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Horizon 2020 Societal challenge 5:
Climate action, environment, resource efficiency and raw materials

# VERIFY

## Observation-based system for monitoring and verification of greenhouse gases

GA number 776810, RIA

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| **Changes with respect to the DoA** |
| Delays were encountered due to the provision of model results and the analysis of the ICOS data. |
| **Dissemination and uptake**<br>**(Who will/could use this deliverable, within the project or outside the project?)** |
| This deliverable represents the first step towards a manuscript, and as such is available for public dissemination with the caveat that the work is still ongoing and conclusions may change. |
| **Short Summary of results (<250 words)** |
| Relationships between growing season temperature anomalies and observed / simulated terrestrial $CO_2$ fluxes across the European continent have been analyzed for gross and net terrestrial $CO_2$ fluxes using eddy covariance data from the ICOS network, atmospheric inversion estimates of net ecosystem exchange and the FLUXCOM data driven models of gross primary productivity, the latter of which are trained with eddy covariance data and remote sensing of surface properties. We show a decreasing interannual sensitivity of GPP to temperature anomalies, with a sign-change threshold of 7°C in the site data analysis and 23°C in the model-based analysis. |
| **Evidence of accomplishment**<br>**(report, manuscript, web-link, other)** |
| This report represents the current state of the accomplishment, though a manuscript is also in preparation depending on the results of further analysis. |

| Version | Date | | Description | Author (Organisation) |
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| V0.1 | 18/06/2021 | | Creation/Writing | Philippe Ciais (CEA) |
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# 1 Glossary

| Abbreviation / Acronym | Description/meaning |
|---|---|
| **CSR** | CarboScopeRegional |
| **GPP** | Gross Primary Productivity |
| **TER** | Terrestrial Ecosystem Respiration |
| **NEE** | Net Ecosystem Exchange |
| **ICOS** | Integrated Carbon Observing System |

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# 2 Executive Summary

We analyzed the interannual sensitivity of terrestrial gross $CO_2$ fluxes to temperature across the European continent, by using eddy covariance flux measurements of the ICOS network and continental scale models for GPP and TER. Both products have been provided by the WP3 of VERIFY. Both site level data and continental scale observation-based fluxes agree on the fact that the sensitivity of GPP to interannual temperature fluctuations is generally positive at colder mean background temperature, and it becomes negative in warmer regions where warming anomalies are associated with soil moisture deficits, thus limiting GPP. The threshold background mean temperature at which the sign of the interannual sensitivity of GPP to temperature goes from positive to negative is 7°C from the site data analysis and 23°C from the continental scale model analysis.

# 3 Introduction

$CO_2$ fluxes between land ecosystems and the atmosphere depend on abiotic factors like climate and weather, as well as on biotic response characteristics related to ecosystem structure, age, plant traits, and biodiversity. For instance, a larger diversity of species was found to increase the resistance and the resilience of natural ecosystems as estimated by the ability of Net Primary Production (NPP) to minimize negative responses to disturbance events and to recover after each disturbance. In most cases, the sensitivities of European ecosystem $CO_2$ fluxes to climate variations are modulated by management through complex interactions given the rather ubiquitous and diverse nature of management activities, and seasonally contrasted influences of climate variables. For instance, dry and hot conditions in spring can be beneficial for photosynthesis and $CO_2$ uptake whereas the same conditions may be adverse in summer. In the case of crops and intensively managed grasslands, farmers have a range of options to adapt their management during the growing season to negative climate conditions in order to maintain production or their economic return, e.g., by adjusting the amount and timing of fertilizers, animal loadings, phytosanitary product applications, irrigation, or cutting frequency for grasslands.

In the long term, the combination of farm level adaptation, regional, national or European policies, and technical progress will also influence $CO_2$ fluxes, e.g., through the choice of varieties, practices and rotations. In the case of forests, management is arguably less adjustable during a growing season, but management-controlled parameters such as tree density, species, and soil carbon inherited from past land use practices also impact the response of forests to climate anomalies. On the other hand, if an extreme climate or weather event causes severe tree mortality, either directly caused by drought or windthrown, or indirectly from previous climate extremes such as insects or pathogen attacks immediately following drought, foresters will harvest dead trees and cause local soil and snag $CO_2$ emissions to the atmosphere. In this deliverable we analyzed how interannual and seasonal anomalies of temperature, radiation and precipitation are statistically associated with observed anomalies of gross photosynthesis uptake (GPP), total ecosystem respiration (TER) and their difference (NEE at site scale, NBP at regional scale). We make the hypothesis that northern ecosystems are positively sensitive to temperature, i.e., that warmer growing season temperatures favor larger gross and net $CO_2$ uptake, and that southern ecosystems are negatively sensitive to warm anomalies, as warmer years come with less precipitation, limiting soil moisture available for plant growth. We look at observations from individual eddy covariance towers from the ICOS network and from spatially-explicit atmospheric inversions estimate of NEE and data driven fields of GPP to quantify the interannual sensitivity of ecosystem fluxes to climate anomalies across the European continent.

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# 4 Analysis of the climate controls on carbon fluxes in Europe

The research question addressed here is whether the inter-annual temperature sensitivity of $CO_2$ fluxes changes in magnitude or in sign across the whole climate gradient of the European continent going from southern summer dry countries to cool Nordic ones. In particular, we intend to determine at which mean temperature and for which biomes there may be a reversal in the sign of the interannual sensitivity. A precursor analysis was performed by Liu et al. 2018 using eddy covariance towers, global DGVM results and one atmospheric inversion, across the contiguous United States. It showed that the eastern wetter part of the United States had an interannual variability of NEE dominated by precipitation, with wetter anomalies leading to a greater abnormal sources of $CO_2$ to the atmosphere in the Eastern US, while the opposite was observed over the Western US, where wetter years were associated with a larger $CO_2$ uptake by NEE and a larger GPP. Such a systematic analysis has not been performed for the European continent. Previous studies have been limited to tree ring growth anomalies that cover long time spans and relate indirectly to growth and woody net primary production. Babst et al. 2013 showed from detrended tree ring chronologies that the northern part of Europe and the Alps region had positive inter-annual correlations between temperature and ring width (a proxy of woody productivity) whereas southern and temperate forests showed negative or near zero ring width – temperature correlations but positive ring width -precipitation correlations, indicating a predominance of water stress covarying with growing season temperature, so that warmer years were associated with a decreased ring width and less woody productivity in those southern and temperate regions. An approximate mean annual temperature if 15.9°C was found as a threshold below which the response of tree NPP to positive temperature anomalies became positive (Klesse et al. 2018).

## 4.1 Analysis of eddy covariance data

We started with an analysis of how climate fluctuations affect the $CO_2$ fluxes from the European continent using eddy covariance data from the ICOS network from 27 long term sites shown in Figure 1. The sites cover a large range of mean annual rainfall and mean annual temperature going from 500 to 1300 mm y-1 and from 0 to 16°C, as shown in Figure 2.

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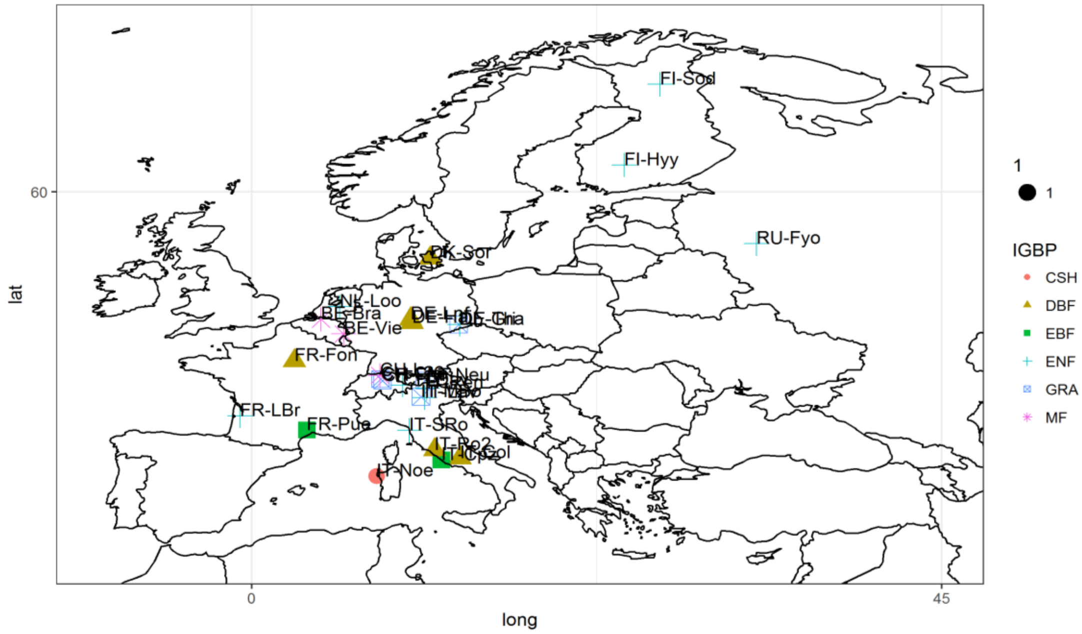


**Figure 1: Distribution of ICOS sites used for this analysis**

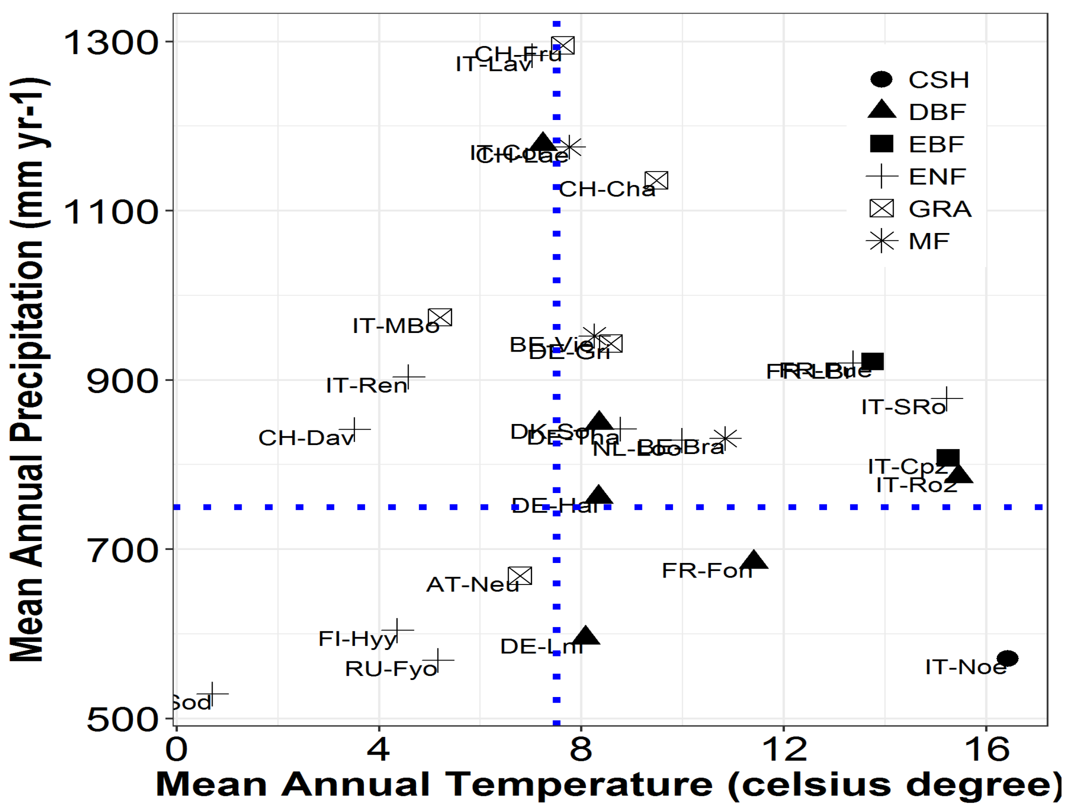


**Figure 2: Distribution of the eddy covariance sites from the ICOS network used in this study in a climate space of mean annual temperature and mean annual precipitation. DBF : deciduous broadleaved forest, EBF : evergreen broadleaved forest, ENF : evergreen needle leaved forest, GRA : grassland, CSH : shrublands**

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We used the same approach as [Liu et al. 2018](#) over North America, separating GPP and TER from NEE data and computed the mean of the inter-annual sensitivity to growing season temperature $\delta^{temperature}$ at each site, defined by a linear fit to the flux anomaly each year as a function of the anomaly of climate. This sensitivity across sites is shown in the figure below.

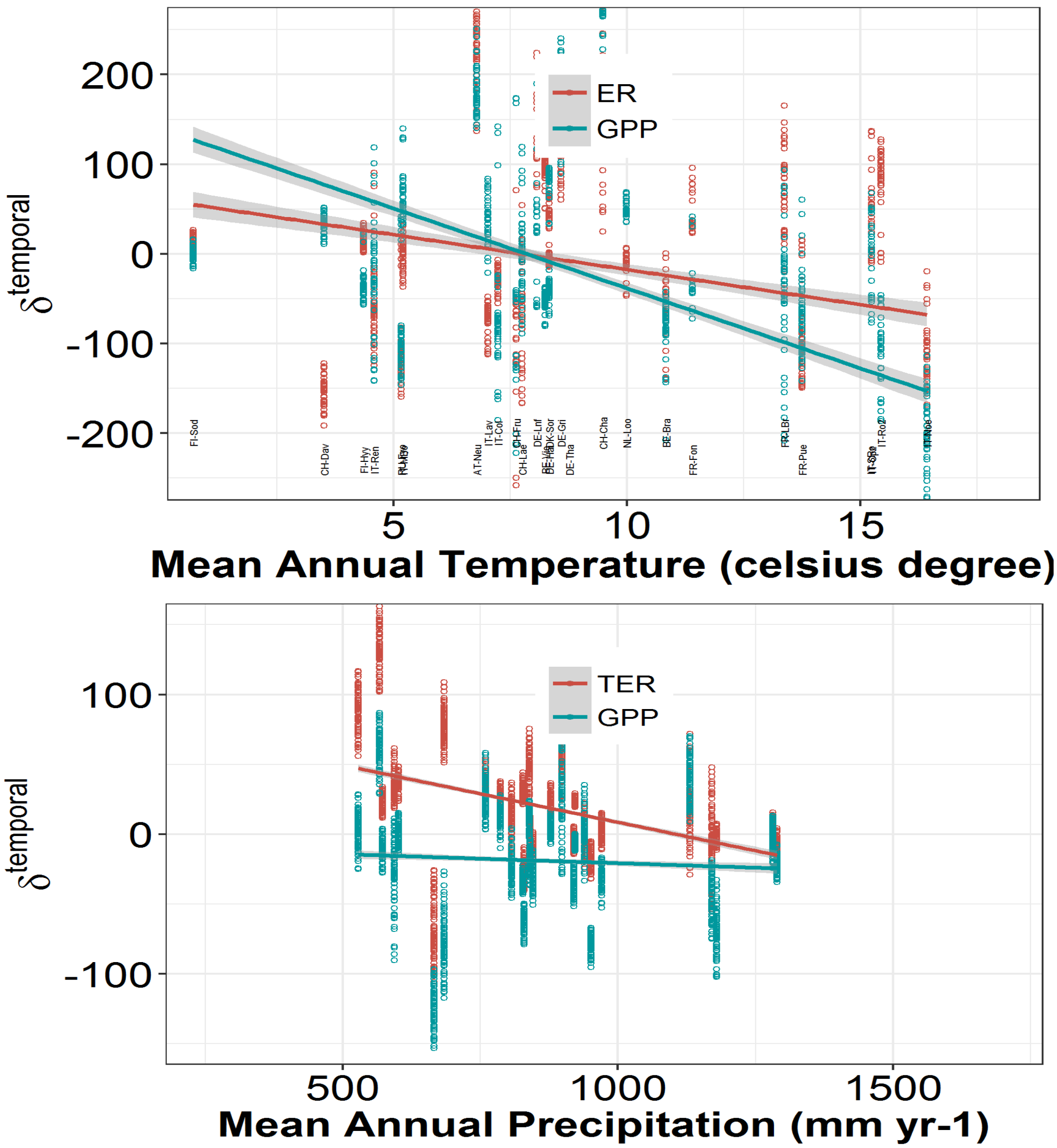


**Figure 3: Interannual sensitivity of GPP and TER to growing season temperature (g C m-2 y-1 per °C) obtained from bilinear regressions of site level growing season GPP and TER anomalies as a function of mean annual temperature going from the coldest to the warmest site (top) and as a function of precipitation (bottom). A linear fit was applied to sensitivities for TER and GPP across sites. The points represent each bootstrapping replicate, and line and shaded area represent mean and one standard deviation of error from the 100 bootstrapping simulations. Site name is indicated below each point.**

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In Figure 3, the Y-axis represents interannual change in GPP and TER (g C $m^{-2}$ $yr^{-1}$) in response to 1-degree temperature change. We can see that on average, the sensitivity of GPP and TER to a warmer growing season is positive below a mean annual temperature of 7°C and negative above. At warmer locations, warmer years or growing seasons are associated with a rainfall deficit and soil drying. This result is consistent with the change in sign of the interannual sensitivity of woody productivity (tree rings width) to growing season temperature in Europe observed from tree ring networks at a threshold of 15.9 ± 1.4 °C for May-August temperature. The relative contribution of precipitation and temperature to GPP variability is shown in Figure 4 below, with temperature explaining 75% of the GPP interannual variability and precipitation explaining less than 25%. The contribution of precipitation to GPP variability increases at wetter sites and decreases at warmer sites.

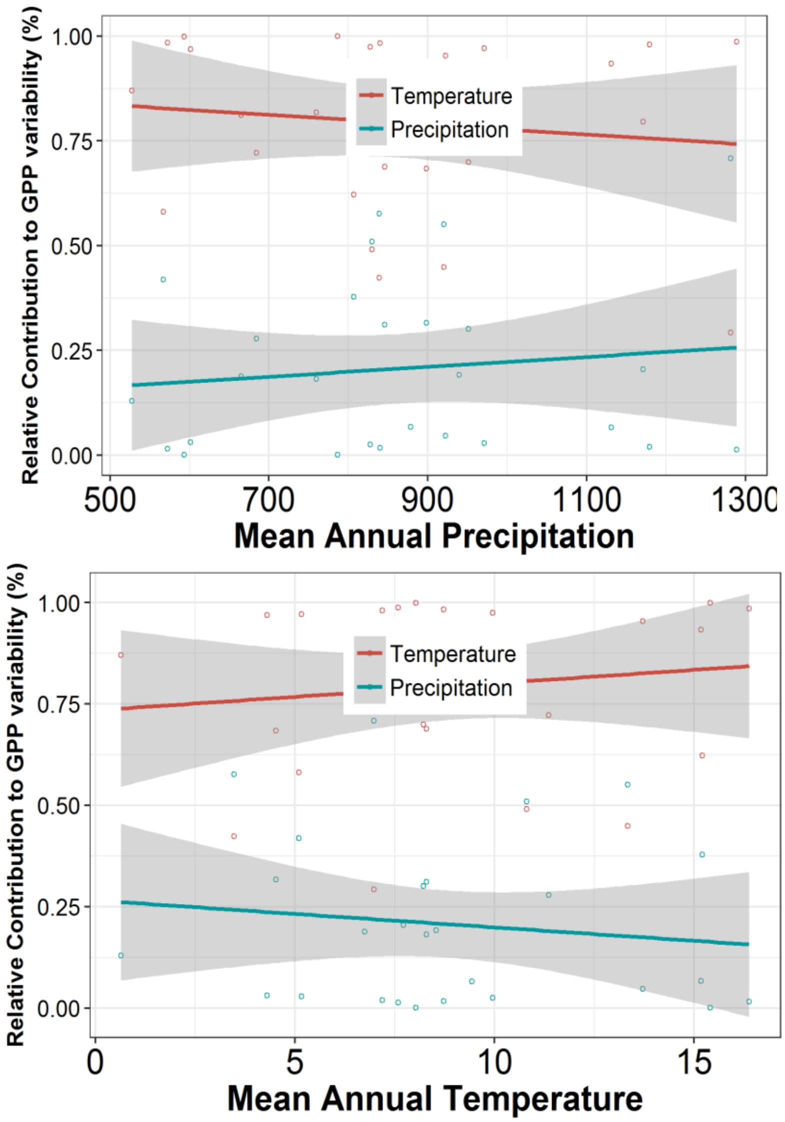


**Figure 4: Relative contribution to GPP variability of temperature and precipitation as a function of mean annual precipitation (top) and mean annual temperature (bottom) for individual ICOS sites.**

The results shown in Figure 2 confirm previous analysis from tree rings with a change in the sign of the sensitivity of GPP to temperature at a threshold of mean annual temperature of ≈ 7°C from 27 sites of the ICOS network that we have analyzed. The crossing point is around a mean annual temperature of 7°C, and below this threshold the absolute value of the temperature sensitivity of GPP exceeds that of TER, so that a warmer year will produce both a higher GPP, a higher TER, and a higher net $CO_2$ uptake (NEE = GPP-TER). On the other hand, above the temperature threshold of 7°C the sensitivity of GPP to temperature is more negative than the one of TER. This means that a warmer year is associated with a decrease in both GPP and TER, but the larger decrease in GPP leads to a lower net $CO_2$ uptake or a greater $CO_2$ source to the atmosphere.

## 4.2 Analysis of continental scale model results

The above results were derived from eddy covariance observations. In the context of the VERIFY project, we also have access to bottom-up and top-down simulations using process-based ecosystem models and atmospheric inversion models. Fig. 3 and 4 depend on having both the GPP and TER for the model. The atmospheric inversion model in VERIFY, CarboScopeRegional (CSR), only provides NEE and not its decomposition into GPP and TER. The same is true for the EUROCOM set of regional inversions. By combining the NEE from CarboScopeRegional and GPP from the Fluxcom statistical upscaling of eddy covariance fluxes, we can generate a TER that corresponds to the inversion model. In the context of the analysis below, the mean of four different CSR simulations was used. The four simulations vary based the set of biogenic priors used (either the Fluxcom model or the VPRM model) and the number of measurement stations assimilated (either 15 or 46). The mean fluxes for all four CSR variants are shown in Figure 5 to give an idea of the spread and the regions where the models differ.

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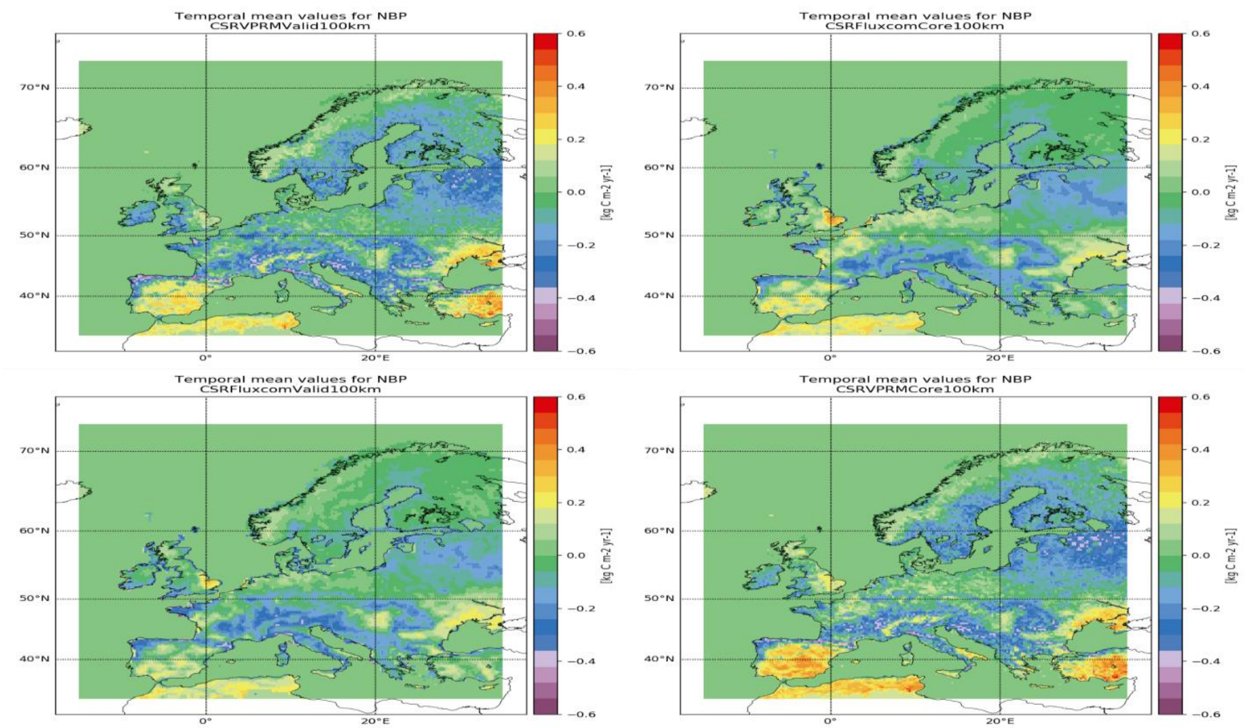


**Figure 5: The mean NEE values of all four CSR inversions used to calculate the mean TER flux**

Figure 6 shows the climate regime in Europe according to the CRUHAR dataset. Several regions of interest include the Alps, Ireland/Scotland, and the Norwegian coast, all of which can be characterized as cool and wet. The rest of Europe is relatively dry.

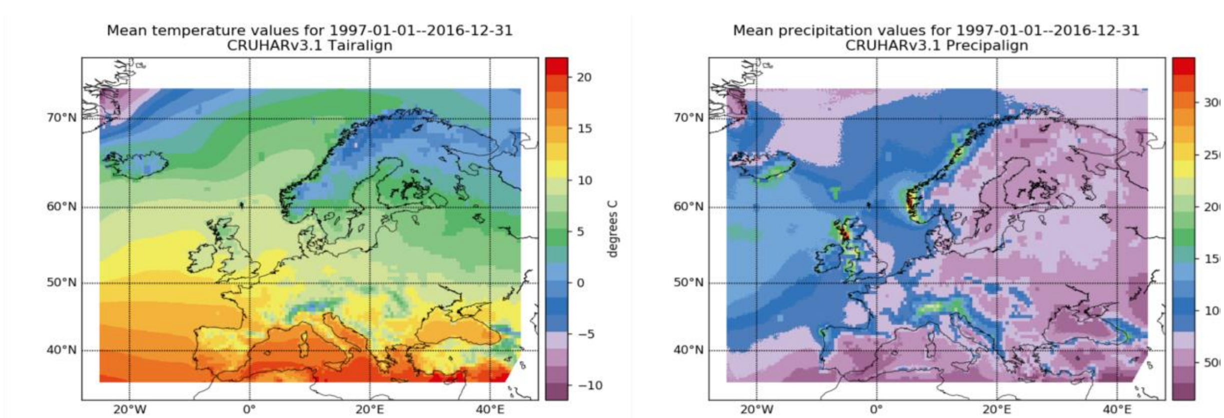


**Figure 6: Climate regime across Europe according to the CRUHAR dataset.**

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Comparing fluxes at the monthly scale identifies obvious correlations which caused by seasonal trends and therefore not scientifically interesting (e.g., the GPP will increase in the springtime due to the start of the growing season). To eliminate seasonal trends, we compare anomalies in the below figures. In particular, we look at the whole set of values across a timeseries in one pixel for a given month (e.g., January), calculate a linear fit, and then subtract the linear fit from all the values of this particular month. Twelve linear models are thus fitted and removed from every pixel. This method is a combination of removing a linear fit to the whole timeseries (i.e., removing long-term drift) and removing a mean for every month (i.e., removing the seasonal cycle). An example of the results is shown in Figure 7. The original timeseries (upper left) shows clear seasonal variations in temperature. Removing a linear fit to the whole timeseries (upper right) removes long-term drift, but not the seasonal means (only five years of data is used, so no long-term drift is seen). The last two methods remove the seasonal cycle completely, showing the anomaly with respect to an "average" month.

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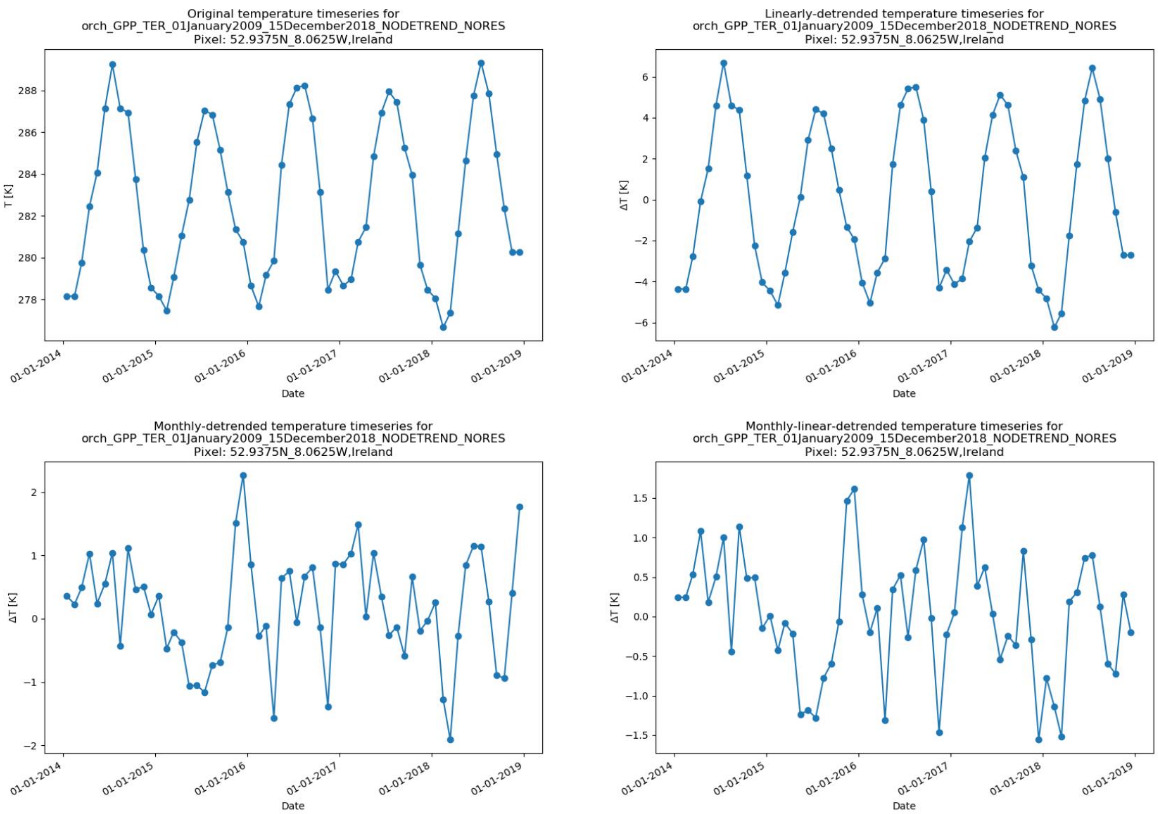


**Figure 7: Examples of detrending timeseries of temperature: original data (upper left); removing a linear trend (upper right); removing a monthly mean (lower left); and removing a monthly linear model (lower right).**

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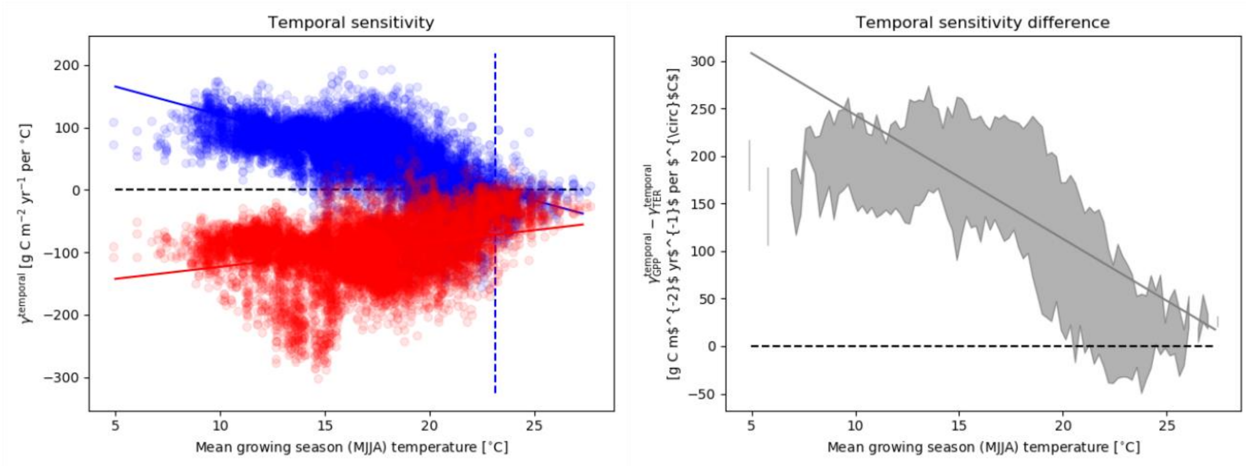


**Figure 8: The temporal sensitivities to the mean growing season surface temperature of MLINEAR detrended Fluxcom GPP (blue) and CSR TER (red), plotted as a function of the mean growing season surface temperature. The growing season is defined as May-June-July-August. Pixels with a low mean annual GPP are not included (i.e., bottom 10%). Left panel: the colored solid lines represent least-squares linear regression for GPP (blue) and TER (red), while the dashed vertical lines indicate where the linear regressions cross 0.0. Right panel: the difference between the sensitivities for GPP and TER, where the shaded values show the standard deviation around the mean.**

Figure 8 and Figure 9 show results for the GPP (Fluxcom) and TER (CSR) fluxes analogous to Fig. 3 and 4 for the eddy covariance towers. Sensitivities are calculated for the mean across the growing season (May-June-July-August) and the results are plotted accordingly. The pixels with the lowest 10% of mean annual GPP are removed to avoid biasing the results from pixels where TER and GPP are nearly equal due to poor growing conditions. For the mean growing season temperature, the cross-over point is relatively high (around 23°C) compared to the eddy covariance towers. For TER, CSR predicts that increasing temperature will always lead to a stronger source of carbon to the atmosphere (i.e., negative values), even if the strength of the increases decreases at higher temperatures. The GPP sensitivity dominates at lower mean growing season temperatures, while the terms are much more balanced at higher temperatures, likely reflecting that GPP is no longer temperature-limited. The sensitivities of temperature plotted as a function of the mean growing season precipitation are plotted in Figure 9, and show that at high precipitation regimes, the GPP temperature sensitivity always dominates. Taken along with Fig. 8, this suggests that the temperature component of the interannual variability of cool, wet areas will be driven primarily by the variability in the GPP.

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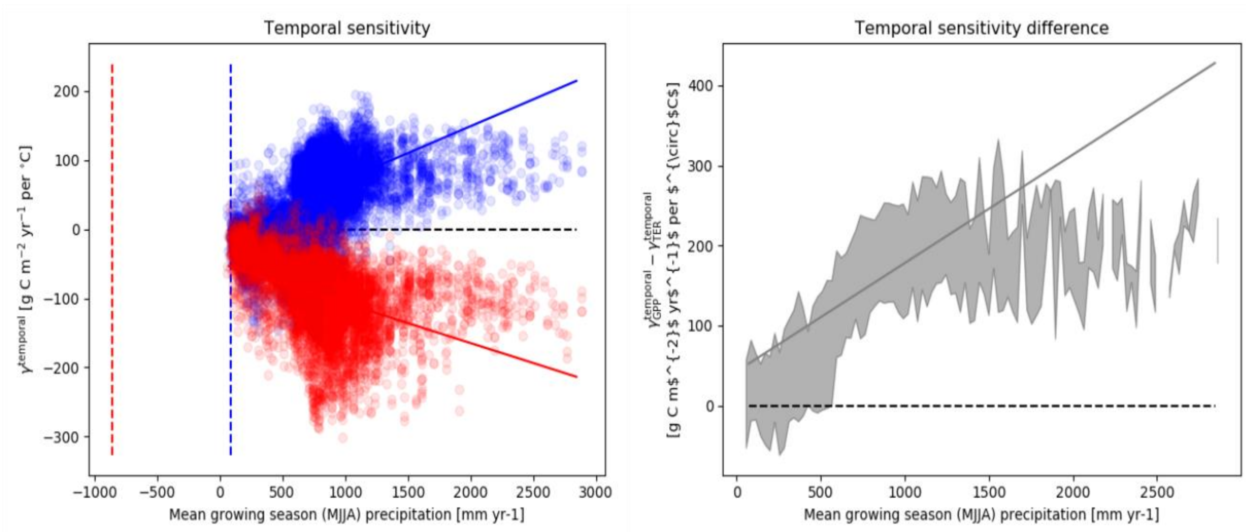


**Figure 9: The temporal sensitivities to the mean growing season precipitation of MLINEAR detrended Fluxcom GPP (blue) and CSR TER (red), plotted as a function of the mean growing season precipitation. The growing season is defined as May-June-July-August. Pixels with a low mean annual GPP are not included (i.e., bottom 10%). Left panel: the colored solid lines represent least-squares linear regression for GPP (blue) and TER (red), while the dashed vertical lines indicate where the linear regressions cross 0.0. Right panel: the difference between the sensitivities for GPP and TER, where the shaded values show the standard deviation around the mean.**

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# 5 Conclusions

We analyzed the interannual sensitivity of terrestrial gross $CO_2$ fluxes to temperature across the European continent, using eddy covariance flux measurements from a subset of the ICOS network and using continental scale models for GPP and TER. At the continental scale, TER is deduced from TER = NEE +GPP, with GPP taken from an empirical model trained on eddy covariance flux tower measurements, and NEE taken as the net land atmosphere $CO_2$ flux deduced from an inversion assimilating $CO_2$ concentration data from the atmospheric network covering Europe. Both products have been provided by WP3 in VERIFY. In the eddy covariance data, we found that the temperature sensitivity of GPP decreases from cold to warm regions, and becomes negative at a mean annual temperature threshold of 7°C. In the European scale models, we found a qualitatively similar result but the mean annual temperature threshold is 23°C. This large difference reflects model errors and the limited sampling of European ecosystems by the ICOS network. We plan to improve the approach by restricting the calculation of sensitivities when there is a high correlation between temperature and GPP or TER and to include more sites from the ICOS network, covering more recent extreme droughts like 2018.

# 6 References

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