Data
Models
Inventories

# PARIS

**Process Attribution of Regional Emissions**

GA 101081430, RIA

## Protocol for the double-blind $CO_2$ verification challenge of WP6 of the Process Attribution of Regional Emissions (PARIS) project

| **Milestone MS21** | | | |
|---|---|---|---|
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| Lead beneficiary: UNIVBRIS | Work package: 6 | Nature: Report | Dissemination level: PU |
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**Horizon Europe Cluster 5: Climate, energy and mobility**

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## Table of content

# 1. Changes with respect to the DoA (Description of the Action)

The milestone MS21 belongs to Task 6.4 of work package WP6 and has been executed as planned in the DoA.

# 2. Dissemination and uptake

The verification experiment will be initially tested by the modelling groups at Wageningen University (WU) and University of Bristol (UoB) according to this protocol. The revised protocol will be available on the ICOS Carbon Portal and the project website. Based on the results the protocol will be revised and the greenhouse gas (GHG) community (i.e. TRANSCOM, Copernicus/COCO$_2$, and other teams funded under this call) is invited to contribute.

For contributions to and inquiries about this project, please contact wouter.peters@wur.nl.

# 3. Short Summary of results

WU set up a protocol for the double-blind $CO_2$ verification experiment of WP6 of the PARIS project. This protocol should reduce the effort required by the rest of the scientific community (e.g. TRANSCOM, Copernicus/CoCO2, and other teams funded under this call) to participate and contribute to this verification experiment. The methodology proposed in this document - and the proposed naming schemes for the files used specifically - could also serve as a starting point for modelling experiments with a similar collaborative nature, in which harmonization of modelling and data management efforts is of high importance.

To maximize the impact of the verification experiment and promote collaboration between modelling groups for this and future verification experiments, this document will be shared to the public domain (on the ICOS Carbon Portal) alongside the fluxes, and forward- and inverse model output of the proposed verification experiment.

# 4. Evidence of accomplishment

## 4.1 Introduction | Background of the deliverable

Inverse modelling of carbon dioxide ($CO_2$) fluxes is subject to uncertainties due to atmospheric transport models and assumptions introduced in the inverse methods used in different inverse models. In the real world, it is difficult to discern the impact of these uncertainties or assumptions on the top-down derived fluxes. To address these issues, we outline a Protocol for a "blind verification challenge", which is a series of experiments under the Process Attribution of Regional emISsions (PARIS) project.

The blind verification challenge aims to test the ability of inverse modelling systems to identify perturbations intentionally introduced into flux fields by other modelling groups, using simulated $CO_2$ mole fractions. The transport model used to generate the mole fraction fields is unlikely to be same for each inverse modelling system and provides a proxy for uncertain atmospheric transport in the real atmosphere.

Comparison of the inverse estimates with an unaltered data set will reveal which signals were detectable from the synthetic data sets, and which were not. An important lesson here is to see which type of errors commonly occur in a realistic model-based verification setting, and which added information is needed to identify a bottom-up flux error with confidence. This study will moreover provide new information on the level of confidence of inverse estimates of $CO_2$ flux and will identify whether the measurement network should be expanded to detect future $CO_2$ flux changes. To increase the value of our effort, the protocol described in this milestone report, but also fluxes, and forward- and inverse model outputs will be shared with the wider community on the ICOS Carbon Portal (WU co-hosts this central facility). This will be done after the verification experiment has been tested buy the modelling groups at WUR and UoB in the first modelling year. Scientific communities such as e.g., TRANSCOM, Copernicus/Co$CO_2$, and other teams funded under this call will then be invited to participate in and contribute to the verification experiment.

## 4.2 Scope of the deliverable

The purpose of this document is to (up to a reasonable extent) formalize the criteria to participate in the verification experiments and is complementary to the Description of the Action (DoA) of the PARIS project. Section 4.3.2 describes the participating modelling groups and the requirements for the atmospheric inversion model configuration. Section 4.3 describes the input data sets used in the experiment. Section 4.3.4 has the details on the required output, and output formats. Section 4.3.5 provides a detailed timeline of the experiment.

## 4.3 Content of the deliverable

### 4.3.1 Execution overview of the blind verification challenge

(1) Each modelling group will start from the same set of "reference" flux fields from the CarbonTracker Europe High-Resolution (CTE-HR) product that cover 2021. These fields consist of one set of unperturbed and five sets of perturbed flux sets (Section 4.3.3.1), for a total of six flux sets. These flux fields will be provided by WU through the ICOS Carbon Portal project space.

(2) Using each of these flux sets in a forward model simulation, each modelling group will produce monthly mean simulated $CO_2$ mole fractions for 58 ICOS and non-ICOS observatories stored in a European ObsPack. The modelling groups will save the results of the simulations back in a copy of the same ObsPack for later use in the inversion simulations as pseudo-observations. A comprehensive model inter-comparison study follows, in which the participating modelling groups will compare these pseudo-observations with the real observations.

(3) Each group will label their six ObsPack output files with a randomly chosen identifier (to be kept private from other groups), and then upload their simulated ObsPacks on the ICOS Carbon Portal project space. Each group can only trace their own six ObsPack files to each of the six flux cases through their private identifier, but not that of the others.

(4) Each group will then perform six inversions using the six synthetic mole fraction ObsPacks from another group and store the optimized fluxes (in gridded and country-aggregated format) and their uncertainties in a prescribed file (based on a template file provided by WU). Then, the participating modelling groups will attempt to match each mole fraction set with one of the perturbed flux cases provided to us all.

(5) Once all groups have completed their inversions, the teams will "unblind" their mole fraction fields, revealing the correspondence of the six flux cases to each of their synthetic ObsPacks. Now, groups can see how well they did in recognizing six flux perturbations from six mole fraction data files, using a different transport model and different inversion setup.

(6) Steps 2-5 will be repeated for additional (unique) perturbation experiments designed by groups other than WU. Where needed, additional modelling tests can be done, such as reducing the number of included measurement sites or using additional atmospheric tracers.

## 4.3.2 Groups and Models

In the first modelling year (described in Section 4.3.3.1), the verification experiment will initially be tested by the modelling groups at: Wageningen University (WU), using CarbonTracker (with WRF-CHEM or ICON-ART) ensemble Kalman filter inversion (Huijnen et al., 2014; Van Der Laan-Luijkx et al., 2017) and University of Bristol (UoB), using Met Office NAME model, hierarchical Bayesian inversion (Ganesan et al., 2014). After this first modelling year, other modelling groups within the scientific community (such as e.g., TRANSCOM, Copernicus/Co$CO_2$,) and other teams funded under this call will be invited to participate in and contribute to the verification experiment.

### *4.3.2.1 Model configuration*

The modelling groups are allowed to use either Lagrangian or Eulerian transport models with the groups free to choose the driving meteorology for these atmospheric transport models. The atmospheric transport models used by the modelling groups should meet the following requirements:

- The model should be able to run simulations for the full year of 2021 (i.e., from 01-01-2021 up to and including 31-12-2021).
- The model should be able to produce hourly output at the atmospheric measurement sites included in the European ObsPack described under Section 4.3.3.3.
- The model should be configured for the regional scale, covering at least the CTE-HR modelling domain (i.e., -15, 35˚E to 33, 72˚N).
- The modelling groups are free to choose the meteorological input fields that drive the atmospheric transport models.

## 4.3.3 Input data sets

### *4.3.3.1 Input fluxes - fixed perturbations year 1 -*

In year 1, the protocol will work with a set of centrally created fluxes to be used by the modelling groups at WU and UoB. For year 1, WU has been designated as the group performing the flux perturbations (hereafter referred to as the 'Creating Group'). In subsequent years, each group can additionally create their own flux perturbations, as outlined in Section 4.3.3.2. The centrally provided fluxes are:

**Base case (1):** WU will distribute a set of unperturbed CTE-HR fluxes (in $\mathrm{mol\,m^{-2}s^{-1}}$) for the year 2021 to UoB (step 2). The fluxes include $CO_2$ flux estimates for the terrestrial and oceanic biosphere, fossil fuel emissions, and biomass burning (i.e., wildfires). The spatial resolution of these flux fields is 0.1 x 0.2 degrees with hourly temporal resolution. To use the provided fluxes in model setups that require fluxes with a different spatio-temporal resolution the provided fluxes can be interpolated or aggregated. The modelling groups are recommended to use nearest-neighbor sampling on the provided fluxes to achieve this.

The same CTE-HR fluxes will later be used as prior emission estimates in all inversion simulations.

**Flux perturbations (2-6):** WU will generate 5 perturbed flux fields and redistribute these to UoB (step 6). The perturbations are centrally done by WU to ensure that we capture errors related to the differences in modelling setups between the participating modelling groups later in the verification experiment. The 5 proposed perturbations are:

- (Base fluxes from CTE-HR 2021) Label: BASE
- Halving the transport-related anthropogenic emissions over Germany (decreasing emissions by 50%). Label: HGER
- Increasing the total anthropogenic emissions within the CTE-HR modelling domain by 10%. Label: ATEN
- Doubling the uptake by forests within Finland (increasing the uptake by 100%). Label: DFIN
- Shutting down the top 10% emitting power plants within the CTE-HR modelling domain. Label: PTEN
- Halving the industry-related anthropogenic emissions in France (decreasing emissions by 50%). Label: HFRA

The input fluxes will adhere to the following naming convention:

*paris_ctehr_perturbedflux_<experiment_phase>_<label_of_experiment>.nc*

in which the label of the experiment adheres to the aforementioned 4-letter codes, and the experiment phase is either 'yr1' or 'yr2'. These labels are different from the private labels that the modelling groups should use for the naming convention of the flux file uploads as described in Section 4.3.3.2. The perturbed fluxes will come in the same format as the base case, which means NetCDF files with hourly fluxes at 0.1 x 0.2 degrees.

#### *4.3.3.2 Input fluxes - flexible perturbations year 2 and beyond -*

After the first year, and an evaluation of this protocol, other modelling groups within the scientific community (such as e.g., TRANSCOM, Copernicus/Co$CO_2$,) and other teams funded under this call will be invited to create their own "perturbed" flux fields to use in the blind verification challenge. These fluxes will constitute a perturbation of the provided common "base" fluxes, where the perturbation applied is only known to the Creating Group, and thus not one of the WU-perturbed options in Section 4.3.3.1. The allowed perturbations will be discussed after year 1, together with all participants, and appended to this section of the protocol in the next version.

For each perturbed flux set, the Creating Group will perform a forward simulation, fill an ObsPack as described in Section 4.3.4.1 to be shared with other modelling groups, which are to be assimilated as "pseudo-observations" in the inversion modelling systems from other groups. These groups will each return a set of optimized fluxes according to Section 4.3.4.2, to be compared to the originally perturbed fluxes from the Creating Group.

The input fluxes will adhere to the following naming convention:

*paris_ctehr_perturbedflux_<creating_group >_<private_label_of_experiment>.nc*

in which the private label of the experiment should be traceable to a specific flux perturbation and stored by the Creating Group.

#### 4.3.3.3 ObsPacks with sites to sample

Simulated site $CO_2$ mole fractions will be produced according to all samples recorded in a European ObsPack. The latest release of this collection carries the name **'obspack_co2_466_GLOBALVIEWplus_v8.0_2023-04-26'** (ICOS RI et al., 2023). The ObsPack collection consists of one unique file for each measurement site and height (with the following name: **co2_<site code>_<project>_<lab number>_<selection tag>.nc**), and contain $CO_2$ mole fraction observations from all Level-2 ICOS stations for 1972 up to 2023.

From this collection, the modelling groups are expected to perform the forward and inversion simulations using the following subset of observations:

- For the period of 2021 (i.e., from 01-01-2021 up to and including 31-12-2021)
- For the highest measurement (inlet) level of each of the measurement sites

The ObsPacks in this protocol are used for multiple purposes:

(a) For each flux set created by WU in Section 4.3.3.1, a corresponding ObsPack with forward-simulated mole fractions must be made by the Creating Group. These will serve as pseudo-observations for other groups to use in an inversion (for year 1).

(b) For each flux set created by the participating modelling groups in Section 4.3.3.2 (for year 2 and beyond), a corresponding ObsPack must be made by the Creating Group to share to the other modelling groups.

The corresponding ObsPack to be shared to other groups will have the name:

*paris_pseudo_obspack_<creating_group >_<private_label_of_experiment>.tgz*

and include inside a full copy of the ObsPack provided in Section 4.3.3.2 (!), but with each model-sampled observation added in a new variable "pseudo_observation" to be created in the proper NetCDF file. To make it easier to later reference the simulated $CO_2$ mixing ratios to the original measurements, this variable should have 'time' and a unique 'obs-id' as a dimension. Note that the private label should not be informative on the applied perturbation to other groups!

#### 4.3.3.4 Boundary and initial conditions

As mentioned by Monteil et al (2020), the differences in extent of the modelling domain and in how the modelling systems are coupled to the boundary conditions would make it difficult to impose a common boundary condition. Similar to leaving the choice of driving meteorology for the modelling setups open, allowing a diversity of boundary condition implementations serves as a measure of uncertainty that is normally present in inversion model intercomparison studies. The modelling groups are therefore free to design their own implementation of boundary conditions into their modelling setup but are recommended to use the fourth generation CAMS reanalysis product (EAC4; Iness et al., 2019) to constrain the initial and boundary conditions. If the modelling groups decide to use CAMS, they shall independently re-grid these boundary conditions to fit the grid of the atmospheric transport model.

### 4.3.4 Required outputs and file conventions

#### *4.3.4.1 Populating an ObsPack with model-simulated mole fractions*

For each inversion done with an ObsPack distributed by the Creating Group, the group performing the inversion will provide an ObsPack with model simulated mole fractions. Where possible, this should include both prior and posterior mole fractions. To create these ObsPacks, a copy will be made of the input ObsPack, and for each sampled pseudo-observation a new value will be added to the duplicated ObsPack, using a new variable called either:

- *simulated_prior_mole_frac* (the set of pseudo-observations used as inversion input)
- *simulated_posterior_mole_frac* (the set of pseudo-observations created by transporting the optimized fluxes)

The corresponding ObsPack will have the same name as the ObsPack used for input, but with the label "pseudo" replaced by "inversion" with the inversion group name added as per the following naming convention:

> *paris_inversion_obspack_<creating_group_name>_<private_label_of_experiment>_<inverting_group_name>.tgz*

An example of such a file would be:

> *paris_inversion_obspack_UOB_GUESSMYFLUX_WU.tgz*

which would signify the optimized/prior mole fractions from the WU inversion, based on the GUESSMYFLUX scenario created by UoB (and carrying their pseudo-observations from 4.3.3.2). Only UoB knows the real fluxes they used to create these pseudo-observations. In year 1, this would be one of the flux scenarios agreed on from section 4.3.3.1, but WU would have to guess which one GUESSMYFLUX was for UoB (and they kept this private).

In year 1, the participating modelling groups are expected to deliver at least six synthetic ObsPacks that adhere to the criteria described in section 4.3.4. One for each of the perturbation experiments. For year 2 and beyond, the modelling groups are required to deliver one additional synthetic ObsPack for each additional flux perturbation experiment.

#### *4.3.4.2 Optimized fluxes*

For each ObsPack with 'pseudo-observations' provided (sections 4.3.3.1 and 4.3.3.2), each group will perform an inversion and estimate the fluxes. These optimized fluxes can be used in various ways:

(a) To identify which of the perturbed scenarios corresponds to which ObsPack (in year 1).

(b) To identify the perturbation performed by each group for each ObsPack (year 2 and beyond).

(c) To analyze differences in fluxes estimated by several groups from the same ObsPacks (a measure of inversion uncertainty).

We expect the inverted fluxes to be in NetCDF format, and we require each group to fill in the variables in a prescribed file. For this, we created a NetCDF "description file" (flux_protocol.cdl, human readable format), which can be changed into an empty NetCDF file using the unix command:

*[ ]> ncgen -b flux_protocol.cdl*

Or using the following command of the python-netcdf module:

*[ ]> netCDF4.data set.fromcdl(cdlfilename = '…', ncfilename = '…', format = 'NETCDF3_CLASSIC')*

Also see **these instructions**. The NetCDF file header is copied in the Appendix of this protocol. We ask each group to fill at minimum the monthly mean values for the variables, and all other variables are desirable but optional:

*flux_ff_exchange_posterior*

*flux_bio_exchange_posterior*

*country_flux_ff_exchange_posterior*

*country_flux_bio_exchange_posterior*

To obtain country fluxes from gridded fluxes, a (fractional) country mask provided in a separate NetCDF file (*paris_countrymask.nc*) can be easily applied. These country masks are made using the Natural Earth data set at a spatial resolution of 10 m. Modelling groups are also allowed to use their own shapefile (potentially based on the same Natural Earth data) to derive the country boundaries if this proves to be more suitable. To test whether the aggregation of the optimized flux estimates to the country scale is done in a consistent manner, the modelling groups should test whether the total calculated country area matches that stored in the variable country_area. To promote the anonymity of the optimized fluxes, the groups are requested to leave the global attributes of the NetCDF files as is.

The resulting flux file should be renamed following the convention:

*paris_invertedflux_<creating_group_name>_<private_label_of_experiment>_<inverting_group_name>.nc*

An example would be:

*paris_invertedflux_BRISTOL_GUESSMYFLUX_WUR.nc*

Which would signify the optimized/prior fluxes from the WU inversion, based on the GUESSMYFLUX ObsPack created by UoB (and carrying their pseudo-observations from 4.3.3.2), as described in the previous section.

#### 4.3.4.3 Optimized flux uncertainty

Where possible, we would like to receive the prior and posterior uncertainty of the estimated fluxes at country level. These can go into the arrays:

*uncertainty_country_flux_ff_exchange_prior*

*uncertainty_country_flux_bio_exchange_prior*

*uncertainty_country_flux_ff_exchange_posterior* *uncertainty_country_flux_bio_exchange_posterior*

Currently, these are prescribed in the *flux_protocol.cdl* file and have the dimensions *time* and *countrynumber*, allowing spatial covariances at country level per month. If the uncertainty estimates come in a different form (for example including temporal covariances from month-month, or as annual uncertainties only), please modify the *flux_protocol.cdl* file to accommodate your uncertainty. Note that it is only for these variables that perturbations are acceptable.

#### 4.3.5 Timeline

This section describes the timeline of the verification experiments. The deliverables of the blind verification challenges are given in Table 1, each with their respective deadline, modelling group(s) that are responsible for meeting these set deadlines, and corresponding WP6 milestone (see 'MS').

Firstly, WU will distribute this protocol, a Common Data form Language (CDL) template file that can be used to create a NetCDF file that stores the posterior flux output from the proposed inversion simulations, and a file that stores fractional country masks which can later be used to aggregate the optimized fluxes to the country level (step 1).

To accommodate the perturbation experiments of the first year, WU will then distribute the unperturbed set of CTE-HR fluxes to participating modelling groups (step 2). The participating modelling groups will then make an effort to transport these fluxes in forward model simulations (step 3). The results of these forward simulations should be stored in a synthetic ObsPack file and should be linked to a unique obs-id to make it easier to later reference the simulated $CO_2$ mixing ratios to the original measurements. These synthetic ObsPack files are to be created by the participating modelling groups and will later be used in a comprehensive model inter-comparison study (in step 6). The requirements for the forward modelling system are described in Section 4.3.2.1, and the requirements of the synthetic ObsPack file are described in Section 4.3.4.1.

After WU has made perturbations to these unperturbed set of CTE-HR fluxes, WU will distribute the perturbed set of CTE-HR fluxes to the participating modelling groups. The perturbed fluxes will then be transported with the same forward modelling systems as the unperturbed fluxes, and the output should be stored in the same synthetic ObsPack files (step 5). A comprehensive inter-comparison study between the forward modelling results follows (step 6), which should provide insight into the usability of the proposed perturbation experiments. If the there is no visible effect of the flux field perturbation on the simulated $CO_2$ mixing ratios, running inversion systems on the same flux fields will be a waste of resources. If this is the case, alternative flux perturbation experiments should be proposed.

After these forward modelling efforts, the participating modelling groups will then perform inversions, using the unperturbed CTE-HR fluxes as prior estimates and the simulated $CO_2$ mole fractions from the forward simulations on the perturbed fluxes as pseudo-observations (step 7). The use of synthetic observations in inversion setups to optimize the prior flux estimates is similar to the approach of an Observing System Simulation Experiment (OSSE). The requirements for these inversion modelling systems are described in Section 4.3.2. The output of these inversion simulations should be stored in a NetCDF file with the structure described in the CDL template file, which should be given a unique name. Further requirements for the inversion output are described in Section 4.3.4.

Lastly, the modelling groups will reveal ("unblind") which case belongs to each of the mole fraction simulation results created and attempt to identify the cause of any difference with the agreed unaltered flux fields (step 8). The groups will make use of the unique identifiers that were given to the output in earlier steps to identify which perturbation experiment belongs to each of the mole fraction simulation results. The goal here is to find the limit of detection of sector-specific changes from the synthetic pseudo-observations.

**Table 1:** Timeline of blind verification challenges of PARIS WP6

| MS | # | Description of deliverable | Due | Responsible |
|---|---|---|---|---|
| 21 | 1 | Distribution of this protocol, fractional country masks, and template file to store posterior flux output from inversions to UoB | 08-05-2023 | WU |
| | 2 | Distribution of unperturbed set of 2021 CTE-HR fluxes to UoB (1 set) | 19-05-2023 | WU |
| | 3 | Forward modelling simulations on unperturbed fluxes and creating a synthetic European ObsPack | 01-07-2023 | WU, UoB |
| | 4 | Distribution of perturbed sets of 2021 CTE-HR fluxes to modelling groups (5 sets) (See Section 4.3.3.1) | 31-07-2023 | WU, UoB, other participating modelling groups |
| | 5 | Forward modelling simulations on perturbed fluxes and ingesting simulation results into unique synthetic ObsPack files (one for each perturbation experiment) (See Section 4.3.4.1) | 04-09-2023 | WU, UoB, other participating modelling groups |
| | 6 | Sharing the synthetic European ObsPack with modelling groups and performing a comprehensive model inter-comparison of all forward simulation results, focusing on the effect of the flux perturbations in the perturbed flux fields | 18-09-2023 | WU, UoB, other participating modelling groups |
| 24 | 7 | Modelling groups perform inversions, using the unperturbed fluxes as a prior and the simulated CO2 mole fractions from the forward simulations on the perturbed fluxes as pseudo-observations | 29-04-2024 | WU, UoB, other participating modelling groups |
| 25 | 8 | Modelling groups reveal ("unblind") which case belongs to each of the simulation results created in step 5, and performance of the inversion systems is evaluated | 23-12-2024 | WU, UoB, other participating modelling groups |
| 24 /25 | 9 | Modelling groups are invited to contribute to the verification expeirment, and step 4 - 9 are repeated for alternative perturbation experiments (See Section 4.3.3.2) | 01-01-2027 | WU, UoB, other participating modelling groups |

### 4.3.6 Data access

All output from PARIS WP6 will be uploaded to the ICOS CP. By participating in the verification experiment, the modelling groups approve of the free use of forward and inversion simulation results created in the experiment.

### 4.3.7 Inquiries

For inquiries regarding contribution to this project as a research group outside of the PARIS project or questions in general can be addressed to wouter.peters@wur.nl.

## 4.4 Conclusion and possible impact

We set up a protocol for the double-blind CO2 verification experiment of WP6 of the PARIS project. This protocol should reduce the effort required by the rest of the scientific community (e.g. TRANSCOM, Copernicus/CoCO2, and other teams funded under this call) to participate and contribute to this verification experiment. The methodology proposed in this document - and the proposed naming schemes for the files used specifically - could also serve as a starting point for modelling experiments with a similar collaborative nature, in which harmonization of modelling and data management efforts is of high importance.

To maximize the impact of the verification experiment and promote collaboration between modelling groups for this and future verification experiments, this document will be shared to the public domain (on the ICOS Carbon Portal) alongside the fluxes, and forward- and inverse model output of the proposed verification experiment. Since this document is not a deliverable of WP6 of the PARIS project, it will not be officially peer-reviewed.

## 4.5 References

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Thematic Centre, ICOS Flask And Calibration Laboratory, ICOS Central Radiocarbon Laboratory, 2023. European Obspack compilation of atmospheric carbon dioxide data from ICOS and non-ICOS European stations for the period 1972-2022; obspack_co2_466_GLOBALVIEWplus_v8.0_2023-04-26. https://doi.org/10.18160/CEC4-CAGK

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# 5. History of the document

| Version | Lead Author(s), contributors | Date | Changes |
|---|---|---|---|
| 1 | **D. Kivits,** R. de Kok, I. Luijkx, W. Peters, A. van der Woude | March 2023 | Set-up protocol |
| | **D. Kivits,** W. Peters, E. Saboya, M. Rigby | May 2023 | Processing and internal feedback |
| | **D. Kivits**, S. Walter | June, July 2023 | Final version and submission |

# Appendix

## netcdf paris_protocol {

```
dimensions:
        time = 12 ;
        longitude = 250 ;
        latitude = 390 ;
        countrynumber = 43;
variables:
        int time(time) ;
                time:standard_name = "time" ;
                time:units = "seconds since 2000-01-01T00:00:00Z" ;
                time:calendar = "standard" ;
                time:axis = "T" ;
        double longitude(longitude) ;
                longitude:standard_name = "longitude" ;
                longitude:long_name = "longitude" ;
                longitude:units = "degrees_east" ;
                longitude:axis = "X" ;
        double latitude(latitude) ;
                latitude:standard_name = "latitude" ;
                latitude:long_name = "latitude" ;
                latitude:units = "degrees_north" ;
                latitude:axis = "Y" ;
        float flux_ff_exchange_prior(time, latitude, longitude) ;
                flux_ff_exchange_prior:long_name = "prior anthropogenic CO2 fluxes" ;
                flux_ff_exchange_prior:comment = "" ;
                flux_ff_exchange_prior:dtype = "float" ;
                flux_ff_exchange_prior:units = "mol m-2 s-1" ;
        float flux_ocean_exchange_prior(time, latitude, longitude) ;
                flux_ocean_exchange_prior:long_name = "prior ocean CO2 fluxes" ;
                flux_ocean_exchange_prior:comment = "" ;
                flux_ocean_exchange_prior:dtype = "float" ;
                flux_ocean_exchange_prior:units = "mol m-2 s-1" ;
        float flux_bio_exchange_prior(time, latitude, longitude) ;
                flux_bio_exchange_prior:long_name = "prior biosphere CO2 fluxes" ;
                flux_bio_exchange_prior:comment = "" ;
                flux_bio_exchange_prior:dtype = "float" ;
                flux_bio_exchange_prior:units = "mol m-2 s-1" ;
        float flux_fire_exchange_prior(time, latitude, longitude) ;
                flux_fire_exchange_prior:long_name = "prior wildfire CO2 fluxes" ;
                flux_fire_exchange_prior:comment = "" ;
                flux_fire_exchange_prior:dtype = "float" ;
                flux_fire_exchange_prior:units = "mol m-2 s-1" ;
        float flux_ff_exchange_posterior(time, latitude, longitude) ;
                flux_ff_exchange_posterior:long_name = "posterior anthropogenic CO2 fluxes" ;
                flux_ff_exchange_posterior:comment = "" ;
```

```
flux_ff_exchange_posterior:dtype = "float" ;
flux_ff_exchange_posterior:units = "mol m-2 s-1" ;
float flux_ocean_exchange_posterior(time, latitude, longitude) ;
flux_ocean_exchange_posterior:long_name = "posterior ocean CO₂ fluxes" ;
flux_ocean_exchange_posterior:comment = "" ;
flux_ocean_exchange_posterior:dtype = "float" ;
flux_ocean_exchange_posterior:units = "mol m-2 s-1" ;
float flux_bio_exchange_posterior(time, latitude, longitude) ;
flux_bio_exchange_posterior:long_name = "posterior biosphere CO₂ fluxes" ;
flux_bio_exchange_posterior:comment = "" ;
flux_bio_exchange_posterior:dtype = "float" ;
flux_bio_exchange_posterior:units = "mol m-2 s-1" ;
float flux_fire_exchange_posterior(time, latitude, longitude) ;
flux_fire_exchange_posterior:long_name = "posterior wildfire CO₂ fluxes" ;
flux_fire_exchange_posterior:comment = "" ;
flux_fire_exchange_posterior:dtype = "float" ;
flux_fire_exchange_posterior:units = "mol m-2 s-1" ;
float country_flux_ff_posterior(time, countrynumber) ;
country_flux_ff_exchange_posterior:long_name = "country-averaged posterior fossil fuel CO₂ fluxes" ;
country_flux_ff_exchange_posterior:comment = "" ;
country_flux_ff_exchange_posterior:dtype = "float" ;
country_flux_ff_exchange_posterior:units = "mol m-2 s-1" ;
float country_flux_ocean_exchange_posterior(time, countrynumber) ;
country_flux_ocean_exchange_posterior:long_name = "country-averaged posterior ocean CO₂ fluxes" ;
country_flux_ocean_exchange_posterior:comment = "" ;
country_flux_ocean_exchange_posterior:dtype = "float" ;
country_flux_ocean_exchange_posterior:units = "mol m-2 s-1" ;
float country_flux_bio_exchange_posterior(time, countrynumber) ;
country_flux_bio_exchange_posterior:long_name = "country-averaged posterior biosphere CO₂ fluxes" ;
country_flux_bio_exchange_posterior:comment = "" ;
country_flux_bio_exchange_posterior:dtype = "float" ;
country_flux_bio_exchange_posterior:units = "mol m-2 s-1" ;
float country_flux_fire_exchange_posterior(time, countrynumber) ;
country_flux_fire_exchange_posterior:long_name = "country-averaged posterior wildfire CO₂ fluxes" ;
country_flux_fire_exchange_posterior:comment = "" ;
country_flux_fire_exchange_posterior:dtype = "float" ;
country_flux_fire_exchange_posterior:units = "mol m-2 s-1" ;
float uncertainty_country_flux_ff_prior(time, countrynumber, countrynumber) ;
uncertainty_country_flux_ff_prior:long_name = "uncertainty matrix of country-averaged prior fossil fuel CO₂ fluxes" ;
uncertainty_country_flux_ff_prior:comment = "" ;
uncertainty_country_flux_ff_prior:dtype = "float" ;
uncertainty_country_flux_ff_prior:units = "mol m-2 s-1" ;
float uncertainty_country_flux_ocean_prior(time, countrynumber, countrynumber) ;
```

uncertainty_country_flux_ocean_prior:long_name = "uncertainty matrix of country-averaged prior ocean $CO_2$ fluxes" ;

uncertainty_country_flux_ocean_prior:comment = "" ;

uncertainty_country_flux_ocean_prior:dtype = "float" ;

uncertainty_country_flux_ocean_prior:units = "mol m-2 s-1" ;

float uncertainty_country_flux_bio_prior(time, countrynumber, countrynumber) ;

uncertainty_country_flux_bio_prior:long_name = "uncertainty matrix of country-averaged prior biosphere $CO_2$ fluxes" ;

uncertainty_country_flux_bio_prior:comment = "" ;

uncertainty_country_flux_bio_prior:dtype = "float" ;

uncertainty_country_flux_bio_prior:units = "mol m-2 s-1" ;

float uncertainty_country_flux_fire_prior(time, countrynumber, countrynumber) ;

uncertainty_country_flux_fire_prior:long_name = "uncertainty matrix of country-averaged prior wildfire $CO_2$ fluxes" ;

uncertainty_country_flux_fire_prior:comment = "" ;

uncertainty_country_flux_fire_prior:dtype = "float" ;

uncertainty_country_flux_fire_prior:units = "mol m-2 s-1" ;

float uncertainty_country_flux_ff_posterior(time, countrynumber, countrynumber) ;

uncertainty_country_flux_ff_posterior:long_name = "uncertainty matrix of country-averaged posterior fossil fuel $CO_2$ fluxes" ;

uncertainty_country_flux_ff_posterior:comment = "" ;

uncertainty_country_flux_ff_posterior:dtype = "float" ;

uncertainty_country_flux_ff_posterior:units = "mol m-2 s-1" ;

float uncertainty_country_flux_ocean_posterior(time, countrynumber, countrynumber) ;

uncertainty_country_flux_ocean_posterior:long_name = "uncertainty matrix of country-averaged posterior ocean $CO_2$ fluxes" ;

uncertainty_country_flux_ocean_posterior:comment = "" ;

uncertainty_country_flux_ocean_posterior:dtype = "float" ;

uncertainty_country_flux_ocean_posterior:units = "mol m-2 s-1" ;

float uncertainty_country_flux_bio_posterior(time, countrynumber, countrynumber) ;

uncertainty_country_flux_bio_posterior:long_name = "uncertainty matrix of country-averaged posterior biosphere $CO_2$ fluxes" ;

uncertainty_country_flux_bio_posterior:comment = "" ;

uncertainty_country_flux_bio_posterior:dtype = "float" ;

uncertainty_country_flux_bio_posterior:units = "mol m-2 s-1" ;

float uncertainty_country_flux_fire_posterior(time, countrynumber, countrynumber) ;

uncertainty_country_flux_fire_posterior:long_name = "uncertainty matrix of country-averaged posterior wildfire $CO_2$ fluxes" ;

uncertainty_country_flux_fire_posterior:comment = "" ;

uncertainty_country_flux_fire_posterior:dtype = "float" ;

uncertainty_country_flux_fire_posterior:units = "mol m-2 s-1" ;

// global attributes:

:summary = "A collection of monthly means of CTE-HR $CO_2$ fluxes for 2021, based on hourly estimates of biospheric fluxes, anthropogenic emissions (total and per sector), GFAS fire emissions and Jena CarboScope ocean fluxes, all re-gridded to match the resolution of the biospheric fluxes." ;

:source = "CTE-HR 1.0. Created using the code from https://git.wageningenur.nl/ctdas/CTDAS/-/tree/near-real-time, hash b8e1a8f" ;

:model_name = "CarbonTracker Europe - High Resolution" ;

:frequency = "monthly" ;

```
        :geospatial_lat_resolution = "0.1 degree" ;
        :geospatial_lon_resolution = "0.2 degree" ;
        :crs = "spherical earth with radius of 6370 km" ;
        :institution = "Wageningen University, department of Meteorology and Air Quality, Wageningen, the Netherlands; \n Rijksuniversiteit Groningen, Groningen, the Netherlands; \n ICOS Carbon Portal, Lund, Sweden" ;
        :contact = "Daan Kivits, Wageningen University & Research, daan.kivits@wur.nl" ;
        :project = "Process Attribution of Regional emISsions (PARIS)"
        :keywords = "carbon flux, carbontracker, emission model, flux product" ;
        :license = "CC-BY-4.0" ;
        :Conventions = "CF-1.8" ;
        :references = "van der Woude et al. (2023), https://doi.org/10.5194/essd-15-579-2023" ;
        :comment = "Positive terrestrial and oceanic biosphere fluxes are emissions, and negative mean uptake. For more information, see https://doi.org/10.5281/zenodo.6477331. The country names that correspond to the given country numbers can be found in the CTE-HR base flux set and accessory country mask file"
        :history = "" ;
}
```