Interactive comment on "Recent changes in the dominant environmental controls of net biome productivity" by Barbara Marcolla et al.

Anonymous Referee #1

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This paper investigated the global sensitivity of NBP to global radiation, temperature and soil water content from weekly to seasonal temporal scales(most at weekly scale) using one version of inversion NBP. What I concerned is the uncertainty of results because only one version of global NBP was used and the data had uncertainty at annual scale, particularly in weekly and monthly scale and the paper lacks the validation analysis, which makes it unconvincing.

Following the suggestion of the reviewer we repeated the analysis with other versions of the Jena Carboscope product that were specifically produced to explore the uncertainty of the inversion driven by the priors and the spatio-temporal correlation of the error (s81oc_v4.3, s85oc_tight_v4.3 with halved prior uncertainty, s85oc_loose_v4.3 with double prior uncertainty, s85oc_short_v4.3 with shorter spatial correlation and s85oc_fast_v4.3 with shorter temporal correlation). In addition, we explored also a previous version of the inversion based on a different number of atmospheric stations (s81oc_v4.3). We limited the analysis of the uncertainty to different versions of the Jena CarboScope CO_2 Inversion since, to our knowledge, all others long-term inversions are produced with a varying observation network (the number of atmospheric stations used in the inversion is changing during the time series) and are therefore not adequate for the scope of our study. In fact, temporal variations in the observation network generates spurious temporal trends in the signal driven by the additional observational constrains in the assimilation process.

The new analyses are fully consistent with the results reported in the manuscript for the large majority of the land surface. In the revised version of the manuscript we included new figures (which are attached below) to show the results of the uncertainty analysis and highlighting the consistency between products. In particular, Figure S1 shows the maps of the dominant drivers at three different time scales, black pixels are those for which less than 5 out of 6 inversion products agreed on the dominant driver selection. The bar-plot in Figure S1 shows that the results of 5 out of 6 products are consistent over about 90% of the land surface in terms of dominant driver. In addition, we repeated also the analysis on the temporal trend of the sensitivity with the other 5 inversion products. The first column of Figure S2 shows the average regression coefficients, the second column the standard deviation among the 6 products, while in the third column we plotted the sign of the trend of the regression coefficients; only pixels which showed an agreement in 5 out of 6 products in terms of sign were plotted in color, while black pixels are those for which less than 5 products agreed. These results were discussed in the manuscript and the figures were put in the supplementary material.

Generally, the abstract and introduction look good but the results and discussions are not good. The authors missed a lot of discussions and just simply describe the results. Throughout the manuscript, it should be more quantitative in nature.

Following the suggestion of the reviewer, we improved and deepened the discussion of the results in the updated version of the manuscript.

Line 16-17, what datasets were used in this study?

The acronym of the datasets has been added to the abstract. A full list and description of the datasets used in the study are reported in the Materials and Methods section.

line 20, how many are the relative contributions of radiation, temperature and soil water content?

Following the reviewer comment, we added the % of total pixels driven by temperature and radiation during CUP and CRP.

Line 21 are you mean that soil water content plays a key role in arid regions of the southern hemisphere both in carbon uptake and release periods?

Yes, according to results shown in Figure 2, SWC is the dominant driver of the arid regions of the Southern Hemisphere both during CUP and CRP. We made it clear in the new version of the manuscript

Line 23, the importance of radiation as a driver is increasing at global scale? Line 23, over what time period?

Figure 4 shows that the temporal sensitivity of radiation regression coefficient is positive in most of the Northern Hemisphere and in a large part of the Southern Hemisphere, which means that the increase of NPB at increasing radiation is increasing with time.
The time frame we are looking at is ~30 years. We clarified this point in the updated version of the manuscript

Line 23-24, So how many are the contribution of the temporal changes in ecosystem sensitivity and the temporal variability of the driver itself, respectively? The title focused on NBP, but the it looks you are working on net ecosystem CO2 exchange (line 16) throughout the abstract. It should be specified rather than say carbon fluxes vaguely. Same problems in Introduction, you mentioned NBP in your questions but talked about NEE in the whole introduction.

The contribution of temporal change in ecosystem sensitivity is about two orders of magnitude larger than the contribution of the temporal variability of the driver itself. The paper focuses on NBP since inversions cannot factor-out the CO_2 emissions driven by natural and anthropogenic disturbances. We changed the text where needed to be consistent.

Line 53-59, But it is at the hourly and daily scales where climate variability is directly acting on ecosystems too.

We agree with the remark of the reviewer, however working with the Inversion product at global scale it is not possible to go beyond the weekly time scale. We pointed this out in the manuscript in the Materials and Methods section.

Line 53, The sensitivity of what?

We specified “the sensitivity of ecosystem NBP to climate variability”

Line 60-70, this paragraph is abrupt. It should be in Method. However, the specific climate factors also should be introduced in introduction before describing your aims.

We agree with the reviewer and have updated the paragraph accordingly.

Line 80, how many observed sites were used in this products? Different versions of Jena CarboScope CO_2 Inversion have different numbers of observations and it is important to the uncertainty of NBP. Why do you choose the version s85_v4.1 rather than others? You only used the one product and version. This is a bit dangerous, how much can we trust your results?

A network of 21 atmospheric sites were used for version s85. Following the reviewer remark we specified it in the text. Since the scope of our study was to investigate the temporal variation in the drivers we selected this version because it was a good compromise between time series length and robustness of the observation network. However, in order to test the dependency of the results on the product version used, we repeated part of the analysis with other versions of the Inversion product.

Line 92, it should be better to include level 3 and 4, especially in forests and savannas.

In ERA-Interim there is a high temporal correlation of the soil water content between levels so we don’t expect relevant changes when using different levels. Given that we had to choose only one value for all vegetation types (at the spatial resolution of the inversion it is not possible to separate PFTs) we assumed that layer 2 (from 0.07 to 0.28 m depth) was the best representative of SWC for all ecosystem types (including woody and herbaceous PFTs).

Line 102 what is the threshold of VIF used?

According to the literature on the subject a VIF value of 5 was considered as a threshold for multi-collinearity. Maps of VIF at three temporal resolutions have been added in the supplementary information. As expected RG and TA show high collinearity, VIF values increase at decreasing time resolution, only SWC shows VIF<5 over most of the land surface.

Line 115, This is very dangerous because the inversion NBP may have large uncertainty at weekly and monthly scale for each pix. So it is hard to convincing to define CUP and CRP.

We agree with the reviewer on the issue of the uncertainty for inversion retrievals at the scale of the single grid-cell; however we believe that the uncertainty leads mostly to random errors that should not mine the validity of the results when derived from a large number of grid-cells at the global scale. In fact, despite these uncertainties, our analysis shows coherent patterns across geographic regions for the CUP/CRP analysis, therefore suggesting that our sensitivities metrics are robust.

Line 129, it is NBP, rather than net ecosystem CO_2 exchange. Line 129, your abstract said the CO_2 exchange over most of the land surface is controlled by temperature, but here you said it is radiation.

We agree with the reviewer and therefore throughout the text we checked for consistency and changed from NEE to NBP where needed. The sentence at line 129 refers to Figure 1 in which results are shown for the whole time series without a distinction into CUP and CRP. The sentence in the abstract is related to the results of Figure 2 in which CUP and CRP are separately analyzed. What we observe is that radiation controls the sub-annual fluctuations of NBP in most of the northern hemisphere, while when the NBP time series is separated into CUP and CRP, radiation is still the most frequent dominant driver during CRP and temperature is the most frequent dominant driver during CUP.

Figure 1, can you show the value for each drivers in the map rather than the dominant drivers simply? How can we know the positive or negative effect from this figure?

The values of regression coefficients for each driver are shown in Figure 4 (left panels) for the weekly time scale. The symbols plus and minus overlaying the color map refer to the sign of the regression coefficient of the dominant driver, hence when a plus is plotted over a pixel it means that in that pixel the dominant driver has a positive impact on NBP.

Line 136, summer drought decreases GPP but not increases TER. But radiation does not decrease GPP in the northernmost latitudes

We agree with the reviewer and changed the sentence as follows "Surprisingly also the northernmost latitudes show a negative correlation to radiation, suggesting a negative impact of sunny weather on the carbon budged, in line with recent findings about the reduction of NBP in the boreal zone, due to the anticipated phenology that reduces the uptake in summer".

Line 140, the reader don't know this number from this figure 1. I strongly recommend the author sperate the results and discussions because it is very unclear now. There are only two sentences in the some paragraphs of results.

The percentages reported at line 140 can be retrieved form the bar plot of Figure 1. Following the reviewer suggestion we separated the results and discussion sections and improved the discussion of the results.

Line 142, As for radiation?

We changed it into "Similarly to radiation…"

Line 144, drier periods show higher uptake. Why?

Our interpretation of this result is that humid/rainy periods at the northernmost latitudes are characterized by a combination of low radiation and low temperature, which may ultimately limit primary productivity. Soil water content controls the boreal latitudes and has a negative effect on the carbon fluxes; while in arid regions of the Southern Hemisphere it has a positive effect (humid periods show higher CO_2 flux).

Line 153, so what?

In the revised version of the manuscript we described in further details the differences between our study and the one by Nemani et al. (2003) which is based on remote sensing retrievals of vegetation indexes to estimate NPP and therefore not accounting for heterotrophic respiration.

Line 158, the temperate zone is mostly radiation-driven. No, the temperate zone is mostly temperature-driven.

Our results show that the short term variations of NBP in the temperate zone is radiation driven during CRP and show a mixed pattern of temperature and radiation limitation during CUP (Figure 2). We changed the sentence at line 158 accordingly.

Line 161, but your results showed NBP is related to radiation and GPP is related to temperature.

Figure 2 shows that NBP during CUP (GPP proxy) in the boreal region is actually controlled by temperature in accordance to Reichstein et al (2007).

Line 164, are you taking about GPP, rather than NBP here?

We are talking about NBP during CUP, which is used as a proxy for GPP.

Line 165, The carbon release period of the Northern hemisphere is mostly driven by global radiation, which positively impacts on the NBP fluxes. So you mean carbon release period positively impacts on the NBP?

What we observe is that radiation is the dominant driver in most of the Northern Hemisphere and that sensitivity to radiation (its regression coefficient) is positive, which means that NBP increases at increasing radiation at the investigated temporal scales.

Line 170-172, how much is the positive or negative effect? Please add more quantitative descrbition.

The absolute magnitude of the sensitivity for the different drivers is reported in Figure 4. The image shows that on average the positive sensitivity to SWC is higher than the negative sensitivity to radiation.

Figure 3, please show the frequency distribution curve.

In Figure 3 we show the frequency distribution of the dominant drivers at the investigated time scales separately for CUP and CRP.

Line 173-176, are these differences between different drivers significant?

We performed a CHI-squared test which proved that the distributions are statistically different.

Line 194, why?

Negative correlations dominate in the Southern Hemisphere, likely due to unfavorable growing condition during the sunny and dry season (that explain the average negative sensitivity) and the large spatial variation in the terrestrial water budget (leading to the heterogeneity in the trends).

Line 199, why does an opposite positive trend of temperature sensitivity occur in North America?

We could not find a robust explanation for this pattern.

Line 200, which regions

Evaporation is supply limited from temperate to Mediterranean and tropical arid regions, while demand limited regions are located in boreal arctic and humid tropics.

Line 206-208, these sentences should move to methods.

The sentence is meant as a link between Figure 4 and Figure 5 description. We would therefore prefer to keep it at the current location.

Line 208, What clear pattern for radiation?

We observed negative sensitivities in regions with high and very low temperature independently from precipitation values, while at intermediate temperatures it has a positive effect on NBP; and this holds also for the temporal trend of the sensitivity. This pattern and its potential causes is resumed and discussed in the revised version of the manuscript.

Line 211-214, need to ref Figure 5 and 6, how about monthly and seasonal scale

Following the reviewer suggestion we performed the analysis also at monthly and seasonal scale; Figures are reported in the supplementary material.

Line 238, you are not working on the weekly variation, rather than the inter-annual variability.

The sentence was reworded as follows: "Soil water content shows an increasing control on the seasonality of NBP also in the US South America and South Africa, confirming the increasing relevance of water stress on primary productivity (Jung et al., 2010) and control of arid zones on variability of the terrestrial carbon budget (Ahlstrom et al., 2015)."

Line 247, how bigger? I don't think you can compare them because you didn't normalize them together.

The contribution of the change in sensitivity to driver is almost two orders of magnitude larger that the contribution due to the temporal change of the driver itself. These two contributions sum up to build the total NBP temporal change (see equation at line 134).
The two terms have the same units and are comparable. They contribute to build up the total temporal variation of NBP and their contribution was disentangled and reported in Figure 7 of the manuscript.

Line 249 per se?

The wording does not appear in the new version of the manuscript.

Line 250, you need to compare this figure with greening map and see if it is true.

Following the suggestion of the reviewer we added in the text a comment about the match of our maps with that of the greening with additional references.

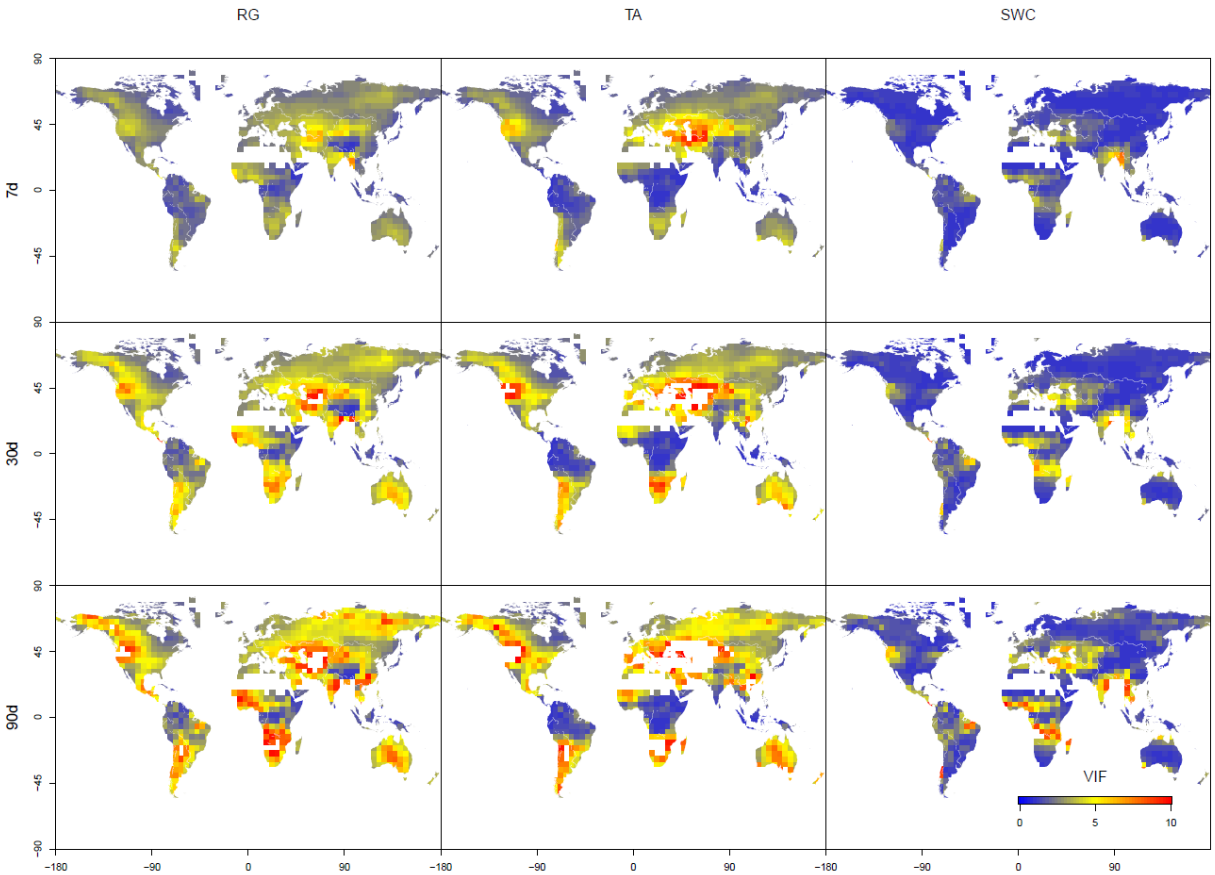

Figure 1s: maps of the Variance Inflation Factor (VIF)

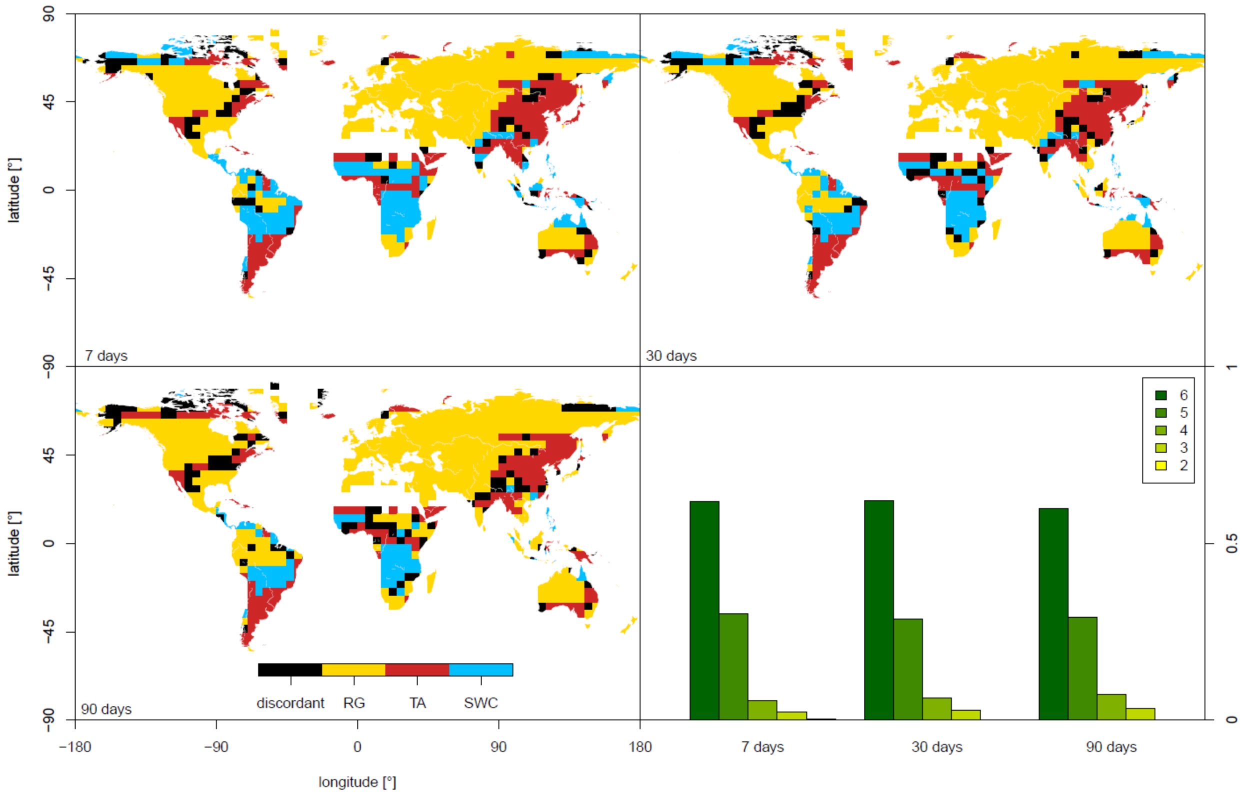

Figure 2s: maps of the dominant drivers calculated over the entire time series. Results are shown for three temporal resolutions, namely 7, 30 and 90 days. Black pixels are those for which less than 5 out of 6 inversion products agreed on the dominant driver selection. The bar-plot in Figure 1s shows that the frequency of pixel for which a certain number of products agree on the dominant driver selection. Outcomes of 5 out of 6 products are consistent over about 90% of the land surface.

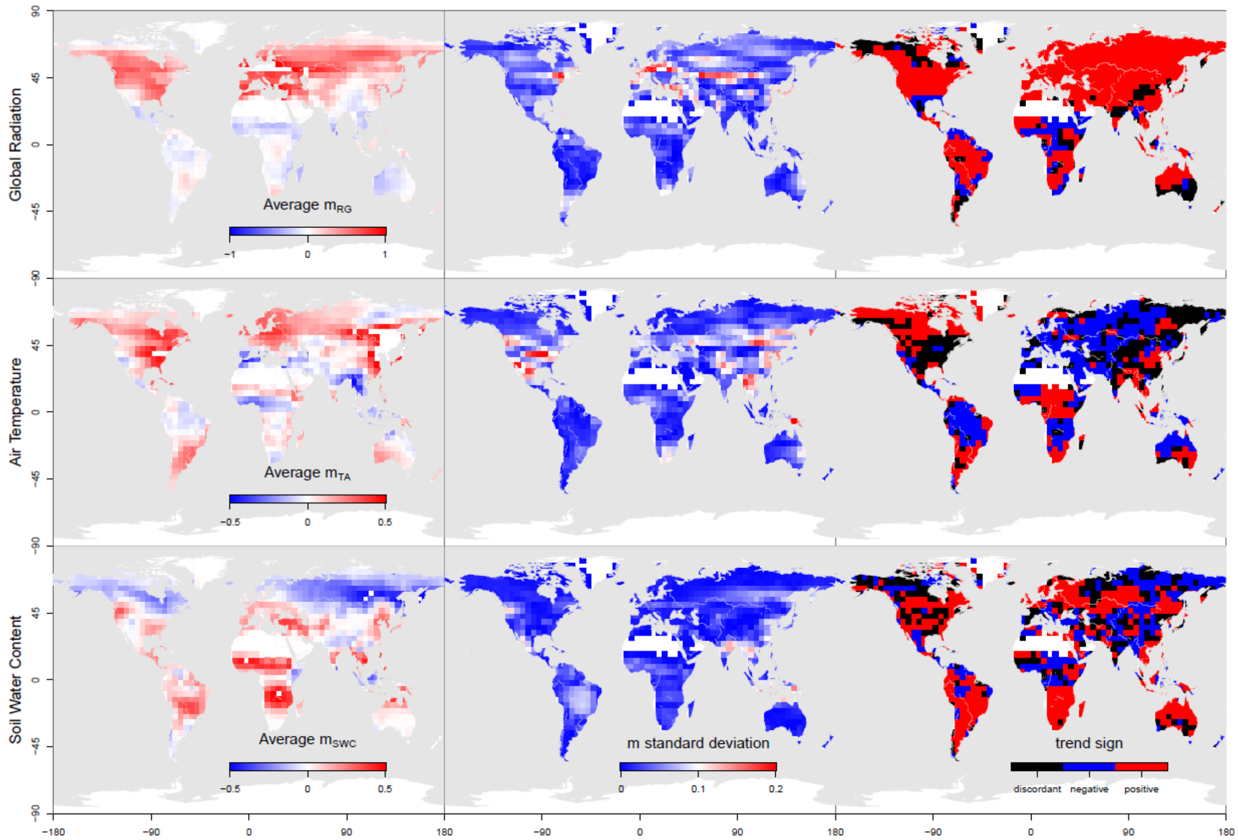

Figure 3s: Maps of magnitude (first column) of the sensitivity (m) of Net Biome Productivity (NBP) to global radiation (first row), air temperature (second row) and soil water content (third row), maps of the standard deviation (second column) of m between products, sign of the temporal trend of m (third column) at weekly time scale. In the third column only pixels which showed an agreement in 5 out of 6 products in terms of sign were plotted in color, while black pixels are those for which less than 5 products agreed.

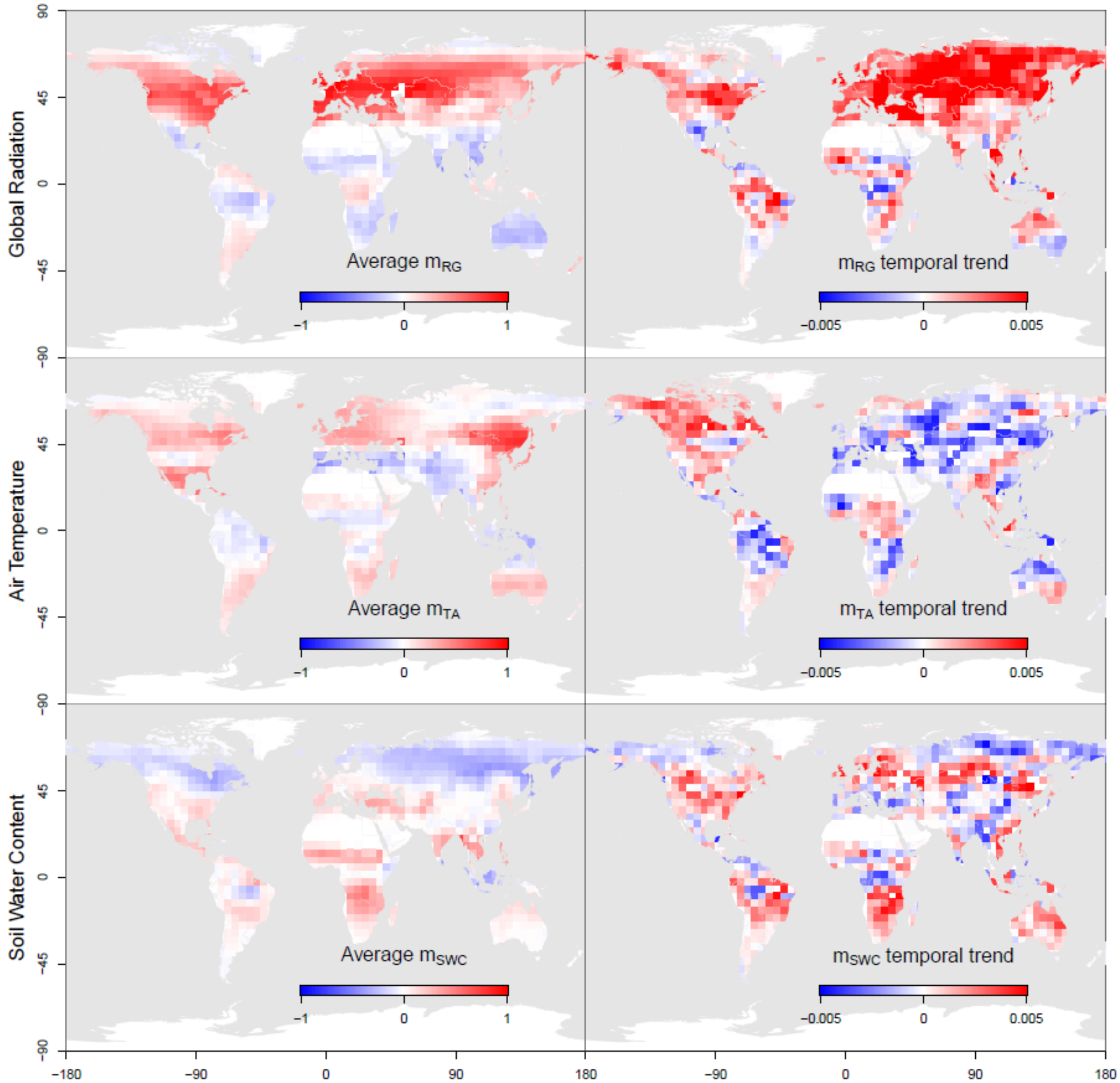

Figure 4s: same as Figure 4 in the main text, but for the 30 day time scale

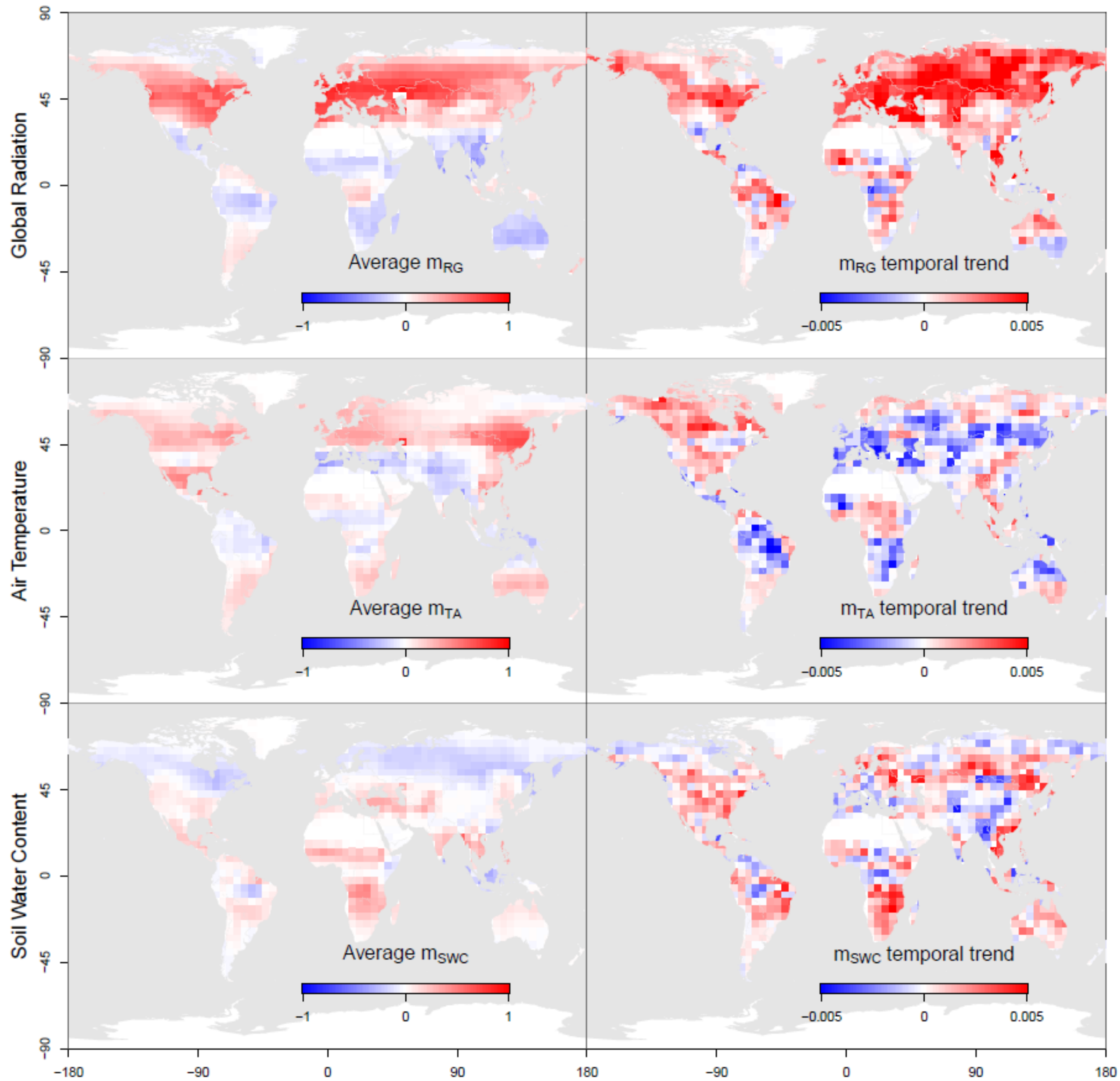

Figure 5s: same as Figure 4 in the main text, but for the 90 day time scale

Interactive comment on “Recent changes in the dominant environmental controls of net biome productivity” by Barbara Marcolla et al.

Anonymous Referee #2

Received and published: 25 November 2019

This manuscript by Marcolla et al investigates global CO_2 fluxes during the carbon uptake and carbon release period and at different time-scales. Overall, the paper is very interesting, the method sound and the manuscript well written. However, I did find that the discussion/broader impact was essentially missing, making it difficult to see what the consequences of this work are for the community. Here are some comments:

1)The title “ Recent changes in the dominant environmental controls of net biome productivity” is misleading. This paper does not look at “recent changes” or what the history of environmental controls was, so I would choose a title that reflects the actual paper better.

Following the reviewer suggestion we changed the title into:

“Patterns and trends of the dominant environmental controls of net biome productivity”

We would like to keep the focus also on the temporal dynamics of the controls since this is a relevant goal of the work (see Fig. 4, 5, 6).

2) Section 2.2 is a little laborious, even though the actual analysis method is obvious once the reader gets to the figures. I would suggest illustrating the described analysis with the evolution of a single pixel, it would help clarify the section.

We reworded Section 2.2 in order to better clarify the applied methodology.

3) Section 3 is a monstrous lock of text describing the figures one by one. The “Discussion” part of this section consists of a few sentences here and there. The paper would greatly improve if 1) The Section was split between “Results” and “Discussion” and 2) the “Results” section was split further into subsection for each type of analysis, just to help guide the reader through the overall progression of the analysis. I think that splitting the “Results” and “Discussion” would force the authors to put this work into perspective and draw conclusions about why this work matters for the different communities that might be interested in these results (flux tower, land surface modelers, global models, etc. . .).

Following the reviewer’s suggestion we separated Results and Discussion into two separate sections. We focused the Results on the most relevant findings and and improved the Discussion section.

4) In the Discussion section, it would also be helpful to include some limitations: how is the way vegetation is modeled influencing the results in one direction? Is the modeled know for modeling some aspects better than others? This would be a very valuable addition.

We agree with the reviewer on this point and we have therefore added a first section in the discussion on the limitation of the method.

5) I would move Figures 3 to the Supporting Information since it doesn't actually show new data, just the same data from Figure 2 plotted differently. It is still nice to see though, so the SI would be a good place for it. Similarly, Figures 4 and 5 show essentially the same data. I found Figure 5 more interesting though, so I would again move Figure 4 into the SI.

We think that the bar plot of Figure 3 contains an additional information which is not evident from Figure 2, i.e. the frequency change across temporal scales and this is the reason why we would prefer to maintain the figure in the main text. We agree with the reviewer that Figure 4 and 5 show the same results but figure 4 gives the spatial information which is lost in Figure 5 where results are plotted in climate coordinates.

Edits: overall, the text was very well written. My only minor comment on the text is that at line 142, I would replace "As for radiation" with "Similarly to radiation". The sentence is technically correct, but I found the use of "as" in this specific context to be confusing.

The sentence was changed accordingly to the reviewer suggestion

~~Recent changes in~~Patterns and trends of the dominant environmental controls of net biome productivity

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Abstract. In the last decades terrestrial ecosystems have reabsorbed on average more than one quarter of anthropogenic emissions (Le Quéré et al., 2018). However, this large carbon sink is modulated by climate and is therefore highly variable in time and space. The magnitude and temporal changes ~~of~~in the sensitivity of terrestrial CO_2 fluxes to climate drivers are key factors to determine future atmospheric CO_2 concentration and climate trajectories. In the literature, there is so far a strong focus on the climatic controls of inter-annual variability, while less is known about the key drivers of the sub-annual variability of the fluxes. This latter temporal scale is relevant to assess which climatic drivers dominate the seasonality of the fluxes and to understand which factors limit the ~~net ecosystem~~ CO_2 exchange~~.~~ during the course of the year. Here, we ~~investigated~~investigate the global sensitivity of net terrestrial CO_2 fluxes, derived from atmospheric inversion, to three key climate drivers (i.e. global radiation~~,~~ and temperature ~~and~~ from WFDEI, soil water content from ERA-Interim) from weekly to seasonal temporal scales, in order to explore the short-term interdependence between climate and the terrestrial carbon budget. We observed that the CO_2 exchange ~~over most of the land surface~~ is controlled by temperature during the carbon uptake period~~,~~ over most of the land surface (from 55 to 52% of the total surface), while radiation is the most widespread dominant climate driver during the carbon release period~~.~~ (from 64 to 70% of the total surface). As expected, soil water content plays a key role in arid regions of the ~~southern hemisphere.~~Southern Hemisphere both during the carbon uptake and the carbon release period. Looking at the decadal trend of these sensitivities (1985-2016) we observed that the importance of radiation as a driver is increasing over time, while we observed a decrease in sensitivity to temperature in Eurasia. Overall, we show that ~~the~~flux temporal variation ~~of the fluxes~~ due to a specific driver ~~is~~has been dominated by the temporal changes in ecosystem sensitivity (i.e. the response of ecosystem to climate) rather than to the temporal variability of the climate driver itself~~.~~ over the last decades. Ultimately, this analysis shows that the ~~response of the~~ ecosystem response to climate ~~drivers~~ is significantly changing both in space and in time, with potential repercussion on the future terrestrial CO_2 sink and therefore on the role that land may play in climate ~~mitigation~~trajectories.

1 Introduction

Just over one quarter of the anthropogenic emissions of carbon dioxide (CO_2) on average are reabsorbed by terrestrial ecosystems (Le Quéré et al., 2018). This large sink is influenced by climate and therefore by its short- and long-term variability (Beer et al., 2010; Ciais et al., 2005; Rödenbeck et al., 2018; Sitch et al., 2015). In fact, key climate drivers, like radiation, temperature, precipitation regime and soil moisture, control the fundamental processes of photosynthesis and respiration that are modulating the net ecosystem CO_2 exchange (Reich et al., 2018). Moreover, climate change is affecting the phenological cycle of plants and, therefore, the functioning of ecosystems which in turn affect climate (Richardson et al., 2013). Due to this interrelation, model studies show that the response of land CO_2 fluxes to climate drivers may ~~strongly~~heavily determine the future climate trajectories (Friedlingstein et al., 2001). Ultimately, the large uncertainty of climate projections could be significantly improved with a better understanding of vegetation response to the climate variability observed in the past (Papagiannopoulou et al., 2017).

In the last decades the climate sensitivity of terrestrial ecosystem CO_2 exchange has been investigated at different temporal and spatial scales and with a variety of measurement techniques ranging from eddy covariance, which continuously monitor fluxes at local scale (Baldocchi, 2003; Baldocchi et al., 2001), to ~~indirect measurements based on remote sensing retrievals. A range of sensors on different satellite platforms are continuously monitoring in different wavebands (i.e. optical, thermal, microwave, etc.) the structural and functional properties of global vegetation. Earth observations proved to be an invaluable source of information to assess land-climate interactions at large scale and to constrain model representation (Alkama and Cescatti, 2016; Duveiller et al., 2018).~~global scale retrievals based on satellite remote sensing.

An increasing range of sensors on different satellite platforms are continuously monitoring the structural and functional properties of global vegetation with different techniques and wavebands (i.e. optical, thermal, microwave, etc.). The combination of multiple sources of Earth observations have proved to be a valuable method to assess land-climate interactions at large scale and to constrain model representation (Alkama and Cescatti, 2016; Duveiller et al., 2018; Jung et al., 2017; Ryu et al., 2019; Tramontana et al., 2016).

Evidence-driven model products based on data assimilation are another ~~valuable source~~important tool to ~~analyze~~analyse the vegetation-climate ~~inter-play~~interplay and can be used to assess the generalizability of ground-based observations (Fernández-Martínez et al., 2019). Among these, atmospheric inversions (such as the Jena CarboScope Inversion used here) combine ~~modeled~~modelled atmospheric transport with high precision measurements of atmospheric CO_2 concentrations to derive surface fluxes (Rödenbeck et al., 2003). Atmospheric inversions are particularly suitable for the assessment of vegetation-climate interactions because these data-products are not assuming a-priori any trend in the inter-play between climate and fluxes. Besides, inversions provide global data over several decades and are therefore useful to assess temporal changes at large spatial scale.

The sensitivity of ~~ecosystems~~ecosystem net biome productivity (NBP) to climate variability has been so far mostly investigated at annual scale, while it is still poorly investigated across multiple sub-annual temporal scales. However, it is at the weekly or monthly scales where climate variability is directly acting on ecosystems (e.g., though heat waves, droughts, or cold spells), while annual anomalies are just the sum over such sub-annual responses. Besides, climate variability can have different impacts on the CO_2 flux (enhancing or dampening its variability) depending on the time period of the year when it occurs (Marcolla et al., 2011; Sippel et al., 2016). Thus, it is important to assess the limiting climate factors that control weekly or monthly evolution of ecosystem carbon fluxes in order to assess the vulnerability and forecast the future evolution of the ecosystem carbon budgets (De Keersmaecker et al., 2015; le Maire et al., 2010).

~~With~~ To this scope, in our ~~analysis~~work we ~~aim at i) analyzing~~explore the ~~limiting factors~~recent patterns and temporal trends of ~~global net biome productivity (~~the environmental drivers of NBP~~) fluctuations from weekly to seasonal time scales ii)~~. In particular, we assess ~~how the NBP sensitivity to~~ the ~~main climate drivers is changing in time and iii) factoring out the~~relative importance of ~~the temporal changes of the~~key drivers ~~and of the sensitivity to drivers in determining the total temporal variability of CO_2 fluxes.~~

~~Global~~like global radiation, temperature and soil water content ~~were chosen among the meteorological drivers of the fluxes~~ (Jung et al., 2017) ~~in order to identify the dominant driving variable at weekly, monthly and seasonal time scale in two key periods of the ecosystem carbon budget, namely the Carbon Uptake Period when the land acts as a sink (CUP) and the Carbon Release Period when it acts as a source (CRP). Finally, the temporal trends of the sensitivities to the three drivers were analyzed separately in order to assess how long-term changes in the background climate may have affected the climate sensitivity of terrestrial biomes.~~at the sub-annual time scales (weekly to seasonal). The analysis was framed to i) identify the limiting factors of global net biome productivity (NBP) from weekly to seasonal time scales ii) assess how the NBP sensitivity to the main climate drivers has been changing in the recent decades and iii) quantify the contribution of the variations in the climate drivers and in the response of ecosystems to climate in determining the total temporal variability of CO_2 fluxes.

2 Materials and Methods

2.1 Datasets

Gridded global flux estimates were obtained from the top-down product Jena CarboScope CO_2 Inversion (version s85_v4.1, 21 atmospheric sites) (Rödenbeck et al., 2003). Atmospheric inversions yield surface flux fields that achieve the best match to high-precision measurements of atmospheric CO_2 concentrations, where the fluxes are linked to atmospheric mole fractions by ~~modeled~~modelled atmospheric transport. ~~Atmospheric~~For this specific inversion, atmospheric transport is simulated ~~here~~ by the global three-dimensional transport model TM3 (Heimann and Körner, 2003) driven by meteorological data from the NCEP reanalysis (Kalnay et al., 1996). The product version used in this analysis covers the period 1985-2016 at daily time scale; however, since the inversion uses temporal a-priori correlations that smooth away any flux variations faster than about a week, the minimum time resolution we ~~analyzed~~analysed is 7 days. The Jena Inversion is particularly suited for the analysis of temporal trends and variability since it is based on a temporally constant observation network for the entire simulation period, in order to minimize spurious influences from the beginning or ending of data records on the spatio-temporal variation of the fluxes. Among the versions of the Jena CarboScope CO_2 Inversion we selected s85_v4.1 since it represent a good compromise between the length of the time series (needed to assess temporal trends) and the density of the observation network (required to have a good spatial representativeness of the dataset). In order to prove the robustness of the results we performed part of the analysis also with other versions of the s85 Jena Carboscope product that were produced to explore the uncertainty of the inversion driven by the priors and by the spatio-temporal correlation of the error (s85oc_tight_v4.3 with halved prior uncertainty, s85oc_loose_v4.3 with double prior uncertainty, s85oc_short_v4.3 with shorter spatial correlation and s85oc_fast_v4.3 with shorter temporal correlation). In addition, we explored also a different version of the product (s81oc_v4.3). We limited the analysis of the uncertainty to different versions of the Jena CarboScope CO_2 Inversion since, to our knowledge, all others long-term inversions are produced with a varying observation network (the number of atmospheric stations used in the inversion is changing during the time series) and are therefore not adequate for the scope of our study.

Concerning climate variables, global radiation (RG), air temperature (TA) and soil water content (SWC) were ~~identified~~used as key drivers for NBP (Jung et al., 2017; Ma et al., 2007; Papagiannopoulou et al., 2017). These environmental variables are generally recognized as the major factors driving the variation of CO_2 fluxes from hourly to multi-day time scale (Chu et al., 2016; Richardson et al., 2007), while the response at longer time scales becomes more complex and often involves indirect effects through functional changes (Teklemariam et al., 2010). Global radiation and air temperature data were retrieved from the WFDEI database (Weedon et al., 2014). The dataset covers the period 1985-2016 with a spatial resolution of 0.5°x0.5° and a temporal resolution of 1 day. The WFDEI meteorological forcing data set has been generated using the same methodology as the WATCH Forcing Data (WFD) by making use of the ERA-Interim reanalysis data. ~~The ERA-Interim dataset, provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), was used for soil water content (level 2, from 0.07 to 0.28 m depth).~~ ERA-Interim is a global atmospheric reanalysis from 1979, continuously updated in real time by the European Centre for Medium-Range Weather Forecasts (ECMWF, (Berrisford et al., 2011). The ERA-Interim dataset was also used to retrieve the soil water content (level 2, from 0.07 to 0.28 m depth).

2.2 Statistical data analysis

All datasets were aggregated at the spatial resolution of the inversion product (5°x3.75°) with the R package "raster" using the mean of the variables as aggregation function (Hijmans, 2017). A moving window of 7, 30, 90 days was then applied to the data to have data at weekly, monthly and seasonal ~~time scale~~temporal resolution, respectively.

Multi-linear regression models have been extensively used to assess the inter-linkages between global vegetation and climate (Barichivich et al., 2014; Nemani et al., 2003). In this study regressions between Jena Carboscope NBP and global radiation (RG), air temperature (TA) and soil water content (SWC) were estimated at pixel level using the R package "glmnet" (Friedman et al., 2010), which is suitable to calculate linear regression coefficients in case of collinearity, as it is often the case with multiple climate drivers. The presence of collinearity was assessed computing the variance inflation factor~~,~~ (Figure S1), which measures how much the variance of a regression coefficient is inflated due to multi-collinearity in the model (Gareth et al., 2014). When multi-collinearity occurs, least squares estimates are unbiased, but their variances are so large that they may be completely inaccurate. Hence, to account for collinearity the loss function is modified in a way that not only the sum of squared residuals is minimized, but also the size of parameter estimates is penalized, in order to shrink them towards zero. ~~The penalization equals the square of the magnitude of coefficients. All coefficients are shrunk by the same factor (so none are eliminated). A tuning parameter (λ) controls the strength of the penalty term. When λ = 0, the regression equals an ordinary least squares regression. If λ = ∞, all coefficients are shrunk to zero.~~ The ideal penalty is ~~therefore~~ somewhere in between 0 (ordinary least square) and ∞ (all coefficients shrunk to 0) and gives the minimum mean cross-validated error.

Regression coefficients for each pixel were estimated first using the entire time series, and then separately for the Carbon Uptake Period (CUP, ~~GPP dominated~~defined as the period when the land acts as a carbon sink since gross primary productivity dominates over respiratory terms) and the Carbon Release Period (CRP, ~~TER dominated).~~when respiration is larger than gross primary productivity and the land is a carbon source). Since gross primary productivity (GPP) and terrestrial ecosystem respiration (TER) cannot be derived from inversion products, we performed the regression analysis using NBP of CUP and of CRP as proxies of GPP and TER, respectively (Migliavacca et al., 2011, 2015). Climatological CUP and CRP were identified using the seasonality of NBP (sign convention: NBP>0 corresponds to uptake) for each pixel, ~~with~~ periods with NBP>0 ~~being~~were classified as CUP and periods with NBP<0 as CRP.

The absolute value of standardized coefficients was used as a measure of the relative importance of the drivers. Hence the dominant driver for each pixel was the one having the largest coefficient. In order to assess the temporal variation of the sensitivity to climate drivers, the observation period was split into 8 sub-periods of 4 years each. For each sub-period a multi-linear regression of NBP versus the selected climate drivers (RG, TA, SWC) was estimated at pixel level, obtaining 8 angular coefficients (i.e. sensitivities) for each driver (m_{driver}). Average values of the drivers were also calculated for each sub-period.

The temporal trend of the sensitivities to climate drivers was investigated with linear regressions versus time at pixel level. The contributions to NBP total temporal variability ~~in land fluxes~~ due to temporal variation in the climate drivers and in the ecosystem sensitivity-to-drivers were ~~estimated and their effect on the total temporal change of NBP was disentangled~~separately estimated according to the following equation:

$$\left.\frac{dNBP}{dt}\right|_{driver} = \frac{dm_{driver}}{dt} driver(t) + m_{driver}(t)\frac{d(driver)}{dt}$$

where m_{driver} is the ~~slope~~coefficient of a driver in the multi-linear regression.

~~In order to assess the temporal variation of the sensitivity, the observation period was split into 8 sub-periods of 4 years each. For each sub-period a multi-linear regression was estimated at pixel level, obtaining 8 angular coefficients (i.e. sensitivities) for each driver (m_{driver}). Average values of the drivers were also calculated for each sub-period.~~

The contribution of the ~~sensitivity-to-driver~~ temporal change in the ecosystem sensitivity-to-driver ($\frac{dm_{driver}}{dt} driver(t)$) was obtained estimating a linear regression ~~for the 8 angular coefficients~~ against time for the 8 angular coefficients (m_{driver}) previously calculated for the 8 sub-periods of 4 years, and the temporal sensitivity obtained from the regression ($\frac{dm_{driver}}{dt}$) was multiplied by the average value of the driver in the sub-periods. The contribution of the ~~driver~~ temporal ~~change~~ changes in the drivers ($m_{driver}(t)\frac{d(driver)}{dt}$) was obtained estimating a linear regression of the sub-periods' average driver values against time, and the temporal sensitivity of the driver was multiplied by the sensitivity-to-driver coefficients. ~~Finally the values obtained for the 8 sub-periods were averaged.~~

3 Results

3.1 Dominant drivers across regions and ~~Discussion~~climates

The analysis of the drivers of sub-annual NBP fluctuations shows clear spatial patterns, where single climate variable dominates specific geographic regions in the different climate zones (Figure 1). In particular, the climate driver that controls the ~~sub-annual~~ fluctuation of ~~the net ecosystem CO_2 exchange in~~ NBP in most of the ~~northern hemisphere~~Northern Hemisphere is radiation, with an increasing ~~relevance~~dominance from the weekly to seasonal temporal scale ~~(Figure 1). In~~, while in the ~~southern hemisphere~~Southern Hemisphere soil water content controls NBP in the driest regions of Africa and South America ~~while~~, and radiation and temperature dominate elsewhere.

~~Positive correlation between drivers and NBP dominate the global picture, meaning that on average C uptake is larger during periods with higher temperature, radiation and soil water content. Surprisingly, negative correlation with radiation occurs in the northernmost latitudes, suggesting a strong increase of respiration at the peak of the growing season. These results are in line with the recent findings about the effect of the anticipation of CUP in the boreal zone on the reduction of NBP due to the summer drought (Buermann et al., 2018). Negative correlation with radiation occurs also in tropical regions where most probably high radiation load is related to stressful conditions (e.g. water limitation, heat stress, or a combination of the two). Overall, the frequency of pixels having radiation as dominant variable, increases at decreasing time resolution (from 49% to 59%), while the relative frequency of positive coefficients slightly decreases.~~

Looking at the sign of the relationships between NBP and drivers, it is interesting to notice that the global maps are dominated by positive correlations between drivers and NBP (regions with + sign in Figure 1), meaning that the terrestrial land sink is larger during periods with higher temperature, radiation and soil water content. As expected, negative correlation with radiation occurs in tropical regions where high radiation loads are related to stressful conditions (e.g. heat stress, water limitation, or a combination of the two).

Looking at the differences between temporal scales, we observe that the area with positive correlation is rather stable at the various time resolution (11% increase from 7 to 90 days), whereas the areas with negative correlations show a much stronger increase (50% increase from 7 to 90 days), suggesting that the negative interplay between radiation and NBP typically occurs at longer timesteps than the positive one. This should be interpreted by considering that positive correlations are likely due to the direct effect of the rapid response of photosynthesis to light, whereas negative correlations are due to indirect effect on the overall growing conditions, typically leading to stomatal limitation (e.g. dry season in the tropical regions with high VPD and low soil water content).

Temperature is the second most frequent dominant variable and controls the tropics in the ~~northern hemisphere~~Northern Hemisphere, the southernmost latitudes and East Asia. ~~As for~~Similarly to radiation, the effect of temperature on the weekly to seasonal variation in NBP is mostly positive (Wu et al., 2015) except in arid regions of the Middle East. Soil water content controls the boreal latitudes and has a negative effect on ~~the~~ carbon fluxes (drier periods show higher uptake); while in arid regions of the ~~southern hemisphere~~Southern Hemisphere it has a positive effect (humid periods show higher ~~CO_2 flux). A similar~~ uptake).

In order to assess the consistency of the results the analysis of the dominant climate controls was repeated with other 5 versions of the Carboscope inversion. Results confirm the robustness of the finding, with an agreement on the dominant driver in 5 out of 6 products over about 90% of the land surface (Figure S2, supplementary material).

3.2 Dominant drivers across temporal phases

Since the processes that dominate the CO_2 exchange are different between the period of carbon uptake when the land is a sink (CUP) and the period of carbon release (CRP), the regression analysis was repeated separately for these two phases of the ecosystem carbon budget (Figure 2, 3).

Results show that the dominant drivers of the high frequency fluctuation in NBP are different between the two periods. In the continental regions of the Boreal Hemisphere, the variability in the period dominated by photosynthesis (CUP) is mostly driven by positive relationships with temperature on NBP, while the temperate zone shows a mixed pattern of ~~sensitivity to~~ temperature and radiation limitation (Figure 2). During CUP in the Southern Hemisphere a key role is played by soil water availability which is positively correlated with NBP fluxes across the Tropical region.

Interesting results emerge from the analysis of the key drivers during the carbon release period (Figure 2, 3). Globally the most common limiting factor is radiation, with a strong positive and negative control in the Northern and Southern Hemisphere, respectively. This distinct pattern is related to the different processes limiting the carbon uptake in the two Hemispheres: the low radiation load occurring off-season in the Boreal Hemisphere and the condition of high radiation and aridity in the Southern Hemisphere (confirmed by the positive effect of soil water content).

Altogether we observed an important asymmetry in the sign of the controlling drivers between the CUP and CRP. While the former is stimulated by the increase in the drivers on a large fraction of the Earth surface (more than 80% on average for all drivers), the latter shows a mixed pattern where the CO_2 sink is stimulated in about half of the planet and depressed in the other half by radiation (Figure 3). Concerning temperature, the key parameter in a global change perspective, the asymmetry is even stronger, with a control overwhelmingly positive in the CUP (in ~85% of the temperature-dominated surface at ~~monthly~~all the investigated temporal resolutions) and mostly negative (in 76%, 68% and 45% of the temperature-dominated surface at 7, 30 and 90 days respectively) in the CRP. This pattern is likely due to the temperature stimulation of the two opposite processes GPP and TER that controls NBP during CUP and CRP, respectively.

3.3 Temporal trends of environmental controls of NBP

In a scenario of rapidly changing climate it is particularly important to assess how the sensitivity of NBP to the different drivers has been changing over time and in which geographic regions. To this end, Figure 4 summarizes global maps of the average values (left panels) and temporal trends (right panels) of the regression coefficients that can be ultimately interpreted as sensitivities to climate drivers. Regressions have been computed at 7 days temporal resolution and for the all-year period.

Concerning radiation, the positive sensitivity shown in Fig 1 and in Fig. 4a is increasing in time (Fig 4b) in most of the Northern Hemisphere. This positive trend observed in the last three decades is likely due to the increasing leaf area index (LAI) and primary productivity of the northern regions, leading to increased light use efficiency and therefore to a stronger control of NBP by light. On the contrary, in the Southern Hemisphere the average sensitivity to radiation is mostly negative and the trends are heterogeneous, since light may exerts a negative indirect effect on the carbon budget in warm/arid climates.

A mostly positive sensitivity of NBP to soil water content occurs in arid regions, where evapotranspiration is supply limited and water stress may limit productivity. On the contrary, in northern regions, where evaporation is limited by atmospheric demand, the sensitivity is negative (Fig 4e). The trend in the sensitivity to water availability does not show a clear spatial pattern, likely due to the complex interplay between changes in precipitation and evapotranspiration in the different regions. Ultimately the sensitivity is likely to decrease where water availability is increasing, and vice versa it may increase in areas that are experiencing increasing water stress (Fig 4f).

This analysis was repeated with other five inversion products to check for result consistency. We observed a low standard deviation of NBP sensitivity to climate drivers among products (Figure S3, second column) and an overall agreement in terms of temporal trends of these sensitivities over most of the land surface (Figure S3, third column).

In order to explore the relationships between sensitivities, trends and background climate, results shown in the global maps of Figure 4 are summarized according to climate coordinates (i.e. annual cumulative rainfall and mean temperature, Figure 5). A clear pattern is emerging for radiation, with negative sensitivities in regions with high and very low temperatures, independently from precipitation values, while at intermediate temperatures radiation has a consistent positive effect on carbon fluxes. Figure 5 shows that the climate dependence of the trend in sensitivity to radiation generally follows the pattern of the mean sensitivity, with positive trends in climate regions characterized by positive sensitivity and vice-versa. Ultimately this combination of mean effects and trends is increasing the spatial variance in the ecosystem response to light, amplifying the differences between regions with positive and negative controls.

Similarly to radiation, temperatures also show positive sensitivities at intermediate mean temperatures. However, the different patterns of temperature and radiation trends suggest that the underlying processes triggered by the two drivers are likely different. In fact, the climate dependence of the trend in sensitivity to temperature doesn't follow the pattern of the mean sensitivity, being opposite in sign at intermediate temperatures and leading in this way to a homogenization of its spatial variability. The sign and magnitude of the sensitivity of NBP to soil water content is clearly controlled by the background mean temperature, with a sharp threshold at about 7 °C between regions with positive and negative sensitivity. On average the sensitivity to soil water content is increasing in regions warmer than 0 °C, but with considerable local variation, suggesting in general an increasing impact of water limitations on the fluctuations of the terrestrial carbon cycle, as also ~~scale is~~ reported ~~in~~by (Jung et al., 2017). It is interesting to highlight the positive trend of the soil water control in cold climates (temperature between -2 and 7 °C), where historically the mean signal has been negative. This finding is in agreement with the recent literature about the increasing control of soil water content on the NBP of boreal ecosystems (Buermann et al., 2018; Lian et al., 2020).

Analysing the trends of NBP sensitivity to climatic drivers separately for CUP and CRP (Figure 6) we noticed that the importance of radiation is increasing in most of the Northern Hemisphere in both periods, suggesting an overall increase in the occurrence of light-limited photosynthesis. This is likely due to a combination of warming, nitrogen deposition and CO_2 fertilization that have led to an extended growing season length and greening. In particular, the large increase in the sensitivity to radiation (likely related to the greening of the Planet, as suggested by the spatial patterns of LAI trends reported by Zhu et al., (2016)) dominates the radiation-related changes of NBP. The increase of light-limitation goes hand in hand with the decline of temperature limitation, in particular during the CRP in Eurasia. Opposite trends of sensitivity to radiation and temperature occur also in the Amazon, where during the CUP we observe an increasing control of radiation and decreasing control of temperature, and the opposite during CRP.

Finally, we factored out the observed total temporal variability in NBP in two components: the variability due to the temporal change in the drivers and that due to variations in the ecosystem response to drivers (i.e. ecosystem sensitivity to climate). Results show that the average contribution of the temporal change in sensitivity (Fig. 7 left column) is on average much larger than the contribution of the driver variability (Fig. 7 right column). This means that indirect climate effects, leading to a change of ecosystem sensitivity (e.g. aridity that increases the NBP sensitivity to water availability), are extremely relevant in determining the overall variability of the global NBC and may eventually amplify (when the two components have the same sign) or dampen (when opposite in sign) the effect of variation in climate drivers on terrestrial ecosystems.

4 Discussion

4.1 Potentials and limitations of the methodology

The analysis presented in this contribution largely builds on the data-driven estimates of NBP performed with the inversion of a global atmospheric transport model constrained by observations of atmospheric CO_2 concentrations. For this reason, the strengths and weaknesses of the study are related to those of the underlying NBP data product.

On the one hand, the atmospheric inversion technique offers the advantage for the specific goals of this assessment that the fluxes at any location are detected by the observational network, and can be spatially attributed on the large scales. That is, the results are not limited by an incomplete representation of ecosystems, that may be inherent in estimates based on point level NBP observations. In addition, the inversion estimates cover more than 3 decades, representing the longest time series of spatially-explicit, observation-driven estimates of the terrestrial carbon fluxes. A third specific advantage of the JENA CARBOSCOPE inversion framework is that both the observation network (i.e. the number and location of stations of atmospheric stations) and the prior fluxes are constant during the simulation period. Consequently, temporal changes in the estimated NBP are most directly driven by the atmospheric concentration field.

On the other hand, the inversion estimates of ecosystem CO_2 fluxes are affected by uncertainties. Probably the largest source of uncertainty is transport model errors, in particular vertical mixing. Transport model errors are expected to affect mean fluxes and the amplitude of flux variations, but are likely also time-dependent themselves. Further, errors in the estimates of anthropogenic fluxes directly affect NBP estimates as the atmospheric signals reflect the total surface flux including anthropogenic emissions of CO_2. Additional limitation of the inversion estimates is that prior fluxes are generated with a land surface model (Sitch et al., 2003) which embeds a priori knowledge of the relationship between climate drivers and terrestrial CO_2 fluxes. As such, prior estimates may affect the mean sensitivities shown in Figures 1 to 3, while they don't affect the trends shown in the other figures given that the priors are mean annual climatology of modelled land fluxes and therefore do not show a temporal trend. Finally, inversion estimates cannot distinguish between the counteracting CO_2 fluxes originated from photosynthesis and respiration and can therefore provide only limited insights into the factors controlling the individual ecosystem processes. As a proxy, we therefore analysed NBP during the CUP and CRP that are dominated by photosynthesis and respiration, respectively. However, the signal in these two sub-periods is actually affected by both GPP and TER and therefore the results cannot be interpreted as they were originated by single processes. For instance the observed dominant role of light during CRP is suggesting that it is actually the light limitation of GPP that is controlling the rapid fluctuation of NBP also off-season.

The overall structural uncertainty of the JENA CARBOSCOPE was evaluated by comparing runs of the same inversion system performed with different number of atmospheric stations (and therefore temporal coverage). Further, uncertainties due to statistical assumptions in the a-priori error covariance structure were evaluated by varying the assumed de-correlation lengths or other covariance parameters.

4.2 Spatial patterns of climatic controls on NBP

The global distribution of the limiting factors of the net biome productivity shows a high level of spatial coherence, so that large regions are controlled by a specific environmental factor, varying with the climate background. The most common driver of the short-term fluctuations in NBP is radiation, with positive correlation in most of the Northern Hemisphere. This pattern is likely due to the favourable growing conditions in the temperate zone, where weekly to seasonal variations in the ecosystem CO_2 flux are controlled by light-limited GPP. On the contrary, negative correlations dominate in the Southern Hemisphere, likely due to unfavourable growing condition during the sunny and dry season. Surprisingly also the northernmost latitudes show a negative correlation to radiation, suggesting a negative impact of sunny weather on the carbon budged, in line with recent findings about the reduction of NBP in the boreal zone, due to the anticipated phenology that reduces the uptake in summer (Buermann et al., 2018; Lian et al., 2020). This finding is of particular relevance since those regions are exposed to accelerated warming (IPCC, 2014) and store large quantity of carbon in terrestrial ecosystem (Carvalhais et al., 2014).

The second most important driver of short-term NBP fluctuations is temperature, with a positive correlation in most regions of the Southern Hemisphere at all the investigated temporal scale. This suggests that tropical ecosystems are still operating below their optimal temperature, as suggested by Huang et al., (2019). The sensitivity to soil water content show the expected strong positive control on NBP in warm and arid regions. A similar reduction in NBP due to soil moisture limitation and the non-linear response of carbon uptake to water stress was reported by ~~Seddon et al., (2016)~~Seddon et al. (2016) and agrees with what was observed by Green et al., (2019) ~~analyzing~~analysing outputs from four Earth system models.~~ They report a reduction in CO_2 uptake due to soil moisture variability justified by the non-linear response of carbon uptake to water stress.~~ According to this study the most affected regions are those characterized by seasonally dry climate, like tropical savannahs and semi-arid monsoonal regions. A faster atmospheric CO_2 growth rate in drier periods is also reported in ~~Humphrey et al., (2018)~~Humphrey et al. (2018), who conclude that drier years are associated with a weakening of the land carbon sink. ~~However, a~~

Our results differ substantially from the outcome of a previous study on the potential climatic constraint on NPP (Nemani et al., 2003) based on monthly climate statistics ~~over two decades at the end of the twentieth century (1982-1999) ascribes different roles to the drivers, with water availability limiting vegetation growth over 40% of the land surface followed by temperature (33%) and radiation (27%).~~ and remote sensing observation of vegetation over two decades (1982-1999). In addition to the different methodology used in the two studies, it is important to stress that our assessment addresses NBP and therefore includes also CO_2 fluxes from heterotrophic respiration and disturbances, while the analysis by Nemani et al. was limited to primary productivity.

~~Since the processes involved in the CO_2 exchange are different between the Carbon Uptake Period (CUP) and the Carbon Release Period (CRP), the regression analysis performed for the entire time series (Figure 1) was repeated separately for CUP and CRP (Figure 2). In the continental regions, the variability in the period dominated by photosynthesis (CUP) is mostly driven by temperature followed by global radiation, and generally both drivers have a positive impact on NBP, while the temperate zone is mostly radiation-driven. In Canada, Siberia, and Russia warmer periods are the most productive during the growing season. These results are in accordance with a study performed on 23 FLUXNET sites (Baldocchi, 2008)~~Additional insights on the environmental controls of NBP can be gained by assessing the fluxes for the periods when land is a net sink or a net source of CO_2 (CUP and CRP, respectively). During CUP the strong control of temperature in the boreal zone is in accordance with a study performed on 23 FLUXNET sites that shows how variations in GPP at northern sites can be explained to a large extent by mean annual temperature (Reichstein et al., 2007). ~~Rödenbeck et al., (2018), working at inter-annual time scale, observed the same correlation sign~~Rödenbeck et al. (2018), working at inter-annual time scale, found similar positive relationships of NBP and temperature during spring and autumn in all northern extra-tropical land areas, a signal which is consistent with photosynthesis being temperature limited in this time of the year. ~~During CUP in the southern hemisphere an important role is played by the soil water content which is positively correlated with NBP fluxes across the Tropical region~~In temperate regions the control of NBP during CUP is on the contrary led by radiation, whereas in the tropical zone by soil moisture.

~~The carbon release period of the Northern hemisphere is mostly driven by global radiation, which positively impacts on the NBP fluxes, with the exception of the most northern latitudes. Interestingly, where temperature is the dominant driver in the northern hemisphere it has a negative impact on CRP fluxes, likely related to the off-season stimulation of ecosystem respiration. The impact of radiation on CRP fluxes clearly depends on the climate zone. In the northern hemisphere, the most productive weeks of CRP are those with higher radiation (which means those at the beginning and at the end of the CRP). On the contrary, radiation has a negative impact on the CRP fluxes in the southern hemisphere, while the effect of the soil water content is generally positive. Temperature controls the most southern latitudes with a positive coefficient, and the intermediate latitudes with a negative one.~~

~~The global frequency and sign of the dominant drivers is summarized in Figure 3 for CUP and CRP at different temporal resolutions. The most frequent dominant variable during CUP is air temperature with a high dominance of positive coefficients, followed by radiation. Where soil water content is the dominant variable it has a positive impact on carbon uptake almost everywhere. During CRP the most frequent variable is global radiation, and the frequency of negative coefficients is much higher if compared to CUP. Temperature is the second most frequent dominant variable and has mostly a negative impact on NBP. This plot shows an important asymmetry in the sign of the controlling drivers between the CUP and CRP. While the former is stimulated by the increase in the drivers on a large fraction of the Earth surface (more than 80% on average for all drivers), the latter shows a mixed pattern where the CO_2 sink is stimulated in about half of the planet and depressed in the other half concerning radiation. Concerning temperature, the key parameter in a global change perspective, the asymmetry is even stronger, with a control overwhelmingly positive in the CUP (in ~85% of the~~

~~temperature-dominated surface at all the investigated temporal resolutions) and mostly negative (in 76%, 68% and 45% of the temperature-dominated surface at 7, 30 and 90 days respectively) in the CRP. This pattern is likely due to the positive response of both photosynthesis and ecosystem respiration to increasing temperatures. This asymmetry in the response of photosynthesis and respiration to temperature~~The relative importance of radiation and temperature is reversed during the carbon release period, when the fluctuations in NBP are mostly controlled by the incoming radiation across most of the Planet. However, during CRP radiation limits NBP in opposite directions in the two hemispheres: positive dependence in the light-limited boreal CRP and negative dependence in the water-limited austral CRP. An important variation in the sign of temperature control occur between the CUP (positive relationship) and the CRP (negative control) (Figure 2&3). This pattern is likely due to the positive response of both photosynthesis and ecosystem respiration to increasing temperatures (Barr et al., 2007; Krishnan et al., 2008; Reichstein et al., 2002; Ueyama et al., 2014). This asymmetry in the thermal response of the CO_2 fluxes originated from photosynthesis and respiration is at the base of the large uncertainty of the terrestrial C budget under climate change (Friedlingstein et al., 2014).

~~In a scenario~~4.3 Temporal variability of ~~rapidly changing climate it is particularly important to assess how~~ the ~~sensitivity of NBP to the different~~key drivers ~~is changing over time~~

Robust and ~~in which geographic regions. To this end, Figure 4 summarizes global maps of the averages (left) and~~ independent estimates of temporal ~~trends (right) of~~ changes in the limiting factors of NBP are particularly relevant, given the relevant changes in the ~~regression coefficients (with respect to all-year time series and at 7 days temporal resolution). The average regression coefficient of global radiation is positive in most of the northern hemisphere, which means~~climate drivers that ~~NBP increases at increasing radiation. This effect has increased~~occurred in the last three decades~~,~~ (IPCC, 2014) and the uncertainties on the ecosystem responses to varying climate drivers. The strongest signal emerging from the analysis is the broad increase in the positive sensitivity to radiation during both CRP and CUP in the Northern Hemisphere, while it is decreasing in most of the Southern Hemisphere where the average signal is negative. This positive trend observed in the last three decades is likely due to the increasing leaf area index (LAI) and primary productivity of the northern regions~~,~~ (Zhu et al., 2016), leading to increased light use efficiency and therefore to a stronger control of radiation on NBP. For the interpretation of these results it is important to consider that the ecosystem carbon exchange is controlled by light only in ideal growing condition, when neither temperatures nor water are limiting photosynthesis. ~~. On the contrary, in the southern hemisphere the average~~The positive trend in sensitivity to solar radiation during CPU in the boreal zone can be therefore interpreted as a tendency toward improved growing conditions due to a reduction of low temperature limitations. From the positive trends in light sensitivity observed here one could infer that the recent changes in climate, CO_2 concentration and nutrient availability have eased the growing conditions of plants (Nemani et al., 2003).~~is mostly negative and the trends are heterogeneous.~~

~~Concerning temperature, NBP in North America and northern Europe shows a positive sensitivity, while southern Europe, large fractions of Asia and the Tropical belt show negative sensitivity. In Eurasia, the sensitivity of NBP to~~

~~temperature~~Interestingly, the trend in sensitivity to radiation generally follows the sign of the mean sensitivity, with positive trends in climate regions characterized by positive sensitivity and vice-versa. This coherence between sensitivity and trend can be likely explained with the acceleration of the terrestrial carbon cycle that is inherently leading to an increased sensitivity of CO_2 fluxes to drivers. Ultimately this phenomenon is leading to an increased spatial variance in the response of ecosystem to radiation.

Concerning temperature, in Eurasia the sensitivity of NBP is decreasing with time, in agreement with Piao et al., (2017), who report a declining temperature response of spring NPP ascribed to reduced chilling during dormancy and emerging light limitation. ~~Interestingly an opposite positive trend of temperature~~ The sensitivity ~~occurs in North America.~~

~~A mostly positive sensitivity of NBP~~ to soil water content ~~occurs in regions where evapotranspiration~~ is ~~supply limited and water stress may limit productivity. On the contrary, in northern regions, where evaporation is limited by atmospheric demand, the sensitivity is negative.~~mostly ~~The trend in the sensitivity to water availability does not show a clear spatial pattern, likely due to the complex interplay between changes in precipitation and evapotranspiration in the different regions. Ultimately the sensitivity is likely to decrease where water availability is~~ increasing, ~~and vice versa it may increase in areas that are experiencing a decline in soil water content. In order to explore the relationships between sensitivities and background climate, results shown in the maps of Figure 4 are summarized in the scatter plots of Figure 5, where sensitivities and their temporal trend for all the pixels are plotted according to climate coordinates (i.e. annual cumulative rainfall and mean temperature). A clear pattern is emerging for radiation, with negative sensitivities in regions with high and very low temperature independently from precipitation values, while at intermediate temperatures it has a positive effect on fluxes. In addition, the climate dependence of the trend in sensitivity to radiation generally follows the pattern of the mean sensitivity, with positive trends in climate regions characterized by positive sensitivity and vice versa. This bimodal distribution of sensitivity and trends is clearly leading to an increase of the spatial (and climatic) variance in the response of ecosystem to radiation. The on-going acceleration of the terrestrial carbon cycle due to the increase of GPP and TER is likely leading to this bipolar pattern. Similarly to radiation, temperatures also show positive sensitivities at intermediate mean temperatures. In addition, the different patterns of temperature and radiation trends suggest that the underlying processes triggered by the two drivers are likely different. The climate dependence of the trend in sensitivity to temperature doesn't follow the pattern of the mean sensitivity, being opposite in sign at intermediate temperatures leading in this way to a homogenization of its spatial variability. The sign and magnitude of the sensitivity of NBP to soil water content is clearly controlled by the background mean temperature, with a sharp threshold at about 7 °C between regions with positive and negative sensitivity. On average the sensitivity to soil water content is increasing in regions warmer than 0 °C, but with considerable local variation, suggesting in general an increasing impact of water limitations on the fluctuations of the terrestrial carbon cycle, as also reported by (Jung et al., 2017).~~

~~Maps of the trends in the sensitivity of NBP to climatic drivers are shown in Figure 6, separately for CUP and CRP. The sensitivity of NBP to radiation is increasing in most of the northern hemisphere both during CUP and CRP, suggesting that NBP seasonality is increasingly controlled by light-limited photosynthesis, likely due to a combination of warming, a~~

~~consequent extended growing season length and greening. The increase of light-limitation goes hand in hand with the decline of temperature limitation,~~ in particular during ~~the CRP in Eurasia. Opposite trends of sensitivity to radiation and temperature occur also in the Amazon, where during the CUP we observe an increasing control of radiation and decreasing control of temperature, and the opposite during CRP. The sensitivity to soil water content is mostly increasing, in particular during CRP in most regions~~CRP in most regions, except Western Europe, in line with the recent findings by Buermann et al., (2018) about the increasing role of water limitation in the boreal zone. ~~In general soil~~Soil water content shows an increasing control on the seasonality of NBP also in the US, South America and ~~in tropical regions~~South Africa, confirming the increasing relevance of water stress on primary productivity ~~(Jung et al., 2010).~~

~~The strongest signal that is emerging from the analysis is the broad increase in the sensitivity to radiation during CUP in the northern hemisphere, while it is decreasing in most of the southern hemisphere. On the contrary, the sensitivity to temperature is generally decreasing everywhere, with the exception of the most northern and southern latitudes which host temperature-limited ecosystems. The pattern of the soil water content is less clear. Arid zones exhibit a weak increase in soil water content control, which confirms recent published results that documents how the inter-annual variability of the planet is controlled by arid zones~~(Humphrey et al., 2018; Jung et al., 2010) and control of arid zones on variability of the terrestrial carbon budget (Ahlstrom et al., 2015). ~~For the interpretation of these results it is important to consider that the ecosystem carbon exchange is controlled by light only in ideal growing condition, when neither temperatures nor water are limiting photosynthesis. From the positive trends in light sensitivity observed here one could infer that global changes in climate have eased the growing conditions of plants (Nemani et al., 2003). In particular, the positive trend in sensitivity to solar radiation during CPU in the boreal zone can be interpreted as a tendency toward improved growing conditions due to a decline of low temperature limitations.~~

Finally, ~~we factored out~~ the ~~two contributions to~~analysis of the sources of variability of NBP revealed that the largest fraction of the signal is coming from the temporal ~~trend~~variation in ~~NBP (Figure 7), namely the temporal trend of the climatic drivers (right column) and the temporal trend of~~ the ecosystem ~~sensitivity to the driver (left column). Results show that the temporal trend in sensitivity is generally bigger than~~response to the environmental drivers and not from the variation of the ~~corresponding contribution due to temporal change in the driver. This finding suggests that the ongoing~~drivers. Temporal variations in ecosystem responses may originate from structural and physiological changes in vegetation ~~functional~~ characteristics ~~are affecting the temporal variability of NBP more than the climate variability per se~~, eventually occurring in response to changing environmental conditions (Marcolla et al., 2011; Richardson et al., 2007). ~~In particular~~For instance, the large increase in the sensitivity to radiation ~~(likely related~~could be due to the ~~greening of~~ increase in LAI and subsequent increase in the ~~planet) dominates the~~ fraction of absorbed radiation ~~related changes~~ occurring in most of ~~NBP in almost~~the Northern Hemisphere. Ultimately, indirect effects of climate on the ~~entire northern hemisphere. In contrast,~~ecosystem response to environmental drivers may amplify the overall impact of climate variability and trends ~~in temperature sensitivity cause a decline in NBP in Eurasia and part of North America, while the temperature increase itself~~

~~causes increasing NBP just like radiation~~on the future dynamic of the terrestrial carbon budget, posing further uncertainty on the efficacy and vulnerability of land-based mitigation strategies.

4 Conclusions

- ~~We focused this analysis on climate drivers of the sub-annual variability of land CO_2 fluxes as derived from an atmospheric inversion in order to characterize the key driver in the different world regions and climates. The short-term drivers of NBP can be interpreted as the limiting factors of the ecosystem carbon budget at weekly to seasonal scale. Advancing the knowledge on the limiting factors and their variation in the recent decades is important to understand and predict the impact of climate change on the terrestrial carbon budget.~~

- We focused this analysis on the climate drivers of the sub-annual variability of land CO_2 fluxes, as derived from an atmospheric inversion system, in order to characterize the key driver in the different World regions and climates. The short-term drivers of NBP can be interpreted as the limiting factors of the ecosystem carbon budget at weekly to seasonal scale. The assessment of the dominant drivers and their temporal trends is essential to understand the potential impact of the changing climate on the terrestrial carbon budget, with the ultimate goal of reducing the large uncertainty about the role of land on the future climate trajectories (Friedlingstein et al., 2014).

- Given that the atmospheric inversion does not allow a direct separation of NBP in gross primary productivity and ecosystem respiration, we ~~analyzed~~analysed two contrasting periods: the carbon uptake periods (CUP) when NBP is dominated by photosynthesis and the carbon release period (CRP) when NBP is dominated by respiration.

- ~~On average, during the year we~~Results show ~~that solar radiation is driving the variations~~drastic differences in the response of the terrestrial carbon budget to environmental drivers in the ~~seasonality of the fluxes in the northern hemisphere, and soil water content in the southern hemisphere.~~two periods. More specifically, during the CUP we ~~can detect~~detected three clear driving factors, temperature in the northernmost regions, radiation in the temperate regions and soil water content in the tropical region, with temperature being the most common driver. During the CRP a large fraction of the planet is radiation-controlled, with positive correlation in the ~~northern hemisphere~~ Northern Hemisphere and negative in the Southern. This contrasting pattern is likely due to the off-season light limited photosynthesis in the boreal hemisphere (triggering the positive correlation), and by the indirect negative effect of high radiation loads on photosynthesis in warm and arid regions of the southern hemisphere.

- ~~Looking at the temporal dynamic of the climatic control~~The rapid changes in the climate drivers and in ecosystem properties observed in the last decades (e.g. greening) have driven important changes in the climatic control of the net biome productivity. In particular, air temperature shows a positive correlation with NBP in Eurasia, but with a decline in sensitivity over time; on the contrary, sensitivity to radiation is increasing almost in the entire ~~boreal~~

~~hemisphere~~Boreal Hemisphere both during CUP and CRP, suggesting that ~~CO_2 fluxes are~~NBP is becoming increasingly light-limited at short-time scales.

- ~~This analysis reveals the strength of the climatic controls on the terrestrial carbon budget and their clear dependence on the background climate. It also shows how the recent trend in climate combined with CO_2 fertilization and photosynthetic potentials is substantially changing the climate response of the terrestrial biosphere.~~

- Factoring out the sources of temporal variability of NBP we showed that ecosystem CO_2 fluxes are ~~more intensively~~ controlled more by the temporal variation in the ecosystem sensitivities to climate drivers than by the temporal changes of the drivers. This ~~means~~finding suggests that the indirect ~~impact~~impacts of climate change on the ecosystem sensitivity may actually be more relevant than the direct impact of the climate variability on the terrestrial CO_2 fluxes. Ultimately, indirect climate effects may trigger an important amplification of direct climate impact on NBP, leading to unexpected and non-linear responses.

- Overall this analysis shows ~~how important~~the spatial complexity and the clear dependencies on the climate ~~is in determining the sensitivities~~background of ~~NBP to~~ the environmental controls ~~and how rapidly these sensitivities are changing in time, likely leading to new and still un-experienced~~on the terrestrial carbon budget. The significant changes in the climate sensitivities occurred in the last three decades demonstrate the rapid, ongoing evolution of the relationships between climate and the terrestrial carbon budget. Advancing the knowledge on the limiting factors and their variation is an important step in the understanding and predicting the impacts of climate change on the terrestrial carbon budget.

Author contribution. AC and BM conceived the study and designed the methods. CR provided the Jena Carboscope data. BM performed the data analysis. AC and BM interpreted the results. MM and CR contributed to the improvement of the methods and to the interpretation of results. AC and BM wrote the manuscript with contributions from the other co-authors.

Competing interests. The authors declare that they have no conflict of interest

Data availability.

The Jena Carboscope database can be found at http://www.bgc-jena.mpg.de/CarboScope/

WFDEI database at http://www.eu-watch.org/data_availability

ERA-Interim database at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim

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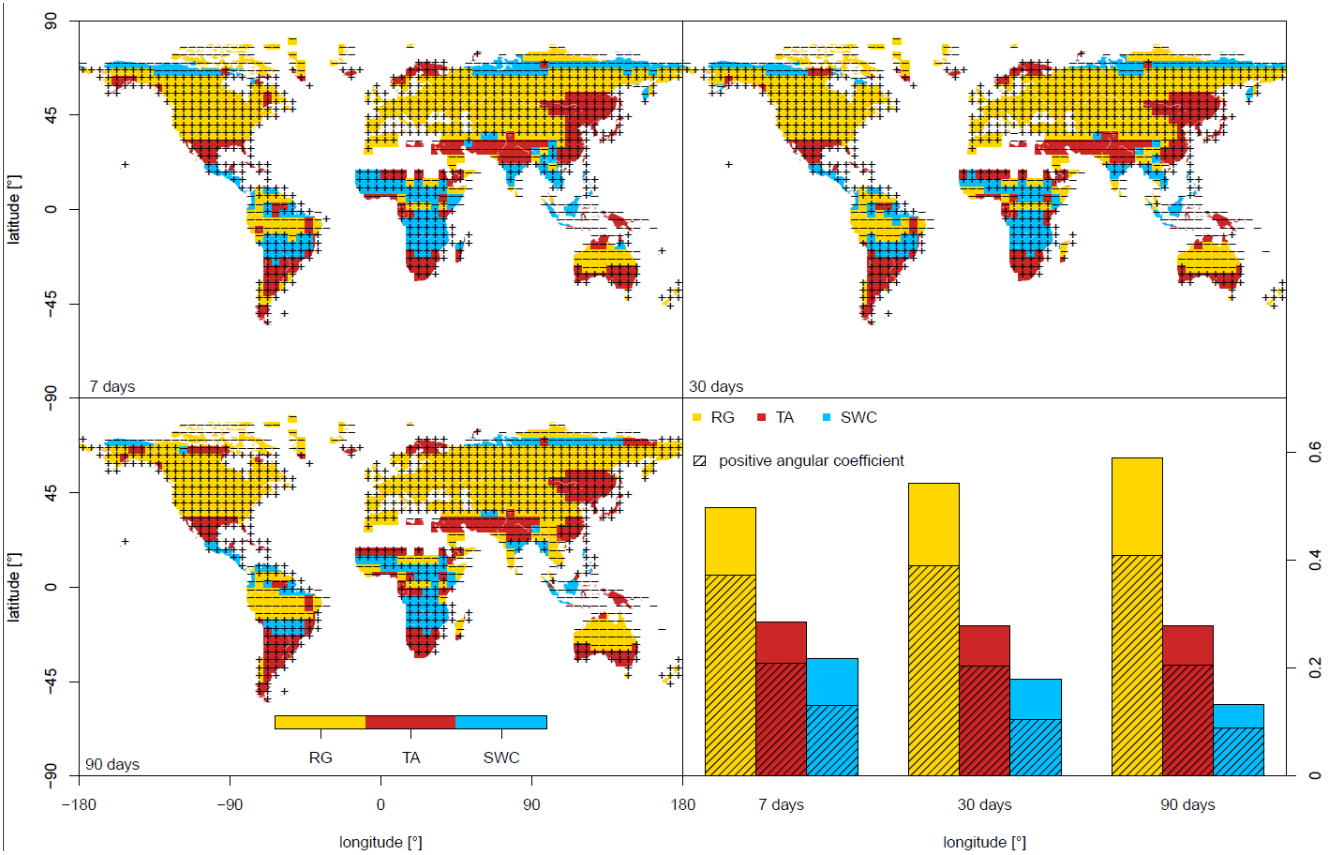
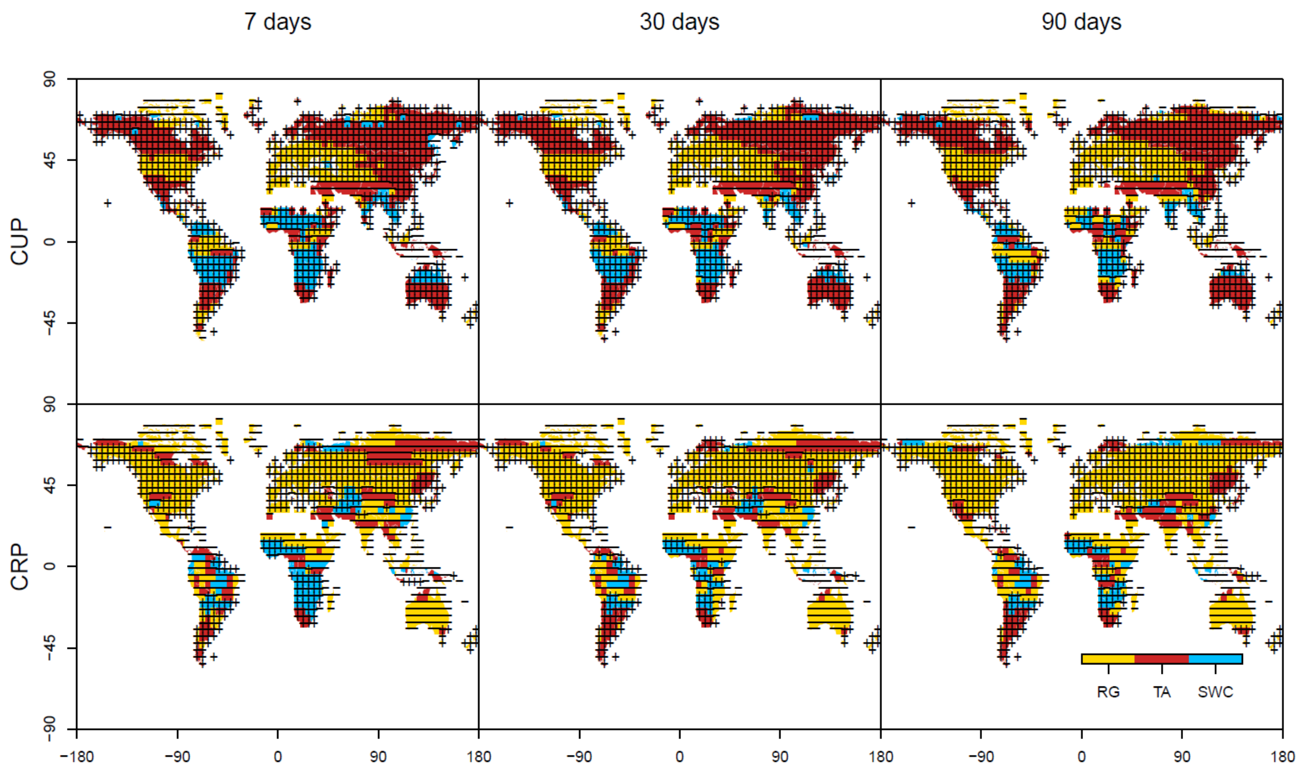


Figure 1 - Maps of the dominant drivers calculated over the entire time series and sign of their angular coefficients in a multi-linear regression. Results are shown for three temporal resolutions, namely 7, 30 and 90 days. Bottom right panel: frequency of each dominant variable for the three ~~analyzed~~analysed temporal resolutions, dashed areas represent the frequency of positive angular coefficients.



735 **Figure 2 - Maps of the dominant drivers and sign of their angular coefficients in a multi-linear regression calculated separately for Carbon Uptake Period (CUP, top row) and Carbon Release Period (CRP, bottom row). Results are shown for three temporal resolutions, namely 7, 30 and 90 days.**

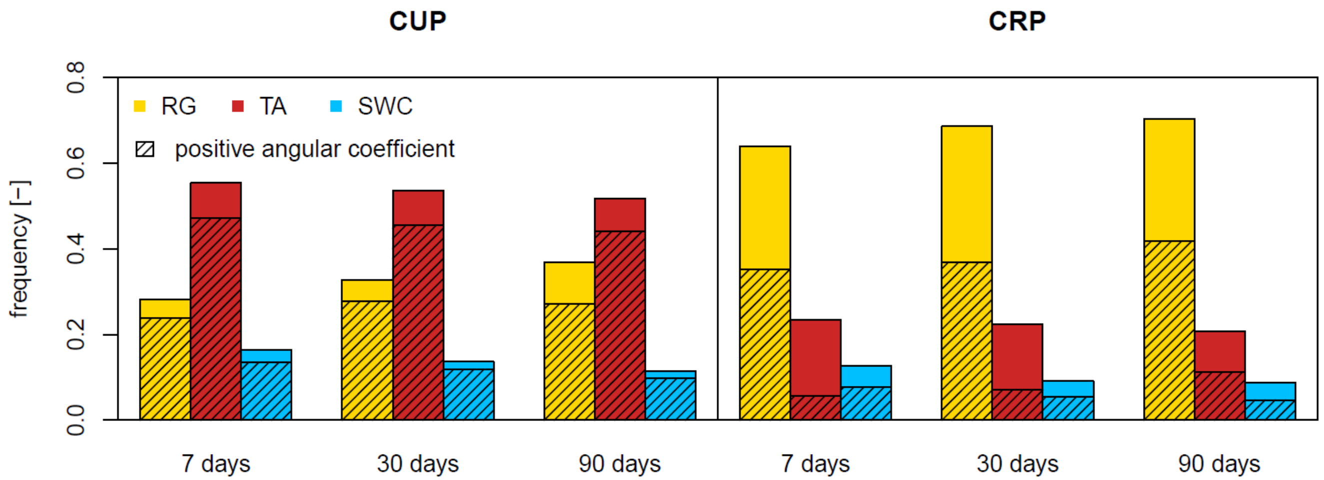


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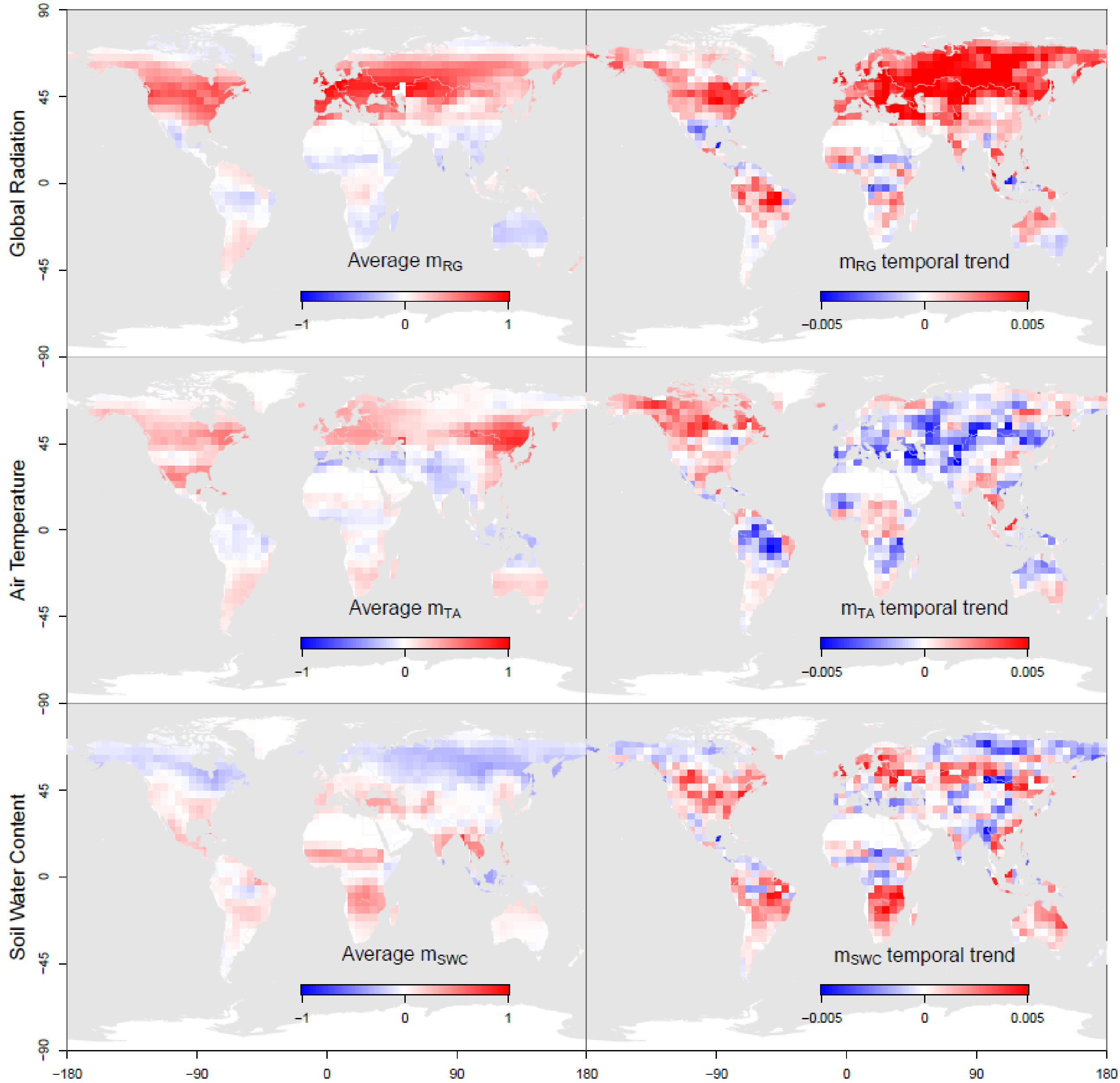
Figure 3 - Frequency of the dominant variables plotted for Carbon Uptake Period (CUP) and Carbon Release Period (CRP) at different temporal resolutions (7, 30 and 90 days), and frequency of dominant variables with positive coefficients (dashed bars).


Global Radiation
Air Temperature
Soil Water Content
Average m_RG
m_RG temporal trend
Average m_TA
m_TA temporal trend
Average m_SWC
m_SWC temporal trend
−1
0
1
−0.005
0
0.005
90
45
0
−45
−90
−180
−90
0
90
180

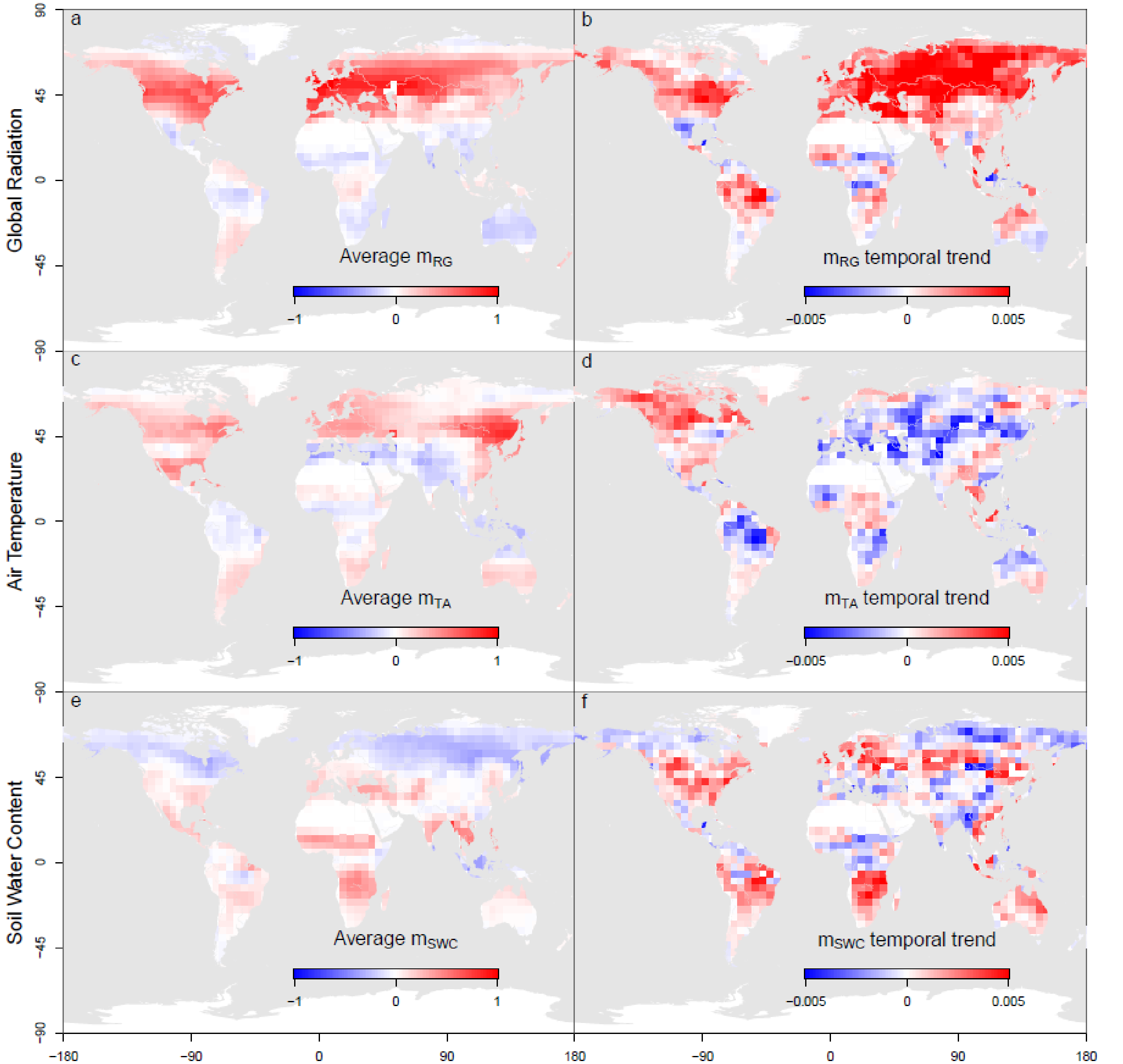


Figure 4 – Maps of magnitude (left column) and trends (right column) of the sensitivity of Net Biome Productivity (NBP) to global radiation (first row), air temperature (second row) and soil water content (third row) at weekly time scale.

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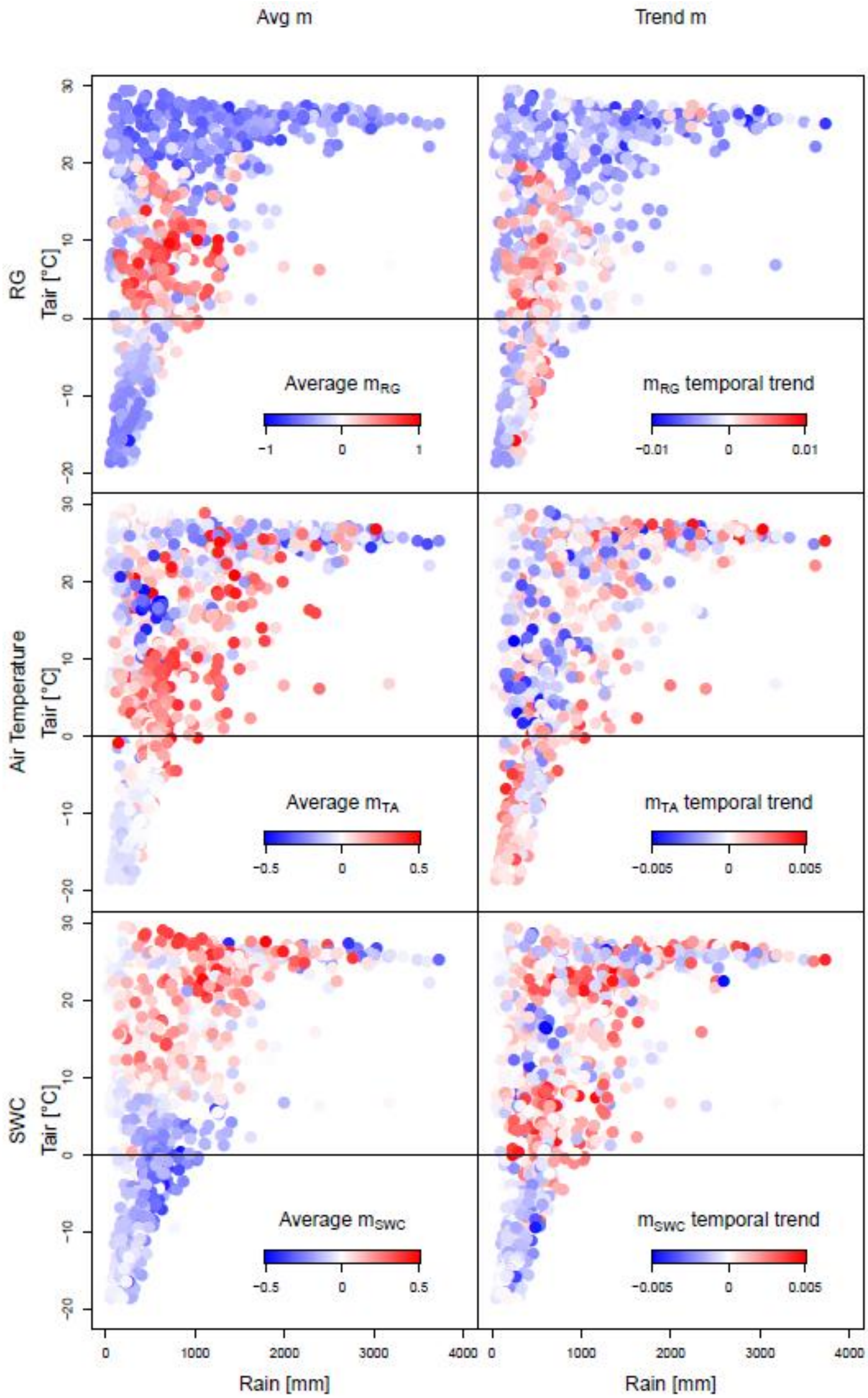
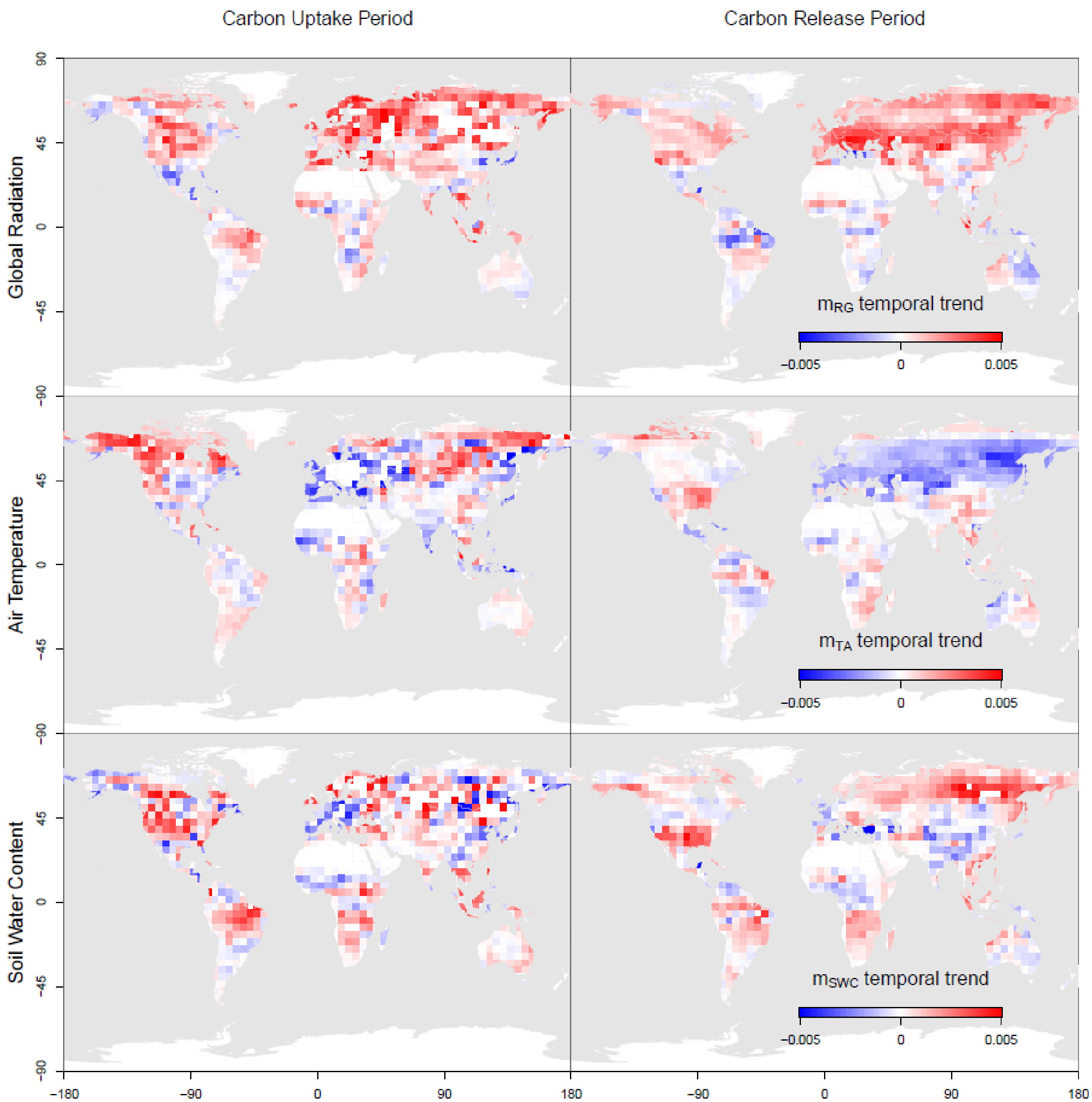


Figure 5 – Scatter plots of sensitivity to climate drivers (left column) and of trends of the sensitivities (right column) plotted in a precipitation- temperature space at weekly time scale.


Carbon Uptake Period
Carbon Release Period
Global Radiation
Air Temperature
Soil Water Content
mRG temporal trend
mTA temporal trend
mSWC temporal trend
−0.005
0
0.005
90
45
0
−45
−90
−180
−90
0
90
180

755

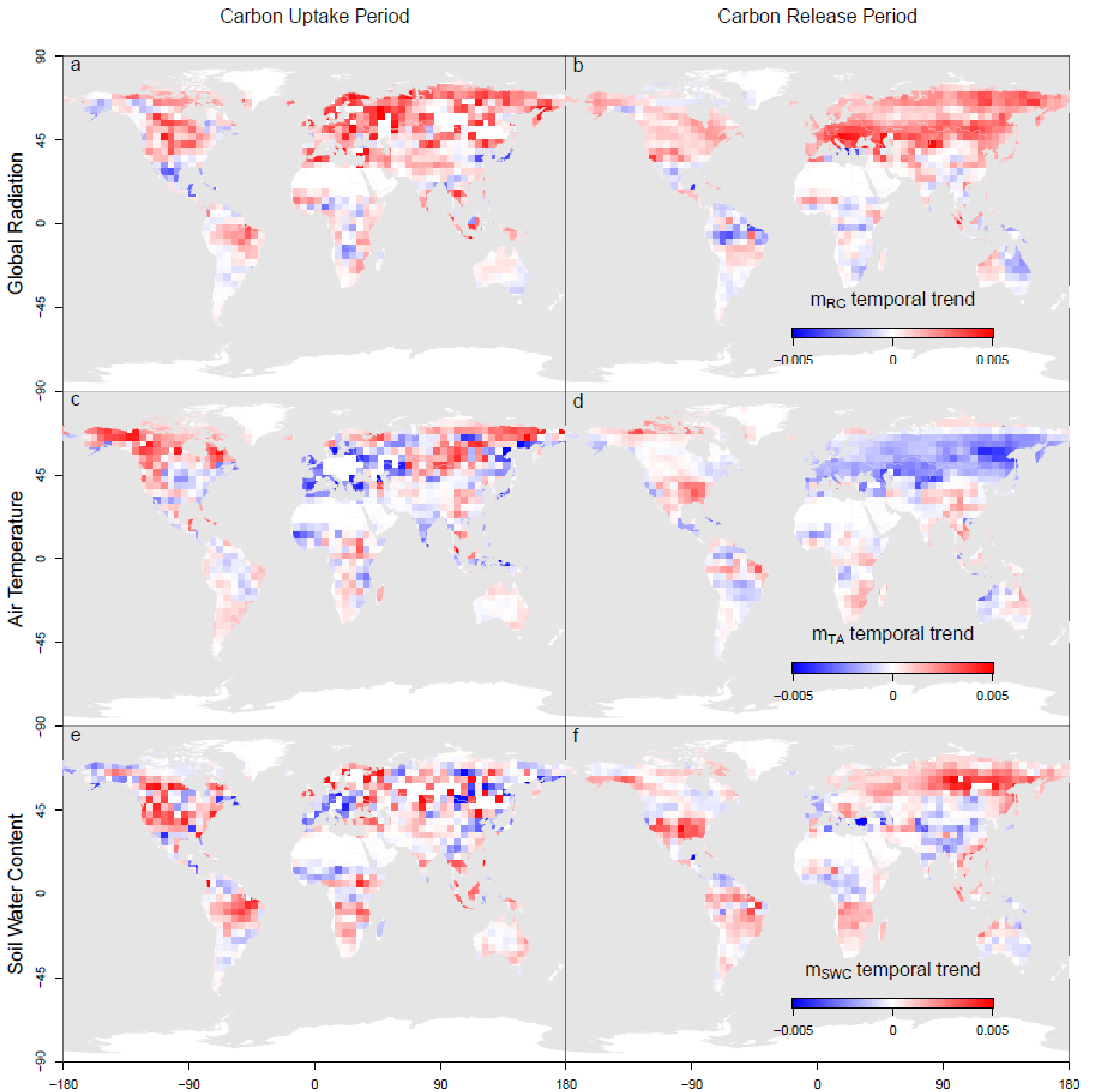
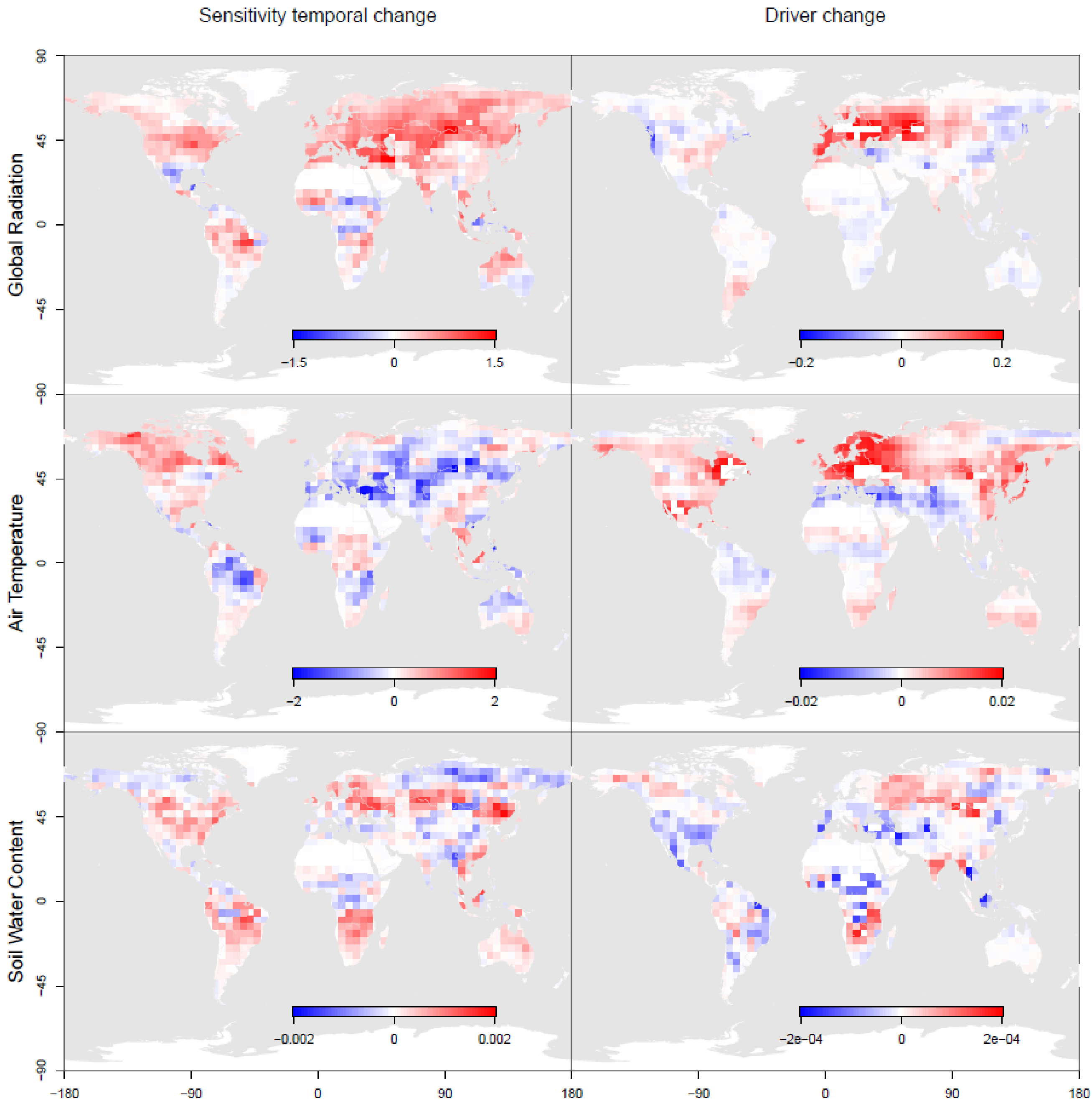


Figure 6 – Maps of sensitivity temporal trends separately shown for Carbon Uptake Period (CUP, left column) and Carbon Release Period (CRP, right column) at weekly time scale. Maps are plotted for global radiation (first row), air temperature
760 **(second row) and soil water content (third row).**



Sensitivity temporal change
Driver change
Global Radiation
Air Temperature
Soil Water Content
90
45
0
−45
−90
−1.5
0
1.5
−0.2
0.2
−2
2
−0.02
0.02
−0.002
0.002
−2e−04
2e−04
−180
−90
0
90
180

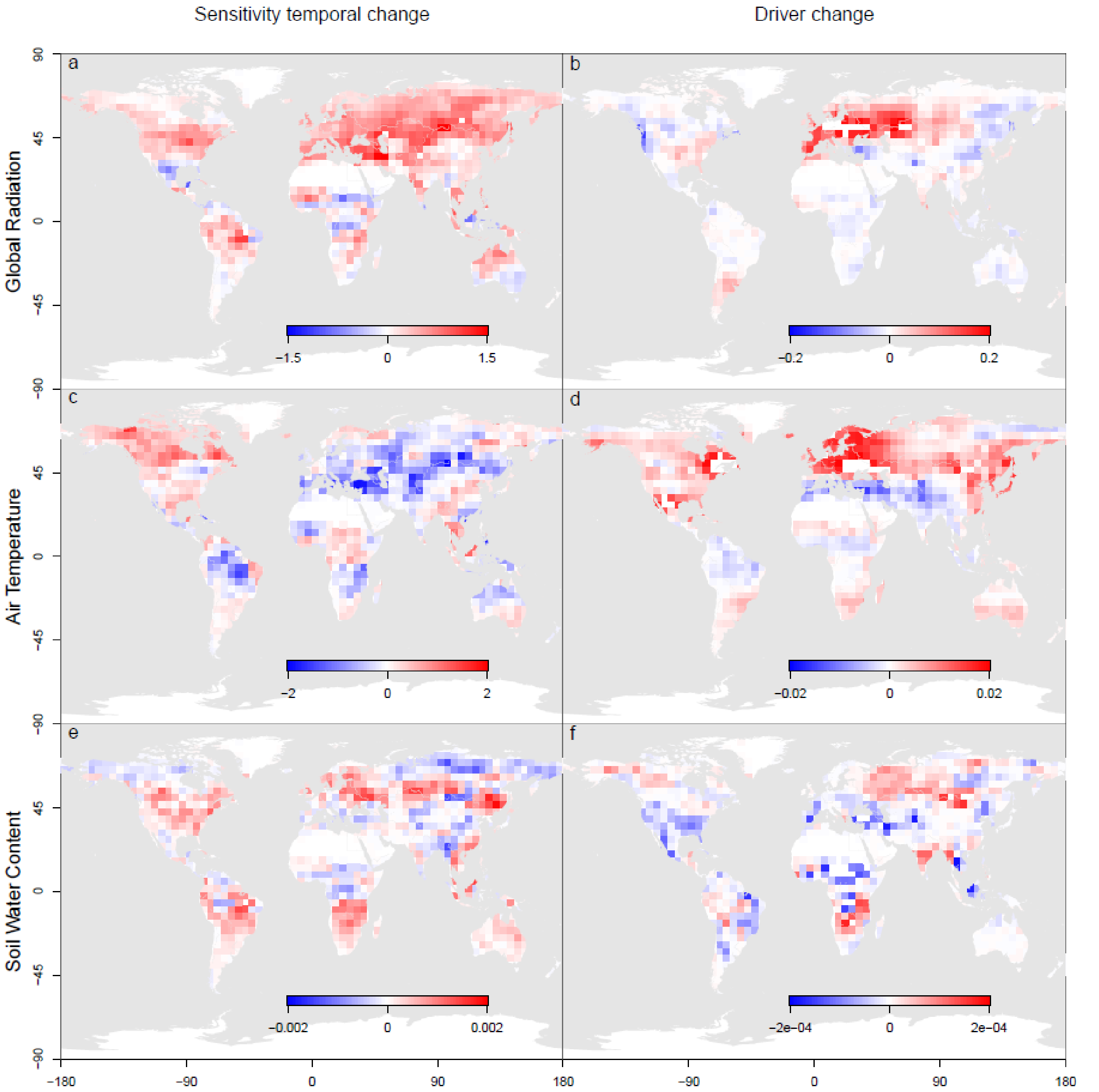


Figure 7 – Maps of the average contribution of sensitivity temporal change (left column) and of the temporal change of the driver (right column) to the total temporal variability of Net Biome Productivity (NBP) in the investigated period. Maps are plotted for global radiation (first row), air temperature (second row) and soil water content (third row).