,
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

Deliverable number (relative in WP)	**D3.13**
Deliverable name:	Third Complete NEE inversions
WP / WP number:	3
Delivery due date:	Month 44 (30/09/2021)
Actual date of submission:	Month 50 (09/03/2021)
Dissemination level:	Public
Lead beneficiary:	MPG
Responsible	Christoph Gerbig
Contributor(s):	Saqr Munassar
Internal reviewer:	Philippe Peylin (CEA), Géraud Moulas (ARTTIC)

Changes with respect to the DoA
None.
Dissemination and uptake **(Who will/could use this deliverable, within the project or outside the project?)**
The inversion results are freely available (with password protection, available from the PI). The results include a priori fluxes (used as initial guess) and posterior fluxes (optimized using atmospheric observations) to be used in the synthesis product in WP5. The web-page for data download is listed in section 3.
Short Summary of results (<250 words)
Biosphere-atmosphere exchange of CO_2 and its interaction with climate drivers is an important player in the carbon cycle. To estimate net ecosystem exchange (NEE) fluxes, VERIFY includes both, biospheric models for bottom-up estimation of fluxes, and a regional inversion for a top-down estimation. The Jena CarboScope-Regional (CSR) inversion system has been deployed for the 2006-2020 period to estimate biosphere-atmosphere exchange fluxes from the top-down perspective, using recent atmospheric observations up to 2020. This deliverable provides details about the inversion. The results include a priori fluxes (used as initial guess) from the diagnostic light use efficiency model VPRM and FLUXCOM model, and posterior fluxes from the CSR inversion.
Evidence of accomplishment **(report, manuscript, web-link, other)**
All the simulation results are accessible though the dedicated data THREDDS server: https://verifydb.lsce.ipsl.fr/thredds/catalog/verify/WP3/catalog.html

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

Version	Date	Description	Author (Organisation)
V0.1	1/09/2021	Creation/Writing	Christoph Gerbig (MPI-BGC)
V1.0	08/03/2021	Formatting/Delivery on the Participant Portal	Philippe Peylin (CEA); Géraud Moulas (ARTTIC)

Contents

1. Glossary

Abbreviation / Acronym	Description/meaning
COFFEE	CO_2 Release and Oxygen Uptake From Fossil Fuel Emission Estimate
CSR	Jena CarboScope-Regional inversion system
EDGAR	Emissions Database for Global Atmospheric Research
EVI	Enhanced vegetation index
FLUXCOM	An initiative to upscale biosphere-atmosphere fluxes from FLUXNET sites to continental and global scales
IAV	Interannual variations
LBC	Lateral boundary conditions
LSWI	Land surface water index
MODIS	Moderate resolution imaging spectroradiometer
NEE	Net ecosystem exchange
STILT	Stochastic Time-Inverted Lagrangian Transport Model
SYNMAP	Synergetic land cover product
VPRM	Vegetation Photosynthesis and Respiration Model

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

2. Introduction

This report describes the NEE inversions for the year 2020 using the Jena CarboScope-Regional (CSR) inversion system. The CSR system uses the combination of the regional transport model STILT (Stochastic Time Inverted Lagrangian Transport) and the global TM3 model. Surface-atmosphere fluxes are estimated from atmospheric observations of CO_2 mole fractions using the two-step scheme inversion (Rödenbeck et al., 2009), consisting of a global inversion to provide lateral tracer transport to the regional domain, followed by a regional inversion. Several inversion runs using different a-priori flux models and two different sets of atmospheric stations have been implemented with three different ocean flux models (one of them using specific coastal ocean flux estimates). Furthermore, three different far-field contributions (or Lateral Boundary Conditions, LBCs) have been used, related to different sets of atmospheric stations in the global inversion run.

Results suggest that NEE estimates show a weaker uptake in 2020 over the full domain in the context of the 2006-2019 period, in particular in comparison with 2019 NEE estimates, but comparable with 2018 estimates. 2018 has been characterized with a distinct drought event as has been explained in (Rödenbeck et al. 2020; Thompson et al. 2020). The domain-integrated weaker uptake in 2020 is robust against using different sets of stations, including e.g., a subset of only 15 stations with best coverage during 2016-2020, as well as using different far-field contributions. Subregions that were heavily impacted are East, North and West Europe. Contrastingly, a larger uptake in 2019 was found over certain regions in Central and North Europe such as Finland, France, and Sweden, which were affected by the drought in 2018.

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

3. Setup

3.1. Regional transport model

The regional transport model STILT (Stochastic Time Inverted Lagrangian Transport) driven by ECMWF meteorological fields from short-term forecasts from the IFS at 3-hourly and 0.2°x0.2° spatial resolution was used to pre-compute footprints for every atmospheric observing site at hourly resolution. STILT includes turbulent transport as well as vertical transport through convective clouds. Backward transport was simulated for 10 days, giving ample time for the regional domain to be flushed by advection. The temporal resolution of each footprint was also one hour, sufficient to fully resolve the coupling between transport and fluxes. The spatial resolution of the footprints is mapped at 0.25° x 0.25°.

3.2. Spatial domain and state space

The CarboScope-Regional inversion system was set up for a European domain covering 33N - 73N in latitude and 15W – 35E in longitude. The full inversion period covers the years 2006 – 2020. The spatial resolution is 0.25° x 0.25°, and the temporal resolution is hourly for the coupling between fluxes and transport.

The state space (or control vector) — i.e., the variables optimized within the inversion, are additive flux corrections to prior fluxes at a spatial resolution of 0.5° x 0.5° and a temporal resolution of three hours. A prior error structure was chosen following Kountouris et al. (2018) using a prior uncertainty at annual and domain-wide scale of 0.44 GtC/yr. The prior uncertainty uses spatial correlations with a length-scale of 100 km in a hyperbolic decay and temporal correlations with a time scale of 1 month.

3.3. A priori fluxes

3.3.1. Biosphere-atmosphere exchange

CarboScope-Regional uses biogenic prior CO_2 fluxes derived from the Vegetation Photosynthesis and Respiration Model, VPRM (Mahadevan et al., 2008). This diagnostic model uses ECMWF (European Centre for Medium-Range Weather Forecasts) operational meteorological data for radiation (downward shortwave radiative flux) and temperatures (T2m), the SYNMAP land cover classification (Jung et al., 2006), and EVI (enhanced vegetation index) and LSWI (land surface water index) derived from MODIS surface reflectance products. Model parameters were optimized for Europe using eddy covariance measurements made during 2007 from 47 sites (Kountouris et al., 2015). VPRM NEE fluxes have been produced at a 0.25 degree spatial and hourly temporal resolution.

FLUXCOM is also used as a prior fluxes model in the CSR system, providing hourly fluxes at 0.50-degree spatial resolution (Jung et al. 2019). The product is based on a machine learning mechanism that combine energy flux measurements from eddy covariance sites, remote sensing (MODIS) and meteorological data. In contrast to the previous version, FLUXCOM now uses non-climatological information from remote sensing, leading to larger interannual variations.

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

3.3.2. Fossil fuel emissions

Anthropogenic emissions from fossil fuel combustion are not optimized in the inversion, but are prescribed in the inversion and treated as fixed boundary conditions. They are taken from EDGARv4.3 fuel type and category specific emissions provided by Greet Janssens-Maenhout (EU-JRC), combined with information on national totals from fuel consumption data in recent years as compiled in the BP statistics 2021 (BP 2021), following the COFFEE approach (Steinbach et al., 2011). This way diurnal, day of week, and seasonal variations from TNO as well as interannual variations from BP are included, providing hourly fluxes at the 0.25-degree resolution.
In addition, in order to better account for changes in emissions related to lock-down periods during the Covid-19 pandemic, also sector-specific daily emission factors were used from Carbonmonitor.org for the year 2020, in contrast to the more climatological daily and seasonal variations that are used in the standard COFFEE approach.

3.3.3. Ocean fluxes

Ocean fluxes taken from pCO_2-based Carboscope ocean flux product are used at 5 x 4 degree of spatial resolution with 6-hourly fluxes, as well as using coastal fluxes combined with these fluxes to investigate the impact of costal fluxes on NEE estimates. The climatological ocean fluxes taken from Mikaloff-Flechter et al. (2007) are also used to investigate the impact of changing ocean fluxes. Since the spatial domain in this project does not contain large areas covered with ocean, ocean fluxes are not adjusted in the inversion but are instead prescribed. This is, apart from the larger domain, the only difference between the CSR setup in this project and that described in Kountouris et al. (2018).

3.4. Atmospheric observations

Atmospheric observations for the 2006-2020 inversion were taken from the dataset collected through the ICOS site network and provided by the ATC, as well as ObsPack dataset for stations located within the regional domain of the inversion. This includes a pre-release of ICOS data. Of these stations, 35 used in the 2020 inversion, and the total number of different sites throughout all years was 46. We excluded in this year two stations: FKL in Greece and LMU in Spain (both showed inconsistent data in 2021 release compared to last year dataset release 2020). The sites are tall towers, coastal stations, mountain sites, short towers or near-surface continental sites, and one station is classified as an urban neighborhood. For tall towers, near-surface or coastal stations, 11:00-16:00 UTC observations (referring to the beginning of the observational hour) where used, while for mountain stations the observations from 23:00-04:00 UTC were used.

A model-data mismatch was assumed to be 1.5 ppm for tall towers, coastal and mountain sites, 2.0 ppm for ground based continental sites, and 4.0 ppm for stations in an urban neighborhood. These refer to uncertainties for weekly averages; for hourly data an error inflation was applied, for example in the case of tall towers the 1.5 ppm mismatch was inflated by the square root of the number of observations per week (42), resulting in 9.7 ppm for hourly data.

3.5. Lateral boundary condition

Lateral Boundary Conditions (LBCs) have been updated to encompass 2020 using the global model TM3 in the CarboScope inversion system to provide far field contributions of CO_2 to the regional

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

domain of Europe. This is performed using the two-step scheme inversion approach (Rödenbeck et al., 2009) which makes use of both gridded global model at coarse resolution of 5 x 4 degrees and the regional model STILT at fine spatial resolution of 0.25 x 0.25 degree. A change was applied in this 2020 update: Rather than using a far-field contribution that is based on stations used within the standard global inversion, now the system uses all stations that are used within the regional inversion. The impact on posterior fluxes was investigated and is presented in the results section on sensitivity runs.

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

4. Results

4.1. NEE for 2019 in context of the 2006-2018 period

Spatial distributions of posterior NEE (Figure 1: Annually integrated posterior NEE for 2020 from 5 inversions (first row) differing in the biosphere flux models (VPRM in column 1, FLUXCOM in column 2), ocean flux models (costal fluxes combined with CarboScope ocean in column 3, climatological ocean fluxes in column 4), and emission products obtained from EDGAR-BP in column 5. Prior NEE used in the respective inversions are shown in the second row. Third row refers to the innovations of fluxes. Green circles in maps indicate the atmospheric observing stations used in the inversion.) fluxes in 2020 estimated using two biosphere models (VPRM and FLUXCOM), two ocean flux models (costal fluxes combined with CarboScope ocean and climatological fluxes), and different emission products (EDGAR updated based on latest British Petroleum report) show a smaller biospheric uptake compared to the prior NEE. This is confirmed by the innovation of fluxes (depicted in Figure 1, third row) in which positive corrections made by the inversion are dominated over the full domain.

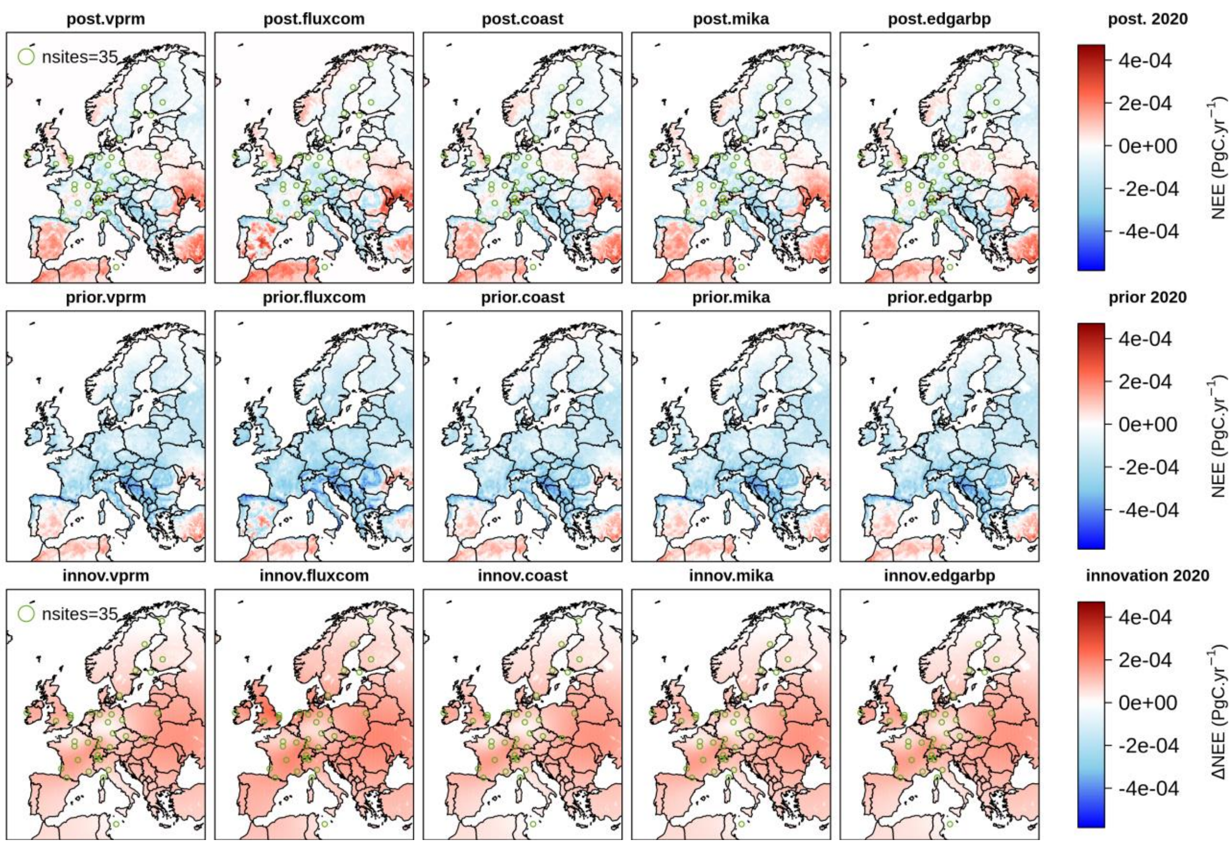

Figure 1: Annually integrated posterior NEE for 2020 from 5 inversions (first row) differing in the biosphere flux models (VPRM in column 1, FLUXCOM in column 2), ocean flux models (costal fluxes combined with CarboScope ocean in column 3, climatological ocean fluxes in column 4), and emission products obtained from EDGAR-BP in column 5. Prior NEE used in the respective

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

inversions are shown in the second row. Third row refers to the innovations of fluxes. Green circles in maps indicate the atmospheric observing stations used in the inversion.

A weaker uptake of biogenic CO_2 is observed in 2020 compared to 2019, in particular in Central and North Europe as well as in the UK as shown in Figure 2. The "recent sites" inversion (second column) is reliable to distinguish the differences between NEE estimates in 2019 and 2020, as there are identical sites that have gap-free observations. Although "all sites" inversion (first column) indicates similar estimates in Central and North Europe, discrepancies in sites in 2019 and 2020 result in some differences in the estimates of NEE as seen in the UK. However, assimilating as much observations as possible strengthens the observational constraint, when the interest is to calculate the annual budget of CO_2. On the other hand, the selective sites inversion that have consistent datasets over years is more robust to compare year-to-year-changes and interannual variations. IAV of aggregated flux estimates over the recent 5 years using such that datasets is presented in Figure 3.

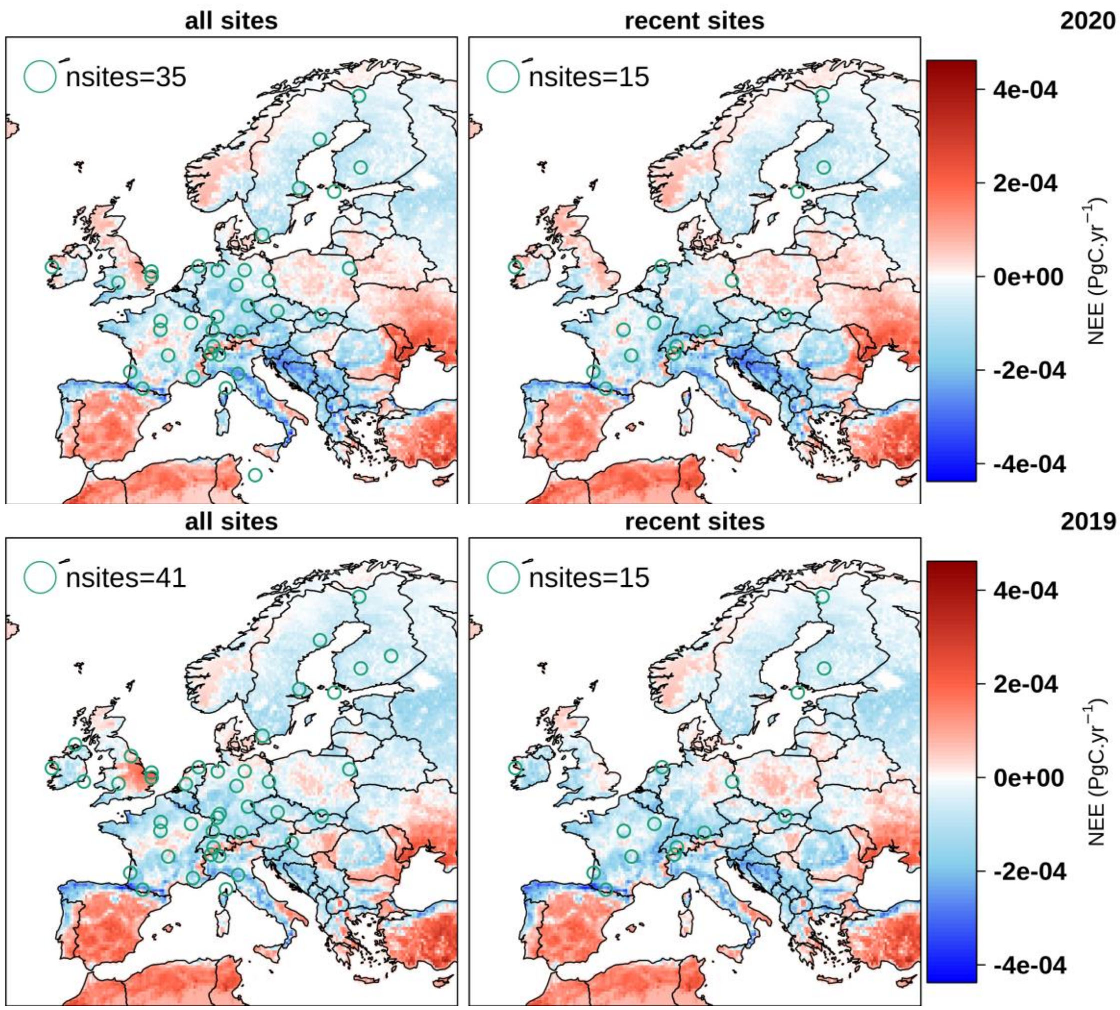

Figure 2: Posterior NEE estimated using all sites available (first column) and only using sites fully covering recent five years 2016-2020 (second column) for 2020 (first row) and 2019 (second row).

In order to put the year 2020 in context of a longer time period, results of annually aggregated flux estimates from the 2006-2019 CSR inversion are shown in Figure 3. Details for different regions as well as the corresponding prior and posterior uncertainties are also present. Despite differences in the amplitude, NEE IAV estimated using VPRM and FLUXCOM suggests good agreement, not only over the full domain but also for subregions and countries. The posterior uncertainty range, indicated by the red shading, shows a notable reduction relative to prior uncertainty (in grey shading). The more the stations installed in a region the larger the uncertainty reduction is. For example, Central Europe and France show quite a consistent a-posteriori variability and have very small uncertainty as a result of strong atmospheric signal and weak dependency on prior fluxes. In contrast, a weak atmospheric constraint leads to a large posterior variability as can be noticed over Turkey, where no atmospheric observations are available. The impact of datasets can also be observed from the decreasing posterior uncertainty in recent years at regions that have a growing number of stations, in particular in northern Europe and its underlying regions such as Finland, Sweden, and Norway.

Additionally, it is obvious that the interannual variations seen in the posterior fluxes from the 2006-2020 inversions are largely data-driven regardless of which prior flux models used.

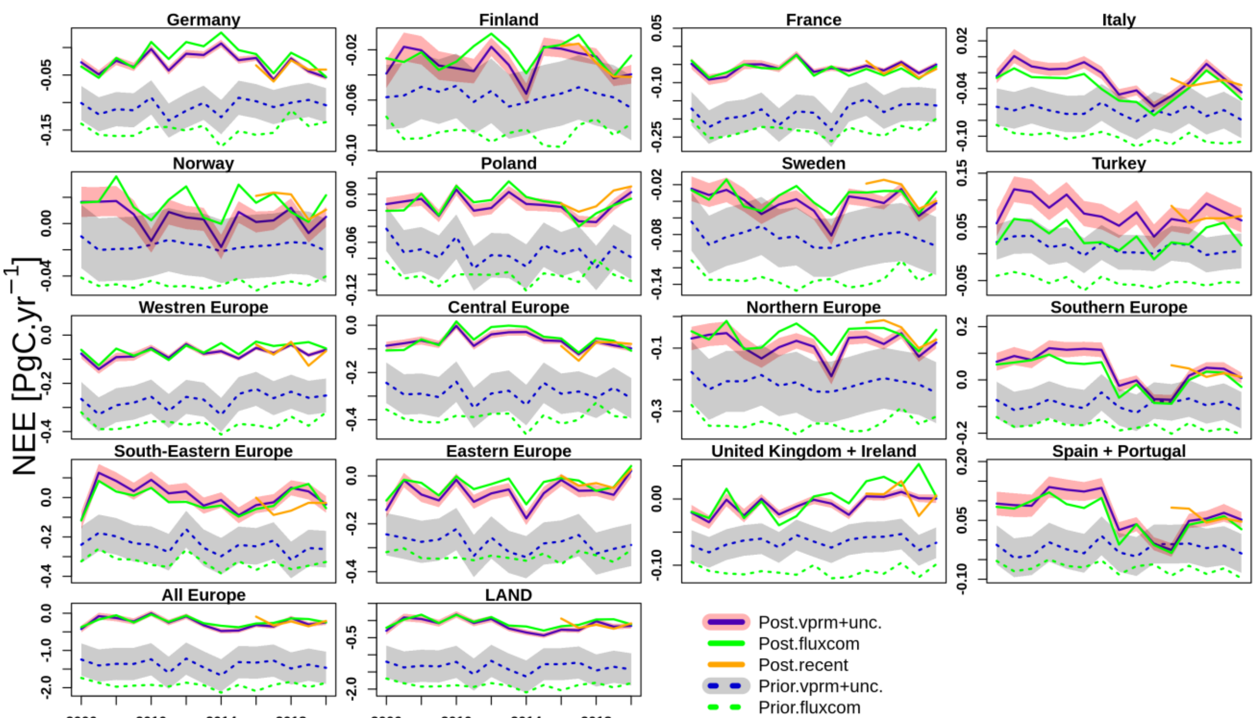

Figure 3: Annual NEE for the period 2006 – 2020 for different countries and partial domains using the EUROCOM region specifications. Prior fluxes from FLUXCOM are shown in dashed green and their corresponding posterior fluxes in solid green lines. Prior fluxes from VPRM are shown in dashed blue lines associated with uncertainties in grey shading, their posterior fluxes are in solid blue associated with uncertainties in red shading. Orange solid line refers to

posterior NEE estimated utilizing datasets from sites with gap-free observations over the period 2016-2020 (mentioned as "Post. recent")

4.2. Sensitivity runs

4.2.1. Far field influence

As sensitivity test of the regional inversion to the boundary conditions, we conducted three inversions using different choice of sites in the global inversion run providing far-field contributions, as can be seen in Figure 4. For the current year inversions, the default set of stations in the global inversion "s10" was augmented by sites used within VERIFY, but not part of s10 set. The results of this regional run are referred to in Figure 4 as "s10+all". This is considered as a difference to the last year inversions (included), where only s10 set was used, added in the plot in the orange lines "inv20". We also performed an inversion (green lines) using the "s10" global run, updated with new dataset release in 2021, to relate the changes made by the extra sites added in the global run. There is a slight difference seen the subregions which can be summed up to around 0.06 GtC/yr for domain-wide annual budgets. "inv20" results

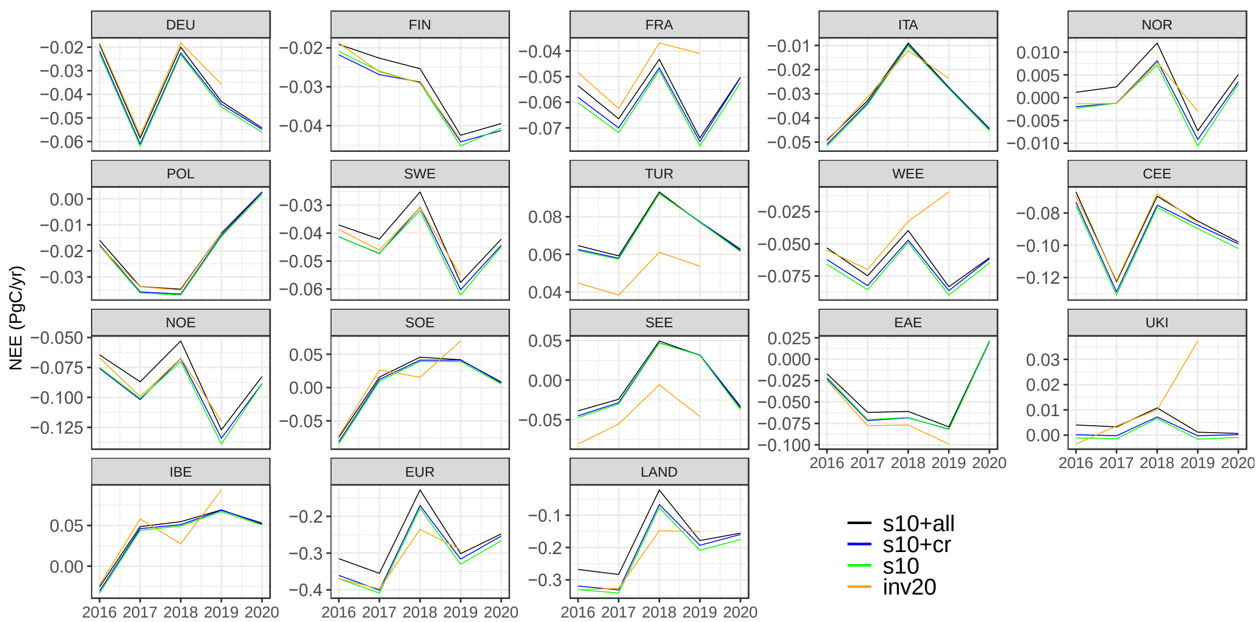

Figure 4: Posterior NEE estimated using different far-field contribution derived from three sets of sites in the global inversion runs: 1) s10 (default sites used in the global run v2021), 2) s10+cr (includes s10 plus sites having best coverage over the recent 5 years as well as those have best coverage from 2006 onward), 3) s10+all (includes s10 plus all sites available across Europe used within VERIFY). For reference, also last year inversion results are shown as "inv20", differing in that two sites in the regional station set were excluded in the current regional inversion (FKL in Greece and LMU in Spain, causing larger difference for southern parts of the domain).

remain more consistent with the regional inversion used s10 set, except for some differences over specific regions, specifically in 2018 and 2019, that can be explained as the impact of the exclusion of the two sites Europe FKL in Greece and LMU in Spain in the current inversion. In the third test, we added sites that have full data coverage in the period 2016-2020 and also best coverage over 2006-2020 to the global set s10. Results do not show large differences with s10 inversion because many of these sites are already included in s10, specifically stations near the domain boundaries as can be seen from the stations map (Figure 5).

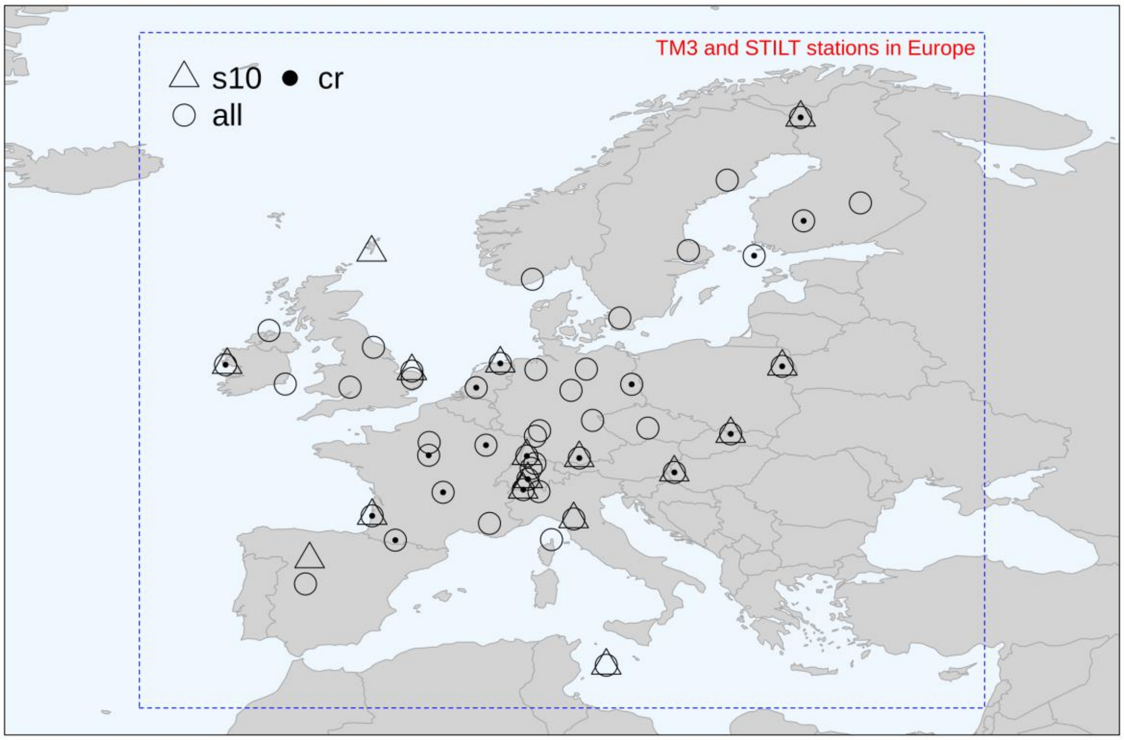

Figure 5: Distribution of the stations used in the global inversion runs to calculate far-field contribution within the domain of Europe. “s10” is the set of stations used as default in the global inversion. “all” represents the regional set of all stations available in the European domain used in the regional inversions that have been added to the global set s10 for this year inversions. “cr” indicates a subset of verify stations that have full coverage of observations over 2016-2020, also consistent coverage over 2006-2020 and added to s10 in a different global inversion run.

4.2.2. Ocean priors

To outline the impact of ocean fluxes, results from three regional inversions differing in the ocean flux models are sown in Figure 6. In the base inversion, ocean fluxes are taken from the pCO_2 Carboscope ocean fluxes and compared to inversions done using climatological fluxes as well as costal fluxes embedded with the CarboScope ocean fluxes. Maps in Figure 6 denote the differences in 2020 flux estimates between the base inversion, the climatological fluxes inversion “diff.climate”, and the costal fluxes inversion “diff.coast”. The differences are quite small and

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

translate to insignificant impact on NEE estimates as can be noticed from the time series NEE of the three inversions (Figure 6, lower left). However, their differences indicate strong systematicity which can be realized through the anticorrelations seen over the period 2006-2020, except in 2013 and 2014 (Figure 6, lower right).

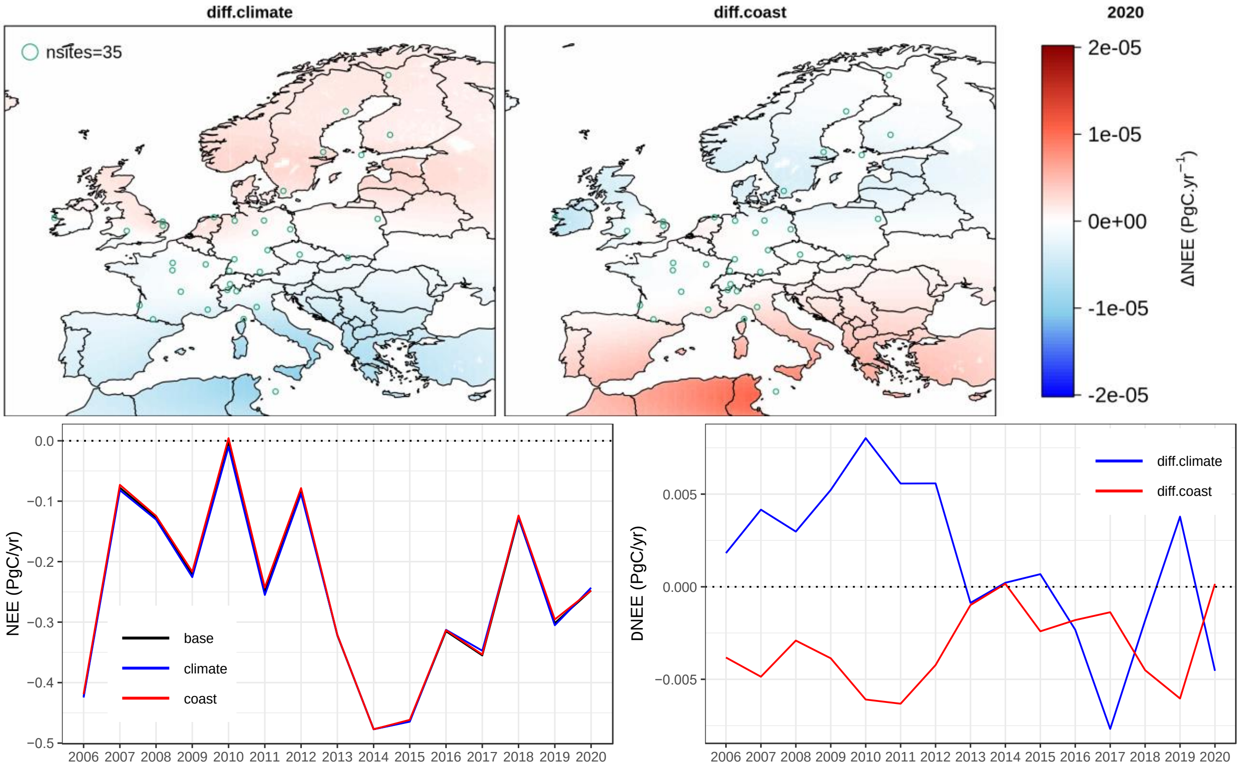

Figure 6: Maps in the upper row show the annually spatial difference of the posterior NEE in 2020 between two inversions used different ocean priors (climatological ocean fluxes and CarboScope ocean fluxes combined with costal fluxes) with respect to the base inversion that utilized Carboscope ocean-based fluxes: 1) "diff.climate" refers to the difference between the base inversion and the one used climatological fluxes, 2) "diff.coast" denotes the difference between the base inversion and the one used Carboscope ocean fluxes in combination with the costal fluxes. Left, below time series plot indicates the annually aggregated flux estimates over the full domain of Europe and their differences relative to the base inversion are shown in corresponding plot (right, below).

5. Conclusions

Inversion results for 2020 NEE fluxes for the European domain have been obtained using the Jena CarboScope-Regional inversion framework, and put into the context of NEE in the 2006-2019 timeframe. The far field contribution to the regional domain of Europe is calculated through a global inversion run within the two-step scheme approach (Rödenbeck et al., 2009) using the standard set of sites in the global run s10v2021 and sites that are used in the regional inversion.
The NEE estimates of 2020 suggest a lower uptake of CO_2 over the full domain, leading to a slightly smaller source than during the drought year 2018. However, the 2018-2020 difference in NEE estimates is also affected by a difference in number of stations used in 2018, 2019, and 2020 — i.e., 46, 41 and 53 respectively. However, an inversion test was performed using identical stations over the last five years (15 sites), which can be robust to compare changes of NEE estimates over such a period of time. Meanwhile, NEE estimates over certain regions such as France, the UK, and North Europe show a larger uptake in 2019 compared to 2020, while a weaker uptake was persistent in 2018, in comparison. This finding is confirmed in the inversion run using a subset of stations having a full coverage of datasets over the years 2016-2020. Ocean fluxes do not show a large impact on NEE estimates. From the experiment done using different sets of sites in the global inversion, far field contributions indicate a difference up to 0.06 GtC of the annually integrated fluxes over the full domain of Europe.

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

6. References

BP, Statistical Review of World Energy, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/xlsx/energy-economics/statistical-review/bp-stats-review-2021-all-data.xlsx, 2021

Kountouris, P., Gerbig, C., Rödenbeck, C., Karstens, U., Koch, T. F., and Heimann, M.: Atmospheric CO_2 inversions on the mesoscale using data-driven prior uncertainties: quantification of the European terrestrial CO_2 fluxes, Atmos. Chem. Phys., 18, 3047–3064, https://doi.org/10.5194/acp-18-3047-2018, 2018.

Kountouris, P., Gerbig, C., Totsche, K.-U., Dolman, A. J., Meesters, A. G. C. A., Broquet, G., Maignan, F., Gioli, B., Montagnani, L., and Helfter, C.: An objective prior error quantification for regional atmospheric inverse applications, Biogeosciences, 12, 7403–7421, https://doi.org/10.5194/bg-12-7403-2015, 2015.

Mikaloff-Flechter, S. E., Gruber, N., Jacobson, A. R., Doney, S. C., Dutkiewicz, S., Gerber, M., Gloor, M., Follows, M., Joos, F., Lindsay, K., Menemenlis, D., Mouchet, A., Müller, S. A., and Sarmiento, J. L.: Inverse estimates of the oceanic sources and sinks of natural CO2 and the implied oceanic transport, Global Biogeochem. Cy., 21, GB1010, https://doi.org/10.1029/2006GB002751, 2007.

Steinbach, J, C Gerbig, C Rödenbeck, U Karstens, C Minejima, and H Mukai: The CO2 Release and Oxygen Uptake From Fossil Fuel Emission Estimate (COFFEE) Dataset: Effects From Varying Oxidative Ratios, Atmospheric Chemistry and Physics 11 (14): 6855–70. doi:10.5194/acp-11-6855-2011, 2011.

Rödenbeck, C., Gerbig, C., Trusilova, K., and Heimann, M.: A two-step scheme for high-resolution regional atmospheric trace gas inversions based on independent models, Atmos. Chem. Phys., 9, 5331–5342, https://doi.org/10.5194/acp-9-5331-2009, 2009.

Jung, M., S. Koirala, U. Weber, K. Ichii, F. Gans, G. Camps-Valls, D. Papale, C. Schwalm, G. Tramontana, and M. Reichstein. 2019. 'The FLUXCOM ensemble of global land-atmosphere energy fluxes', *Sci Data*, 6: 74.

Rödenbeck, C., Keeling, R. F., Bakker, D. C., Metzl, N., Olsen, A., Sabine, C., & Heimann, M. (2013). Global surface-ocean p-CO_2 and sea–air CO_2 flux variability from an observation-driven ocean mixed-layer scheme. Ocean Science, 9(2), 193-216.

Rödenbeck, C., S. Zaehle, R. Keeling, and M. Heimann. 2020. 'The European carbon cycle response to heat and drought as seen from atmospheric CO_2 data for 1999-2018', *Philos Trans R Soc Lond B Biol Sci*, 375: 20190506.

Thompson, R. L., G. Broquet, C. Gerbig, T. Koch, M. Lang, G. Monteil, S. Munassar, A. Nickless, M. Scholze, M. Ramonet, U. Karstens, E. van Schaik, Z. Wu, and C. Rodenbeck. 2020. 'Changes

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.

in net ecosystem exchange over Europe during the 2018 drought based on atmospheric observations', *Philos Trans R Soc Lond B Biol Sci*, 375: 20190512.

Mahadevan, P., Wofsy, S.C., Matross, D.M., Xiao, X., Dunn, A.L., Lin, J.C., Gerbig, C., Munger, J.W., Chow, V.Y. and Gottlieb, E.W., 2008. A satellite-based biosphere parameterization for net ecosystem CO_2 exchange: Vegetation Photosynthesis and Respiration Model (VPRM). Global Biogeochemical Cycles, 22(2).

Jung, Martin & Henkel, Kathrin & Herold, Martin & Churkina, Galina. (2006). Exploiting synergies of global land cover products for carbon cycle modeling. Remote Sensing of Environment. 101. 534-553. 10.1016/j.rse.2006.01.020.

VERIFY is a research project funded by the European Commission under the H2020 program. Grant Agreement number 776810.