Responses to

Interactive comment on "Abrupt seasonal transitions in land carbon uptake in 2015" *by* Chao Yue et al.

Anonymous Referee #1

Received and published: 19 February 2017

The article "Abrupt seasonal transitions in land carbon uptake in 2015" by C. Yue and coauthors presents a detailed analysis of anomalies in carbon sinks and sources, climate and vegetation greenness during recent decades with an emphasis on the year 2015. Understanding the carbon cycle and its interaction with climate change is a highly relevant research topic, and the authors refer to state-of-the-art literature and datasets. The authors combine a number of observational datasets and model results, and my impression is that their methods and results are sound. The description of the work steps is clear and the data sources are well documented. In this regard, the article is good at what it does.

My major concern however is that it remains unclear what the authors are trying to achieve with this article. I would guess that the results might tell us something about how climate affects vegetation and the carbon cycle. What do the results imply about the relevant processes, about past climates and potential future developments, or about our potential to model these processes? The authors address such questions only briefly in the last paragraph of Sect. 4 and in the very short Sect. 5, stating that they go beyond the scope of the article.

[Response] We thank the general positive comments by the reviewer. We were originally aiming for two purposes in this article: (a) to diagnose the anomaly of large scale CO_2 fluxes for 2015 given the specific nature of that year, as a case study (high CO_2 growth rate, anomalously strong vegetation greenness and the historically highest annual temperature), using atmospheric inversion data, and (b) to diagnose whether abrupt transitions have occurred in terrestrial carbon uptake in 2015, and briefly infer the reasons for such transitions.

We agree with reviewer that the exploration of the general links among vegetation greenness, land carbon uptake dynamics and climate variations is necessary in order to put the 2015 case into a more general picture, to infer general patterns of land carbon dynamics that could be useful for future prediction of land carbon dynamics. We add this point as one of the research aims of our paper. According changes are made in revised abstract, and the 3rd paragraph of the revised Introduction section.

We have extensively revised the manuscript to incorporate correlations of land carbon uptake anomalies with vegetation greenness anomalies and climate anomalies related with ENSO dynamics. Two new figures (Fig. 3, Fig. 4) are added in the main text, and three new figures (Fig. S4, S5, S7) are added in the Supplementary Material. Results and discussion sections are substantially expanded to include more discussions on the mechanisms underlying land carbon dynamics relevant to the purpose of this study.

I also wonder why the authors focus so much on the year 2015. What is so special about this year (apart from being relatively recent) that would justify this focus, and what can we learn from this case study that is valid in a greater context? If there is something I am overlooking, I suggest that the authors reframe their article to bring out their message more explicitly, and that they stress what the progress is compared to previous articles. I believe that this would improve the impact of their article. For example, the authors could systematically relate anomalies in climate, carbon fluxes and NDVI using the whole record, and not only focus on 2015. They should also consider to include the year 2016 (if possible) to capture the full recent El Nino event. It appears a bit arbitrary that they pick the year 2015 and one other previous El Nino event for their analysis, using the rest of their data only to calculate linear trends. A more comprehensive statistical analysis of the available data might allow more general conclusions without the need of running climate models.

So far, the main selling points of the paper seem to be

(i) the (arguably) counterintuitive combination of high NDVI and negative carbon uptake anomaly (ii) large anomaly of the year 2015.

Regarding (i), I find it little surprising that greening and carbon loss (or a reduced carbon sink) can go together since both anomalies can be dominated by different locations and different seasons, and because they are not linearly related given the complex ecological processes involved. The authors point this out themselves, hence invoking a “paradox” seems a little exaggerated to my taste. (But I would be curious if this anti- correlation is a temporal feature or a robust trend that can be expected to continue in the future; something the authors might choose to give more attention to.) Regarding (ii), I find it misleading to speak of an “abrupt transition” (title, abstract and line 263+). This term gives the impression of a singular event with long-lasting consequences, like a forced non-reversible switch to another state or regime. However, the phenomenon discussed in the paper appears to be an anomaly that is the realisation of natural variability, hence an extreme but temporal event. This comes on top of a gradual trend to larger growth rates, so the year 2015 will most likely not be unique. In fact, the atmospheric growth rate of CO2 in 2016 was even higher than in 2015. I therefore wonder whether the term “abrupt transition” is useful here, and would suggest a more suitable term, e.g. the land carbon uptake anomaly in 2015. I therefore also strongly suggest a change in the paper’s title.

[Response]

(1) We now use the full 1981–2015 data and performed statistical analysis of vegetation greenness, land carbon uptake and climate anomalies for different regions and seasons. These results are incorporated in the revised manuscript in both result and discussion sections, with findings from previous studies being extensively referred to and discussed as well.

(2) We maintain the “paradox” expression because we think it is adequate to describe the year 2015, which comes with extreme greenness and an only moderate land carbon sink. Higher greenness is sometimes simply assumed to be associated with higher sink, but this is not necessarily true, as is also pointed out by the reviewer. We now examine in more detail in the revised the relationship between land carbon uptake and vegetation greenness for different seasons and regions.

(3) As explained in the response to the previous comment, now the manuscript is restructured around two research aims: to examine general relationships among vegetation greenness, land carbon uptake and climate variations, and to examine the 2015 as a special case on how land carbon dynamics have responded to a combination of extreme greenness and ENSO climate variations. This is made clear in the revised manuscript. According changes are made in the title of the paper, abstract, 3rd paragraph of the “Introduction” section, results and discussion.

(4) We mostly drop the word ‘abrupt’ given its potential confusion in an ecological context and, instead, the word “strong” is used.

(5) We change the title to reflect the revision in the manuscript content to “Vegetation greenness and land carbon flux anomaly associated with climate variations with a special focus on the year 2015”.

(6) We did not include the year 2016 into the current analysis because the inversion data are not available yet. But we believe focusing on the year 2015 could already generate meaningful conclusions from our manuscript.

Minor comments

- line 85-86: “We used ... includes”

[Response] we changed 'includes' to 'including'.

- line 89: What is a validity period, and in what sense are the other years are not valid?

[Response] Site observations used in the Jena CarboScope inversion are coherent over time within the so-called "validity period", but are not outside the validity period. More specifically, the validity period is defined by the one using a consistent number of sites, i.e., all sites that have observations over such a period. Outside the validity period, site numbers changed depending on their availability or operation time. It is optimal to examine the temporal trend within the validity period, but this does not mean the data outside this period are invalid and should not be used. In fact, the same situation also happens for the CAMS inversion, which considers a variable number of sites during the full study period. Because our analysis has to reconcile the need of a large site number in 2015 and long historical period for a robust anomaly estimate, using the s04_v3.8 run outside its validity period is therefore a compromise. Besides the responses here, we made the according changes in Section 2.1.1.

- line 108: Why do the authors pick MAI to characterise the ENSO state?

[Response] We believe the reviewer means MEI rather than MAI. MEI (Multivariate ENSO Index) is the first unrotated principal component of six variables over the tropical Pacific that are closely linked with ENSO. Among the six variables sea-level pressure, sea surface temperature and surface air temperature are included. MEI has been widely used in literature as an indicator for the ENSO state, for instance, Nemani et al., 2003; Wang et al., 2013; van der Werf et al., 2008. The MEI should, therefore, summarize not only the ocean component of ENSO (El-Niño), but also the atmospheric component (the Southern Oscillation).

As a complement to MEI, we also used the Oceanic Niño Index (ONI, http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_change.shtml) when comparing the evolution of El Niño events of 1997 and 2015 in Supplementary Figure S10. The ONI tracks the running 3-month average sea surface temperatures in the east-central tropical Pacific between 120°-170°W (the Niño 3.4 region). Supplementary Figure S10 shows very similar temporal patterns of MEI and ONI during El Niño evolution especially when El Niño reached its peak, indicating the suitability of MEI being used in ENSO-related analysis.

The pieces of information described above are also included in the revised manuscript in appropriate sections (section 2.1.3, 1st paragraph of section 4.2).

- line 141-148. At the first reading I did not understand the role of the "historical trend" for the growth rate in a given year. I understand now that specific anomalies in 2015 are later related to climate anomalies, with anomalies being defined as residuals after removing a linear trend. The reasoning behind this could be explained more explicitly here.

[Response] We added the following text in this paragraph (1st paragraph of section 2.2.2) to make it more explicit and hope it will help clarify better: “The record-breaking AGR in 2015 thus must be put into an historical perspective to reconcile evidence for extreme greening and the highest atmospheric CO2 growth rate. For example, if 2015 comes up with a large increase in carbon emissions accompanied by droughts (browning) in the northern hemisphere and the tropics, then the highest AGR might not be regarded as a big surprise. Therefore, to understand the contributing factors for the highest AGR in 2015, it must be separated into a long-term trend and interannual anomalies.”

- line 201: both instead of bother

[Response] This has been corrected.

- line 136: It would help non-experts to briefly explain how the sources and sinks are quantified in the GCP. How independent is this dataset from the inversion calculations?

[Response] Estimates of land and ocean carbon uptakes are largely independent from the two inversions used in this study. We have inserted the following text in this paragraph (last paragraph of section 2.1.1) to clarify this: “Estimates of ocean carbon uptake in GCP are based on observation-based mean CO_2 sink estimate for the 1990s and variability in the ocean CO_2 sink for 1959–2015 from global ocean biogeochemistry models. Estimates of land carbon uptake in GCP are calculated as the difference between anthropogenic emissions, atmospheric CO2 growth and ocean sink. The estimates of land and ocean carbon uptake in GCP are largely independent from the two inversions used here, except that the CO_2 records from atmospheric stations which are used in inversions are also used in GCP to derive global AGR.”

- Sect. 2.2.1: It would help me to already see time series and a map as a visualisation of the rank analysis. I understand the structure of the paper and find it reasonable, but it could make sense to merge the data analysis section 2.2 with Results Sect. 3. Otherwise, one has to read the methods section without visualisation, and later remember each methodological detail when the results are shown. This is a matter of taste and I leave it to the authors to reconsider the structure.

[Response] Relevant figures (Fig. 1, Supplementary Fig. S1, Supplementary Fig. S3) are now cited in this section in the revised manuscript to help readers understand better the methods. But we maintained the methods and result as two separate sections mainly for the clarity of the structure.

- line 226: “the seemingly paradox” is grammatically wrong.

[Response] “seemingly” is changed to “seeming”.

- line 350: data suggests (not suggest)

[Response] Corrected.

- Supplementary Material: I suggest to put captions underneath (not above) the figures and increase the space between the figures. There is too much space between the caption of Fig. 2 and Fig. 2. These things make it difficult to identify the right caption for each figure.

[Response] Figure captions are now put below figures.

Responses to

Review comments of "Abrupt seasonal transitions in land carbon uptake in 2015" by Chao Yue et al.

Matthias Forkel, 2017-03-08

1. Does the paper address relevant scientific questions within the scope of ACP?

The article by C. Yue et al. addresses annual and seasonal variabilities in global land carbon uptake and the relations with climate and vegetation. This paper is within the scope of ACP.

2. Does the paper present novel concepts, ideas, tools, or data?

The paper is based on well established datasets and methods to generate such data (CO_2 measurements, NDVI data, atmospheric inversion). The title and the abstract of the paper mainly highlights one finding of the study about "abrupt seasonal transitions in land carbon uptake". This finding is not really new (except the focus on 2015) but the results of the study are a good opportunity to remind the land carbon cycle community about such mechanisms and to point to the year 2015 as a remarkable example of such seasonal transitions.

3. Are substantial conclusions reached?

The entire study is focussed on anomalies of the land carbon uptake in the year 2015 relative to the period 1981 to 2015. Consequently, the conclusions are very specific for climate/carbon cycle mechanism in this year. To make this paper more interesting for the land carbon cycle community and to reach more substantial and less specific conclusions, I would recommend to perform similar analyses also for other years and to finally draw conclusions about general mechanisms in comparison to specificities in single years. In this point, I completely agree with Anonymous Referee #1.

[Response] We examined extensively the relationship between anomalies in land carbon uptake, NDVI and climate variations. These new analyses are incorporated in the substantially revised results and discussion section.

4. Are the scientific methods and assumptions valid and clearly outlined?

Overall, yes. For some datasets, I would expect scientific references additionally to the URLs from which the data was obtained (especially in Sections 2.2.2 and 2.2.3). The only exception is the analysis of NDVI data (Section 2.2.1): For example, the authors calculated "seasonal mean standardized NDVI". Although I have some experience with NDVI data (Forkel et al., 2013), I cannot imagine what this term means. How were NDVI values standardized? Why? Furthermore, mean NDVI values of winter seasons in northern regions are not very useful to draw conclusions about vegetation productivity or land carbon uptake. As NDVI is a land surface property it is not only affected by vegetation but outside the peak of the growing season strongly by changes in snow cover and soil reflectance. Consequently, a certain ranking in a season espcially in northern regions might be due to the variability in snow cover but not in vegetation. The authors need to appropriate filter the NDVI time series to separate vegetation signals from other non-vegetation distortions (Hird and McDermid, 2009; Holben, 1986; Kandasamy et al., 2013). Furthermore, NDVI datasets from different sensors show large differences which are especially important for seasonal anomalies that are outside of the peak of the growing season (D'Odorico et al., 2014; Fensholt and Proud, 2012; Kern et al., 2016; Scheftic et al., 2014). Consequently, I'm wondering if the shown ranking of seasonal NDVI values (Fig. 1) is a robust result given the noise of NDVI data and the differences between datasets. This rises the question if 2015 is indeed the greenest year.

[Response] The scientific citations for MEI and NDVI are provided in additional to URL links. NDVI reflects in general vegetation green fraction, and is considered as a proxy of green leaf area (Gamon et al., 1995; Ide et al., 2010) Its temporal magnitudes have been used to infer changes in vegetation productivity (Myneni et al., 1997; Zhao and Running, 2010). In response to the reviewer's comments, we have updated our results by using a new NDVI data set that went through rigorous quality control, with the cloud- and snow-contaminated pixels being removed and gap-filled. Note that the original NDVI values, rather than standardized anomalies, are used. Seasonal NDVI values lower than 0.1 were further removed to make sure the used NDVI values reflect the dominance of vegetation information.

Because of filtering NDVI values by a minimum of 0.1, we are cautiously confident that the vegetation greenness reflects (at least partly) the vegetation information even in the first (Q1) and fourth (Q4) trimester of the year when snow is present in the northern hemisphere. In fact, October is frequently considered within the growing season and some evergreen coniferous forests show significant photosynthetic activities in March in regions of mild winter, e.g., Tanja et al., 2003). Here we show that, most of the grid cells where 2015 shows the highest NDVI for northern land (Fig. CS1, region with latitude > 30°N) are in fact dominated by Q2 (April–June) and Q3 (July–September), corresponding roughly to northern hemisphere growing season. The vegetated land area (i.e., with a seasonal NDVI value higher than 0.1 in either of the four seasons of 2015) with the highest NDVI rank in 2015 in the northern land accounts for 36% of all land area, in contrast with an expected mean of 6.25% if the land is equally green over all years of 2000–2015. This highlights again the extreme greening during the growing season in the northern hemisphere in 2015, as has been examined in more detail in Bastos et al. (2017).

Q1 and Q4 account for 34% of the land area where 2015 NDVI ranks the highest in northern land. These grid cells are either dominated by evergreen forests (central Canada, northwestern Europe), or by oceanic climate where evergreen forests prevail (eastern Canada and US, Europe) (Fig. CS2). As shown in Fig. CS3, the land north to 23.5°N contributes primarily to the overall highest annual NDVI in 2015, whereas in tropics (23.5°S–23.5°N) and southern extra-tropics (latitude > 23.5°S), the NDVI in 2015 is only moderately high (0–23.5°N) or around the multi-annual mean value (southern hemisphere).

Therefore, we conclude that, globally, 2015 is the greenest year of 2000–2015, in terms of both the mean annual NDVI value, and the number of grid cells where NDVI shows the highest rank in 2000–2015. This greenest signal is dominated by the extreme greenness in the growing season of the northern hemisphere, which has been examined in details in Bastos et al. (2017) and identified as a robust phenomenon independent of different satellite sensors used, or quality control procedures of the data. The Fig. S1 in Bastos et al. (2017) confirmed that both data from Terra and Aqua sensors show that 2015 has the highest growing season NDVI in 2000–2015. They also confirmed that such a conclusion is consistent among three quality control strategies of the Terra MODIS data used (Page 3, Bastos et al. 2017).

As the extreme greenness in 2015 is used as a starting point for our study and the main objective of our paper is to report the carbon dynamics and seasonal shifts in land carbon uptake associated with climate variations. We're fairly confident that sufficient evidences have been provided regarding the vegetation greenness for this specific year.

Relevant revisions are made in the main text and the Supplement (section 2.1.2, section 2.2.1, and 2nd paragraph of section 3.1 in the main text, and Supplement Fig. S2, Fig. S3).

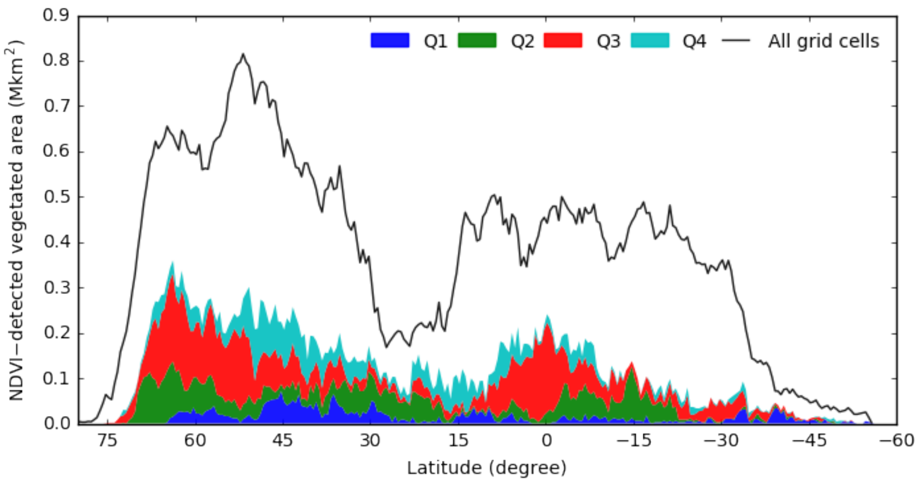

Fig. CS1 Seasonal distributions of land areas where 2015 shows the highest NDVI since 2000 as a function of latitude. Shaded areas represent different seasons stacked on top of each other.

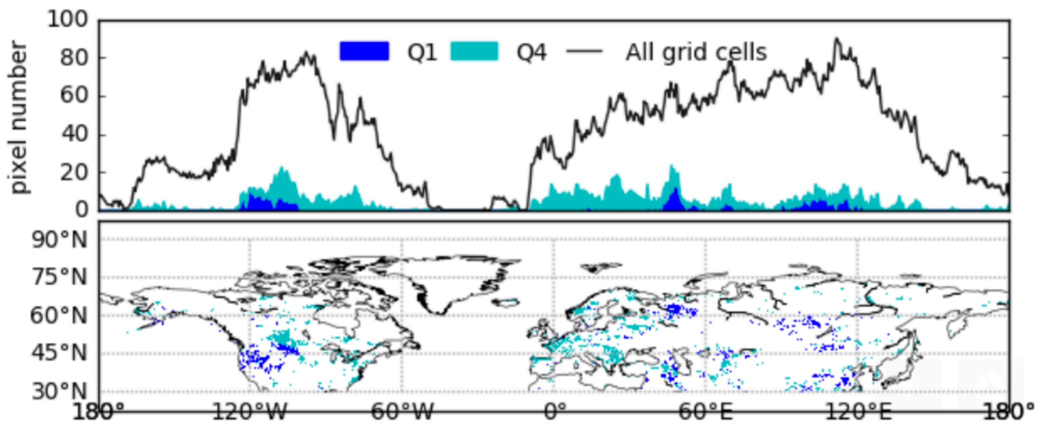

Fig. CS2 (Top) Longitudinal distribution of the number of grid cells where 2015 NDVI ranks the highest in Q1 or Q4 of 2015 for the northern lands (latitude > 30°N). (Bottom) Spatial distribution of grid cells where NDVIs rank the highest for 2015 in Q1 or Q4 for the northern land (latitude > 30°N).

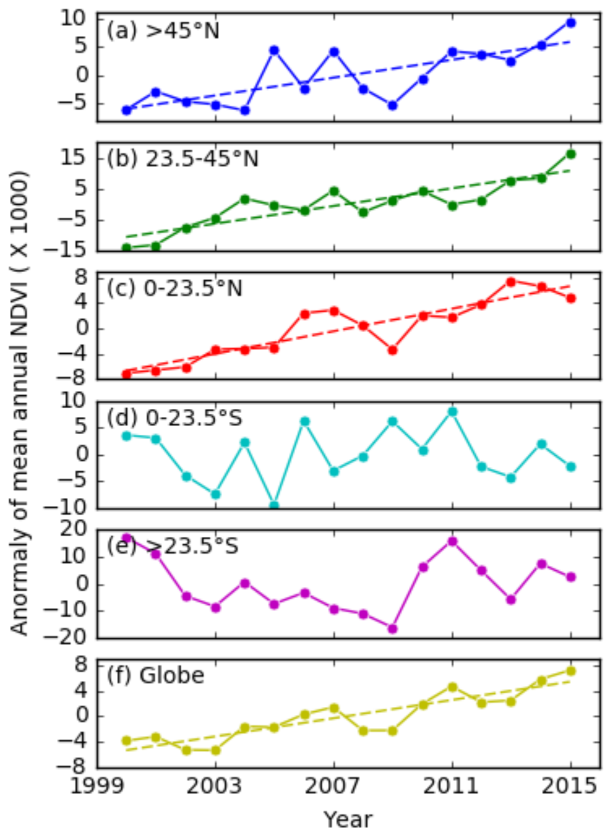

Fig. CS3 Annual NDVI anomalies for different latitudinal bands. The trend line is shown only for regions where significant simple linear regression over time is obtained.

5. Are the results sufficient to support the interpretations and conclusions?

Apart from the NDVI issues described above, the results are described in great detail and support the interpretation and conclusions.

[Response] Please refer to the responses to the comment above regarding the NDVI.

6. Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)?

The calculations are mostly well described. The calculation of seasonal NDVI ranks seems to be a new approach to analyse NDVI time series (at least no reference is provided). Therefore I would recommend that the authors present some more details on this approach (at least in the Supplement) and ideally could provide also the code.

[Response] The NDVI ranking is mainly used to show the spatial distribution of abnormal greening in

2015, and that 2015 is in general the greenest year over 2000-2015 across the globe, which is dominated by extreme greening in northern land. Please also refer to our responses to the Comment 4 for more information. Fig. S3 in the revised Supplement shows the NDVI anomalies for different latitude bands, which clearly indicate that the highest annual NDVI over the globe is driven by the extreme green anomaly in the northern land (>23.5°N). The code used to generate Figure 1 in the texts is made available through a public repository (https://github.com/ChaoYue/ACPD-2016-1167).

7. Do the authors give proper credit to related work and clearly indicate their own new/original contribution?

Yes. The cited literature is relevant for this study. The own contributions of the authors are clear. However, I would recommend to provide a more detailed discussion on the link between vegetation greenness from satellites and carbon cycle or atmospheric CO_2 variability in order to improve the discussion section that is currently strongly focussed on the specificities of the year 2015. The results of this paper could be for example discussed with respect to the following relevant papers (Angert et al., 2005; Forkel et al., 2016; Gonsamo et al., 2017; Keenan et al., 2016; Myneni et al., 1997; Thomas et al., 2016).

[Response] We have substantially strengthened the discussion by making new analysis regarding the links among vegetation greenness, land carbon uptake anomalies and climate variations (Fig. 3, Fig. 4 in revised manuscript, Fig. S4, S5, S7 in the revised Supplement). Please also refer to our responses to the #2 Response to the comments by #1 reviewer.

8. Does the title clearly reflect the contents of the paper?

Yes. However, I recommend to extent the analysis to more years to draw less specific concluisons for a single years. This might imply to change the title accordingly.

[Response] We extended the analysis by including more years and provided new figures in both main texts and the Supplement. Please also refer to our responses to the first and second comment by #1 reviewer. The manuscript title is also changed to: Vegetation greenness and land carbon flux anomaly associated with climate variations with a special focus on the year 2015.

9. Does the abstract provide a concise and complete summary?

Yes. The abstract is well written.

[Response] The abstract is updated to reflect the additional analysis that is conducted.

10. Is the overall presentation well structured and clear?

Yes.

11. Is the language fluent and precise?

Yes (as far as I can judge this). Some sentences are however too long and thus difficult to read, for example: lines 74-78, 90-93,

[Response] These sentences are re-phrased to enhance their readability.

12. Are mathematical formulae, symbols, abbreviations, and units correctly defined and used?

Yes. Units and proper axis descriptions are missing in Fig. 4.

[Response] This is fixed.

13. Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated?

Lines 71-74 are repeating lines 58-61 and can be merged.

[Response] Lines 58–61 are removed as they're repeated in section 2.1.1.

Lines 81-93: The affect of station network density on the inversion is well described for the CarboScope product. According to my understanding, the CAMS inversion should have the same problems. Please clarify how these issued are handled in the CAMS inversion.

[Response] The CAMS inversion uses sites with at least 5-year worth of data. It therefore has a denser (during the recent decade) but temporally evolving data coverage than Carboscope. The evolving network in CAMS causes changes in inverted CO_2 fluxes that are superimposed on changes from biogeochemical drivers during the whole period. Relevant revised texts are inserted in lines 116–119, on Page 4.

Lines 131-139: Please make clear why the conversion from ppm to PgC was done and if there is any relevant uncertainty in this conversion factor.

[Response] The conversion of ppm to PgC is to express the atmospheric 'sink' of CO_2 in the same unit as carbon fluxes diagnosed from inversions, in order to coherently assess contributions from different fluxes to the AGR in 2015. This is explained in the revised texts. We used a conversion factor of 1ppm CO_2 = 2.12 Pg C (Ciais et al., 2014; Prather et al., 2012). For multi-decadal analysis, this ratio is correct given the sufficient mixing of CO_2 in the atmosphere because the value of 2.12 Pg C ppm^{-1} considers the effect of a flux equilibrated with the troposphere (mixed in ≈ 1.2 years) and the stratosphere (mixed in ≈ 5 years). However we used this ratio on an annual basis, with the assumption that the entire atmosphere is well mixed within one year. This approximation is explicitly stated in the main text.

Such a ratio is mainly based on Ballantyne et al. (2012) & Le Quéré et al. (2016). We admit there are uncertainties in this ratio. Ballantyne et al. (2012) gave a relatively detailed discussion in their methods. On the one hand, the stratosphere is less well mixed with CO_2 than the troposphere, using CO_2 measurements at marine boundary layer (MBL) might overestimated the atmospheric CO_2 sink (thus implying a ratio that should be smaller than 2.12). But on the other hand, there is also CO_2 gradient from the continental boundary layer to marine boundary layer, which could compensate for the insufficient mixing in the stratosphere. Ballantyne et al. (2012) finally reached the conclusion that these two factors roughly cancel out each other by citing the close estimated MBL and whole atmosphere CO_2 concentrations. In our case, the partitioning of the AGR anomaly in 2015 is not our central purpose. The majority of conclusions reached by our analysis in the paper are based on the inversion-based land carbon uptake anomalies by the two inversion data sets used. Thus we argue the uncertainty of this conversion factor does not significantly impact our results.

No revised texts are made in the main text because we think the uncertainty introduced by this factor is minor to the robustness of our conclusion, and because the underlying assumption to use such a factor is already well stated in the text (line 194–195, Page 7).

Lines 163-164: What do you mean with “numerical instability”? Why could such an instability happen and why in 1993?

[Response] We mean rounding errors that accumulate rather than cancel. We have been experiencing these artifacts more often with increasing assimilation periods over the years, because the grid-point scale inversion problem becomes larger. To our knowledge, there is no particular reason why it happens in 1993 rather than in another year. We usually manage to remove these instabilities by re-running the inversion under slightly changed inversion configuration parameters, but this has not been done for this version.

Line 296: I thought that the Jena inversion system uses flat land prior fluxes. Are results from the LPJ model really used?

[Response] LPJ is used as a time-average spatial pattern, but concerning time variability as relevant here, the CarboScope prior is indeed flat (no prior interannual variations by periodical seasonal variations).

Figure 4: The figure could be much easier to read if you do some changes: #1 The red-green colour scale is not needed because the same information is already provided by the x-axis. Additionally, this colour scale might be not visible for colour-blind people. #2 The main purpose of this figure is to compare distributions of seasonal transitions from CAMS and Jena04. Overlaid histograms are not a good graphical choice. I would recommend to rather show distributions in terms of density lines, boxplots or violins which would make it easier to compare the distribution of CAMS and Jena04. The vertical lines for the year 2015 can be still added if you want to keep the focus on this year. #3 Please provide labels and units for the x-axis.

[Response] We removed the color in the vertical bars, and changed this plot into line plot of histograms for clarity. Labels and units are provided for x-axis.

14. Are the number and quality of references appropriate?

Yes, but also refer to my answer to the question #7.

[Response] We expanded substantially the discussion by citing relevant previous studies. The reference list is updated accordingly.

15. Is the amount and quality of supplementary material appropriate?

Yes, but an improved processing and uncertainty assessment of NDVI data might require more details in the supplementary material.

[Response] We provide further figures (Fig. S2, Fig. S3) in the Supplement regarding the 2015 extreme greening.

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Vegetation greenness and land carbon flux anomalies associated with climate variations with a focus on the year 2015

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Abstract

Enhanced vegetation greening during the past decades over the northern hemisphere was found to be linked with an increasing land sink. In the meantime, interannual variability in the atmospheric CO_2 growth rate is strongly coupled with land carbon uptake dynamics in the tropics, driven by the El Niño–Southern Oscillation (ENSO) climate variations. One may thus wonder how land ecosystems respond to the co-occurrence of extreme greening and an El Niño event. The year 2015 provided an ideal case study for such examination. It was the greenest year since 2000 according to satellite observations of vegetation greenness, but a record atmospheric CO_2 growth rate also happened, associated with a weaker than usual land carbon sink. To reconcile these two observations that may seem paradoxical at first sight, we examined the patterns of large-scale CO_2 fluxes using two atmospheric inversions and the general links among vegetation greenness, seasonal land carbon uptake and climate variations. Inversion results indicate that the year 2015 had a higher than usual northern land carbon uptake in spring and summer, consistent with the greening anomaly. This higher uptake was however followed by a larger source of CO_2 in autumn, suggesting that the extra uptake during the growing season was coupled to and offset by a larger release in the late growing season. Vegetation greenness shows strong positive correlation with land carbon uptake in the northern hemisphere during the

growing season, but outside growing season their relation is rather weak. For the tropics and Southern Hemisphere, a strong and abrupt transition toward a large carbon source for the last trimester of 2015 is discovered, concomitant with the El Niño development. This transition of terrestrial tropical CO_2 fluxes between two consecutive seasons is the largest ever found in the inversion records. Although such strong transition to carbon source is consistent with historical observation of a strong dependence of land carbon uptake on tropical temperature and dryness, the detailed underlying mechanisms remain to be elucidated.

1 Introduction

The first monitoring station for background atmospheric CO_2 concentration was established at Mauna Loa in 1958. Its record shows that atmospheric CO_2 has continued to rise in response to anthropogenic emissions. However, the atmospheric CO_2 growth rate (AGR) has been lower than that implied by anthropogenic emissions alone, because land ecosystems and the oceans have absorbed part of the emitted CO_2 (Canadell et al., 2007; Le Quéré et al., 2016). Although on multi-decadal time scale carbon uptake by land and ocean has kept pace with growing carbon emissions (Ballantyne et al., 2012; Li et al., 2016), large year-to-year fluctuations occur in the terrestrial carbon sink, mainly in response to climate variations induced by El Niño–Southern Oscillation (ENSO) (Wang et al., 2013, 2014) and other occasional events such as volcanic eruptions (Gu et al., 2003). In northern latitude regions, increasing seasonal amplitude of atmospheric CO_2 is found to be linked with an increased land sink, associated with vegetation greening driven partly by long-term warming and CO_2 fertilization (Forkel et al., 2016; Graven et al., 2013; Myneni et al., 1997). The interannual variations in vegetation activity in the northern hemisphere are found to be mainly driven by temperature variations (Piao et al., 2014).

In 2015, the global monthly atmospheric CO_2 concentration surpassed 400 $\mu mol \cdot mol^{-1}$ (ppm) for the first time since the start of background measurements, with an unprecedented large annual growth rate of 2.96±0.09 ppm yr^{-1} (https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html#global_growth). This record-breaking AGR occurred simultaneously with a high value of the ENSO index (Betts et al., 2016) and the warmest land temperature on record since 1880 (https://www.ncdc.noaa.gov/cag/time-series/global/globe/land/ytd/12/1880-2015). At the same time, 2015 was also shown to have the greenest growing season of the Northern Hemisphere since 2000 (Bastos et al., 2017). Widespread abnormally high positive anomalies of the normalized difference vegetation index (NDVI) were observed from Moderate-resolution imaging spectroradiometer (MODIS) sensor aboard the Terra satellite, in particular over eastern North America and large parts of Siberia. On the one hand, strong greening is expected to enhance northern land carbon uptake during the growing season (Myneni et al., 1997); on the other hand, the strong El Niño event in the second half of 2015 increased fire emissions in tropical Asia (Huijnen et al., 2016; Yin et al., 2016) and likely caused a loss of plant biomass and reduced carbon uptake, possibly associated with the prevailing high temperatures and reduced rainfall (Ahlström et al., 2015; Jiménez-Muñoz et al., 2016).

To reconcile the observed maximum global land greening with the record-high AGR in 2015, we examined land-atmosphere carbon fluxes estimated from two atmospheric inversions. We examine the relationship between land carbon uptake anomalies and NDVI anomalies and climate anomalies, with a special focus on seasonal patterns in the land carbon uptake in 2015 relative to the long-term trend of 1981-2015. The aim here is to infer general patterns in factors driving the land carbon uptake anomalies and to examine how the carbon dynamics in 2015 fit into this pattern. We then focus how land ecosystems responded to the joint occurrences of record-breaking warming, extreme greening, and the end-of-year El Niño event, to understand how land ecosystems contributed to the high AGR in 2015.

2 Data and methods

2.1 Data sets

2.1.1 Atmospheric inversion data

We used two gridded land and ocean carbon uptake data sets based on atmospheric CO_2 observations, namely those from the Copernicus Atmosphere Monitoring Service (CAMS) inversion system developed at LSCE (Chevallier et al., 2005, 2010) and from the Jena CarboScope inversion system developed at the MPI for Biogeochemistry Jena (update of Rödenbeck, 2005; Rödenbeck et al., 2003). Atmospheric inversions estimate land- and ocean-atmosphere net carbon fluxes by minimizing a Bayesian cost function, which accounts for the mismatch between observed and simulated atmospheric CO_2 mixing ratios. To do this, they use atmospheric CO_2 concentration at observation sites, combined with an atmospheric transport model as well as prior information on carbon emissions from fossil fuel burning and on carbon exchange between the atmosphere and land (and ocean). Detailed information inversions could be found in respective sources as mentioned above.

The CAMS inversion data (version r15v3) were provided for 1979-2015 with a weekly time-step and a spatial resolution of 1.875° latitude and 3.75° longitude. The Jena CarboScope inversion provides daily fluxes at a spatial resolution of 3.75° latitude and 5° longitude. It offers a series of runs that use differently large station sets with complete data coverage over time, in order to avoid spurious flux variations from a changing station network. From these runs, we used s04_v3.8 (shortened as Jena04 in the main text and supplementary material) using the largest number of measurement sites and therefore the most detailed constraint on carbon exchanges in 2015 (see http://www.bgc-jena.mpg.de/CarboScope/ for more details on other configurations). The s04_v3.8 run has a validity period as 2004–2015, although it does provide the data for the whole time span of 1981–2015. Site observations used over the validity period are coherent over time and it is optimal to examine the temporal trend within such a period. But results outside the validity period are still technically feasible and the temporal trend could thus be examined over the whole entire time span. We compared the linear trends over the larger latitudinal regions examined in this study between the s04_v3.8 and the long s81_v3.8 runs, and confirmed that the derived trends are similar. Therefore, in the calculation of the long-term linear trend used as a reference of interannual anomalies (see Sect. 2.2.2 below), we exceptionally use the s04_v3.8 run outside its period of validity. The CAMS inversion uses sites with at least 5-year worth of data. It therefore has a denser (during the recent decade) but temporally evolving data coverage than Carboscope. The evolving network in CAMS causes changes in inverted CO_2 fluxes that are superimposed on changes from biogeochemical drivers during the whole period.

In order to compare with the inversion data, land and ocean net carbon uptakes for 1981–2015 from the Global Carbon Project (Le Quéré et al., 2016) were used. For this purpose, an annual global carbon flux of 0.45 Pg C yr^{-1} is subtracted from the inversion-derived land carbon uptakes and is added to ocean carbon uptakes to account for the pre-industrial land-to-ocean carbon fluxes induced by river transport (Jacobson et al., 2007), following Le Quéré et al. (2016). Estimates of ocean carbon uptake in GCP are based on observation-based mean CO_2 sink estimate for the 1990s and variability in the ocean CO_2 sink for 1959–2015 from global ocean biogeochemistry models. Estimates of land carbon uptake in GCP are calculated as the difference between anthropogenic emissions, atmospheric CO_2 growth and ocean sink. The estimates of land and ocean carbon uptake in GCP are largely independent from the two inversions used here, except that the CO_2 records from atmospheric stations which are used in inversions are also used in GCP to derive global AGR.

2.1.2 Atmospheric CO_2 growth rates, NDVI and climate data

Atmospheric CO_2 growth rates were retrieved from the Global Monitoring Division, Earth System Research Laboratory (ESRL), NOAA (http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html). We used NDVI data between 2000 and 2015 from MODIS Terra Collection 6 (Didan, 2015), on a resolution of 0.05° and 16-day time step. NDVI data is processed from MODIS land surface reflectance data and thoroughly corrected for atmospheric effects. We strictly applied quality assurance (QA) controls to maintain distinct seasonal trajectory of vegetative radiometric observations and minimize spurious signals (e.g., snow or cloud). Detected unexpected non-vegetative observations were first excluded and then filled by the adaptive Savitzky–Golay filter (Chen et al., 2004; Jönsson and Eklundh, 2004). The Savitzky–Golay filter is a simplified convolution over a set of consecutive values with weighting coefficients given by a polynomial least-square-fit within the filter window (Savitzky and Golay, 1964). After this procedure, the linearly interpolated daily NDVI data was used to calculate mean seasonal NDVI and re-gridded at 0.5° resolution, with pixels of seasonal NDVI lower than 0.1 being further masked to ensure robustness. We examined four seasons: Q1 (January–March), Q2 (April–June), Q3 (July–September) and Q4 (October–December). Climate fields are from the ERA interim reanalysis (Dee et al., 2011) at 0.5° resolution and monthly time-step. We used air temperature, precipitation and volumetric soil water content (%) integrated over the soil column to a depth of 2.89 m.

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

We examined the seasonal variations of the carbon cycle in 2015 in relation to ENSO events and compared the 2015 El Niño event with that of 1997–1998. The Multivariate ENSO Index (MEI, http://www.esrl.noaa.gov/psd/enso/mei/, Wolter and Timlin, 2011) was used to indicate the ENSO state. MEI is a composite index calculated as the first un-rotated principal component of six ENSO-relevant variables (including sea level pressure and sea surface temperature) over the tropical Pacific for each of the twelve sliding bi-monthly seasons. MEI was widely used in previous studies as an indicator for ENSO states to examine land carbon dynamics (Nemani et al., 2003; van der Werf et al., 2008). The 12 bi-monthly MEI values of each year are summed to obtain the annual MEI. The interannual variations in climate and land carbon uptake are linked with MEI to infer general relationship between land carbon dynamics and ENSO climate oscillations. To examine the potential role of fire emissions in the land carbon balance in 2015, we used the GFED4s carbon emission data at daily time-step and 0.25° spatial resolution (http://www.globalfiredata.org/data.html). Monthly fire-carbon emissions were calculated for the regions and were examined for 1997–2015.

2.2 Data analysis

2.2.1 NDVI rank analysis and greening trend

Given a season and a pixel, the annual time series of seasonal NDVI for 2000-2015 were ranked in ascending order so that each year could be labelled by a rank, with 1 being the lowest and 16 being the highest. A spatial map of NDVI rank was then obtained for each year for the given season (Fig. S1). A composite map was made for year 2015, by merging pixels with the highest rank of all four seasons in 2015 (Fig. 1a). Vegetated area fraction with the highest rank for different years was obtained, with the sum of these fractions yielding unity. This procedure was repeated for all four seasons to generate four seasonal time series, with each containing the vegetation land fractions with highest NDVI for different years (Fig. 1b). It is noted that NDVI values for the northern hemisphere for Q1 and Q4 mostly fall outside the growing season (although October is frequently considered within the growing season and some evergreen coniferous forests show significant photosynthetic activities in March in regions of mild winter, e.g., Tanja et al., 2003), so that a valid NDVI might not necessarily be associated with significant seasonal vegetation activity. But as we applied a minimum value of 0.1 on seasonal NDVI, we expect that this issue is partly alleviated. Such seasonal segregation is adopted mainly because of its general applicability across the globe, especially for tropical ecosystems where seasonality in vegetation activities is minimal.

2.2.2 Analysis of land carbon uptake dynamics associated with climate variations

Annual land and ocean carbon uptakes and carbon emissions from the two inversions were calculated for the globe over their period of overlap, 1981–2015. AGRs from NOAA/ESRL over 1981–2015 were converted into Pg C using a conversion factor of 2.12 Pg C ppm^{-1} (Ballantyne et al., 2012; Prather et al., 2012; Quéré et al., 2016) to examine the closure of the global carbon balance. The conversion factor used here assumes that the entire atmosphere is well mixed within one year. Because the record high AGR in 2015 was a composite effect collectively determined by carbon emissions from fossil fuel burning and industry, and land and ocean carbon uptakes, all being impacted by a historical trend (Fig. 2), it thus must be put into an historical perspective to reconcile evidence for extreme greening and the highest atmospheric CO_2 growth rate. For example, if 2015 comes up with a large increase in carbon emissions accompanied by droughts (browning) in the northern hemisphere and the tropics, then the highest AGR might not be regarded as a big surprise. Therefore, to understand the contributing factors for the highest AGR in 2015, we separated it into a long-term trend and interannual anomalies. For this reason, annual time series of carbon emissions, land and ocean carbon uptakes, and AGRs from NOAA/ESRL over 1981-2015 were linearly de-trended. The percentages of anomalies in carbon emissions, land and ocean sink in 2015 to the 2015 AGR anomaly were then calculated as relative contributions by each factor to the 2015 AGR anomaly.

Seasonal land carbon uptake anomaly time series were also calculated (the 0.45 Pg C yr^{-1} annual correction was not applied) by subtracting the same linear trend for 1981–2015. The globe was divided into three latitude bands: boreal Northern Hemisphere (BoNH, latitude > 45°N), temperate Northern Hemisphere (TeNH, 23.5° < latitude < 45°N), and tropics and extratropical Southern Hemisphere (TroSH, latitude < 23.5°N). The BoNH and TeNH are grouped as Boreal and temperate Northern Hemisphere (BoTeNH, latitude > 23.5°N) when examining seasonal carbon transitions. Seasonal land carbon uptake anomalies are then calculated for each region and the whole globe, with positive anomalies indicating enhanced sink (or reduced source) against the linear trend (i.e., the normal state), and negative ones indicating the opposite. The same seasonal linear de-trending was also performed for climate fields of air temperature, precipitation and soil water content. The relationship between anomalies in land carbon uptake, temperature and precipitation are then examined using partial correlation coefficients in a multivariate linear regression framework with an ordinary least squares method. The relationship between seasonal land uptake anomalies and NDVI anomalies are also examined using simple linear regression.

We then examined especially the seasonal anomalies of land carbon uptake in 2015 and the carbon uptake transitions between two consecutive seasons, trying to reconcile extreme greening and a moderate land sink for this year. Seasonal land carbon uptake transitions are calculated as the land sink anomaly in a given season minus that of the previous one. When examining transitions of land carbon uptake anomalies by the CAMS inversion, we found the year 1993 has an extreme negative Q3→Q4 global transition (-2.85 Pg C within 6 months, < -4σ, the second lowest being the year 2015 with -1.0 Pg C) albeit with a reasonable annual land carbon uptake (3.75 Pg C yr^{-1}). This is linked with an extreme high Q3 and low Q4 uptake in this year, which could not be explained by any known carbon cycle mechanisms. This is thus identified as a result of numerical instability of the inversion system for that release and consequently the year 1993 has been removed from all the aforementioned seasonal analyses.

3 Results

3.1 Vegetation greening in 2015

Figure 1a illustrates where and when higher-than-normal greening conditions were observed in different seasons of the year 2015, compared to other years of 2000–2015 (see Supplementary Fig. S1 for greenness distribution for each season). On average over the four seasons of 2015, 16% of vegetated land shows record seasonal NDVI. The year with the second highest NDVI is 2014 with 9% vegetated area having record NDVI. An increase of the record-breaking NDVI occurrence over time is clearly seen in Fig. 1b. In short, 2015 clearly stands out as a greening outlier, having the highest proportion of vegetated land being the greenest for all four seasons except for the first season (despite the fact that for Q1, 2015 is still the third highest, Q1 = January to March).

For boreal and temperate regions of the Northern hemisphere, the seasons with highest NDVI in

2015 are dominated by Q2 and Q3 (Q2 = April to June; Q3 = July to September), corresponding to the growing season from spring to early autumn (Supplementary Fig. S2). A pronounced greening anomaly in Q2 occurred in western to central Siberia, western Canada and Alaska, and eastern and southern Asia (Supplementary Fig. S1). Central and eastern Siberia and eastern North America showed marked greening in Q3. Strong and widespread greening also occurred in the tropics during Q3 over Amazonia and the savanna (or cerrado) of eastern South America and tropical Africa, but this strong positive greening signal greatly diminished in Q4 (Q4 = October to December) especially over central to eastern Amazonia with the development of El Niño (Supplementary Fig. S1). The strongest greening in 2015 across the globe is overall dominated by the northern land (latitude > 23.5°N), while for the northern tropics (0–23.5°N) only moderately strong greening is found, and for the southern hemisphere the greening of 2015 is close to the average state of the period of 2000–2015 (Supplementary Fig. S3). The extreme growing-season greening in the northern land is confirmed by Bastos et al. (2017) as robust by using Terra MODIS NDVI data with different quality control procedures, and consistent between Terra and Aqua sensors (Fig. S1 in Bastos et al., 2017).

3.2 Global carbon balance for 1981-2015

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

For 2015, the prescribed anthropogenic carbon emissions in the CAMS inversion are 9.9 Pg C yr^{-1}, of which 2.0 Pg C are absorbed by ocean, 1.7 Pg C by land ecosystems, with 6.2 Pg C remaining in the atmosphere, which matches the AGR from background stations of 6.3 Pg C assuming a conversion factor of 2.12 Pg C ppm^{-1} (Ballantyne et al., 2012; Le Quéré et al., 2016) and considering a measurement uncertainty of AGR as 0.09 ppm (0.2 Pg C) for 2015. When land carbon fluxes from the inversion are linearly de-trended over 1981-2015, the terrestrial sink in 2015 is by 1.2 Pg C lower than normal (i.e., the trend value), but this is not an extreme value — it is only the seventh weakest sink since 1981. This weaker land uptake accounts for 82% of the positive AGR anomaly, which is 1.45 Pg C in 2015 by subtracting a linear temporal trend. Jena04 yields an AGR in 2015 that is 0.13 ppm lower than the AGR based on background stations only, a difference close to the observation uncertainty. After removing the linear trends over time similarly as for the CAMS inversion, the land carbon uptake anomaly for Jena04 is -0.3 Pg C yr^{-1} in 2015, or 20% of the observed AGR anomaly, the remaining being explained by a positive anomaly in fossil fuel emissions (34%), a negative anomaly in the ocean sink (20%), and the difference between modelled AGR and NOAA/ESRL reported AGR. Note that the land sink by GCP for 2015 is much lower than in the two inversions, with de-trended anomaly lower than that of CAMS, indicating even larger contribution from land to the high anomaly of AGR.

In general, the warm phases of ENSO events are associated with positive anomalies in land air temperature, negative precipitation anomalies, and lower land carbon uptake anomalies (Fig. 3), consistent with previous studies (Cox et al., 2013; Wang et al., 2014). The lower precipitation during El Niño is due to a shift of precipitation from tropical land to the ocean (Adler et al., 2003), and higher land temperature might be due to reduction in evaporative cooling. The two extreme El Niño years of 1997 and 2015 have rather close MEI values. Compared with the 'standard' El Niño state of temperature and precipitation represented by the regression line, the year 1997 was relatively 'cool' and 'wet', while 2015 was rather 'warm' and 'dry' (with an extremely negative precipitation anomaly). Year 1998 has a smaller value of MEI than 1997/2015, but has a higher temperature anomaly than 2015, and a much lower land carbon uptake anomaly than 1997 and 2015 in both inversions, while the land carbon uptake anomalies in 1997 and 2015 are similar. More detailed comparison of these three years and their carbon cycle dynamics will be presented in the discussion section.

3.3 Seasonal land carbon uptake dynamics associated with climate variations with a focus on 2015

The partial correlation coefficients between anomalies in seasonal land carbon uptake and those in seasonal temperature and precipitation for different regions are shown in Fig. 4. The simple, individual (univariate) linear relationships between de-trended anomalies in land carbon fluxes and those in temperature and precipitation, are presented in Supplementary Fig. S4 and S5. Land carbon fluxes show consistent relationships with temperature between the two inversions for BoNH: positive relationship for Q2 and a negative one for the other three seasons (with Q1 by Jena04 being the only insignificant one). Partial correlations between land fluxes and precipitation are absent or non-significant for BoNH. This points to the fact that vegetation productivity in BoNH is in principle dominated by temperature, with warmer spring and early summer (Q2, April–June) enhancing vegetation net carbon uptake, but a higher temperature in later summer, autumn and early winter mainly reduces the land capacity to sequester carbon, consistent with previous studies (Piao et al., 2008). For TeNH, a significant negative relationship is found between land fluxes by the CAMS inversion and temperature for Q3, and both inversions show negative relationship between land fluxes and precipitation for Q4, probably due to enhanced early autumn respiration under wetter conditions. For TroSH, land carbon uptakes in Q1, Q2 and Q4 are all negatively related with temperature ($p<0.05$ for both inversions), while increase in precipitation in Q1 is found to be associated with enhanced land uptake.

To explain the seeming paradox in 2015 between the strong greening and an only moderate terrestrial uptake, we examined in detail the seasonal land carbon flux anomalies in 2015 (Fig. 5, refer to Supplementary Fig. S6 for the spatial distribution of flux anomalies). At seasonal scale, both inversions indicate positive carbon uptake anomalies during Q2 and Q3 for boreal and temperate Northern Hemisphere (BoTeNH, latitude > 23.5°N), consistent with marked greening in central to eastern Siberia, eastern Europe and Canada (Fig. 1) as outlined above. Indeed, both BoNH and TeNH show positive relationships between seasonal land carbon flux anomalies and

NDVI anomalies for Q2 and Q3, with BoNH showing moderate greenness (after a linear trend being removed) for Q3 and TeNH showing extreme greenness for Q2 in 2015 (Supplementary Fig. S7). However, an extreme follow-up negative (source) anomaly occurred in Q4 (Fig. 5a). These negative anomalies were lower than the 10th percentile of all anomalies in Q4 over time for both inversions and they partly cancelled the extra uptake in Q2 and Q3. As a result, on the annual time scale, the CAMS inversion shows an almost neutral land flux anomaly in BoTeNH, while the Jena04 inversion still indicates a significant positive annual anomaly.

For the tropics and extratropical Southern Hemisphere (TroSH, latitude < 23.5°N), both inversions show a weak negative land carbon anomaly for Q1 (mean value of -0.10 Pg C) in 2015, moderate anomalies in Q2 (of differing signs, with a negative one of -0.3 Pg C in CAMS and a positive one of 0.2 Pg C in Jena04). Q3 anomalies are almost carbon neutral for both inversions. In stark contrast, between Q3 and Q4, both inversions show a strong shift toward an abnormally big land carbon source (i.e., negative anomalies of ~ -0.7 Pg C against a carbon source expected from the linear trend, lower than 10th percentile over time in both inversions). On the annual time scale, CAMS shows a large negative anomaly of -1.2 Pg C. For Jena04, sink and source effects in Q1–Q3 cancelled each other, leaving the annual anomaly the same as in Q4.

Over the globe, the Jena04 inversion shows an abnormally strong sink during Q2 (normal state being a net carbon sink), owing to synergy of enhanced Q2 uptakes in both BoTeNH and TroSH. This abnormally enhanced uptake partly counteracted the strong shift toward source in Q4 (normal state being a net carbon source), leaving a small negative annual land carbon balance of -0.3 Pg C. For the CAMS inversion, because of the co-occurrence of enhanced carbon release in BoTeNH and the sudden shift toward a large carbon source in TroSH both in Q4 (normal states being both net carbon sources), the land shows a strong global shift toward being a source in Q4, leaving a negative annual carbon anomaly of -1.2 Pg C (i.e., carbon sink being reduced compared with the normal state).

These consistent results from both inversions point to very strong seasonal shifts in the land carbon balance as an emerging feature of 2015. We thus calculated ***transitions*** in land carbon uptake anomaly as the first-order difference in flux anomalies between two consecutive seasons (defined as the anomaly in a given season minus that in the previous one) for all years of the period 1982-2015 (Fig. 6). The ranks of transitions for different seasons relative to other years between the two inversions are broadly similar, except for Q1→Q2 and Q2→Q3 in TroSH, mainly due to the differences between the two inversions in seasonal land-carbon uptake anomaly in Q2 (Fig. 5b). On the global scale, both inversions show an extreme transition to a negative uptake anomaly for Q3→Q4, with 2015 being the largest transition of the period 1982-2015 (a transition towards an enhanced carbon source of -1.0 Pg C in 6 months). The abnormal transitions for Q3→Q4 on the global scale are located in the TroSH region, where both inversions show that during 1982-2015 the largest transition occurred in 2015. For BoTeNH, both inversions showed strong transitions toward positive anomaly for Q1→Q2; however, the same strong transition toward source anomaly occurred in Q3→Q4, partly cancelling the sink effects during growing seasons.

4 Discussion

4.1 Land carbon uptake dynamics with climate variations in northern latitudes and seasonal transitions of land carbon uptakes in 2015

The two inversions consistently allocate a strong positive carbon uptake anomaly in the region of BoTeNH during spring, which persists through the summer (Q2–Q3): an extreme sink anomaly is estimated in Q2 by Jena04, but a more moderate one by CAMS (still above the 75th percentile). The strong sinks in Q2 in both inversions are dominated by temperate Northern Hemisphere regions (TeNH, 23.5° < latitude < 45°N, Supplementary Fig. S8). For this region, both inversions show strong positive correlation between carbon uptake anomalies and NDVI in Q2, with an extremely high NDVI anomaly in 2015 (Supplementary Fig. S7f). Therefore, the strong sinks in Q2 are evidently linked with the extreme greening, although temperature and precipitation are only moderate (Fig. S4f, Fig. S5f).

For Q3, an extreme carbon sink anomaly occurs in boreal Northern Hemisphere (BoNH, latitude > 45°N) in CAMS; however, an equally strong negative anomaly (i.e., reduced sink) was found in TeNH in the same season, leaving the whole boreal and temperate Northern Hemisphere (BoTeNH) only a moderately enhanced sink anomaly (Fig. S8). Thus for TeNH alone, CAMS indicates extreme seasonal shift from a positive anomaly in Q2 to a negative one in Q3, implying abrupt seasonal transitions probably resulting from enhanced ecosystem CO_2 release after growing-season uptake. For TeNH in 2015, NDVI persisted from a high extreme in Q2 to high values in Q3 (Fig. S7), and temperature remained moderate for both Q2 and Q3 (Fig. S4f, S4g), but precipitation shifted from a moderate anomaly in Q2 to an extremely low one (Fig. S5f, S5g). Therefore, the shift from a high Q2 sink anomaly to a big Q3 source anomaly by CAMS might be partly linked with the shift in precipitation and drought in Q3, such as the prevailing drought in Europe as shown in Fig. S9 (see also a detailed discussion of the European drought in Orth et al., 2016).

Inversion Jena04 agrees with a higher-than-normal sink in TeNH (23.5° < latitude < 45°N) during spring (Q2). It also reports a moderate positive anomaly for Q3 in BoNH, but does not show a strong negative anomaly (i.e., reduced sink) in TeNH in Q3 as CAMS does (Fig. S8). This is possibly related to differences in the measurement station data used, to different land prior fluxes (from the ORCHIDEE model in CAMS, and the LPJ model in Jena CarboScope), or to the fact that Jena inversion has a larger a-priori spatial error correlation length scale for its land fluxes (1275 km) than CAMS (500 km) (Chevallier et al., 2010; Rödenbeck et al., 2003). Nonetheless, both inversions consistently indicate that the enhancement of CO_2 uptake during spring and summer at the northern hemispheric scale was subsequently offset by an extreme source anomaly in autumn (Q4).

The large carbon source anomalies in Q4 shown by the two inversions in BoTeNH seem to be dominated by different factors in BoNH versus TeNH. In BoNH the source anomaly in 2015 is more linked with elevated temperature in Q4, which shows significant negative correlations with carbon uptake anomalies by both inversions (Fig. S4d). In contrast, precipitation in Q4 has no correlation with carbon uptake anomalies, and precipitation in 2015 was close to the normal state (Fig. S5d). The prevailing high temperature in Q4 of 2015 is especially evident over most of northern America, and central to eastern Siberia and Europe (Supplementary Fig. S9a).

In TeNH, the roles of temperate and precipitation are reversed compared to BoNH. Q4 precipitation is found to have significant negative correlation with land carbon uptake anomalies for both inversions, and Q4 in 2015 was characterized by a very high precipitation anomaly, leading to reduced land carbon uptake (Fig. S5h). While temperature in Q4 of 2015 was moderately high, no significant correlation is found between carbon uptake anomalies and temperature (Fig. S4h). However, for both BoNH and TeNH, NDVI remained moderately high in Q4 of 2015 (Fig. 7d, 7h).

The positive relationship between land carbon uptake and temperature in Q2 (spring and early summer), and a negative one for Q3 and Q4 (autumn) for BoNH, are in line with previous studies. Several studies reported an enhanced greening during spring and summer in the northern hemisphere (Myneni et al., 1997; Zhou et al., 2001), as driven by increasing spring and summer temperature (Barichivich et al., 2013; Nemani et al., 2003), leading to enhanced land carbon uptake and a long-term increase in the seasonal amplitudes of atmospheric CO_2 in northern latitudes (Forkel et al., 2016; Graven et al., 2013). However, for autumn, even though growing season in autumn has been delayed because of autumn warming (Barichivich et al., 2013), land carbon uptake termination time is found to have advanced as well, mainly due to enhanced autumn respiration (Piao et al., 2008), which ultimately reduced net ecosystem carbon uptake (Hadden and Grelle, 2016; Ueyama et al., 2014). For TeNH, we also found significant negative relationship between land carbon uptake anomalies and temperature for Q3 using the CAMS inversion data, consistent with the enhanced respiration by autumn warming found in aforementioned studies. For Q4, however, both inversions point to decreasing land carbon uptakes with increasing precipitation. This might be due to enhanced respiration by ameliorated soil moisture condition, but this finding needs further examination on site scale in future studies.

For BoNH and TeNH, land carbon uptake anomalies are closely coupled with NDVI anomalies for Q2 (positive correlation, albeit an insignificant one for TeNH Q2 using Jena04 data), but they are generally de-coupled for Q3 and Q4, except that for Q3 of BoNH the CAMS-based land carbon uptake show positive correlation with NDVI. This suggests high NDVI in autumn might not necessarily relate to a high land carbon uptake. This is mainly because of two reasons. First, NDVI is found to correlate well with leaf-level CO_2 uptake for deciduous forest for different seasons, but is largely independent of leaf photosynthesis for evergreen forests (Gamon et al., 1995). Second, even though a higher NDVI is associated with larger photosynthetic capacity and a higher gross photosynthesis, autumn warming might increase ecosystem respiration more than photosynthesis, leaving still a net carbon source effect. Furthermore, other studies also pointed out that severe summer drought can negate the enhanced carbon uptake during warm springs (Angert et al., 2005; Wolf et al., 2016).

4.2 Seasonal land carbon uptake transitions in the tropics and influences of El Niño and vegetation fire

The strong transition to abnormal source in the tropics and extratropical Southern Hemisphere was paralleled by a marked decrease in precipitation and an increase in temperature in Q4, with the development of El Niño in Q2–Q3 (Supplementary Fig. S4l, S5l, S10). Here El Niño development is indicated by the rise of the MEI and Oceanic Niño Index (ONI, http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_change.shtml). This strong transition is consistent with the expected response of tropical and sub-tropical southern ecosystems during previous El Niño events (Ahlström et al., 2015; Cox et al., 2013; Poulter et al., 2014; Wang et al., 2013, 2014). The small abnormal source in Q1 in TroSH is consistent with a low precipitation anomaly. While temperature anomalies are abnormally high in Q2 and Q3, accompanied by extremely negative precipitation anomalies, the extremely low carbon flux in Q4 is largely explained by temperature, because correlations between land carbon uptake and precipitation in Q4 are very weak (Fig. S4i–l, Fig. S5i–l). Vegetation greenness has significant positive correlation with land carbon uptake anomalies for only Q1 in the tropics, and for the rest three seasons the correlation is very weak (Fig. S7i–l).

Compared with the 1997–98 El Niño, which was of similarly extreme magnitude, the 2015 El Niño started much earlier with positive MEI and ONI appearing during the first half of 2014. Since then until Q3 and Q4 in 2015 when El Niño began to reach its peak, the tropics and Southern Hemisphere saw continuous higher-than-normal temperatures, with continually decreasing precipitation and accumulating deficit in soil water content (Supplementary Fig. S10). From Q3 to Q4, a steep decline is further observed in both precipitation and soil moisture with stagnating high temperature anomaly, which is probably a major cause of the strong shift toward a carbon source anomaly. The CAMS inversion shows a carbon source anomaly in Q4 of 2015 slightly smaller than that in Q3 of 1997, while the Jena04 inversion shows almost equal magnitudes of loss in land sink strength between these two extreme El Niño events. On the one hand, El Niño in late 2015 started with an early onset and built upon the cumulative effects of the drought since the beginning of the year; it thus came with larger negative anomaly in precipitation and soil water content than the 1997–98 El Niño. This sequence of events might favour a stronger land carbon source. On the other hand, the fire emission anomaly in the tropics in 2015 was less than half of that in 1997 at the peak of El Niño (Fig. S10), which might contribute to a smaller land source anomaly in 2015 than in 1997–98.

El Niño events are usually associated with increased vegetation fires, and these have a large impact on the global carbon cycle (van der Werf et al., 2004). Global fire emissions of carbon reached 3.0 and 2.9 Pg C in 1997 and 1998 according to the GFED4s data. These two years produced the largest source of fire-emitted carbon for the entire period 1997–2015. Global fire emissions in 2015 reached 2.3 Pg C, close to the 1997-2015 average (2.2 Pg C yr^{-1}) but 23–24% lower than 1997–98 — the difference mainly occurring in the southern tropics (0–23.5°S, Fig. S10). In particular, carbon emissions from deforestation and peat fires were two times lower in 2015 (0.6 Pg C) compared with 1997 (1.2 Pg C) (GFED4s data), and emissions for these types of fires are more likely to be a net source contribution, because they cannot be compensated by vegetation regrowth within a short time. Fire emission data thus suggests a smaller contribution from fires to AGR in 2015 than 1997–98. If both annual time series of AGR and global fire-carbon emissions are de-trended within their overlapping period of 1997-2015, fire-carbon emissions have an anomaly of 0.4 Pg C yr^{-1} in 2015, explaining only 29% of the AGR anomaly.

There has been a long debate on whether tropical vegetations show enhanced greenness as indicated by vegetation indices (i.e., NDVI and enhanced vegetation index or EVI) during dry seasons or drought periods in tropical forest (Huete et al., 2006; Morton et al., 2014; Saleska et al., 2007; Samanta et al., 2010; Xu et al., 2011), and whether there is an accompanying decrease in long-term vegetation productivity associated with droughts (Medlyn, 2011; Samanta et al., 2011; Zhao and Running, 2010). Some studies show enhanced green-up in Amazonian forest during dry seasons mainly due to the release of radiation control on vegetation activities (Huete et al., 2006; Zhao and Running, 2010), while Samanta et al. (2010) argued such observed green-up is an artefact of atmosphere-corrupted data. A recent study by Morton et al. (2014) rather argued that if errors of satellite observation angle are corrected, no increase in EVI could be observed during dry seasons.

While forest plot level data demonstrated consistent negative effect of droughts on tropical carbon uptake mainly through enhanced tree mortality (Lewis et al., 2011; Phillips et al., 2009), site level observations failed to see immediate reduction in forest net primary productivity (Doughty et al., 2015) or even saw increased gross photosynthesis or photosynthesis capacity when dry seasons initiate (Huete et al., 2006; Wu et al., 2016). Further, a large mortality event for trees will cause a legacy source over several years rather than a rapid release of CO_2 to the atmosphere during the year when trees died.

Both Wang et al. (2013) and Wang et al. (2014) found a higher correlation coefficient between interannual variability in tropical land carbon fluxes (as inferred from interannual variations in AGR) of temperature than precipitation, which is confirmed by our analysis of inversion-based tropical land flux anomalies with climate variations (Fig 4). However, forest plot level observations point to the prevailing drought as the dominant factor to reduce forest carbon storage (Phillips et al., 2009). It remains challenging to reconcile the findings of temperature dominance at large spatial scale and precipitation/moisture dominance at fine scale. Recently, Jung et al. (2017) suggested that the dominant role of soil moisture over land carbon flux anomalies has shifted to temperature when the scale of spatial aggregation increases, due to the compensatory water effects in spatial upscaling. We also find that for all seasons except Q3, inversion-based land carbon uptake anomalies in the tropics and southern extratropics are positively correlated with soil water content, with 2015 having an extreme low soil water content anomaly in Q4 (data not shown), echoing the extreme high temperature anomaly shown in Fig. S4l. This might indicate that temperature impacts the land carbon uptake mainly by increasing evaporative demand and decreasing soil water content. Besides, except Q1, we found no strong link between seasonal land carbon uptake anomalies and NDVI anomalies.

4.3 Data uncertainties and perspective

On the global and hemispheric scales, the inversion-derived land- and ocean-atmosphere fluxes are well constrained by the observed atmospheric CO_2 growth rates on measurement sites.

However, because the observational network is heterogeneous and sites are sparsely distributed (Supplementary Fig. S11), land CO_2 fluxes cannot be resolved precisely over each grid cell (Kaminski et al., 2001) and some regions are better constrained than others. This could hinder the precise pixel-scale matching between gridded CO_2 flux maps and climate states or the occurrence of climate extremes to investigate how climate extreme impact carbon fluxes. Although we have identified carbon uptake transitions for some regions and seasons might be related with certain climate extremes (e.g., the role of precipitation in TeNH of Q4 shown in Fig. S5h), but in general exact attribution of carbon uptake transitions into different climate drivers could be elusive. Further, a few other uncertainties matter for the specific objective of this study. First, the atmospheric network increased over time, so that the inversions have a better ability to detect and quantify a sharp transition in CO_2 fluxes occurring in the last than in the first decade of the period analysed. This might hide the detection of other more extreme end-of-year carbon transitions during early years of our target period (1981-2015). Second, because measurements for the early 2016 are not used in the CAMS inversion and not completely available in the Jena inversion, the constraining of last season in 2015 is weaker than for the other three seasons. This could partly influence the exact magnitude of the extreme Q4 negative anomaly in land carbon uptake reported here. Third, the sparse sites located in the boreal Eurasia and tropical regions might diminish the ability of inversion systems to robustly allocation carbon fluxes spatially, which could yield high uncertainty in the carbon fluxes diagnosed for these regions (van der Laan-Luijkx et al., 2015; Stephens et al., 2007).

Despite these uncertainties, the strong transition of CO_2 fluxes from Q3 to Q4 analysed here is the largest ever found in the inversion records. Although 2015 shows extreme greening in the northern hemisphere, this strong greenness has been only translated into a moderate annual carbon sink anomaly in 2015, because vegetation greenness and land uptake anomalies are largely decoupled outside growing season. The strong transition to carbon source in TeNH in Q4 is consistent with extreme precipitation that might have largely increased respiration loss. In the tropics, the transition to a strong source in TroSH in Q4 is congruent with the expected response of ecosystems to the peak of an El Niño event. However, given the ambiguous findings regarding changes in vegetation greenness during dry seasons or drought periods by previous studies (Saleska et al., 2007; Xu et al., 2011), and the uncertain roles of climate variations in driving the regional land carbon balance, more work is needed to reveal how these processes have evolved during opposing ENSO events. For the boreal and temperate Northern Hemisphere, further investigation is still needed to verify whether a coupling between strong spring/summer uptake and autumn release is something intrinsic to natural ecosystems, or if strong transitions to autumn release are triggered more by abrupt climate shifts. This could be evaluated by process-based and data-driven models to partition the overall sink anomaly into individual responses of photosynthesis and respiration, but that is beyond the scope of this work. Our results point to the need to better understand the drivers of carbon dynamics at seasonal, or even shorter time scales at the regional to global level, especially the link between such dynamics and climate extremes. Such understanding would help better predictions of the response of the carbon cycle to multiple long-term drivers such as atmospheric CO_2 growth and climate change.

5 Conclusions

We investigated the links among vegetation greenness, interannual land carbon flux variations and climate variations for 1981–2015 using inversion-based land carbon flux data sets. Consistent positive correlations between satellite-derived vegetation greenness and land carbon uptakes are found for the northern hemisphere during growing season, but outside the growing season, vegetation greenness and land carbon uptake are largely decoupled. Carbon uptake in the boreal northern hemisphere (>45°N) is more consistently associated with temperature than precipitation, while such a pattern is less evident for the temperate northern hemisphere (23.5–45°N). Consistent with previous studies, we found a strong negative impact by temperature in the land carbon uptakes in tropics and southern hemisphere, probably driven by the role of temperature in soil water content.

We made an emphasis on the seasonal dynamics of land carbon uptake in 2015 due to its seeming paradox between the greatest vegetation greenness and the highest atmospheric CO_2 growth rate. We found that lands in Northern Hemisphere started with a higher-than-normal sink for the northern growing seasons, consistent with enhanced vegetation greenness partly owing to elevated warming, however this enhanced sink was partly balanced by enhanced carbon release in autumn and winter, associated with extremely high precipitation in Q4 in temperate northern hemisphere (23.5–45°N). For tropics and Southern Hemisphere, a strong and abrupt transition toward a large carbon source for the last quarter of 2015 was found, concomitant with the peak of El Niño development. This strong transition of terrestrial CO2 fluxes in the last quarter is the largest in the inversion records since 1981. The transitions in CO_2 fluxes diagnosed in this study form an interesting test bed for evaluating ecosystem models and gaining understanding of their controlling processes.

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Author contributions

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

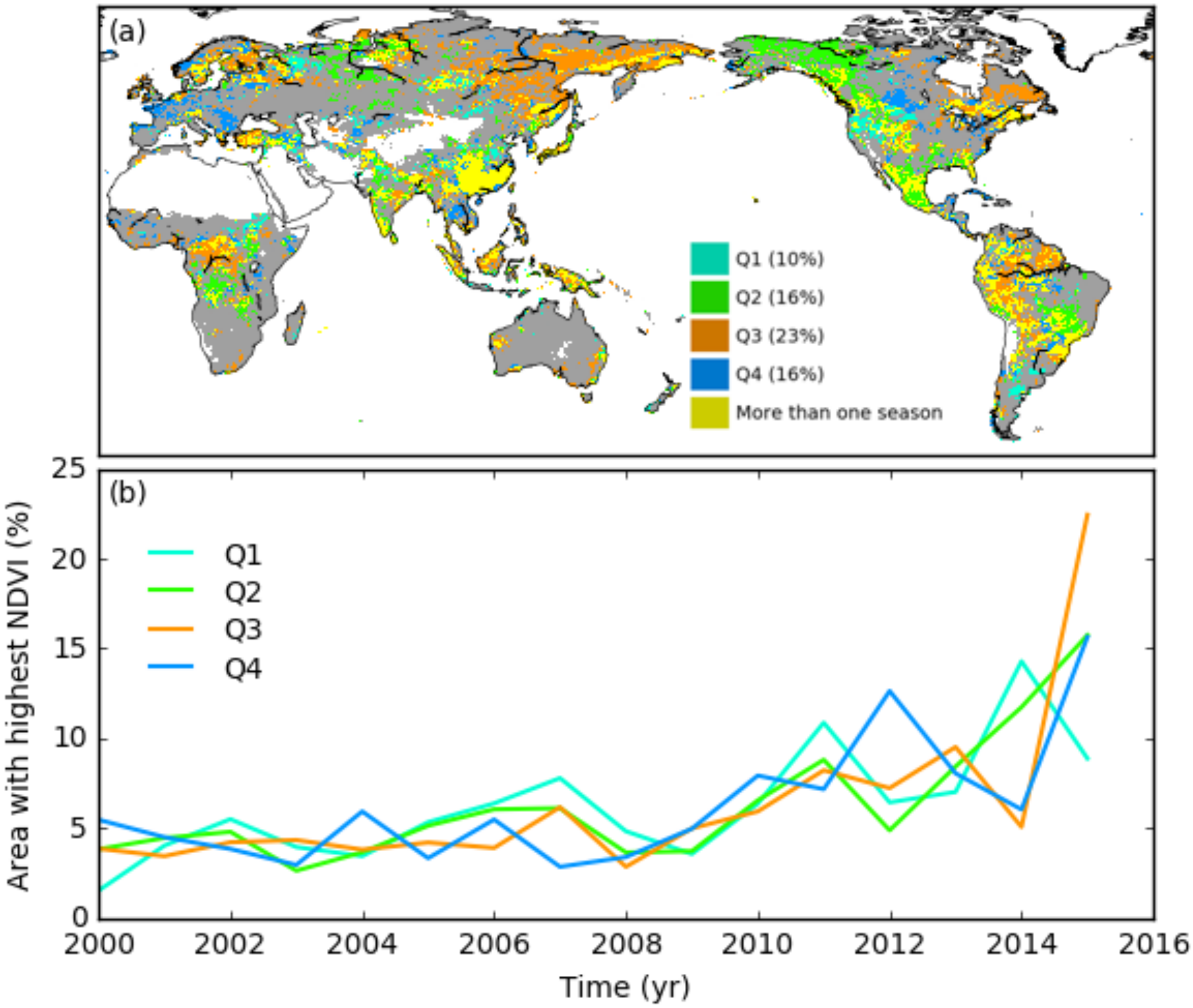

Figure 1 Year 2015 as the greenest year over the period 2000-2015. (a) Distribution of seasons for which 2015 NDVI ranks the highest during the period 2000-2015. Yellow-coloured pixels indicate grid cells where 2015 NDVI ranks highest for more than one season. For each season, the fraction of global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

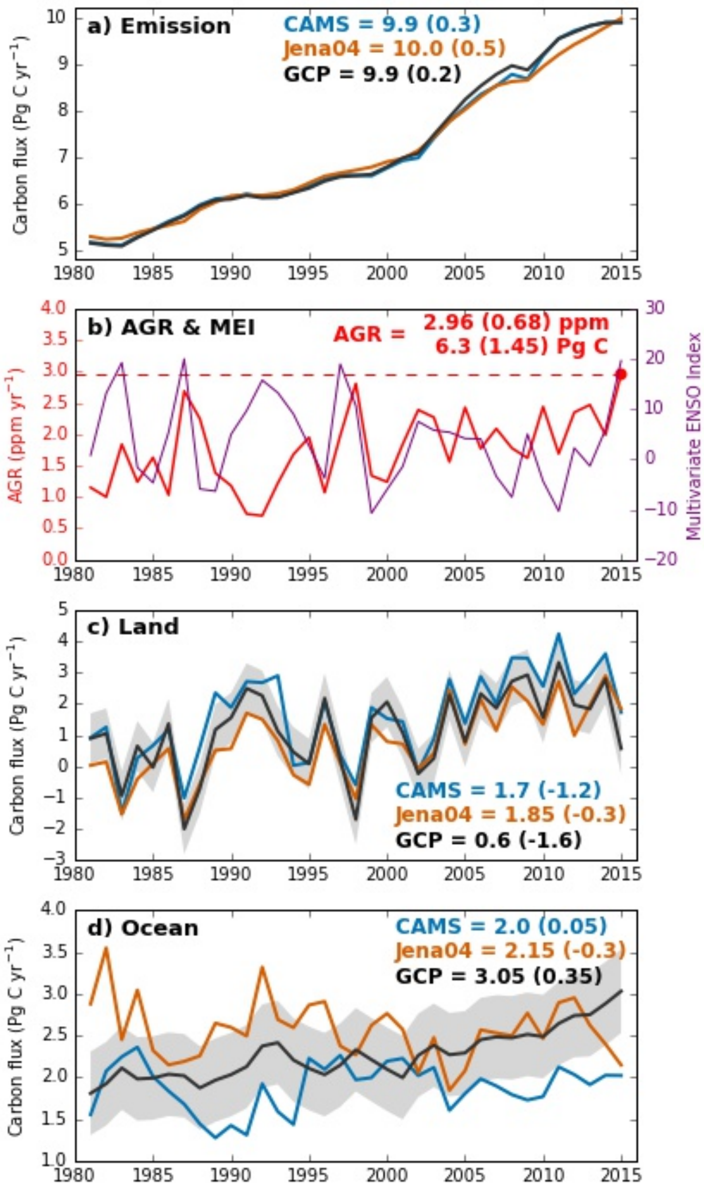

Figure 2 Global carbon fluxes and atmospheric CO_2 growth rates for 1981–2015. (a) Carbon emissions from fossil fuel and industry used in the CAMS (blue) and Jena04 (orange) inversions, (b) annual atmospheric CO_2 growth rate (AGR, in red) from NOAA/ESRL linked with Multivariate ENSO Index (in purple), and (c) land and (d) ocean carbon sinks for 1981-2015. Emissions and land and ocean carbon sinks from the Global Carbon Project (GCP, in black) are also shown for comparison. In subplots c and d, a carbon flux of 0.45 Pg C yr^{-1} was used to correct inversion-derived land and ocean sinks to account for pre-industrial land-to-ocean carbon flux as in Le Quéré et al. (2016). All numbers indicate values in 2015 (Pg C yr^{-1}, rounded to ±0.05 Pg C yr^{-1}), with those in brackets showing linearly de-trended anomalies for the same

year.

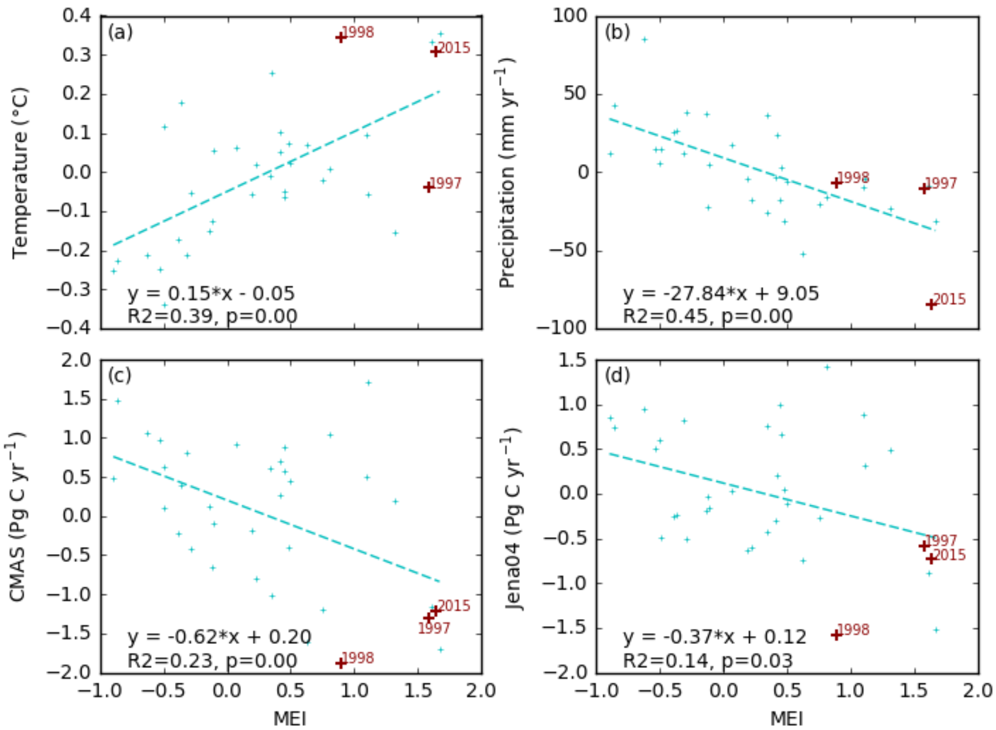

Figure 3 Relationships between anomalies of (a) land air temperature, (b) land precipitation, (c) land carbon fluxes by the CAMS inversion, (d) land carbon fluxes by the Jena04 inversion, and the Multivariate ENSO Index (MEI). All variables are linearly de-trended over 1981–2015.

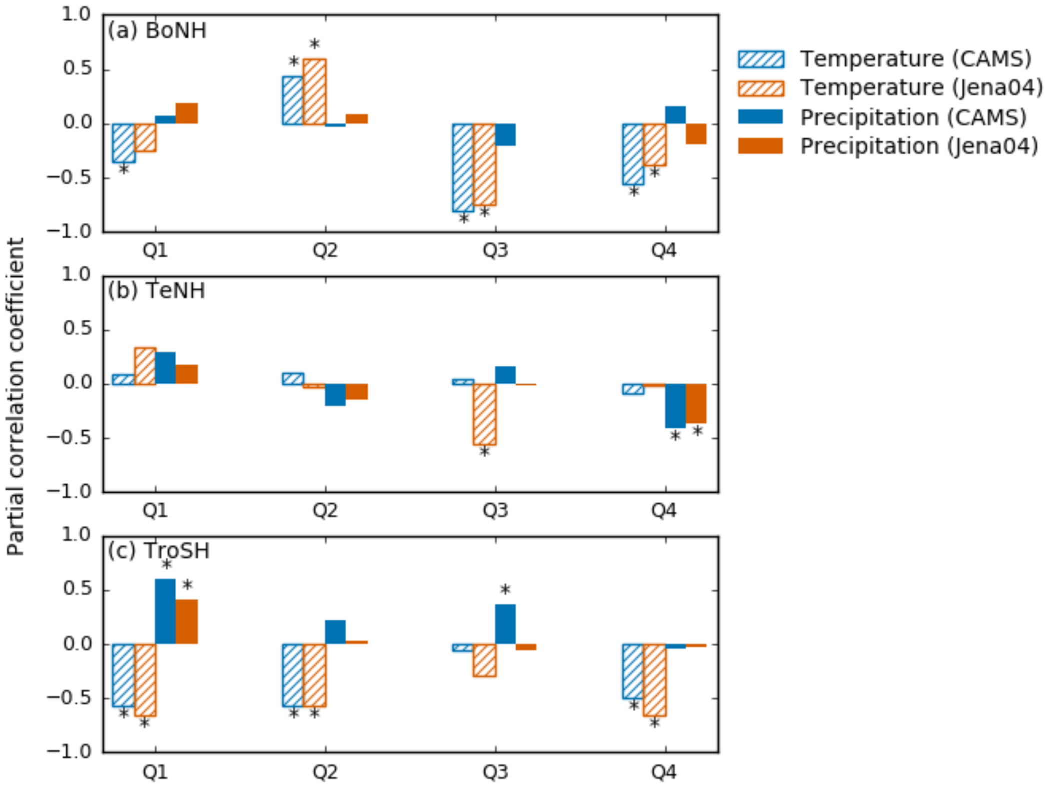

Figure 4 Partial correlation coefficients of de-trended annual anomalies of land carbon fluxes by CAMS and Jena04 inversions against the anomalies in temperature and precipitation of different seasons. n = 34. The asterisk indicates significant correlation ($p<0.05$).

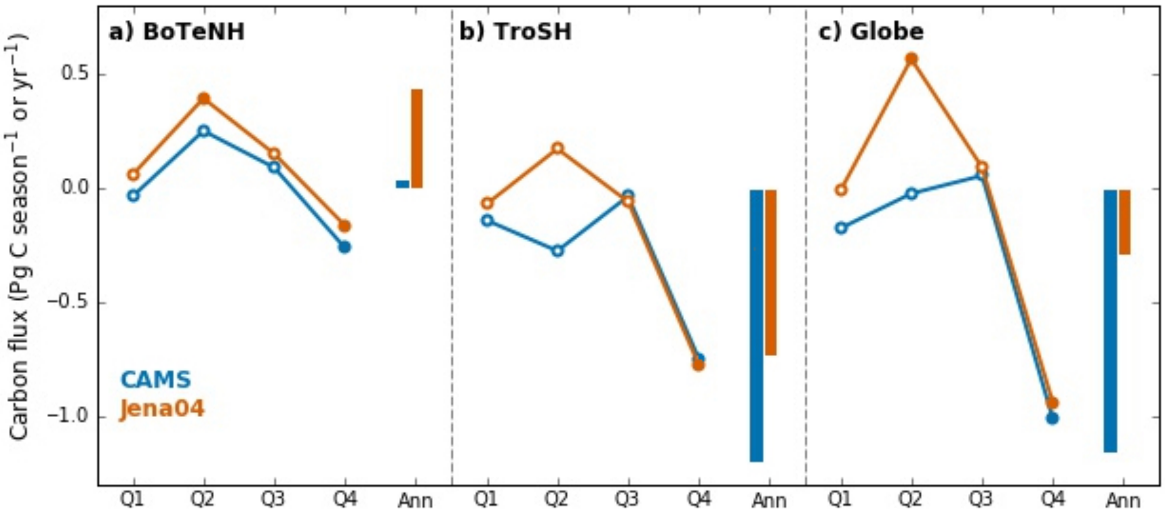

Figure 5 Seasonal land carbon uptake anomalies in 2015. Data are linearly de-trended over 1981-2015 for different seasons in 2015, by CAMS (blue) and Jena04 (orange) inversion data. Open or solid dots indicate seasonal values (Pg C seasaon^{-1}) and vertical bars indicate annual sum (Pg C yr^{-1}). Data are shown for: (a) boreal and temperate Northern Hemisphere (BoTeNH, > 23.5°N), (b) tropics and southern extratropical hemisphere (TroSH, < 23.5°N) and (c) the whole globe. Solid dots indicate seasonal land carbon uptake anomalies below 10th or above 90th percentiles over 1981-2015.

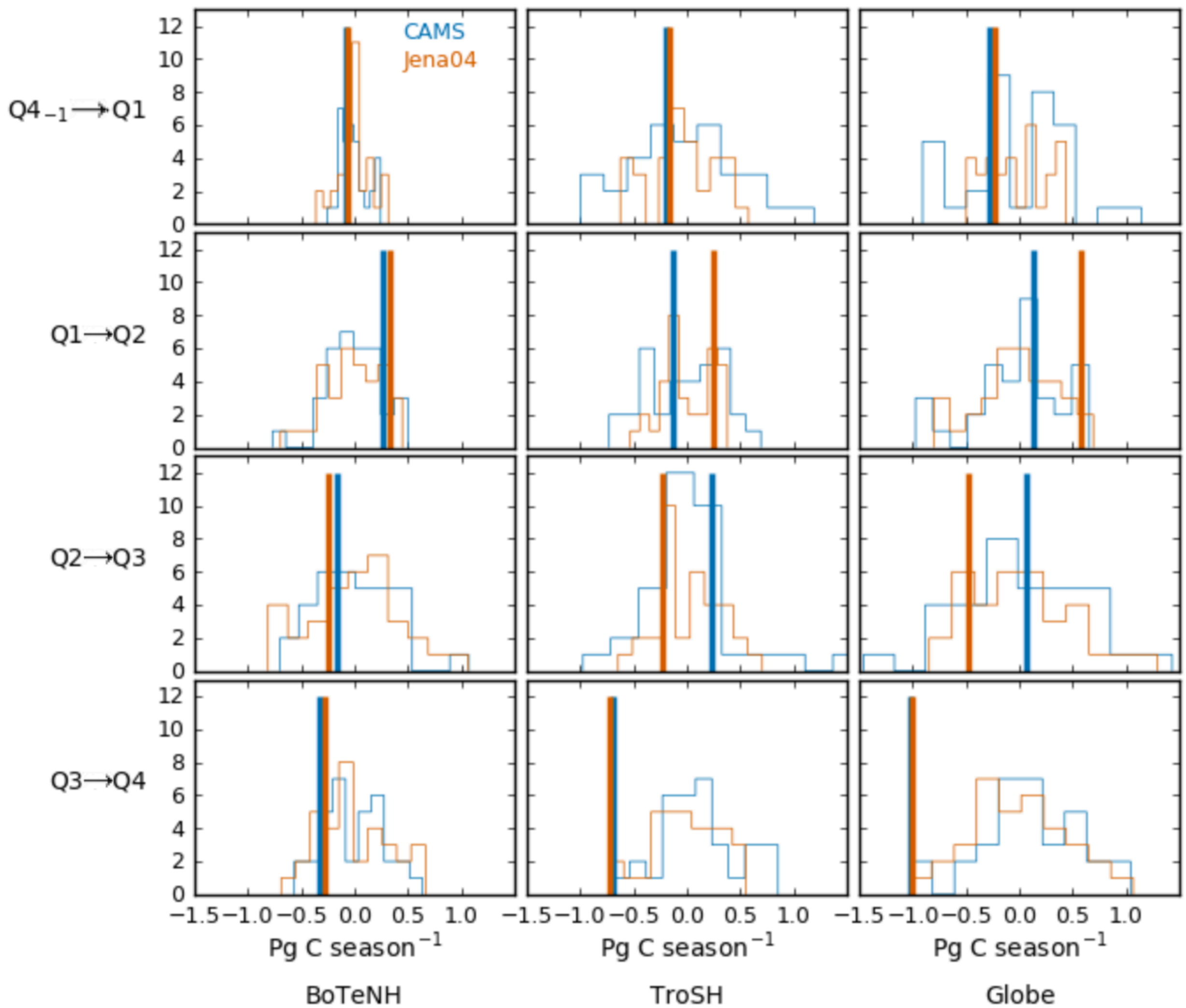

Figure 6 Extremeness of transitions in seasonal land carbon uptake anomaly in 2015. Lines of histograms for seasonal land carbon uptake transitions over 1981-2015 are shown for boreal and temperate Northern Hemisphere (BoTeNH, latitude > 23.5°N), tropics and extratropical Southern Hemisphere (TroSH, latitude < 23.5°N) and the whole globe. Transition between two consecutive seasons is defined as the linearly de-trended land carbon uptake anomaly in a given season minus that in the former one. X-axis shows the seasonal transitions in land carbon uptake anomalies (Pg C season^{-1}). Vertical orange solid lines indicate values for 2015.