



1 **Abrupt seasonal transitions in land carbon uptake in 2015**

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10

11 **Abstract**

12

13 The year 2015 saw a record atmospheric CO₂ growth rate associated with a weaker than usual
14 land carbon sink. Paradoxically, it was also the greenest year since 2000 according to satellite
15 observations of vegetation greenness. To reconcile these two seemingly paradoxical observations,
16 we examined the patterns of CO₂ fluxes using two atmospheric inversions. Inversion results
17 indicate that the year 2015 had a higher than usual northern land carbon uptake in spring and
18 summer, consistent with the greening anomaly. This higher uptake was however followed by a
19 larger source of CO₂ in autumn, suggesting a coupling between growing season uptake and late
20 season release of CO₂. For the tropics and Southern Hemisphere, a strong and abrupt transition
21 toward a large carbon source for the last trimester of 2015 is discovered, concomitant with the El
22 Niño development. This abrupt transition of terrestrial tropical CO₂ fluxes between two
23 consecutive seasons is the largest ever found in the inversion records.

24

25 **1 Introduction**

26

27 The first monitoring station for background atmospheric CO₂ concentration was established at
28 Mauna Loa in 1958. The record since then shows that atmospheric CO₂ continued to rise in
29 response to anthropogenic emissions. However, the atmospheric CO₂ growth rate (AGR) has
30 been lower than that implied by anthropogenic emissions alone, because land ecosystems and the
31 oceans have absorbed part of the emitted CO₂ (Canadell et al., 2007; Le Quéré et al., 2016).



32 Although on multi-decadal time scale, carbon uptake by land and ocean has kept in pace with
33 growing carbon emissions (Ballantyne et al., 2012; Li et al., 2016), large year-to-year
34 fluctuations occur in the terrestrial carbon sink, mainly in response to climate variations induced
35 by El Niño–Southern Oscillation (ENSO) (Wang et al., 2013, 2014) and other occasional events
36 such as volcanic eruptions (Gu et al., 2003).

37

38 In 2015, the global monthly atmospheric CO₂ concentration surpassed 400 p.p.m. for the first
39 time since the start of the measurements, with an unprecedented large annual growth rate of
40 2.96 ± 0.09 p.p.m. yr⁻¹ (https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html#global_growth).

41 This record-breaking AGR occurred simultaneously with a high value of the ENSO index (Betts
42 et al., 2016) and the warmest land temperature on record since 1880
43 (<https://www.ncdc.noaa.gov/cag/time-series/global/globe/land/ytd/12/1880-2015>). But at the
44 same time, 2015 was also shown to have the greenest growing season of the Northern
45 Hemisphere since 2000 (Bastos et al., 2016). Widespread abnormally high positive anomalies of
46 the normalized difference vegetation index (NDVI) were observed from the Terra satellite's
47 Moderate-resolution imaging spectroradiometer (MODIS) sensor, in particular over eastern
48 North America and large parts of Siberia. On the one hand, strong greening is expected to
49 enhance northern land carbon uptake during the growing season; on the other hand the strong El
50 Niño event in the second half of 2015 increased fire emissions in tropical Asia (Huijnen et al.,
51 2016; Yin et al., 2016) and likely caused a loss of plant biomass and reduced carbon uptake,
52 possibly associated with the prevailing high temperatures and reduced rainfall (Ahlström et al.,
53 2015; Jiménez-Muñoz et al., 2016).

54

55 To reconcile the observed maximum global land greening with the record-high AGR in 2015, we
56 examined land-atmosphere carbon fluxes estimated from two atmospheric inversions
57 encompassing the last three decades and assimilating atmospheric CO₂ mole fraction records
58 from a large number of *in situ* and flask records: the Copernicus Atmosphere Monitoring Service
59 inversion (CAMS, version r15v3) (Chevallier et al., 2005, 2010) and the Jena CarboScope
60 atmospheric inversion (version s04_v3.8, hereafter abbreviated as Jena04, update from
61 Rödenbeck, 2005; Rödenbeck et al., 2003). We focus on seasonal patterns in the land carbon
62 uptake during 2015, relative to the long-term trend of 1981-2015. We then investigate how land



63 ecosystems responded to the joint occurrences of record-breaking warming, extreme greening,
64 and the end-of-year El Niño event, to understand how land ecosystems contributed to the high
65 AGR in 2015.

66

67 **2 Data and methods**

68 **2.1 Data sets**

69 **2.1.1 Atmospheric inversion data**

70 We used two gridded land and ocean carbon uptake data sets based on atmospheric CO₂
71 observations, namely the Copernicus Atmosphere Monitoring Service (CAMS) inversion system
72 developed at LSCE (Chevallier et al., 2005, 2010) and the Jena CarboScope inversion system
73 developed at the MPI for Biogeochemistry Jena (update of Rödenbeck, 2005; Rödenbeck et al.,
74 2003). Atmospheric inversions use atmospheric CO₂ concentration at observation sites,
75 combined with an atmospheric transport model as well as prior information on carbon emissions
76 from fossil fuel burning and on carbon exchange between the atmosphere and land (and ocean),
77 to estimate land- and ocean-atmosphere net carbon fluxes that minimize a Bayesian cost function,
78 which measures the mismatch between observed and simulated atmospheric CO₂ mixing ratios.
79 Detailed information inversions could be found in respective sources as mentioned above.

80

81 The CAMS inversion data (version r15v3) were provided for 1979-2015 with a weekly time-step
82 and a spatial resolution of 1.875° latitude and 3.75° longitude. The Jena CarboScope inversion
83 provides daily fluxes at a spatial resolution of 3.75° latitude and 5° longitude. It offers a series of
84 runs that use differently large station sets with complete data coverage over time, in order to
85 avoid spurious flux variations from a changing station network. From these runs, we used
86 s04_v3.8 (shortened as Jena04 in the main text and supplementary material) includes the largest
87 number of measurement sites, to allow more robust constraining of carbon exchanges in 2015
88 (see <http://www.bgc-jena.mpg.de/CarboScope/> for more details on other configurations). The
89 s04_v3.8 run has a validity period as 2004–2015, although it does provide the data for the whole
90 time span of 1981–2015. In the calculation of the long-term linear trend, we exceptionally use
91 this run outside its period of validity; from a comparison of the linear trends over the latitudinal
92 regions examined in this study between the s04_v3.8 and the long s81_v3.8 runs we established
93 that this was possible in this case.



94

95 **2.2.2 Atmospheric CO₂ growth rates, NDVI and climate data**

96 Atmospheric CO₂ growth rates were retrieved from the Global Monitoring Division, Earth
97 System Research Laboratory (ESRL), NOAA
98 (<http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html>). We used NDVI data between 2000 and
99 2015 from MODIS Terra Collection 6, re-gridded at 0.5° resolution and monthly time-step. The
100 NDVI anomalies are calculated at pixel level as the standardized monthly NDVI (i.e., de-
101 seasonalized) relative to the reference period of 2000–2014. Climate fields are from ERA interim
102 reanalysis (Dee et al., 2011) at 0.5° resolution and monthly time-step. We used air temperature,
103 precipitation and volumetric soil water content (%) integrated over the soil column to a depth of
104 2.89 m.

105

106 **2.1.3 Indices for El Niño–Southern Oscillation (ENSO) states and fire emission data**

107 We examined the seasonal variations of the carbon cycle in 2015 in relation to ENSO events and
108 compared the year 2015 with the 1997–1998 El Niño event. The Multivariate ENSO Index (MEI,
109 <http://www.esrl.noaa.gov/psd/enso/mei/>) was used to indicate the ENSO state. MEI is a
110 composite index calculated as the first unrotated principal component of six ENSO-relevant
111 variables for each of the twelve sliding bi-monthly seasons. The 12 bi-monthly MEI values of
112 each year are summed to obtain the annual MEI. To examine the potential role of fire emissions
113 in the land carbon balance in 2015, we used the GFED4s carbon emission data at daily time-step
114 and 0.25° spatial resolution (<http://www.globalfiredata.org/data.html>). Monthly fire-carbon
115 emissions were calculated for the regions and were examined for 1997–2015.

116

117 **2.2 Data analysis**

118 **2.2.1 NDVI rank analysis and greening trend**

119 First, we calculated seasonal mean standardized NDVI for each pixel and each year of the period
120 2000–2015. We examined four seasons: Q1 (January–March), Q2 (April–June), Q3 (July–
121 September) and Q4 (October–December). Given a season and a pixel, the annual time series of
122 seasonal NDVI for 2000–2015 were ranked in ascending order so that each year could be labelled
123 by a rank, with 1 being the lowest and 16 the highest rank. A spatial map of NDVI rank was then
124 obtained for each year for the given season. Vegetated area fraction with the highest rank for



125 different years was obtained, with the sum of these fractions yielding unity. This procedure was
126 repeated for all four seasons to generate four seasonal time series, with each containing the
127 vegetation land fractions with highest NDVI for different years. Finally, a composite map was
128 made for year 2015, by merging pixels with the highest rank of all four seasons in 2015.

129

130 **2.2.2 Analysis of 2015 land carbon uptake dynamics**

131 Annual land and ocean carbon uptakes and carbon emissions from the two inversions were
132 calculated for the globe over their period of overlap, 1981–2015. AGRs from NOAA/ESRL over
133 1981–2015 were converted into Pg C using a conversion factor of 2.12 Pg C p.p.m.⁻¹ (Ballantyne
134 et al., 2012; Le Quéré et al., 2016), assuming that all the atmosphere is well mixed within one
135 year. For comparison, land and ocean net carbon uptakes for 1981–2015 were retrieved from the
136 Global Carbon Project (Le Quéré et al., 2016). For this purpose, a carbon flux of 0.45 Pg C yr⁻¹
137 subtracted from the inversion-derived land carbon uptakes and is added to ocean carbon uptakes
138 to account for the pre-industrial land-to-ocean carbon fluxes (Jacobson et al., 2007), following
139 Le Quéré et al. (2016).

140

141 The record high AGR in 2015 was a composite collectively determined by carbon emissions
142 from fossil fuel burning and industry, and land and ocean carbon uptakes, all being impacted by
143 a historical trend. Thus to properly attribute the 2015 AGR to historical trend and interannual
144 variation, annual time series of carbon emissions, land and ocean carbon uptakes, and AGRs
145 from NOAA/ESRL over 1981–2015 were linearly detrended to generate the detrended anomalies
146 of AGR, emissions, and land and ocean carbon uptakes. The percentages of anomalies in carbon
147 emissions, land and ocean sink in 2015 to the 2015 AGR anomaly were then calculated as
148 relative contributions by each factor to the 2015 AGR anomaly.

149

150 Seasonal land carbon uptakes were also calculated (the 0.45 Pg C yr⁻¹ correction was not applied).
151 We then examined the seasonal anomalies of 2015 land carbon uptake over different regions and
152 the globe, and the seasonal transitions. The same linear detrending was done for 1981–2015. The
153 globe was divided into two latitude bands: Boreal and temperate Northern Hemisphere (BoTeNH,
154 latitude > 23.5°N) and tropics and extratropical Southern Hemisphere (TroSH, latitude < 23.5°N).
155 The BoTeNH is further divided into boreal Northern Hemisphere (BoNH, latitude > 45°N) and



156 temperate Northern Hemisphere (TeNH, $23.5^{\circ} < \text{latitude} < 45^{\circ}\text{N}$) for further discussion.
157 Seasonal land carbon uptake transitions are calculated as the land sink anomaly in a given season
158 minus that of the former one. When examining transitions of land carbon uptake anomalies by
159 the CAMS inversion, we found the year 1993 has an extreme small Q3→Q4 global transition (-
160 2.85 Pg C within 6 months, $< -4\sigma$, the second lowest being the year 2015 with -1.0 Pg C) albeit
161 with a reasonable annual land carbon uptake ($3.75 \text{ Pg C yr}^{-1}$). This is linked with an extreme high
162 Q3 and low Q4 uptake in this year, which could not be explained by any known carbon cycle
163 mechanisms. This is thus identified as a result of numerical instability of the inversion system
164 and consequently the year 1993 has been removed from all the seasonal analyses. Finally,
165 seasonal linear detrending was also performed at grid-cell level for land carbon uptakes for both
166 inversions, as well as air temperature, precipitation and soil water content.

167

168 **3 Results**

169 **3.1 Vegetation greening in 2015**

170 Figure 1a illustrates where and when higher-than-normal greenness conditions were observed in
171 different seasons of the year 2015, compared to other years of 2000–2015 (see Supplementary
172 Fig. 1 for greenness distribution for each season). On average 17% of vegetated land shows
173 record seasonal NDVI in 2015. The year with the second highest NDVI is 2014 having only 11%
174 vegetated area with record NDVI. An increase of the record-breaking NDVI occurrence over
175 time was clearly demonstrated (Fig. 1b). In short, 2015 clearly stands out as a greening outlier,
176 having the highest proportion of vegetated land being the greenest for all four seasons except for
177 the first season (despite the fact that for Q1, 2015 is still the second highest, Q1 = January to
178 March).

179

180 For Northern Hemisphere boreal and temperate regions, the seasons with highest NDVI in 2015
181 are Q2 and Q3 (Q2 = April to June; Q3 = July to September), corresponding to the growing
182 season from spring to early autumn. A pronounced greening anomaly in Q2 occurred in western
183 to central Siberia, western Canada and Alaska and eastern and southern Asia (Supplementary Fig.
184 1). Central and eastern Siberia and eastern North America showed marked greening in Q3.
185 Strong and widespread greening also occurred in the tropics during Q3 over Amazonia and the
186 savanna (or cerrado) of eastern South America, but this positive greening disappeared in Q4 (Q4



187 = October to December) especially over central to eastern Amazonia with the development of El
188 Niño (Supplementary Fig. 1).

189

190 **3.2 Global carbon balance for 1981-2015**

191 Figure 2 shows the time series of fossil and industry carbon emissions, NOAA/ESRL AGR rates
192 linked with ENSO climate oscillations as indicated by the Multivariate ENSO Index (MEI), and
193 land and ocean carbon sinks for the common period of the two inversions (1981–2015) and the
194 estimates by the Global Carbon Project (GCP). Emissions show a clear increase with time,
195 however AGRs are more varying. The record high AGR of 2.96 p.p.m. in 2015 exceeds those in
196 all other previous years including the extreme El Niño event in 1997–98. Interannual variability
197 in AGR is mainly caused by land carbon sink fluctuations, with Pearson’s correlation
198 coefficients between detrended AGR and land sink < -0.8 ($p < 0.01$) for both inversions
199 (Pearson’s correlation coefficient between detrended AGR and MEI being 0.27, $p < 0.1$). The root
200 mean square differences between inversion and GCP carbon sinks are 0.70 and 0.65 Pg C yr⁻¹ for
201 CAMS and Jena04 respectively for the land, and ~ 0.5 PgC yr⁻¹ for the ocean for both
202 inversions, within the uncertainties of 0.8 and 0.5 Pg C yr⁻¹ over 1981–2015, respectively for
203 land and ocean as reported by GCP. The interannual variability of detrended sink anomalies for
204 the land agrees well between inversions and GCP (with Pearson’s correlation coefficient being
205 0.9 for both inversions, $p < 0.01$).

206

207 For 2015, the prescribed carbon emissions in the CAMS inversion are 9.9 Pg C yr⁻¹, of which 2.0
208 Pg C are absorbed by ocean, 1.7 Pg C by land ecosystems, with 6.2 Pg C remaining in the
209 atmosphere, which matches the AGR from background stations of 6.3 Pg C assuming a
210 conversion factor of 2.12 Pg C p.p.m.⁻¹ (Ballantyne et al., 2012; Le Quéré et al., 2016) and
211 considering a measurement uncertainty of AGR as 0.09 p.p.m. (0.2 Pg C) for 2015. When land
212 carbon fluxes from the inversion are linearly detrended over 1981-2015, the terrestrial sink in
213 2015 is 1.2 Pg C lower than normal (i.e., the trend value), but this is not an extreme value — it is
214 only the seventh weakest sink since 1981. This weaker land uptake accounts for 82% of the
215 positive AGR anomaly, which is 1.45 Pg C in 2015 by subtracting a linear temporal trend.
216 Jena04 yields an AGR in 2015 that is 0.13 p.p.m. lower than the AGR based on background
217 stations only, a difference close to the observation uncertainty. After removing the linear trends



218 over time similarly as for CAMS inversion, the land carbon uptake anomaly is $-0.3 \text{ Pg C yr}^{-1}$ in
219 2015 by Jena04 data, or 20% of the observed AGR anomaly, the remaining being explained by
220 positive anomaly in fossil fuel emissions (34%), negative anomaly in ocean sink (20%), and the
221 difference between modelled AGR and NOAA/ESRL reported AGR. Note that the land sink by
222 GCP for 2015 is much lower than the two inversions, with detrended anomaly lower than that of
223 CAMS, indicating even larger contribution from land to the high anomaly of AGR.

224

225 **3.3 Seasonal land carbon uptake dynamics in 2015**

226 To explain the seemingly paradox in 2015 between high greening and an only moderate
227 terrestrial uptake, we examined seasonal land carbon flux dynamics using both inversions. The
228 land carbon flux anomalies for each season and different regions of the globe are calculated
229 (linearly detrended over 1981-2015), and shown in Fig. 3 (refer to Supplementary Fig. 2 for
230 spatial distribution of flux anomalies). Positive anomalies indicate enhanced sink (or reduced
231 source) against the linear trend (i.e., the normal state), while negative ones indicate the reverse.

232

233 At seasonal scale, both inversions indicate positive carbon uptake anomalies during Q2 and Q3
234 for boreal and temperate Northern Hemisphere (BoTeNH, latitude $> 23.5^\circ\text{N}$), consistent with
235 marked greening in central to eastern Siberia, eastern Europe and Canada (Fig. 1) as outlined
236 above. However, an extreme follow-up negative (source) anomaly occurred in Q4 (Fig. 3b).
237 These negative anomalies were lower than the 10th percentile of all anomalies in Q4 over time
238 for both inversions and they partly cancelled the extra uptake in Q2 and Q3. As a result, on the
239 annual time scale, the CAMS inversion shows an almost neutral land flux anomaly in BoTeNH,
240 while the Jena04 inversion still indicates a significant positive annual anomaly.

241

242 For the tropics and extratropical Southern Hemisphere (TroSH, latitude $< 23.5^\circ\text{N}$), both
243 inversions show a weak negative land carbon anomaly for Q1 (mean value of -0.10 Pg C) in
244 2015, moderate anomalies in Q2 (of differing signs, with a negative one of -0.3 Pg C in CAMS
245 and a positive one of 0.2 Pg C in Jena04). Q3 anomalies are almost carbon neutral for both
246 inversions. In stark contrast, between Q3 and Q4, both inversions show an abrupt shift toward an
247 abnormally big land carbon source (i.e., negative anomalies of $\sim -0.7 \text{ Pg C}$ against a carbon
248 source expected from the linear trend, lower than 10th percentile over time in both inversions).



249 On the annual time scale, CAMS shows a large negative anomaly of -1.2 Pg C. For Jena04, sink
250 and source effects in Q1–Q3 cancelled each other, leaving the annual anomaly the same as in Q4.

251

252 Over the globe, the Jena04 inversion shows an abnormally strong sink during Q2 (normal state
253 being a net carbon sink), owing to synergy of enhanced Q2 uptakes in both BoTeNH and TroSH.

254 This abnormally enhanced uptake partly counteracted the strong shift toward source in Q4
255 (normal state being a net carbon source), leaving a small negative annual land carbon balance of

256 -0.3 Pg C. For the CAMS inversion, because of the co-occurrence of enhanced carbon release in
257 BoTeNH and the sudden shift toward a large carbon source in TroSH both in Q4 (normal states

258 being both net carbon sources), the land shows a strong global shift toward being a source in Q4,
259 leaving a negative annual carbon anomaly of -1.2 Pg C (i.e., carbon sink being reduced

260 compared with the normal state).

261

262 These consistent results from both inversions point to very strong seasonal shifts in the land
263 carbon balance as an emerging feature of 2015. We thus calculated *transitions* in land carbon

264 uptake anomaly as the first-order difference in flux anomalies between two consecutive seasons
265 (defined as the anomaly in a given season minus that in the former one) for all years of the

266 period 1982-2015 (Fig. 4). The ranks of transitions for different seasons relative to other years
267 between the two inversions are broadly similar, except for Q1→Q2 and Q2→Q3 in TroSH,

268 mainly due to the differences between the two inversions in seasonal land-carbon uptake
269 anomaly in Q2 (Fig. 3b). On the global scale, both inversions show an extreme transition to a

270 negative uptake anomaly for Q3→Q4, with 2015 being the largest transition of the period 1982-
271 2015 (a transition towards an enhanced carbon source of -1.0 Pg C in 6 months). The abnormal

272 transitions for Q3→Q4 on the global scale are located in the TroSH region, where both
273 inversions show that during 1982-2015 the largest transition occurred in 2015. For BoTeNH,

274 both inversions showed strong transitions toward positive anomaly for Q1→Q2; however, the
275 same strong transition toward source anomaly occurred in Q3→Q4, partly cancelling the sink

276 effects during growing seasons.

277

278 **4 Discussion**

279 **4.1 Seasonal land carbon uptake transitions in northern latitudes**



280 The two inversions consistently allocate a strong positive carbon uptake anomaly in the BoTeNH
281 during spring, which persists through summer (Q2–Q3): an extreme sink anomaly is simulated in
282 Q2 by Jena04, but a more moderate one by CAMS (still above the 75th percentile). The strong
283 sink in Q2 simulated by CAMS is dominated by temperate Northern Hemisphere regions (TeNH,
284 $23.5^\circ < \text{latitude} < 45^\circ\text{N}$, Supplementary Fig. 3). For Q3, an extreme carbon sink anomaly occurs
285 in boreal Northern Hemisphere (BoNH, latitude $> 45^\circ\text{N}$) in CAMS; however, an equally strong
286 negative anomaly (i.e., reduced sink) was found in TeNH in the same season, leaving the whole
287 boreal and temperate Northern Hemisphere (BoTeNH) only a moderate enhanced sink anomaly.
288 Thus for TeNH alone, CAMS indicates extreme seasonal shift from a positive anomaly in Q2 to
289 a negative one in Q3, implying abrupt seasonal transitions probably resulting from enhanced
290 ecosystem CO_2 release after growing-season uptake.

291

292 Jena04 inversion agrees with a higher-than-normal sink in TeNH ($23.5^\circ < \text{latitude} < 45^\circ\text{N}$)
293 during spring (Q2). It also reports a moderate positive anomaly for Q3 in BoNH, but does not
294 show a strong negative anomaly (i.e., reduced sink) in TeNH in Q3 as CAMS does. This is
295 possibly related to differences in the measurement station data used, to different land prior fluxes
296 (from the ORCHIDEE model in CAMS, and the LPJ model in Jena CarboScope), or to the fact
297 that Jena inversion has a larger a-priori spatial error correlation length scale for its land fluxes
298 (1275 km) than CAMS (500 km) (Chevallier et al., 2010; Rödenbeck et al., 2003). Nonetheless,
299 both inversions consistently indicate that the enhancement of CO_2 uptake during spring and
300 summer at the northern hemispheric scale was subsequently offset by an extreme source anomaly
301 in autumn (Q4).

302

303 The transition from carbon sink anomalies during Q2 and Q3 in the Northern Hemisphere to a
304 source anomaly during Q4 could be related with prevailing high temperatures in Q4, especially
305 over most of northern America, and central to eastern Siberia and Europe (Supplementary Fig.
306 4a). The strong source anomaly in temperate regions during summer (Q3) as indicated by CAMS
307 may also be partly due to the extreme drought that affected Europe (Supplementary Fig. 4b, see
308 also Orth et al., 2016) and led to vegetation browning (decreased NDVI) in this region (Bastos et
309 al., 2016). The transition toward carbon source in Q4, albeit strong uptake and high greening
310 during the preceding seasons (especially in southern to eastern Asia in Q4), highlights the



311 importance of carbon release in the autumn (Piao et al., 2008) and the carry-over effect of higher
312 leaf and fine root biomass produced in spring and summer being decomposed a few months later
313 at the end of the year.

314

315 **4.2 Seasonal land carbon uptake transitions in tropics and influences of El Niño and** 316 **vegetation fire**

317 The abrupt transition to abnormal source in the tropics and extratropical Southern Hemisphere
318 was paralleled by a marked decrease in precipitation and an increase in temperature in Q4, with
319 the development of El Niño in Q2–Q3 (Supplementary Fig. 5). Here El Niño development is
320 indicated by the rise of the MEI. This abrupt transition is consistent with the expected response
321 of tropical and sub-tropical southern ecosystems during previous El Niño events (Ahlström et al.,
322 2015; Cox et al., 2013; Poulter et al., 2014; Wang et al., 2013, 2014).

323

324 Compared with the 1997–98 El Niño, which was of similarly extreme magnitude, the 2015 El
325 Niño started much earlier with positive MEI appearing during the first half of 2014. Since then
326 until Q3 and Q4 in 2015 when El Niño began to reach its peak, the tropics and Southern
327 Hemisphere saw continuous higher-than-normal temperatures, with continually decreasing
328 precipitation and accumulating deficit in soil water content (Supplementary Fig. 5). From Q3 to
329 Q4, a steep decline is further observed in both precipitation and soil moisture with stagnating
330 high temperature anomaly, which is probably a major cause of the abrupt shift toward carbon
331 source anomaly. The CAMS inversion shows a carbon source anomaly in Q4 of 2015 slightly
332 smaller than that in Q3 of 1997, while the Jena04 inversions shows almost equal magnitudes of
333 loss in land sink strength between these two extreme El Niño events. On the one hand, El Niño in
334 late 2015 started with an early onset and built upon the cumulative effects of the drought since
335 the beginning of the year; it thus came with larger negative anomaly in precipitation and soil
336 water content than the 1997–98 El Niño. This sequence of events might favour a stronger land
337 carbon source. On the other hand, the fire emission anomaly in the tropics in 2015 was less than
338 half of that in 1997 at the peak of El Niño (Fig. S5), which might contribute to a smaller land
339 source anomaly in 2015 than in 1997–98.

340

341 El Niño events are usually associated with increased vegetation fires, and these have a large



342 impact on the global carbon cycle (van der Werf et al., 2004). Global fire emissions of carbon
343 reached 3.0 and 2.9 Pg C in 1997 and 1998 according to the GFED4s data. These two years
344 produced the largest source of fire-emitted carbon for the entire period 1997–2015. Global fire
345 emissions in 2015 reached 2.3 Pg C, close to the 1997–2015 average (2.2 Pg C yr⁻¹) but 23–24%
346 lower than 1997–98 — the difference mainly occurring in the southern tropics (0–23.5°S, Fig.
347 S5). In particular, carbon emissions from deforestation and peat fires were two times lower in
348 2015 (0.6 Pg C) compared with 1997 (1.2 Pg C) (GFED4s data), and emissions for these types of
349 fires are more likely to be a net source contribution, because they cannot be compensated by
350 vegetation regrowth within a short time. Fire emission data thus suggest a smaller contribution
351 from fires to AGR in 2015 than 1997–98. If both annual time series of AGR and global fire-
352 carbon emissions are detrended within their overlapping period of 1997–2015, fire-carbon
353 emissions have an anomaly of 0.4 Pg C yr⁻¹ in 2015, explaining only 29% of the AGR anomaly.

354

355 **4.3 Data uncertainties and perspective**

356 On the global and hemispheric scales, the inversion-derived land- and ocean-atmosphere fluxes
357 are well constrained by the observed atmospheric CO₂ growth rates on measurement sites.
358 However, because the observational network is heterogeneous and sites are sparsely distributed
359 (Supplementary Fig. 6), land CO₂ fluxes cannot be resolved precisely over each grid cell
360 (Kaminski et al., 2001) and some regions are better constrained than others. This could hinder
361 the precise matching between gridded CO₂ flux maps and climate states or the occurrence of
362 climate extremes; consequently, exact attribution of carbon uptake transitions into different
363 climate drivers could be elusive. Further, a few other uncertainties matter for the specific
364 objective of this study. First, the atmospheric network increased over time, so that the inversions
365 have a better ability to detect and quantify a sharp transition in CO₂ fluxes occurring in the last
366 than in the first decade of the period analysed. This might hide the detection of other more
367 extreme end-of-year carbon transitions during early years of our target period (1981–2015).
368 Second, because measurements for the early 2016 are not used in the CAMS inversion and not
369 completely available in the Jena inversion, the constraining of last season in 2015 is weaker than
370 for the other three seasons. This could partly influence the exact magnitude of the extreme Q4
371 negative anomaly in land carbon uptake reported here. Third, the sparse sites located in the
372 boreal Eurasia and tropical regions might diminish the ability of inversion systems to robustly



373 allocation carbon fluxes spatially, which could yield high uncertainty in the carbon fluxes
374 diagnosed for these regions (van der Laan-Luijkx et al., 2015; Stephens et al., 2007).

375

376 Despite these uncertainties, the abrupt transition of CO₂ fluxes analysed here is the largest ever
377 found in the inversion records. While transition to a strong source in TroSH is congruent with the
378 expected response of ecosystems to the peak of an El Niño event, it is not completely clear which
379 mechanisms are driving the reported abrupt seasonal transitions on the global scale. For instance,
380 for the tropics and Southern Hemisphere, it is unclear whether the dry conditions already in place
381 before the full development of El Niño implied moderate Q2 and Q3 vegetation carbon uptakes
382 followed by moderate respiration as well in Q4, or if it is mainly due to enhanced respiration in
383 late 2015 that dominated such a transition. For the boreal and temperate Northern Hemisphere,
384 further investigation is still needed to verify whether a coupling between strong spring/summer
385 uptake and autumn release is something intrinsic to natural ecosystems, or if strong transitions to
386 autumn release are triggered by abrupt climate shifts. This could be evaluated by process-based
387 and data-driven models to partition the overall sink anomaly into individual responses of
388 photosynthesis and respiration, but that is beyond the scope of this work. Our results point to the
389 need to better understand the drivers of carbon dynamics at seasonal, or even shorter time scales
390 at the regional to global level, especially the link between such dynamics and climate extremes.
391 Such understanding would help better predictions of the response of the carbon cycle to multiple
392 long-term drivers such as atmospheric CO₂ growth and climate change.

393

394 **5 Conclusions**

395 We investigated seasonal dynamics of land carbon uptake in 2015 using data from two
396 atmospheric inversions, focusing on reconciling the seemingly paradox between the greatest
397 vegetation greenness and the highest atmospheric CO₂ growth rate. We found that lands in
398 Northern Hemisphere started with a higher-than-normal sink for the northern growing seasons,
399 consistent with enhanced vegetation greenness partly owing to elevated warming, however this
400 enhanced sink was partly balanced by enhanced carbon release in autumn and winter. For tropics
401 and Southern Hemisphere, a strong and abrupt transition toward a large carbon source for the last
402 quarter of 2015 was found, concomitant with the peak of El Niño development. This abrupt
403 transition of terrestrial CO₂ fluxes in the last quarter is the largest in the inversion records since



404 1981. The abrupt transitions in CO₂ fluxes diagnosed in this study form an interesting test bed
405 for evaluating ecosystem models and gaining understanding of their controlling processes.



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507

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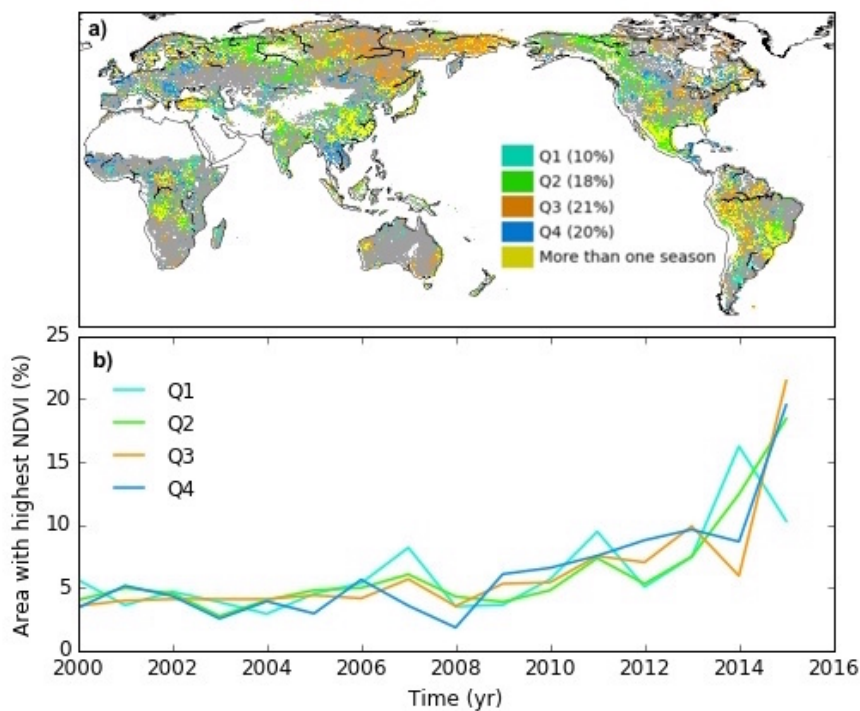
517

518 **Author contributions**

519 P.C., F.C., C.Y. and A.B. conceived the study. C.Y. performed the analysis and made the first
520 draft. F.C. and C.R. provided the inversion data. All authors contributed to interpretation of the
521 results and drafting the paper.



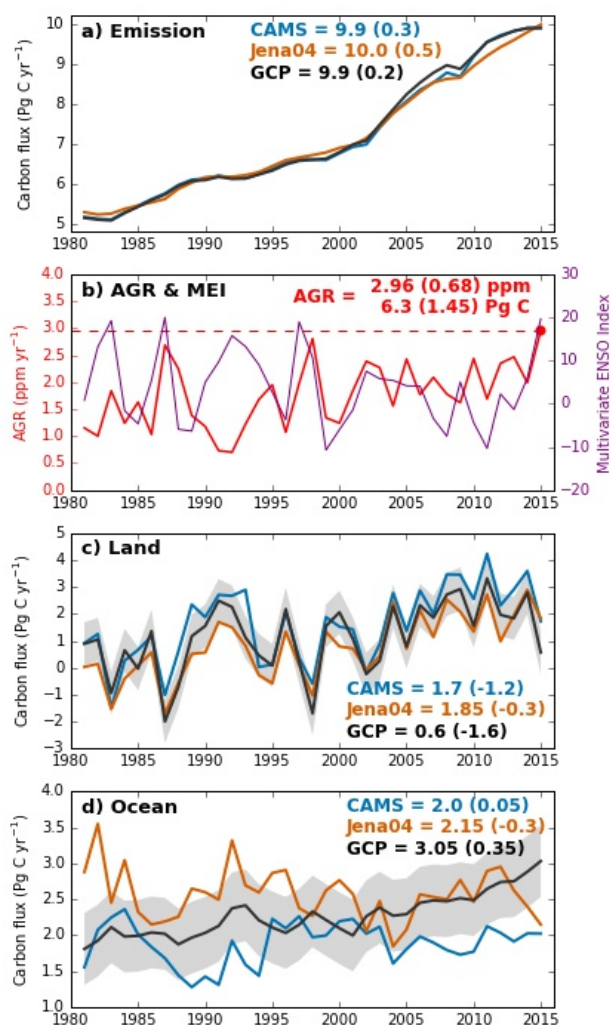
522 **Figure 1 Year 2015 as the greenest year over the period 2000-2015.** (a) Distribution of
523 seasons for which 2015 NDVI ranks the highest during the period 2000-2015. Yellow-coloured
524 pixels indicate grid cells where 2015 NDVI ranks highest for more than one season. For each
525 season, the fraction of global vegetated land area for which 2015 NDVI ranks highest is shown
526 in the inset colour bar. (b) Temporal evolution of the percentage of vegetated land with highest
527 NDVI over 2000-2015 for each season and different years. The sum total of vertical-axis values
528 for each season over all years is 100%. Q1 = January–March; Q2 = April–June; Q3 = July–
529 August; Q4 = September–December.



530



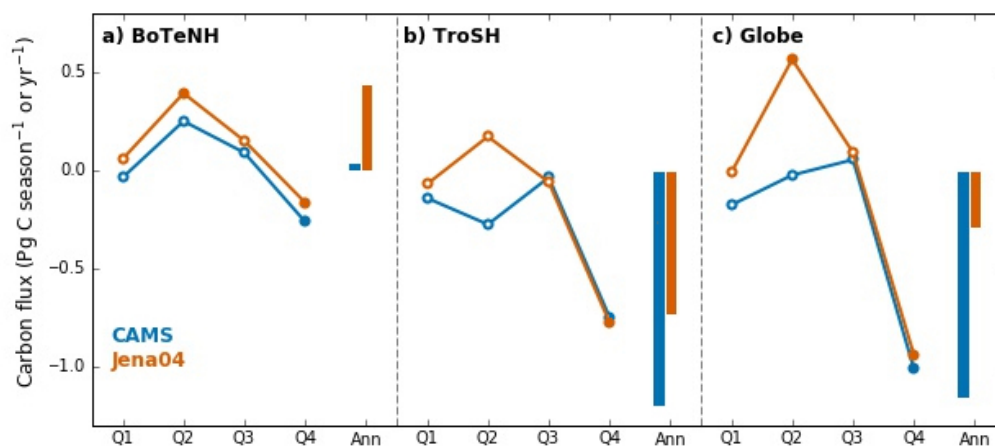
531 **Figure 2 Global carbon fluxes and atmospheric CO₂ growth rates for 1981–2015.** (a) Carbon
532 emissions from fossil fuel and industry used in the CAMS (blue) and Jena04 (orange) inversions,
533 (b) annual atmospheric CO₂ growth rate (AGR, in red) from NOAA/ESRL linked with
534 Multivariate ENSO Index (in purple), and (c) land and (d) ocean carbon sinks for 1981-2015.
535 Emissions and land and ocean carbon sinks from the Global Carbon Project (GCP, in black) are
536 also shown for comparison. In subplots c and d, a carbon flux of 0.45 Pg C yr⁻¹ was used to
537 correct inversion-derived land and ocean sinks to account for pre-industrial land-to-ocean carbon
538 flux as in Le Quéré et al. (2016). All numbers indicate values in 2015 (Pg C yr⁻¹), with those in
539 brackets showing linearly detrended anomalies for the same year.



540



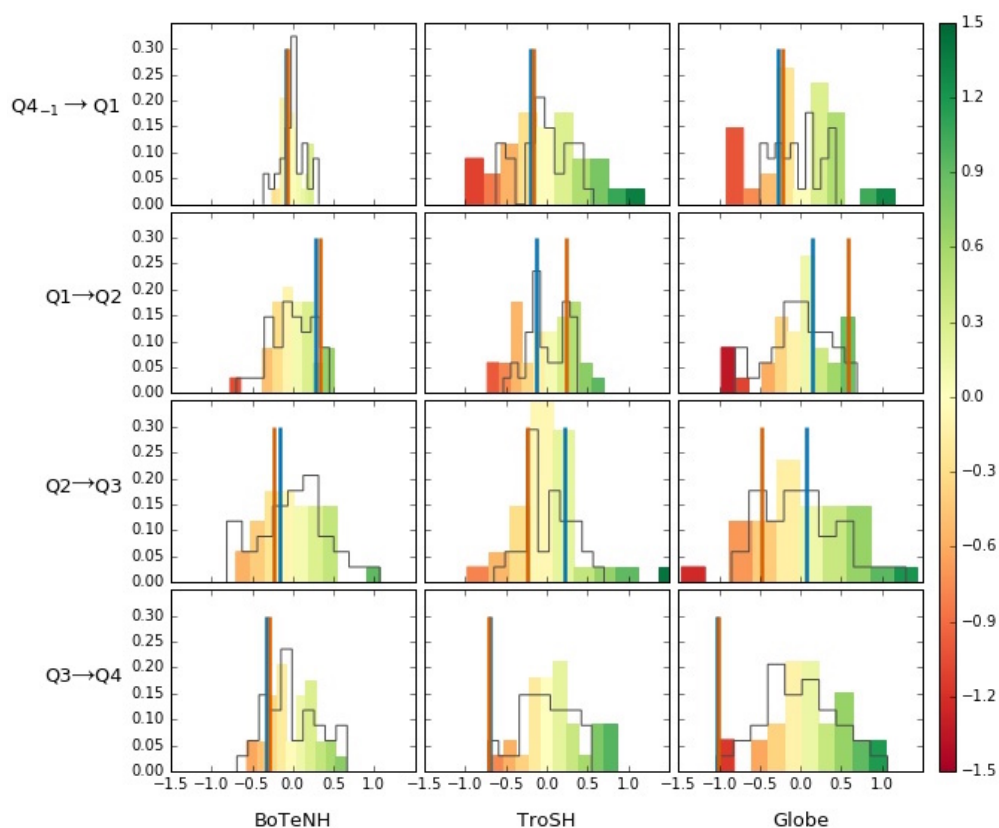
541 **Figure 3 Seasonal land carbon uptake anomalies in 2015.** Data are linearly detrended over
542 1981-2015 for different seasons in 2015, by CAMS (blue) and Jena04 (orange) inversion data.
543 Open or solid dots indicate seasonal values (Pg C season^{-1}) and vertical bars indicate annual
544 sum (Pg C yr^{-1}). Data are shown for: **(a)** boreal and temperate Northern Hemisphere (BoTeNH, >
545 23.5°N), **(b)** tropics and southern extratropical hemisphere (TroSH, $< 23.5^\circ\text{N}$) and **(c)** the whole
546 globe. Solid dots indicate seasonal land carbon uptake anomalies below 10th or above 90th
547 percentiles over 1981-2015.



548



549 **Figure 4 Extremeness of transitions in seasonal land carbon uptake anomaly in 2015.**
550 Histograms for seasonal land carbon uptake transitions over 1981-2015 for boreal and temperate
551 Northern Hemisphere (BoTeNH, latitude $> 23.5^{\circ}\text{N}$), tropics and extratropical Southern
552 Hemisphere (TroSH, latitude $< 23.5^{\circ}\text{N}$) and the whole globe. Transition between two
553 consecutive seasons is defined as the linearly detrended land carbon uptake anomaly in a given
554 season minus that in the former one. Coloured bars show histograms for CAMS data (red colour
555 for a negative transition and green colour for a positive one), with the vertical-axis indicating
556 frequency and blue solid vertical line indicating year 2015. Grey step lines indicate histograms
557 for Jena04 data overlaid on top of CAMS data, with vertical orange solid lines indicating values
558 for 2015.



559