CO2 Human Emissions

The CHE Tier1 Global Nature Run

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Co-ordinated by ECMWF

CO2 Human Emissions

D2.2 Global Run V1

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1 Executive Summary

This report presents the first (Tier 1) 9-km global nature run of the CO_2 Human Emission (CHE) project. The main purpose of this simulation is to provide boundary conditions to the regional simulations to be performed at higher resolution (down to 1 km for urban scale and 100m for point source simulations) as part of the CHE library of simulations. This library of simulations will allow to conduct observing system simulation experiments (OSSEs) to the CHE consortium and wider scientific community. The configuration of the Tier 1 nature run is the same as that of the Copernicus Atmosphere Monitoring Service (CAMS) CO_2 forecast with the Integrated Forecasting System (IFS) at the European Centre for Medium-range Weather Forecasts (ECMWF). This facilitates the timely delivery of the Tier 1 CHE nature run.

The meteorological aspects of the nature run have not been evaluated in this report because they are consistent with the ECMWF analysis and short-range forecasts which have been extensively investigated and evaluated in various ECMWF Technical Memoranda.

This report illustrates the capability of the nature run to represent the variability of CO_2 at different scales from seasonal and inter-hemispheric to synoptic, local and diurnal. Comparison with in situ and total column data shows a realistic variability of CO_2. The systematic errors are in the range of 1 to 2ppm for the total column on monthly timescales and less than 1ppm on global scales at baseline sites. These systematic errors are associated in large part to the prescribed and modelled surface fluxes which are not constrained by observations. The seasonal cycle, synoptic and diurnal cycle are all within the range of observed variability recorded by surface and total column observations. A preliminary evaluation of column-averaged CH_4 and CO also show a realistic representation of variability at synoptic and diurnal time-sales. An improved Tier 2 global nature run will be provided at the end of 2019 with improved fluxes and the newest NWP model version. In addition to the upgrades in the 9-km resolution nature run, the Tier 2 simulations will also be done using an ensemble approach to include information on uncertainties in the fluxes and transport.

2 Introduction

The CO_2 Human Emission (CHE) project has been tasked with providing a library of simulations that can be used as a reference -- referred to as nature run -- in Observing System Simulation Experiments (OSSEs) for the exploration and design of future space-based carbon observing systems. The nature run presented in this report is the first step to build this library, as it is based on the operational CAMS global CO_2 forecasting system (https://atmosphere.copernicus.eu/maps/global-carbon-dioxide-forecast) which means it could be run straight away without requiring previous testing or preparation in order to provide boundary conditions for the regional simulations in a timely manner. The focus of the simulation is 2015, giving the opportunity to compare the high resolution global simulation with GOSAT and OCO-2 satellite data, as well as in situ and Total Carbon Column Observing Network (TCCON) data. The background and scope of this Tier1 nature run in the context of the CHE project are presented below.

2.1 Background

A part of the commitment to support climate change policy, the CHE project is addressing the challenges of developing a CO_2 emissions monitoring support capacity. Among these challenges, there is the assessment of the requirements for a future space missions dedicated to the monitoring of CO_2. This assessment need to be done in the framework of OSSEs which are based on a reference simulation or nature run used as the truth, from which synthetic observations can be produced. As the nature run is taken to be the truth, the simulation is required to represent a realistic variability of the observed parameters. In this context, the CHE project aims to provide a library of simulations at different scales from global to regional to local which can be used as nature runs to sample the atmospheric variability associated with regional and local sources/sinks to point sources. The CHE deliverable D2.1 describes the configuration of the different nature runs and their domains/resolutions.

2.2 Scope of this deliverable

The main scope of the Tier1 nature run is to provide boundary conditions to regional models over Europe and Asia. The objectives and work done associated with this Tier 1 nature run can be found below.

2.2.1 Objectives of this deliverable

The objective of this deliverable is to document the model configuration and the available model output of the CHE Tier1 global nature run. A preliminary evaluation is also provided together with snapshots of atmospheric column-averaged CO_2 that illustrate the detailed structure and realism of the high resolution global simulation.

2.2.2 Work performed in this deliverable

A year-long simulation has been performed based on the CAMS CO_2 forecast configuration in order to provide atmospheric CO_2 and meteorological fields required by CHE regional models in a timely manner. The experiment has been monitored and optimised to deliver the fields as fast as possible to the CHE partners in WP2. An evaluation of CO_2 has also been performed based on surface and total column observations.

2.2.3 Deviations and counter measures

There have been no deviations or counter measures required.

3 Model configuration

The CHE Tier 1 global nature run is a 9-km free-running tracer simulation with state-of-the-art IFS model transport based on the CAMS cyclic forecast configuration which provides 3-hourly 3-D fields depicting realistic seasonal cycle, day-to-day synoptic variability and diurnal cycle throughout the year 2015. Details of the experiment setup and the model output available can be found in the two sections below.

3.1 Experiment set up

The Tier 1 global nature run has adopted the same configuration as the CAMS high CO_2 resolution forecast (https://atmosphere.copernicus.eu/maps/global-carbon-dioxide-forecast), with 1-day forecasts of atmospheric CO_2, CH_4 and linear CO and all the standard Numerical Weather Prediction (NWP) fields issued every day from 00UTC based on the NWP framework. The meteorological initial conditions of each 1-day forecast come from the ECMWF operational NWP analysis, while the CO_2, CH_4 and linear CO tracers are initialised with the previous 1-day forecast, in a cyclic mode, which means they are essentially free-running fields. The nature run extends the period from 1st January 2015 to 31 December 2015. The initial conditions for CO_2 and CH_4 on 1 January 2015 are extracted from the CAMS GHG analysis (Massart et al., 2014, 2016) for CO_2 and CH_4 and from the CAMS near-real time analysis (Inness et al., 2015) for CO. NWP analysis of meteorological fields is one of the main elements determining the quality of the transport (Locatelli et al. 2013). Therefore, ensuring the meteorological fields are close to the analysis by having a sequence of 1-day forecasts will ensure the transport is as realistic as possible.

The tracer transport and CO_2 biogenic fluxes which are two of the largest contributors to the variability of CO_2 are modelled online in the IFS (Agusti-Panareda et al., 2014 and Agusti-Panareda et al. 2016). The model advection is computed by a semi-Lagrangian scheme (Hortal, 2002; Untch and Hortal, 2006) which is not mass conserving by default. Thus, a mass fixer is required to ensure mass conservation at every time step (Agusti-Panareda et al., 2017). The latest version of the mass fixer is documented in Diamantakis and Agusti-Panareda (2018). The turbulent mixing scheme is described in Beljaars and Viterbo (1998) and Koehler et al. (2011). The convection scheme is based on Tiedtke (1989) (see Bechtold et al., 2008, for further details). Full documentation of the IFS can be found in https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model/ifs-documentation. The CO_2 emissions from land vegetation are modelled online using the CTESSEL Carbon module integrated in the land surface model of the IFS (Boussetta et al., 2013). The fluxes have been evaluated with FLUXNET data and compared to different models (e.g. CASA and ORCHIDEE) with a comparable performance on synoptic to seasonal scales (Balzarolo et al., 2014). An online bias correction scheme (Agusti-Panareda et al., 2016) is applied to the modelled Gross Primary Production (GPP) and ecosystem respiration (Reco) fluxes to correct for biases in the Net Ecosystem Exchange (NEE) budget compared to a climatology of optimized fluxes (Chevallier et al., 2010).

All the tracer surface fluxes, excluding the biogenic CO_2 fluxes from land, are prescribed (see Table 3 in Annex). The prescribed emissions in the Tier 1 nature run are the same as the ones used in the current CAMS operational forecast system. The EDGAR v4.2FT2010 (Olivier and Janssens—Maenhout, 2012) is used for CO_2 and CH_4 and CAMS MACCity emissions (Granier et al., 2011) for CO. There is no day-to-day variability in these prescribed emisions. Anthropogenic and biogenic emissions for CO have a month-to-month variation and CH_4 also has a seasonal cycle for the emissions from rice paddies. The wetland CH_4 emissions are from a climatology of LPJ-HYMN data set (Spanhi et al. 2011) with an original resolution of 1x1 degree.

Because the IFS is a state-of-the-art operational NWP model, the meteorological fields of each model version are extensively evaluated. IFS model version used in this Tier 1 nature run is CY43r1 which was operational weather forecast model at ECMWF from 22 November 2016 to 10 July 2017. A full evaluation this model cycle can be found in Haiden et al. (2017).

The 9km simulation is based on a new model grid (Malardel et al. 2016) used in the current operational NWP forecast at ECMWF which comprises up to 904 million model grid points, 137 levels and a time step of 7.5 minutes.

3.2 Model output

The Tier 1 global nature run will be used as boundary conditions to the WP2 regional models, and therefore there are several meteorological and tracer 2D and 3D fields that need to be provided as model output. A list of the required model outputs necessary for the nesting of the other simulation domains have been provided by the WP2 partners (see Tables 1 and 2). Additionally, the CO_2 and CH_4 surface fluxes and the experimental tagged tracers have also been archived as model output which may be useful for other applications (e.g. global OSSEs).

The output fields are provided as 3-hourly data with a maximum horizontal resolution of 0.1x0.1 degree on a regular latitude/longitude grid. The data can be accessed via ECMWF MARS archiving system: experiment ID is “gvri” (stream=LWDA, class=RD). The data will also be available from the Copernicus Climate Data Store at the end of 2018. Users can also contact Copernicus User Support (copernicus-support@ecmwf.int) to make enquiries about data access.

Table 1: List of 3D meteorological outputs of the global simulation

Variable name	Variable abbreviation
Specific humidity	Q
Temperature	T
Pressure	P
Wind components	U,V
Cloud liquid water content	CLWC
Cloud ice water content	CIWC

Table 2: List of 2D meteorological outputs of the global simulation

Variable name	Variable abbreviation
Geopotential and land mask	Z/LSM
Snow depth	SD
Snow temperature	TSN
Skin temperature	SKT
Skin Reservoir Content	SRC
Soil temperature	STLi
Soil wetness	SWLi
Logarithm of surface pressure	LNSP
Mean sea-level pressure	MSL
Sea-ice cover	CI
Sea surface temperature	SSTK
10 metre wind components	10U, 10V
2 metre temperature	2T
2 metre dewpoint temperature	2D

3D tracers

- CO_2 [kg/kg]
- CO [kg/kg]
- CH_4 [kg/kg]

Conversion of units from kg/kg to dry molar fraction in ppm requires the application of the conversion factor $f=10^6$ x Mair/Mtracer, where Mair and Mtracer are the molar masses of dry air and tracer respectively.

Tagged tracers associated with different emissions (e.g. anthropogenic, biogenic, fires, oceans) are also provided by using a flux-denial configuration, where extra tracers are initialised with the realistic tracer fields with all the emissions, but are evolving without the influence of a specific type of emission during the 1-day forecast. The pattern of enhancement associated with a specific emission during the 1-day forecast can then be obtained by subtracting the full tracer with the flux-denial tracer. The sum of all the enhancements from the different fluxes add up to the enhancement of the total flux, thus showing that the assumption of linearity in the transport also holds in the IFS model.

2D tracers

- XCO_2 [ppm] (tcco2)
- XCH_4 [ppb] (tcch4)
- TCCO [kg/m^2] (tcco)

Surface fluxes

- NEE [kg m^{-2}s^{-1}] archived as instantaneous flux (fco2nee) or accumulated (aco2nee). Note that positive values are associated with a sink and negative values with a source (following IFS convention).
- CO_2, CH_4 and CO fire emissions [kg m^{-2}s^{-1}] (co2fire/ch4fire/cofire with positive values indicating a source).
- CO_2 anthropogenic emissions [kg m^{-2}s^{-1}] (co2apf with negative values indicating a source following IFS convention).
- CO_2 ocean fluxes [kg m^{-2}s^{-1}] (co2of with negative/positive values corresponding to source/sink following IFS convention).
- CH_4 total emissions excluding fires [kg m^{-2}s^{-1}] (ch4f with negative/positive values indicating source/sink following IFS convention).
- Note that anthropogenic emissions for CO are not archived, but the prescribed emissions will be made available to users (positive values indicate source).

4 Atmospheric tracer variability on seasonal, synoptic and diurnal scales

The global nature run displays the variability of CO_2 at different scales, from seasonal large-scale patterns such as the gradients between southern and northern hemispheres, to zonal gradients associated with synoptic weather systems. The high resolution can also add to the detail and intricacies of the mesoscale variations and the plumes emanating from point sources.

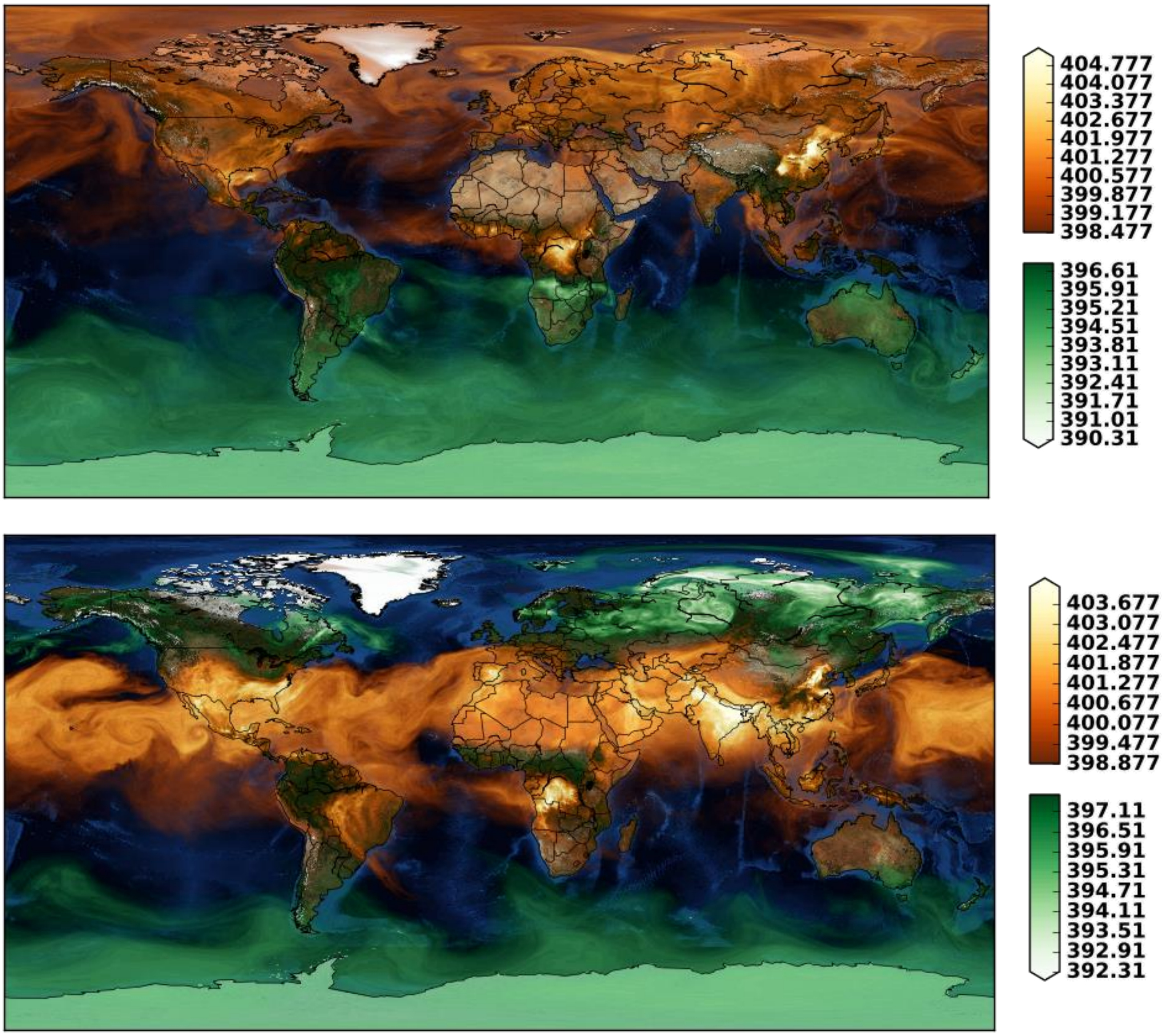


Figure 1: XCO_2 [ppm] spatial distribution on 15 January (top) and 15 July (bottom) at 00 UTC showing values above and below the global mean in reds and greens respectively (see colour bar).

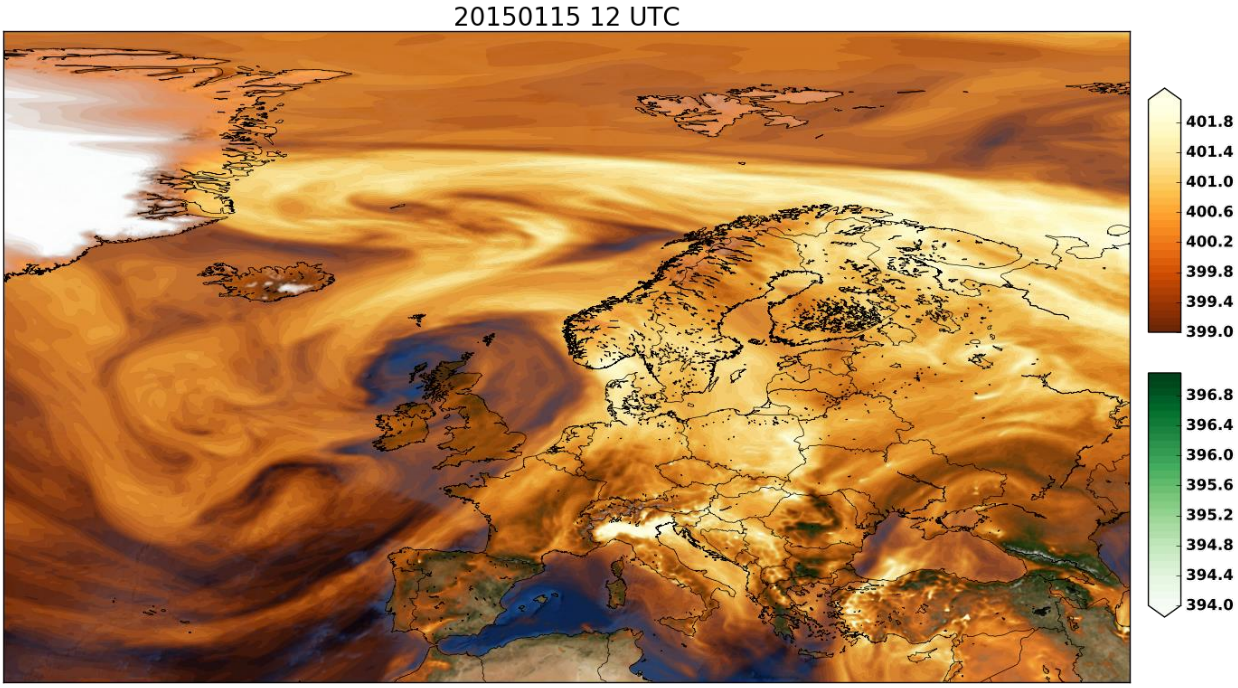


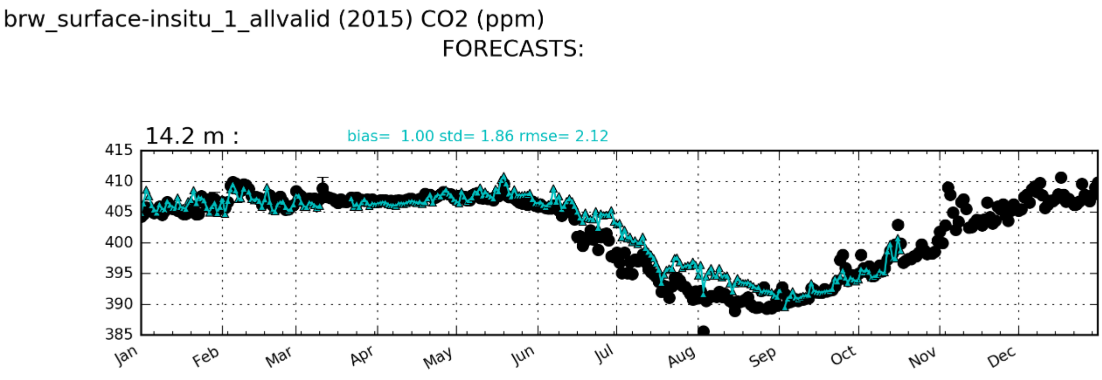
Figure 2: XCO_2 [ppm] spatial distribution on 15 January 2015 12 UTC over Europe. Values above and below the global mean in reds and greens respectively (see colour bar).

Great detail can be found in the variability at regional scale as shown in Fig. 2. The complex distribution associated with distinct weather patterns, such as the narrow cold front sweeping across western Europe, point sources associated with anthropogenic emissions as depicted by the bright dots scattered over the continent and the lower XCO_2 over the northern British Isles associated with a stratospheric intrusion at the centre of a low-pressure system.

A range of observations have been used to evaluate the realism of the nature run at seasonal and synoptic and diurnal timescales at the surface (section 4.1) and the total atmospheric column (section 4.2).

4.1 Surface

The inter-hemispheric gradient and the seasonal cycle of CO2 are depicted by the baseline National Oceanic and Atmospheric Administration (NOAA) observatories at Barrow (Alaska, USA), Mauna Loa (Hawaii, USA), Samoa and South Pole. Although the amplitude of the seasonal cycle is slightly underestimated, the biases of the background air are less than 1ppm.



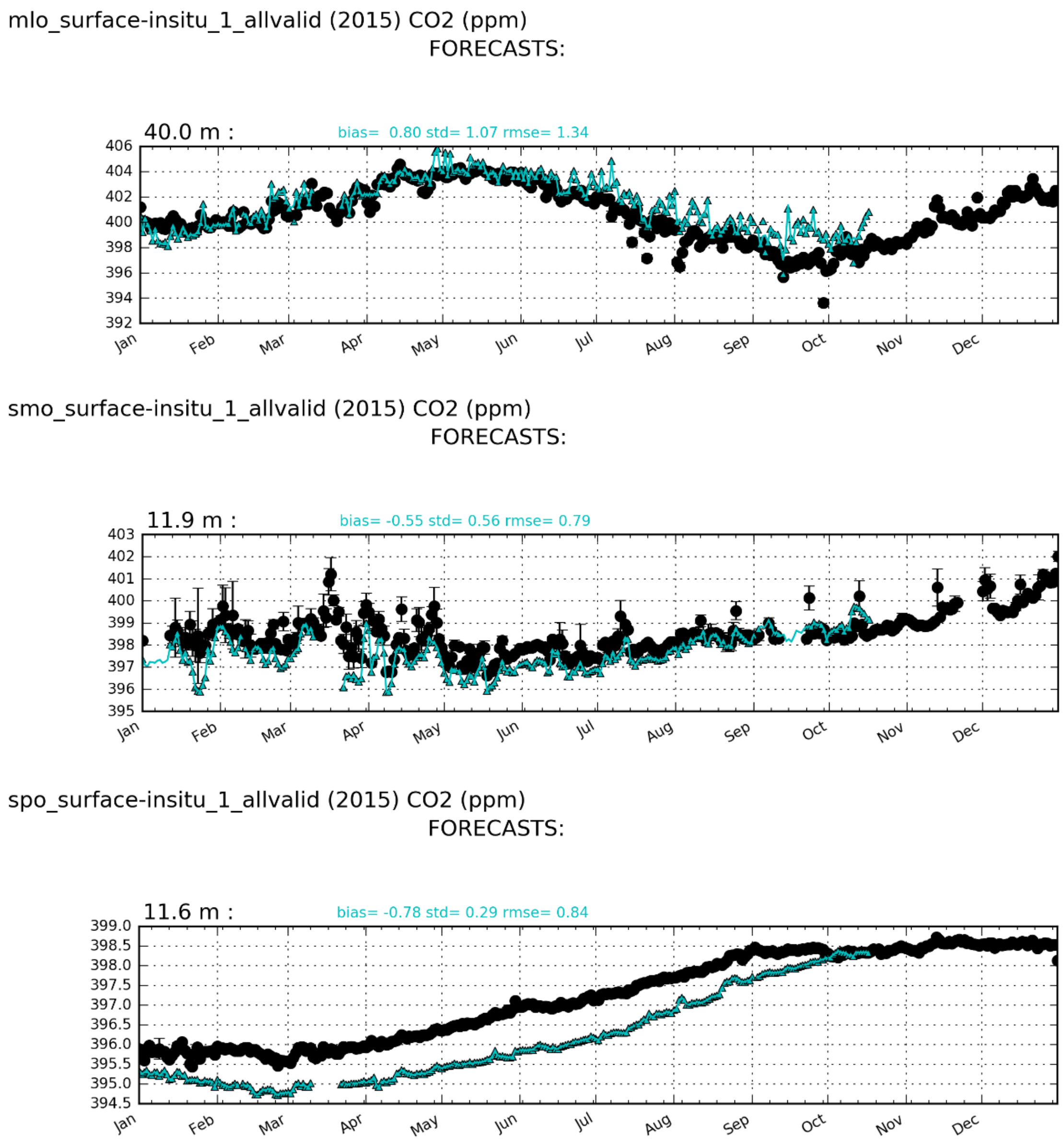
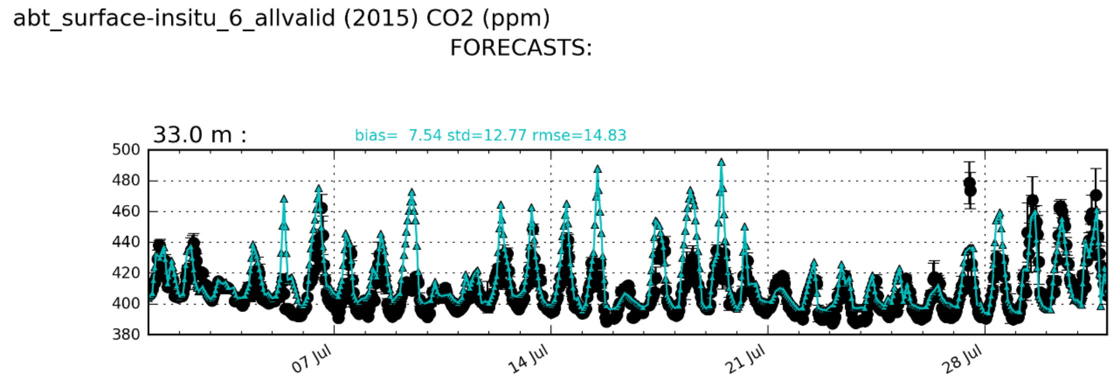


Figure 3: Daily mean surface CO_2 at four NOAA baseline stations: brw (Barrow, Alaska, USA), mlo (Mauna Loa, Hawaii, USA at 71.3ºN 156.6ºW, 11 m a.s.l), smo (Tutuila, American Samoa, USA at 14.25ºS 170.6ºW, 42 m a.s.l), spo (South Pole, Antarctica at 89.9ºS 24.8ºW, 2810 m a.s.l) from the Tier 1 nature run (blue) and observations (black). The observations have been obtained from the NOAA ObsPack (2017). The bias, standard error and root mean square error (rmse) are shown at the top of each panel, together with the sampling height [m] for each station. Note that the model data stops in October because at the time of writing the deliverable the nature run experiment had not finished.



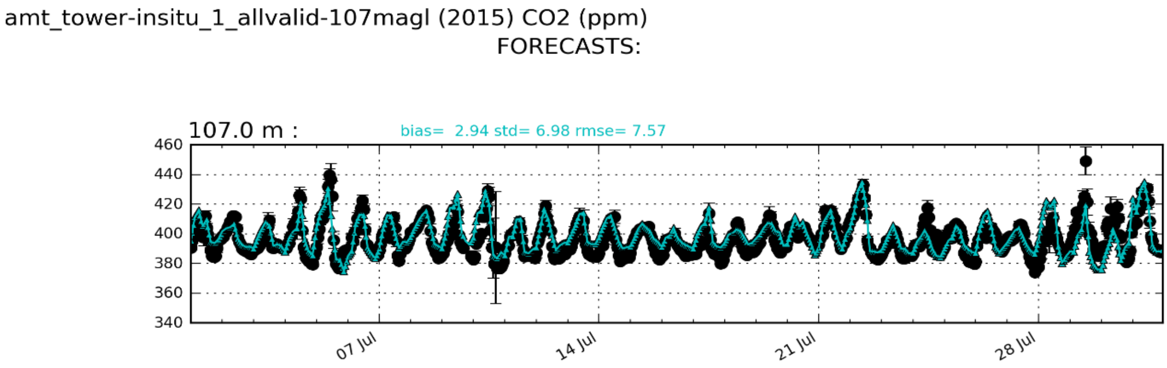


Figure 4: Hourly surface CO_2 at three in situ stations in North America: abt (Abbotsford, British Columbia, Canada at 49.03N 122.37W and 100 masl, Environment Canada); amt (Argyle, Maine, USA at 45.03N 68.68W and 53 masl, National Oceanic and Atmospheric Administration) from the Tier 1 nature run (blue) and observations (black) in July 2015. The observations have been obtained from the NOAA ObsPack (2017). The bias, standard error and root mean square error (rmse) are shown at the top of each panel, together with the sampling height [m] for each station.

The amplitude of the diurnal cycle is generally well captured, as well as its variation with synoptic conditions. It is worth noting that the online modelling of the biogenic CO_2 fluxes over land contributes to the pronounced diurnal cycle with photosynthesis uptake during the day and ecosystem respiration during the night time, in addition to the diurnal cycle associated with the boundary layer mixing (Agusti-Panareda et al., 2014).

4.2 Total column

The averaged atmospheric column dry molar fraction is also evaluated over Europe with TCCON observations (Wunch et al., 2010) as several regional models will be run on the European domain. For XCO_2, the standard error of daily mean model data is around 1 ppm, while the bias ranges between 1 and 2ppm, with largest errors during the growing season when the biogenic fluxes are most active. The amplitude of the seasonal cycle is underestimated by 2ppm but the synoptic variability day-to-day variability is well captured.

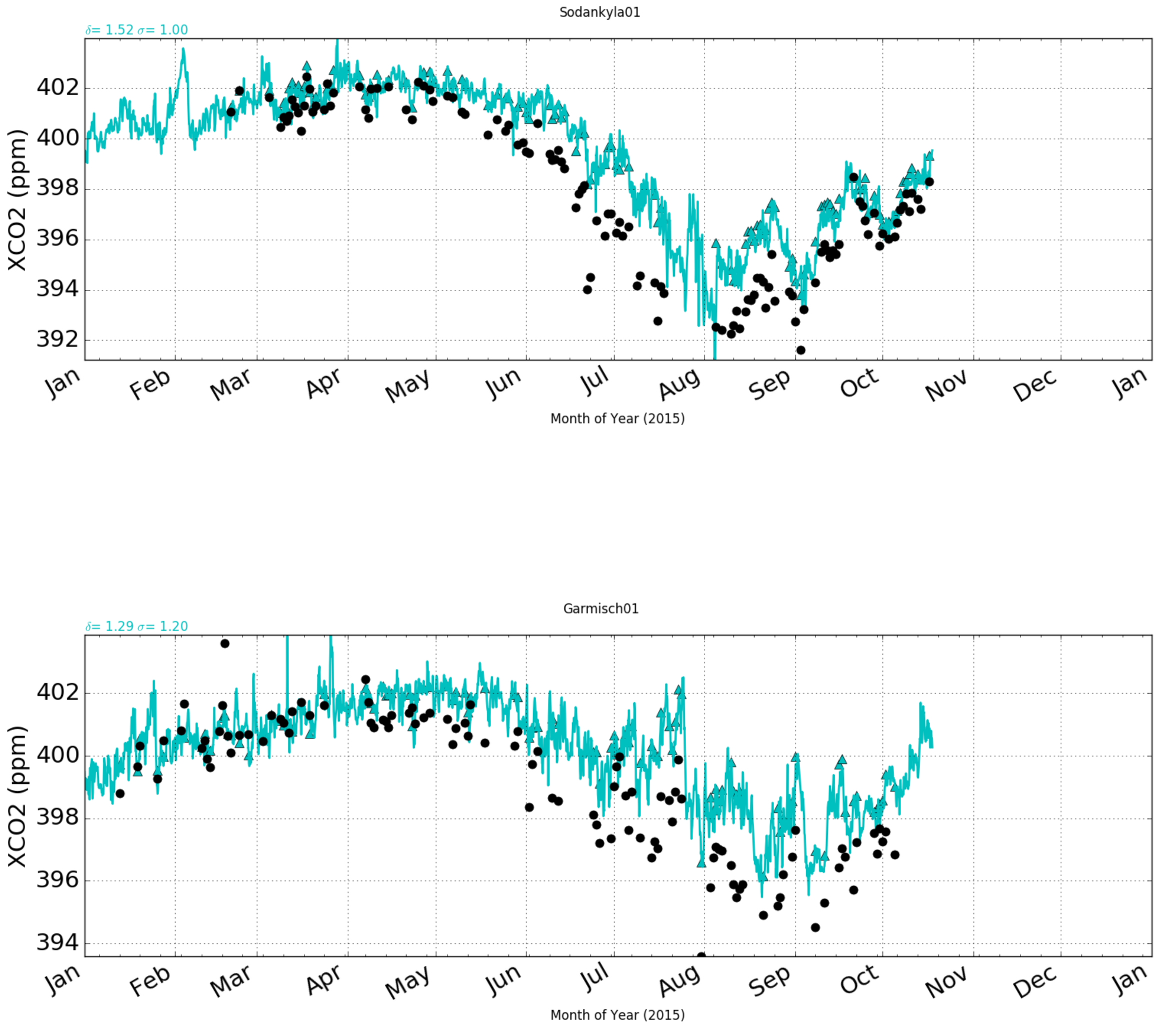


Figure 5: Daily averaged atmospheric column dry molar fraction XCO_2 [ppm] at Sodankyla, Finland (Kivi et al 2017) and Garmisch, Germany (Sussman and Rettinger, 2017) from the Tier 1 nature run (blue) and observations (black). The model columns are weighted vertically using the TCCON averaging kernels and priors. Note that the model data stops in October because at the time of writing the deliverable the nature run experiment had not finished. The mean error (δ) and standard error (σ) are shown at the top left of each panel.

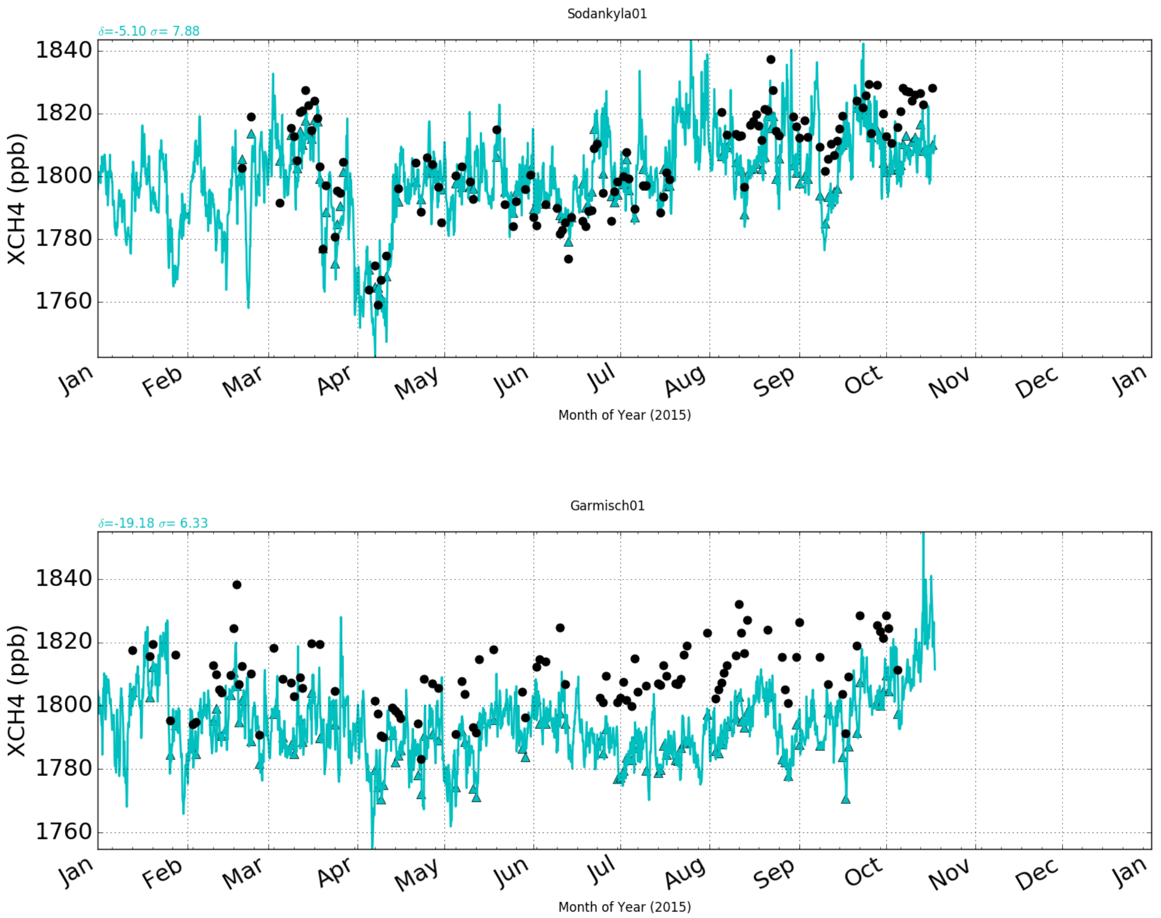


Figure 6 Daily averaged atmospheric column dry molar fraction XCH_4 [ppb] at Sodankyla, Finland (Kivi et al 2017) and Garmisch, Germany (Sussman and Rettinger, 2017) from the Tier 1 nature run (blue) and observations (black).The model columns are weighted vertically using the TCCON averaging kernels and priors. Note that the model data stops in October because at the time of writing the deliverable the nature run experiment had not finished. The mean error (δ) and standard error (σ) are shown at the top left of each panel.

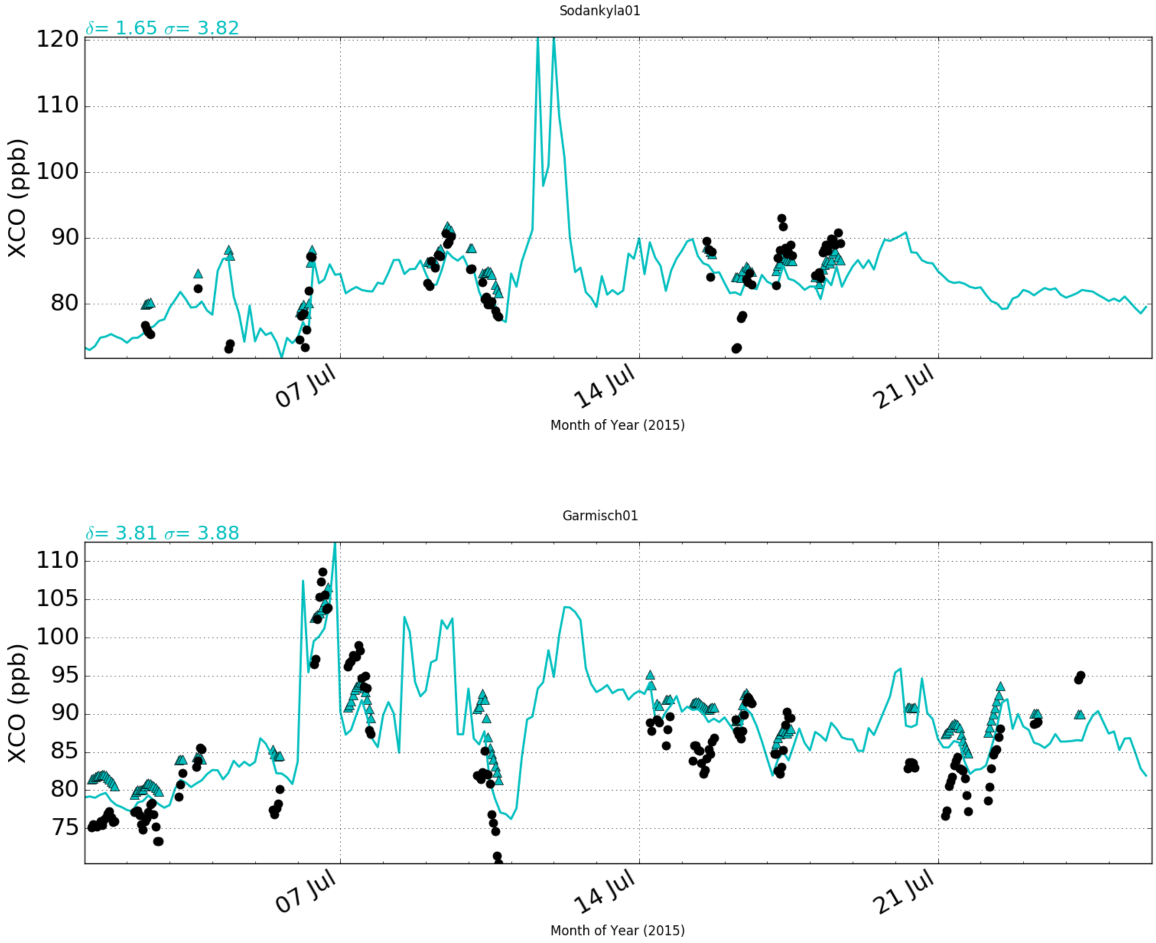


Figure 7 Hourly atmospheric column dry molar fraction XCO [ppb] in July at Sodankyla, Finland (Kivi et al 2017) and Garmisch, Germany (Sussman and Rettinger, 2017) from the Tier 1 nature run (blue) and observations (black).The model columns are weighted vertically using the TCCON averaging kernels and priors. The mean error (δ) and standard error (σ) are shown at the top left of each panel.

For XCH_4, there is a global negative bias in the nature run ranging between 5 and 25 ppb (Fig. 6). The synoptic variability is well represented by the model with a standard error generally lower than 10ppb. The diurnal and synoptic variability is also well captured for XCO (Fig. 7).

5 Conclusion

This report documents the production of the first (Tier 1) global nature run of the CHE project. The main scope of the Tier 1 nature run is to provide boundary conditions to the higher resolution regional models in WP2, as part of an effort to create a library of simulations that can be used in OSSEs to support the design of new CO_2 observing systems. Because time was of essence, this nature run has used the CAMS high resolution CO_2 forecast configuration, which did not require any previous testing. The results shown in this report illustrate the realism of the CO_2 variability at different scales and document the biases and standard errors at several surface and TCCON sites. The errors are partly associated with the prescribed fluxes (e.g. anthropogenic emissions and ocean fluxes) some of which will be upgraded to newer versions in the next Tier 2 global nature run. The next nature run will also include an ensemble of simulations at lower resolution in order to include information on the uncertainty of the anthropogenic emissions from WP3 and the uncertainty of the transport based on the Ensemble Data Assimilation system at ECMWF.

6 Acknowledgements

The evaluation of the nature run has been performed with observations from Environment Canada (Doug Worthy), National Oceanic and Atmospheric Administration (Arlyn Andrews) and the TCCON data at Sodankylä (Kivi, Heikkinen and Kyrö from the Finnish Meteorological Institute, Finland) and at Garmisch (Ralf Sussmann, KIT, Germany).

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8 Annex: Prescribed emissions

Table 3: List of prescribed surface fluxes used in Tier1 global nature run

Surface flux	Horizontal resolution	Temporal resolution	Source	References	Notes	Archived
CO2 ocean fluxes	4.0x5.0 deg.	Monthly	Takahashi monthly mean climatology 2000	Takahashi et al. (2009)	Prescribed parameter. Mass conserving interpolation to model grid and linear temporal interpolation.	Yes
CO2 anthropogenic emissions	0.1x0.1 deg.	Annual	EDGARv4.2 FT2010	Olivier and G. Janssens-Maenhout, CO2 Emissions from Fuel Combustion -- 2012 Edition, IEA CO2 report 2012, Part III, Greenhouse-Gas Emissions, ISBN 978-92-64-17475-7 Source: European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL). Emission Database for Global Atmospheric Research (EDGAR), release EDGARv4.2 FT2010, http://edgar.jrc.ec.europa.eu, 2013.	Prescribed parameter. Mass conserving interpolation to model grid. Country-dependent extrapolation factor is applied to 2010 gridded dataset.	Yes
CO2, CO and CH4 biomass burning	0.1x0.1 deg.	Daily	GFAS v1.2	Kaiser et al. (2012)	Prescribed parameter. Mass conserving interpolation.	Yes

Total CH4 emissions excluding biomass burning	0.1x0.1 deg. for anthropogenic emissions and various resolutions for other data sets.	Monthly	Various sources including EDGARv4.2 FT2010 HYMN-LPJ wetland flux climatology Sanderson (1996) for termites, Ridgwell et al. (1999) for soil sink, ocean fluxes from Lambert and Schmidt (1993) and Houweling et al. (1999) for wild animals	CO2 report 2016: Olivier J, Janssens-Maenhout G, Muntean M, Peters J. Trends in global CO2 emissions: 2016 Report. European Commission; 2016. JRC 10342 (November 2016) http://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-in-global-co2-emissions-2016-report-103425.pdf Spanhi et al. (2011) for wetland emissions	Prescribed parameter. Mass conserving interpolation to model grid and combination of different climatologies with EDGAR4.2 FT2010 emissions in 2010.	Yes
CO anthropogenic emissions	0.5x0.5 deg.	Monthly	MACCity	Granier et al.	Prescribed parameter. Mass conserving interpolation to model grid.	No

[1] Note that all prescribed fluxes are kept constant throughout the forecast

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