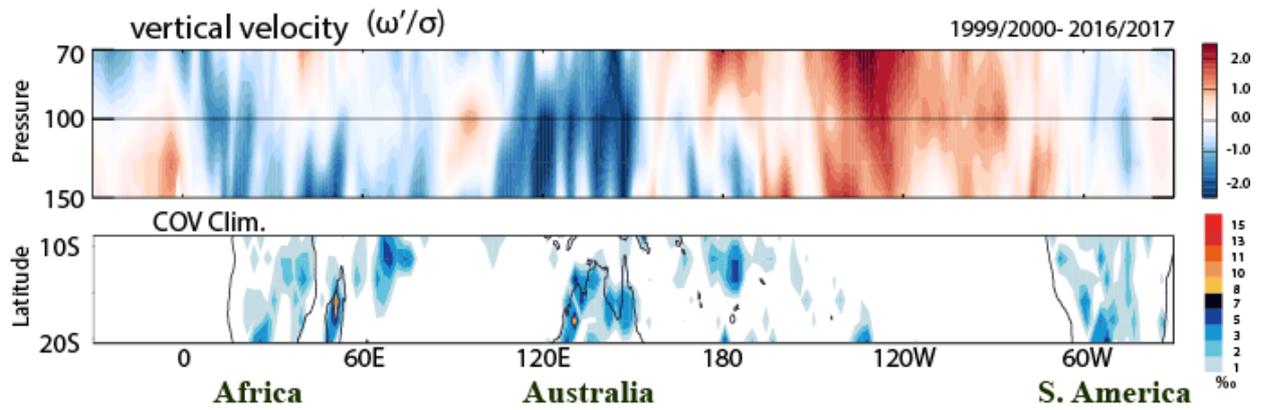
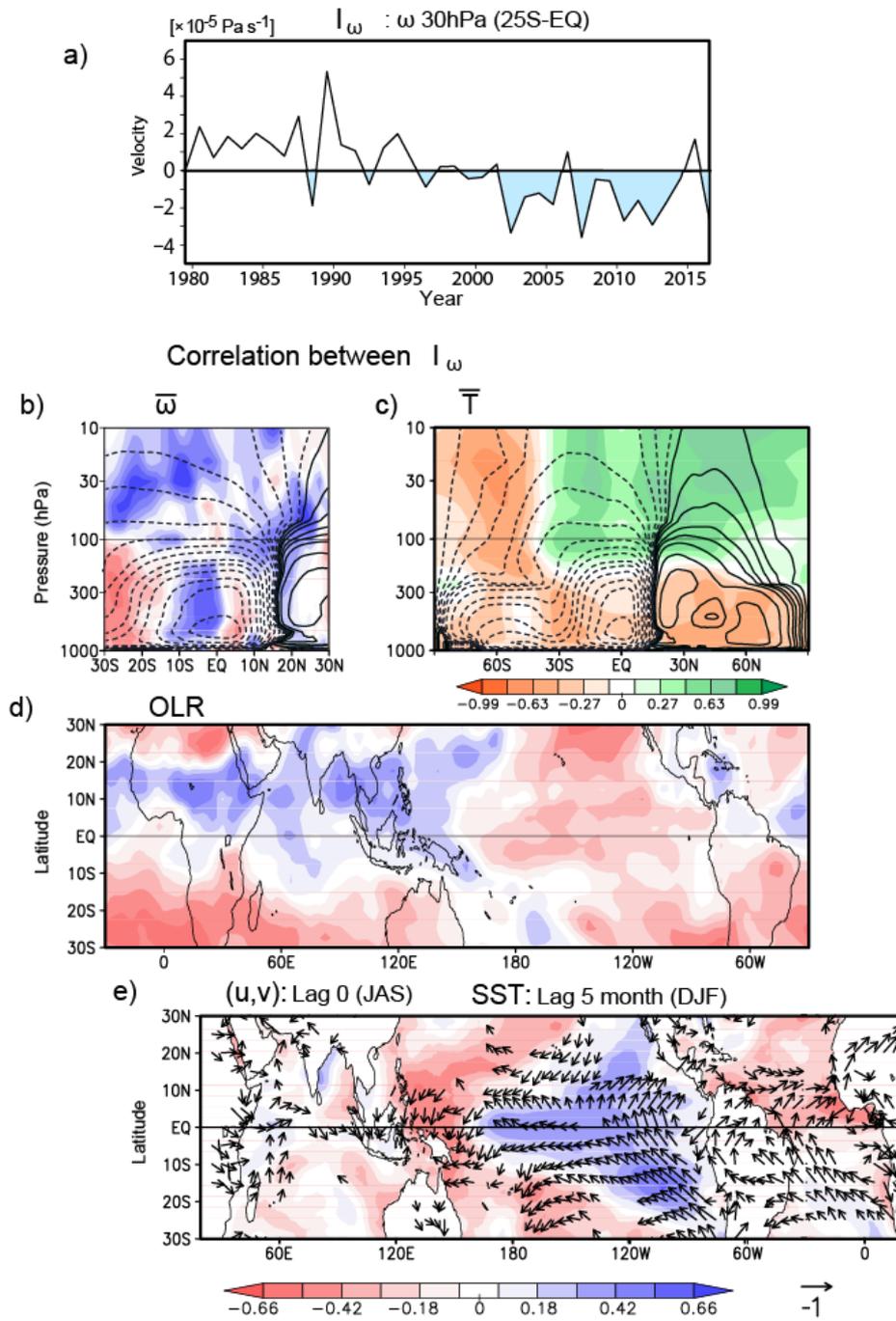
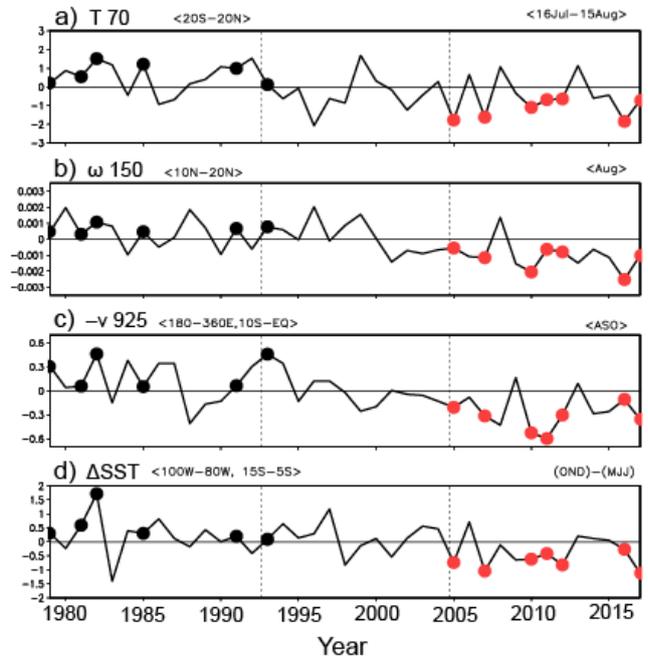
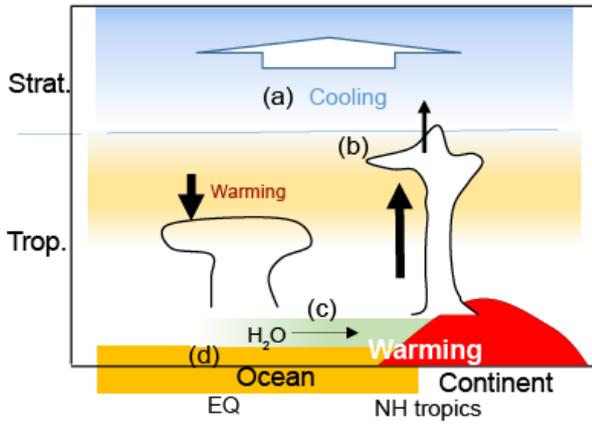


Figure 8: (a) (top) Height–longitude section of the standardized (with respect to the interannual variation) anomalous pressure vertical velocity averaged over 10°N–20°N during boreal summer (JAS) 1999–2016; (bottom) climatological (2007–2017) occurrence frequency of convective overshooting (COV) in the same latitudinal zone (units of parts per thousand); and (b) as in (a) but for 10°S–20°S during austral summer (DJF).



5 **Figure 9:** (a) Time series of JAS mean pressure vertical velocity ( $\omega$ ) at 30 hPa averaged over  $0^{\circ}$ – $25^{\circ}$ S as an index for tropical stratospheric vertical velocity ( $I_{\omega}$ ); correlation coefficients between  $I_{\omega}$  and (b) zonal-mean  $\omega$ , (c) zonal-mean temperature  $T$  at each grid, (d) OLR, and (e) horizontal winds at 925 hPa (arrows). A lagged correlation with DJF mean SST is also presented by colour shading in (e). Contours in (b) and (c) indicate the climatological residual mean meridional circulation in JAS. Solid and dashed lines indicate clockwise and counter clockwise directions, respectively.



5 Figure 10: (left) Schematic of recent changes in the tropics (see text), in which the labels (a) to (c) indicate the location of the variable shown in the right panels; (right) time series of four key variables as departures from the climatology: (a) lower stratospheric temperature, (b) upwelling in the TTL, (c) cross-equatorial near-surface winds, and (d) time tendency of SST from summer to autumn. Black and red dots indicate years when the four variables are of the same polarity (positive and negative, respectively).