



1 Study of the footprints of short-term variation in XCO₂ observed by TCCON
2 sites using NIES and FLEXPART atmospheric transport models

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26



1 **Abstract**

2 The Total Carbon Column Observing Network (TCCON) is a network of ground-based
3 Fourier Transform Spectrometers (FTS) that record near-infrared (NIR) spectra of the Sun.
4 From these spectra, accurate and precise observations of CO₂ column-averaged dry-air mole
5 fraction (denoted XCO₂) are retrieved. TCCON FTS observations have previously been used to
6 validate satellite estimations of XCO₂; however, our knowledge of the short-term spatial and
7 temporal variations in XCO₂ surrounding the TCCON sites is limited.

8 In this work, we use the National Institute for Environmental Studies (NIES) Eulerian
9 three-dimensional transport model and the FLEXPART (FLEXible PARTicle) Lagrangian
10 Particle Dispersion Model (LPDM) to determine the footprints of short-term variations in
11 XCO₂ observed by operational, past, future, and possible TCCON sites. We propose a footprint-
12 based method for the colocation of satellite and TCCON XCO₂ observations, and estimate the
13 performance of the method using the NIES model and five GOSAT XCO₂ product datasets.
14 Comparison of the proposed approach with a standard geographic method shows higher
15 number of colocation points and average bias reduction up to 0.15 ppm for a subset of 16
16 stations for the period from January 2010 to January 2014. Case studies of the Darwin and La
17 Réunion sites reveal that when the footprint area is rather curved, non-uniform and
18 significantly different from a geographical rectangular area, the differences between these
19 approaches are more noticeable. This emphasizes that the colocation is sensitive to local
20 meteorological conditions and flux distributions.

21

22 **Keywords:** XCO₂, TCCON, GOSAT, atmospheric transport

23



1. Introduction

Satellite observations of the column-averaged dry-air mole fraction of CO₂ (XCO₂) have the potential to significantly advance our knowledge of carbon dioxide (CO₂) distributions globally and provide new information on regional CO₂ sources and sinks. Observations of XCO₂ are available from space-based instruments such as the SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographyY (SCIAMACHY; Bovensmann et al., 1999), the Greenhouse gases Observing Satellite (GOSAT; Kuze et al., 2009, 2016; Yokota et al., 2009), and the Orbiting Carbon Observatory-2 (OCO-2; Crisp et al., 2004). These satellites provide unprecedented spatial coverage of the variability in XCO₂ around the world, with the exception of polar regions and areas with dense clouds. These observations are, however, limited by the orbit of the satellites, which typically measure in the local afternoon.

Ground-based Fourier Transform Spectrometer (FTS) observations available from the Total Carbon Column Observing Network (TCCON) (Wunch et al., 2011) provide dense temporal resolution and are more precise and accurate than space-based instruments. However, the number of ground-based FTS sites is limited, with just 23 operational sites and several approved for the future. These sites are sparsely distributed, and Siberia, Africa, South America, and the oceans from middle to high latitudes are poorly covered. Despite this limitation, FTS observations are used to validate satellite retrievals in order to assess bias, variability, and other key parameters (e.g., Wunch et al., 2011; Lindqvist et al., 2015).

The spatial and temporal coverage of satellite observations over TCCON sites is sparse due to cloud and aerosol filters, retrieval selection criteria, and post-retrieval data quality filters. To obtain satellite observation data with small uncertainties it is necessary to apply a colocation method for aggregating neighboring soundings. Currently available methods for XCO₂ colocation include geographical (e.g., Cogan et al., 2012; Inoue et al., 2013; Reuter et al., 2013), T700 (it implies that the air with the same history of transport derived from the 700 hPa potential temperature has the same XCO₂; Wunch et al., 2011), model-based (Guerlet et al., 2013), and geostatistical approaches (Nguyen et al., 2014).

In the geographical colocation method a spatial region around a TCCON site is selected together with a temporal window. Inoue et al. (2013) used daily mean observations within a 10° × 10° area, Reuter et al. (2013) selected the monthly median of all observations within a 10° × 10° area, and Cogan et al. (2012) implemented narrower limits, using a two-hour mean period within a ±5° × ±5° area.

To increase the number of soundings, the spatial region may be expanded and additional



1 selection criteria imposed. In the T700 colocation method proposed by Wunch et al. (2011),
2 all observations within $\pm 30^\circ$ longitude, $\pm 10^\circ$ latitude, ± 5 days, and ± 2 K of the selected TCCON
3 location are employed.

4 The model-based method proposed by Oshchepkov et al. (2012) and improved by
5 Guerlet et al. (2013) uses daily mean values within 0.5 ppm of the 3 day-averaged model XCO₂
6 values and located within $\pm 25^\circ$ longitude and $\pm 7.5^\circ$ latitude of a TCCON site.

7 Nguyen et al. (2014) developed a geostatistical colocation methodology that selects
8 observations using a “distance” function, which is a modified Euclidian distance in terms of
9 latitude, longitude, time, and mid-tropospheric temperature at 700 hPa.

10 Bremen, Garmisch, Four Corners, JPL, and Izaña are influenced by local effects or
11 complex terrain and are not included in averages (Kulawik ATM 2016). Limitations of the
12 techinks !!!

13 The majority of colocation methods described above have a common disadvantage; i.e.,
14 they work with a rectangular spatial domain, which is convenient for technical handling but
15 does not reflect the impact of surface sources or sinks of CO₂ and the local meteorology in the
16 area of interest. The spatial domains in colocations should take into account these features to
17 ensure that only appropriate observations are selected. Keppel-Aleks et al. (2011, 2012)
18 showed that the largest gradient in XCO₂ is formed mainly by the north-south flux
19 distribution, with variations in XCO₂ caused mainly by large-scale advection. TCCON and
20 satellite XCO₂ observations have pronounced temporal variability and are thus important in
21 studies of short-term variations in XCO₂.

22 In this paper we study short-term variations in XCO₂ observed at TCCON sites. Although
23 the XCO₂ is derived from column-averaged concentrations of CO₂, XCO₂ observations are most
24 sensitive to near-surface fluxes. The XCO₂ variations are thus related to changes in the CO₂
25 mole fraction occurring near the surface surrounding the TCCON sites (hereafter known as
26 the footprints of the TCCON sites).

27 The remainder of this paper is organized as follows: an overview of the method for
28 estimating the footprints of TCCON sites is presented in Section 2. The results of the footprint
29 estimation and a new method for colocation are presented and discussed in Sections 3,4, and
30 the conclusions are given in Section 5.



2. Method

To estimate the footprints of TCCON sites we used forward simulations employing the NIES Eulerian three-dimensional transport model (TM) and backward trajectory tracking using the FLEXPART LPDM model. NIES TM CO₂ concentrations sampled at 1 km above ground at 13:00 local time were used to initialize backward tracer simulations with the FLEXPART model. FLEXPART, like other Lagrangian Particle Dispersion Models (LPDMs), considers atmospheric tracers as a discrete phase and tracks the pathway of each individual particle (Stohl et al., 2009). The level of 1 km above ground typically corresponds to the top of the daytime planetary boundary layer (PBL). The PBL is the lowest part of the atmosphere and its behavior is directly influenced by its contact with the planetary surface. Turbulence causes intensive vertical mixing of the air within the PBL, so CO₂ released from the surface is roughly uniformly distributed throughout the column of air in the PBL at local noon, when the maximum extent of vertical mixing occurs. The selected sampling time is also favorable for minimizing errors in the initial CO₂ concentration calculated by NIES TM, as this type of chemical transport model has proved to be successful in resolving the diurnal vertical profiles of tracers (Belikov et al., 2013a).

The NIES model has previously been used to study the seasonal and inter-annual variability in CO₂. Belikov et al. (2013b) reported that the NIES model is able to successfully reproduce the vertical profile of CO₂ as well as the seasonal and inter-annual variability in XCO₂. A comparison of modeled output with TCCON observations (Belikov et al., 2013b) revealed model biases of $\pm 0.2\%$ for XCO₂; on this basis we assume that the NIES TM is able to successfully reproduce the vertical profile of CO₂ at the locations of TCCON sites.

The key features of the NIES TM are as follows: a reduced horizontal latitude–longitude grid with a spatial resolution of $2.5^\circ \times 2.5^\circ$ near the equator (Belikov et al., 2011); a vertical flexible hybrid sigma–isentropic (σ – θ) grid with 32 levels up to the level of 5 hPa (Belikov et al., 2013b); separate parameterization of the turbulent diffusivity in the PBL and free troposphere (provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim reanalysis); and a modified Kuo-type parameterization scheme for cumulus convection (Belikov et al., 2013a). The NIES TM was run using fluxes obtained with the GELCA-Eof (Global Eulerian-Lagrangian Coupled Atmospheric model with Empirical Orthogonal Function) inverse modeling scheme (Zhuravlev et al., 2013). A priori fluxes consist of four types: 1) the Open source Data Inventory of Anthropogenic CO₂ (ODIAC) (Oda et al., 2011) and the Carbon Dioxide Information Analysis Center's (CDIAC) (Andres et al.,



1 2011) anthropogenic fluxes; 2) the Vegetation Integrative Simulator for Trace gases (VISIT)
2 (Ito, 2010) biosphere fluxes; 3) the Offline ocean Tracer Transport Model (OTTM) (Valsala et
3 al., 2013) oceanic fluxes; and 4) the Global Fire Emissions Database (GFED) (Van der Werf et
4 al., 2010) biomass burning emissions. The NIES and FLEXPART models are driven by the
5 Japanese Meteorological Agency Climate Data Assimilation System (JCDAS) datasets (Onogi et
6 al., 2007).

7 Variations in TCCON XCO₂ are influenced by a large spatial footprint. Keppel-Aleks et al.
8 (2012) presented a robust relationship between weekly and monthly aggregated total column
9 CO₂ and local net ecosystem exchange, while column drawdown has only a weak correlation
10 with the regional flux on daily timescales. The maximum trajectory duration for the model
11 was therefore set to one week. The model was run to analyze TCCON site footprints for a 14-
12 month period from January 2010 to February 2011. The FLEXPART model was then used to
13 identify the areas in which TCCON soundings are most sensitive to variations on a short-term
14 scale.



3. Results

3.1. Sensitivity of TCCON site footprints

We analyzed two groups of TCCON sites: operational sites (Table 1; Figs. 1 and 2) and past, future, and possible sites (Table 2; Fig. 3). We included Arrival Heights (Antarctica) and Yekaterinburg (Russia) in the second group, though the status of these monitoring stations is unclear. The footprint estimation is restricted to the summer season for high-latitude sites (Arrival Heights, Eureka, Ny Ålesund, Poker Flat, and Sodankylä), due to limitations relating to the solar zenith angle.

3.1.1. Operational sites

North America

The five active American sites are located in the US and Canada, so they are sensitive to the western and central part of North America, the northern part of Canada and Greenland, and the eastern part of the Pacific Ocean. There are no TCCON sites in Alaska or on the east coast of North America, which is a region of intense anthropogenic activity (Fig. 1).

European sites

The European region contains eight operational sites (Fig. 2). We also include Izaña, which does not belong to this region but is located very close to it. This region has a good spatial coverage of operational TCCON sites; however, most sites are located near the coast and are thus very sensitive to the Atlantic and Arctic oceans. The maximum footprint sensitivity occurs in western Europe where there is a high density of operational TCCON sites; five sites (Bremen, Garmisch, Karlsruhe, Orléans, and Paris) are concentrated within a small area. The sensitivity decreases quite rapidly towards the east and south, and only parts of eastern Europe and north Africa are covered.

Asia

The footprints of Asian sites mainly span countries bordering the Sea of Japan; i.e., Japan, Korea, the Russian Far East, and east China. These sites are also able to capture signals from Mongolia, eastern Siberia, and Southeast Asia. Although the coverage of these sites is relatively small, the main industrial centers in the region are included.

Australia and New Zealand

The footprint sensitivity of TCCON sites in this region covers almost all of Australia. Chevallier et al. (2011) shows TCCON data could constrain flux estimates over Australia



1 equally well as the existing in situ measurements. Our footprint estimations are, however,
2 more sensitive to the ocean regions between Australia and New Zealand as well as adjacent
3 coastal areas.

4 ***Oceanic sites: Ascension Island and La Réunion Island***

5 Ascension Island is in the Trade Wind belt of the tropical Atlantic, ideally located to
6 measure the South Atlantic marine boundary layer. The South East Trade Winds, which are
7 almost invariant and are derived from the deep South Atlantic Ocean with little contact with
8 Africa. Surface measurements of CO₂ at Ascension Island are used as a background (Gatti et al.,
9 2010). However, above the Trade Wind Inversion (TWI), at about 1200–2000 m above sea
10 level, the air masses are very different, coming dominantly from tropical Africa and
11 occasionally South America (Swap et al., 1996). The FLEXPART simulation with tracers
12 released at an altitude of 3000 m detected some hotspots in Africa (Fig. 1b). The study of
13 biomass burning in Africa is essential, but lies outside of the scope of this paper.

14 La Réunion island situated in the Indian Ocean at about 800 km east of Madagascar. For
15 this site the seasonal trend of wind mainly remains in the easterly sector, so the footprint
16 covers mainly ocean regions. La Réunion site is further discussed in Section 4.3.2.

17 **3.1.2. Past, future, and possible TCCON sites**

18 The footprints of past, future, and possible TCCON sites are presented in Fig. 3. The
19 Oxfordshire site enhances the sensitivity of the region, which is already well covered by
20 existing TCCON sites in Europe. The East Trout Lake, Four Corners, and Poker Flat sites fill
21 sensitivity gaps in the Canadian Boreal forest, the southwestern US, northern Mexico, and
22 Alaska. Nevertheless, there are no TCCON sites near the Atlantic coast of North America,
23 which is a key region of interest.

24 In South America, the Manaus site (briefly in operation during 2014 and will operate
25 after reconstruction) was ideally located in central Amazonia. However, meteorological
26 conditions meant that a signal was only detected in a very narrow section towards the east.
27 Observations at this site are more sensitive to anthropogenic activity on the Atlantic coast of
28 South America, compared with the surrounding Amazonian biosphere. Additional use of CO
29 observations will be necessary to isolate the Net Primary Production signal in Central
30 Amazonia (Keppel-Aleks et al., 2012). Another site in this region is Paramaribo located in
31 Suriname which is part of Caribbean South America. The footprint of the Paramaribo site is
32 narrowly focused towards the Atlantic Ocean due to site location and meteorological



1 conditions as stated above.

2 Burgos in the northern Philippines extends the Asian footprint southward. The location
3 of the Yekaterinburg site is ideal, as it quite evenly covers a large area of western Russia. The
4 site reduces the gap between the European and Asian TCCON domains. The Arrival Heights
5 site is located on the Antarctic coast and currently cannot be used for satellite data validation.
6 Given the air circulation near the South Pole, this site can be useful for measuring the
7 background value of XCO₂.

8 In general, the operational stations cover some regions well (North America, Europe, the
9 Far East, Southeast Asia, Australia, and New Zealand), and the planned sites will improve this
10 coverage. However, on a global scale there are major gaps that highlight the difficulty in
11 generalizing the available data along latitude for bias correction.

12 The short-term variations in CO₂ in the near surface and free troposphere (<3000 m)
13 have the same form, but different intensity (Fig. 1b), as a smaller number of tracers from the
14 middle troposphere reached the surface during the simulation time.

15 **3.2. Seasonal variability in footprints**

16 Some TCCON stations have strong seasonal variations in their footprint due to changes
17 in wind direction; i.e., Białystok, Darwin, Izaña, Park Falls, and Tsukuba (Fig. 4). For other
18 sites (e.g., Ascension and Manaus) the weather conditions are less variable throughout the
19 year. The depth of the PBL changes with season and is thus an important factor that influences
20 the footprint. In winter the PBL lowers, causing less vertical mixing and enhancing horizontal
21 tracer transport; this leads to a wider spatial coverage of the footprints.

22 **4. Applying the model-derived footprints to the colocation of XCO₂**

23 In the next two sections we assess the performance of the footprint-based method of
24 collocating TCCON XCO₂ against the NIES model and GOSAT product datasets. The colocation
25 domain size for each site is determined by sensitivity values (ppm (μmol (m²s)⁻¹)⁻¹) with the
26 limits of log₁₀(x) equal to -0.5, -1.0, -1.5, and -2.0 (cases C1-C4). These sensitivity values
27 were selected to approximately correspond to the domain sizes in standard geographical
28 colocation techniques, which have rectangular dimensions of 2.5° × 2.5°, ±5.0° × ±5.0°, ±5.0° ×
29 ±10.0°, and ±7.5° × ±22.5° (cases C5-C8). Only coincident observations were used, and
30 observations with differences of ≥3 ppm were discarded from the comparison. Considered
31 period for comparison is January 2010 and January 2014.



1 TCCON observations were used from 16 sites: Białystok, Caltech, Darwin, Eureka,
2 Garmisch, Izaña, Karlsruhe, Lamont, Lauder (125HR), Orléans, Park Falls, La Réunion Island,
3 Saga, Sodankylä, Tsukuba (125HR), and Wollongong. These observations were obtained from
4 the 2014 release of TCCON data ("GGG2014"), available from the TCCON Data Archive
5 (<http://tccon.ornl.gov>).

6 **4.1. Colocation of XCO₂ from TCCON and the NIES model**

7 The TCCON and NIES TM datasets are initially compared using a geographical colocation
8 of $2.5^\circ \times 2.5^\circ$ that corresponds to selecting the nearest NIES TM cell (Table 3). The resolution
9 of the model grid is rather coarse, so we observe that the results depend mainly on the size of
10 the colocation area but not on the form. With increasing size of the colocation area the
11 correlation between XCO₂ from TCCON and NIES TM slightly increases from 0.96 to 0.97 and
12 the standard deviation decreases from 1.1 to 0.96 ppm. This is due to an increase in the
13 number of observations, which results in a larger average bias.

14 For Darwin, Eureka, Izaña, Lauder, La Réunion, Sodankylä, and Wollongong, the
15 residuals between the datasets are small and similar for all methods (see Fig. 5a for Darwin;
16 cases C1, C4, C5, and C8). Here, XCO₂ is under the influence of global long-term variations that
17 are included in the NIES TM. The low sensitivity of the model to local sources does not cause a
18 significant difference between the colocation methods. For the second group (non-operational
19 sites), local sources are essential and even coarse-grid models can capture their signal. As a
20 result, the shape of the colocation area is important (see Fig. 5b for Garmisch; cases C1, C4, C5,
21 and C8).

22 **4.2. Colocation of XCO₂ from TCCON and GOSAT products**

23 A comparison of colocation methods was performed for five GOSAT XCO₂ products: NIES
24 v02.11 (Yoshida et al., 2013) and PPDF-S v02.11 from the NIES, Japan (Oshchepkov et al.,
25 2013); ACOS B3.4 from the NASA Atmospheric CO₂ Observations from Space (ACOS) team
26 (O'Dell et al., 2012); RemoTeC v2.11 from the Netherlands Institute for Space
27 Research/Karlsruhe Institute of Technology, Germany (Butz et al., 2011; Guerlet et al., 2013);
28 and UoL-FP v4 from the University of Leicester, UK (Boesch et al., 2011; Cogan et al., 2012).

29 The results of the comparison of eight colocation methods employed for the five GOSAT
30 XCO₂ products are presented in Tables 4–8. Only coincident observations were used, and
31 observations with differences of ≥ 3 ppm were discarded from the comparison. The number of
32 observations selected for colocation between the methods with the smallest areas (C1 and C5)



1 and largest areas (C4 and C8) differs by about 5 times. There is, however, no clear dependence
2 of the colocation efficiency on the number of observations. The correlation coefficient and
3 standard deviation are within 0.81–0.93 ppm and 1.02–1.22 ppm, respectively, regardless of
4 the method used. Mean bias values are within 0.50–0.87 ppm, with the footprint method
5 typically having a slightly lower bias by 0.02–0.15 ppm and higher number of colocations. For
6 individual stations, these statistics may lie slightly outside the specified ranges.

7 **4.3. Case study**

8 In this section we demonstrate the developed colocation method for GOSAT
9 observations over the Darwin and La Réunion Island TCCON sites.

10 **4.3.1. Darwin site**

11 Darwin lies in the Northern Territory, Australia, which has two distinctive climate zones.
12 The northern zone, including Darwin, has distinct wet and dry seasons and the average
13 maximum temperature is remarkably similar all year round. The dry season (May to
14 September), the build-up season (high humidity, but little rain: October to December) and the
15 wet season associated with tropical cyclones and monsoon rains (December to April). The
16 southern zone is mainly desert with a semi-arid climate and little rain. To the north of Darwin,
17 the territory is bordered by the Timor Sea, the Arafura Sea, and the Gulf of Carpentaria. The
18 Northern Territory therefore has a pronounced seasonal variability that affects the spatial and
19 temporal distribution of CO₂ and thus the footprint (Figs 4 and 6a).

20 Figures 6b and 6c show the locations of GOSAT observations selected using a
21 geographical method within an area of $\pm 7.5^\circ \times \pm 22.5^\circ$ and a footprint-based method with the
22 limit $\log_{10}(x) = -2.0$. Sizes of selected colocation areas (C4 and C8 methods) are close to ones
23 used in others works (Wunch et al., 2011, Guerlet et al., 2013, Inoue et al. 2013, Reuter et al.
24 2013, Nguyen et al., 2014).

25 For ACOS, NIES, and RemoTeC GOSAT products the distributions of XCO₂ datasets for the
26 Darwin site are similar and cover an area to the west of Darwin, including ground-based
27 observations from central Australia (Fig. 6c). The comparison of colocation methods shows
28 the footprint-based method (C4) outperforms the geographical method (C8) for these three
29 GOSAT products (Fig. 7), with approximately 3 times as many observations.

30 Although currently the UoL GOSAT XCO₂ version 6 includes ocean-glint observations, in
31 this study we use slightly outdated the UoL-FP GOSAT product v4, which has only overland



points. In this case the difference between colocations subsets is the observations towards the south over land, which provide a similar distribution as the ACOS product, but without marine observations (Fig. 6b and Fig. 6c). These differences in the covered areas have a significant negative effect on the result (Fig. 7). From that it can be concluded that XCO₂ patterns towards the south over land are rather different from those around Darwin, the sun-glint observation over the ocean are important and must be included into analysis. Thus, XCO₂ at the Darwin site is under the influence of the three different fluxes coming from surrounding land area, central part of Australia and oceanic regions. The oceanic observation over the Coral sea is quite important, though substantially removed from the station.

4.3.2. *La Réunion site*

La Réunion is a small island east of Madagascar surrounded by the Indian Ocean. The nearest land territory to La Réunion is Mauritius, located ~175 km to the northwest. The meteorological conditions in the region mean that the footprint of the La Réunion site mostly covers a large area of ocean to the southeast of the island and a small area of northern Madagascar (Fig. 8).

The geographical colocation method does not take into account local conditions. Therefore, despite the fact that the site is predominantly oceanic, the geographical method includes observations made over land in Madagascar and the southeast coast of Africa (Fig. 8b). In contrast, the footprint method takes into account the local meteorology, so observations are predominantly taken from the ocean (Fig. 8c). Since the UoL-FP dataset has no observations over the sea, the observations for this dataset are located only over Madagascar (Fig. 9).

Unlike Darwin, La Réunion receives clean air from the ocean and thus has very little CO₂ variation. The selection of areas for colocation therefore did not reveal any significant advantages of the footprint-based method, with the exception of a slightly smaller bias for the NIES and RemoTec products (Fig. 10). The comparison of the UoL-FP product for method C4 and method C8 shows that the XCO₂ cycles over Madagascar and the eastern coast of Africa are quite different (Fig. 10). This highlights that the exclusion of marine observations leads to poor results over marine-based TCCON sites.

A comparison of TCCON data and NIES model results for Darwin and La Réunion shows that XCO₂ for these sites is controlled mainly by large-scale changes. However, analysis of GOSAT products emphasizes that the influence of local sources is also important. The



1 geographical method of colocation assumes a fairly even distribution of GOSAT observations
2 near TCCON sites, while the calculated footprints have strongly curved shapes and an uneven
3 distribution. We therefore expect the proposed footprint method to be useful for other sites
4 with rather curved and non-uniform footprints, such as the Ascension Island and Manaus
5 sites.

6 **5. Summary**

7 We have developed a method for assessing the footprints of short-term XCO₂ variations
8 observed by TCCON ground-based FTS sites. The method is based on one-week FLEXPART
9 backward trajectory simulations that are initiated at an altitude of 1 km (the upper border of
10 the PBL) in the afternoon using the vertical CO₂ distribution calculated by the NIES transport
11 model.

12 We applied this method to estimate footprints of the operational, past, future, and
13 possible TCCON sites, and revealed some basic patterns. Most sites located near coastal
14 regions are strongly influenced by ocean regions; thus, there is a large seasonal variability in
15 footprints for Białystok, Darwin, Izaña, Park Falls, and Tsukuba. The Ascension Island,
16 Manaus, and La Réunion sites have very narrow footprints that show small seasonal
17 variations.

18 We proposed the footprint-based method for the colocation of satellite observations
19 with TCCON sites, and assessed the performance of the method using the NIES model and
20 GOSAT product datasets. The colocation footprint area is determined by yearly averaged
21 sensitivity values with limits of $\log_{10}(x)$ equals -0.5 , -1.0 , -1.5 and -2.0 . These were selected
22 to approximately correspond to the areas of standard geographical colocation techniques that
23 have rectangular shapes of $2.5^\circ \times 2.5^\circ$, $\pm 5.0^\circ \times \pm 5.0^\circ$, $\pm 5.0^\circ \times \pm 10.0^\circ$, and $\pm 7.5^\circ \times \pm 22.5^\circ$,
24 respectively. Comparison of the proposed method with the geographical method showed
25 similar but smaller biases for a subset of 16 stations for the period from January 2009 to
26 January 2014. Case studies of the Darwin and La Réunion TCCON sites revealed that the
27 footprint has a very different colocation area to that of the geographical method, especially
28 near marine coast.

29 This study shows the use of colocation methods similar to geographical, which are based
30 on tracking long-term trends of tracers (i.e. derived from global model calculations) has its
31 limitations and works up to a certain accuracy threshold, after which it is impossible to ignore
32 the influence of local sources. Given that the GOSAT XCO₂ products are sensitive to local



1 sources, proposed footprint method is promising and requires further fine-tuning. The
2 potential for further improvement includes moving from gross annual averaging to more
3 accurate seasonal or monthly averaging. In addition, it is possible to study the sensitivity of
4 XCO₂ observations using adjoint of the global Eulerian–Lagrangian coupled atmospheric
5 transport model (Belikov et al., 2016), which can resolve long-term, synoptic and hourly
6 variation patterns.

7 We believe, however, that the footprint analysis should be considered important in the
8 appraisal of new TCCON sites, along with assessments of the number of cloudless days, the
9 surrounding landscape, and the reflectivity of the Earth’s surface.



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22



1 **Table 1.** Details of operational TCCON sites.

Number	Site	Latitude (Degrees)	Longitude (Degrees)	Altitude (km)
1	Anmyeondo, Korea	36.54	126.33	0.03
2	Ascension Island	7.92	-14.33	0.03
3	Białystok, Poland	53.23	23.03	0.18
4	Bremen, Germany	53.10	8.85	0.03
5	Caltech, USA	34.14	-118.13	0.23
6	Darwin, Australia	-12.42	130.89	0.03
7	Edwards, USA	34.96	-117.88	0.70
8	Eureka, Canada	80.05	-86.42	0.61
9	Garmisch, Germany	47.48	11.06	0.74
10	Izaña, Tenerife	28.30	-16.50	2.37
11	Karlsruhe, Germany	49.10	8.44	0.12
12	Lamont, USA	36.60	-97.49	0.32
13	Lauder, New Zealand	-45.04	169.68	0.37
14	Ny Ålesund, Spitsbergen	78.90	11.90	0.02
15	Orléans, France	47.97	2.11	0.13
16	Park Falls, USA	45.95	-90.27	0.44
17	Paris, France	48.85	2.32	0.10
18	La Réunion Island, France	-20.90	55.49	0.09
19	Rikubetsu, Japan	43.46	143.77	0.36
20	Saga, Japan	33.24	130.29	0.01
21	Sodankylä, Finland	67.37	26.63	0.19
22	Tsukuba, Japan	36.05	140.12	0.03
23	Wollongong, Australia	-34.41	150.88	0.03

2

3 **Table 2.** Past, future, and possible TCCON sites.

Number	Site	Latitude (Degrees)	Longitude (Degrees)	Altitude (km)
1	Arrival Heights, Antarctica	-77.83	166.66	0.25
2	Burgos, Philippines	18.50	120.85	0.10
3	East Trout Lake, Canada	54.35	-104.98	0.49
4	Four Corners, USA	36.80	-108.48	1.64
5	Manaus, Brazil	-3.10	-60.02	0.09
6	Oxfordshire, UK	51.57	-1.32	0.07
7	Paramaribo, Suriname	5.80	-55.20	0.05
8	Poker Flat, USA	65.12	-147.47	0.21
9	Yekaterinburg, Russia	57.04	59.55	0.30

4



Table 3. Averaged results of different collocation methods implemented for XCO₂ from NIES TM calculated for 16 TCCON sites. *The number of FLEXPART cells with resolution 1.0° × 1.0° is counted for methods based on the footprint (1–4), while for other methods NIES TM cells (2.5° × 2.5°) are used.

Case	Method of collocation	Mean number of cells*	Mean correlation coefficient	Absolute value of mean bias	Mean standard deviation
C1	Footprint limit $\log_{10}(x) = -0.5$	35	0.96	0.75	1.01
C2	Footprint limit $\log_{10}(x) = -1.0$	160	0.96	0.81	0.98
C3	Footprint limit $\log_{10}(x) = -1.5$	507	0.97	0.85	0.97
C4	Footprint limit $\log_{10}(x) = -2.0$	1071	0.97	0.88	0.96
C5	Within area of 2.5° × 2.5°	1	0.96	0.76	1.03
C6	Within area of ±5.0° × ±5.0°	16	0.96	0.79	1.00
C7	Within area of ±5.0° × ±10.0°	32	0.96	0.79	0.98
C8	Within area of ±7.5° × ±22.5°	108	0.97	0.80	0.97

Table 4. Averaged results of different collocation methods implemented for XCO₂ from the GOSAT ACOS product calculated for 16 TCCON sites.

Case	Method of collocation	Mean number of observations	Mean correlation coefficient	Absolute value of mean bias	Mean standard deviation
C1	Footprint limit $\log_{10}(x) = -0.5$	1190	0.93	0.65	1.18
C2	Footprint limit $\log_{10}(x) = -1.0$	3046	0.92	0.61	1.21
C3	Footprint limit $\log_{10}(x) = -1.5$	4880	0.93	0.62	1.15
C4	Footprint limit $\log_{10}(x) = -2.0$	6016	0.93	0.64	1.12
C5	Within area of 2.5° × 2.5°	976	0.93	0.81	1.11
C6	Within area of ±5.0° × ±5.0°	2042	0.92	0.67	1.19
C7	Within area of ±5.0° × ±10.0°	3111	0.92	0.65	1.19
C8	Within area of ±7.5° × ±22.5°	5002	0.93	0.64	1.16



Table 5. Averaged results of different colocation methods implemented for XCO₂ from the GOSAT NIES product calculated for 16 TCCON sites.

Case	Method of colocation	Mean number of observations	Mean correlation coefficient	Absolute value of mean bias	Mean standard deviation
C1	Footprint limit $\log_{10}(x) = -0.5$	1049	0.89	0.63	1.14
C2	Footprint limit $\log_{10}(x) = -1.0$	2890	0.92	0.52	1.20
C3	Footprint limit $\log_{10}(x) = -1.5$	4823	0.92	0.60	1.19
C4	Footprint limit $\log_{10}(x) = -2.0$	5922	0.92	0.56	1.16
C5	Within area of $2.5^\circ \times 2.5^\circ$	907	0.89	0.63	1.17
C6	Within area of $\pm 5.0^\circ \times \pm 5.0^\circ$	1845	0.91	0.56	1.15
C7	Within area of $\pm 5.0^\circ \times \pm 10.0^\circ$	2976	0.93	0.58	1.15
C8	Within area of $\pm 7.5^\circ \times \pm 22.5^\circ$	4874	0.92	0.60	1.17

Table 6. Averaged results of different colocation methods implemented for XCO₂ from the GOSAT PPDF product calculated for 16 TCCON sites.

Case	Method of colocation	Mean number of observations	Mean correlation coefficient	Absolute value of mean bias	Mean standard deviation
C1	Footprint limit $\log_{10}(x) = -0.5$	357	0.84	0.50	1.11
C2	Footprint limit $\log_{10}(x) = -1.0$	870	0.86	0.62	1.12
C3	Footprint limit $\log_{10}(x) = -1.5$	1536	0.81	0.73	1.16
C4	Footprint limit $\log_{10}(x) = -2.0$	1911	0.81	0.67	1.17
C5	Within area of $2.5^\circ \times 2.5^\circ$	331	0.86	0.66	1.02
C6	Within area of $\pm 5.0^\circ \times \pm 5.0^\circ$	749	0.85	0.64	1.15
C7	Within area of $\pm 5.0^\circ \times \pm 10.0^\circ$	1114	0.83	0.69	1.19
C8	Within area of $\pm 7.5^\circ \times \pm 22.5^\circ$	1733	0.86	0.68	1.17

Table 7. Averaged results of different colocation methods implemented for XCO₂ from the GOSAT RemoTeC product calculated for 16 TCCON sites.

Case	Method of colocation	Mean number of observations	Mean correlation coefficient	Absolute value of mean bias	Mean standard deviation
C1	Footprint limit $\log_{10}(x) = -0.5$	795	0.81	0.71	1.17
C2	Footprint limit $\log_{10}(x) = -1.0$	1898	0.83	0.66	1.19
C3	Footprint limit $\log_{10}(x) = -1.5$	3212	0.83	0.61	1.22
C4	Footprint limit $\log_{10}(x) = -2.0$	4091	0.83	0.59	1.21
C5	Within area of $2.5^\circ \times 2.5^\circ$	769	0.90	0.87	1.15
C6	Within area of $\pm 5.0^\circ \times \pm 5.0^\circ$	1491	0.85	0.63	1.18
C7	Within area of $\pm 5.0^\circ \times \pm 10.0^\circ$	2325	0.86	0.70	1.19
C8	Within area of $\pm 7.5^\circ \times \pm 22.5^\circ$	3818	0.86	0.64	1.25



Table 8. Averaged results of different colocation methods implemented for XCO₂ from the GOSAT UoL-FP product calculated for 16 TCCON sites.

Case	Method of colocation	Mean number of observations	Mean correlation coefficient	Absolute value of mean bias	Mean standard deviation
C1	Footprint limit $\log_{10}(x) = -0.5$	634	0.88	0.78	1.31
C2	Footprint limit $\log_{10}(x) = -1.0$	1454	0.87	0.76	1.34
C3	Footprint limit $\log_{10}(x) = -1.5$	2450	0.88	0.80	1.28
C4	Footprint limit $\log_{10}(x) = -2.0$	3017	0.89	0.70	1.23
C5	Within area of $2.5^\circ \times 2.5^\circ$	629	0.86	0.73	1.33
C6	Within area of $\pm 5.0^\circ \times \pm 5.0^\circ$	1215	0.88	0.76	1.30
C7	Within area of $\pm 5.0^\circ \times \pm 10.0^\circ$	1852	0.86	0.74	1.27
C8	Within area of $\pm 7.5^\circ \times \pm 22.5^\circ$	2799	0.85	0.72	1.25

Table 9. Comparison of colocation methods C4 versus C8 using ACOS, NIES, PPDF, RemoTeC, and UoL GOSAT products near the Darwin site.

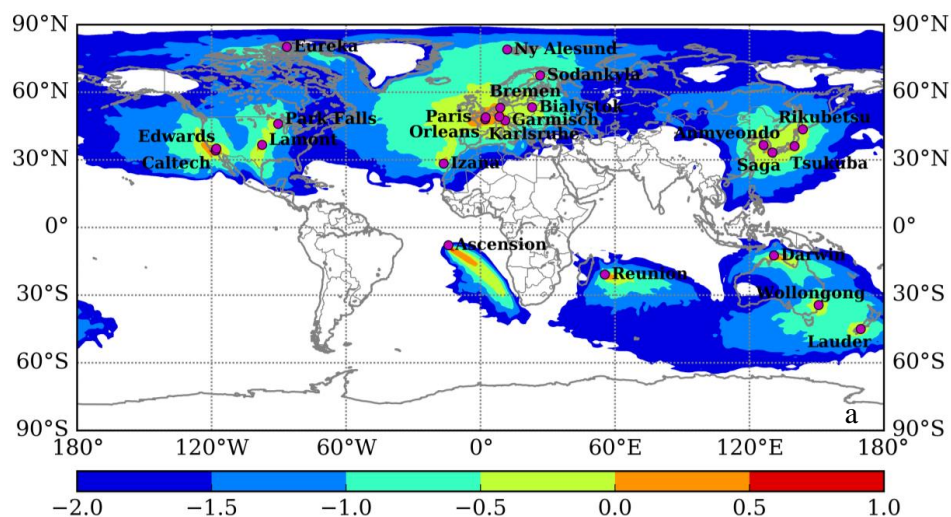
GOSAT Product	Case	Correlation coefficient	Mean bias	Standard deviation	Number of observations
ACOS	C4	0.96	0.36	0.77	36292
	C8	0.94	0.50	0.90	10872
NIES	C4	0.94	0.09	0.88	26652
	C8	0.93	0.13	1.00	6924
PPDF	C4	0.70	0.24	1.02	13681
	C8	0.64	0.08	1.10	4333
RemoTeC	C4	0.91	0.44	0.95	23915
	C8	0.89	0.77	1.07	7130
UoL	C4	0.82	0.34	1.17	14376
	C8	0.86	0.17	1.10	4727

Table 10. Comparison of colocation methods C4 versus C8 using ACOS, NIES, RemoTeC, and UoL GOSAT products near the La Réunion site. The PPDF GOSAT product does not include any observations near the La Réunion site.

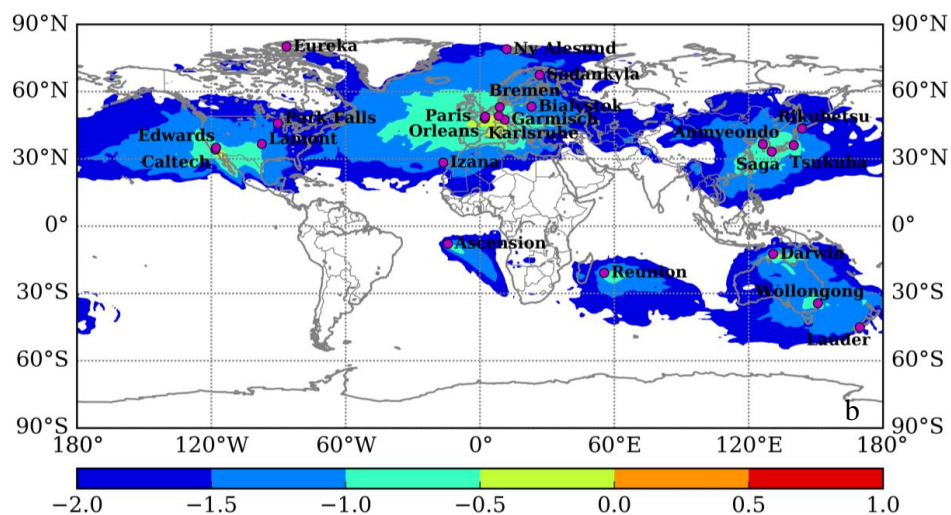
GOSAT Product	Case	Correlation coefficient	Mean bias	Standard deviation	Number of observations
ACOS	C4	0.82	0.70	0.83	11873
	C8	0.83	0.65	0.76	9640
NIES	C4	0.70	0.25	1.07	7720
	C8	0.73	0.45	1.02	6505
RemoTeC	C4	0.51	0.92	1.07	2482
	C8	0.61	1.16	1.04	3414
UoL	C4	0.45	0.75	0.94	860
	C8	0.36	0.71	1.00	2239



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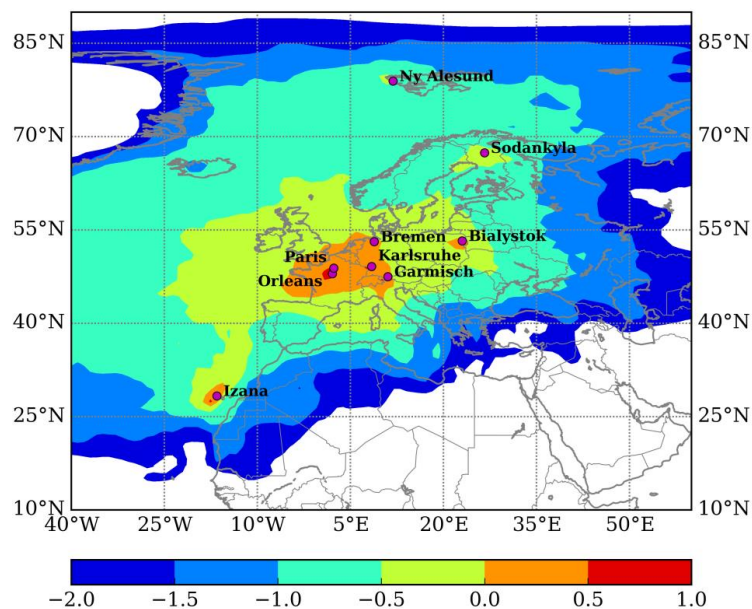
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3

4 **Fig. 1.** Global distribution of the sensitivity of CO₂ concentrations (ppm (μmol (m²s)⁻¹)⁻¹) with
 5 respect to the concentrations in adjacent cells, calculated using the FLEXPART model with a
 6 resolution of 1.0° for the 23 TCCON operational sites: a) tracer simulation initialized at the
 7 level of 1000 m, b) tracer simulation initialized at the level of 3000 m that corresponds to
 8 700 hPa based on the International Standard Atmosphere for dry air.

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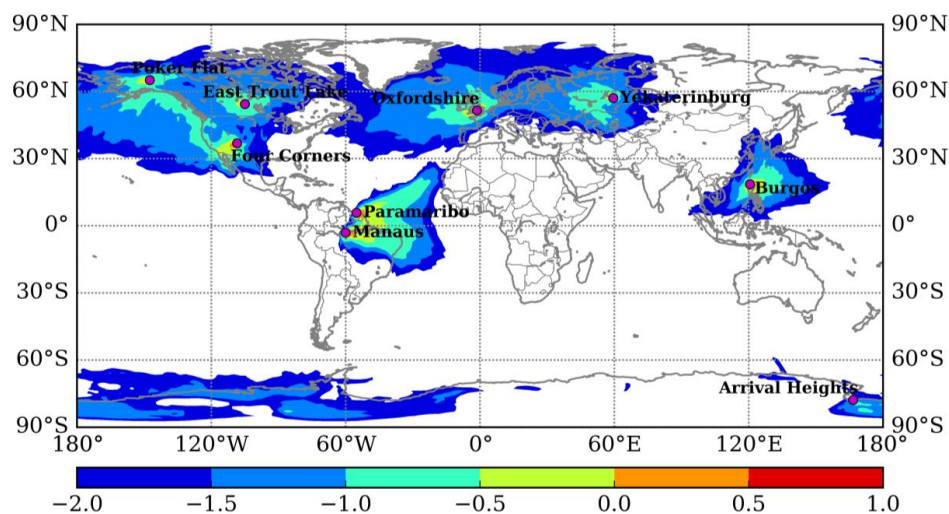


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2 **Fig. 2.** Distribution of the sensitivity of CO₂ concentrations (ppm (μmol (m²s)⁻¹)⁻¹) in Europe with
 3 respect to the concentrations in adjacent cells, calculated using the FLEXPART model with a
 4 resolution of 1.0° for TCCON operational sites within Europe, using a tracer simulation
 5 initialized at the level of 1000 m.
 6



1



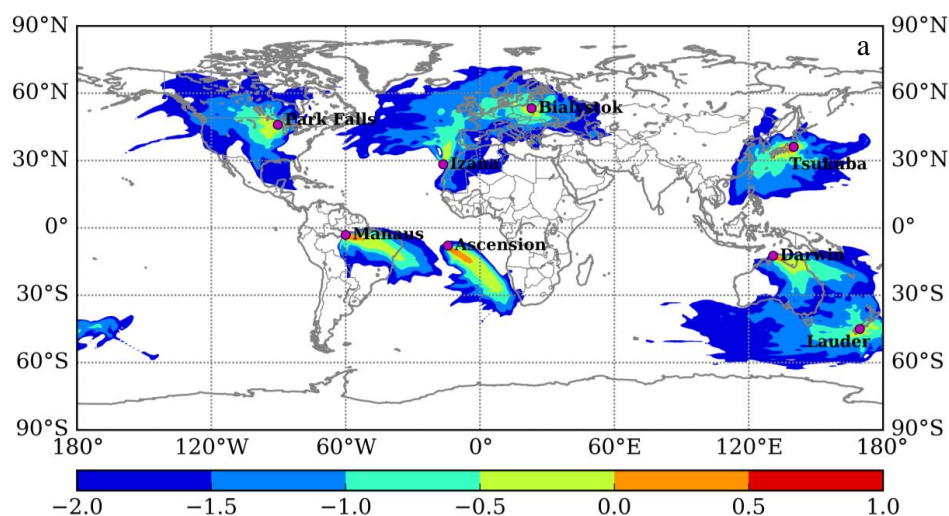
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3 **Fig. 3.** Global distribution of the sensitivity of CO₂ concentrations (ppm (μmol (m²s)⁻¹)⁻¹) with
 4 respect to the concentrations in adjacent cells, calculated using the FLEXPART model with a
 5 resolution of 1.0° for 9 past, future, and possible TCCON operational sites, using a tracer
 6 simulation initialized at the level of 1000 m.

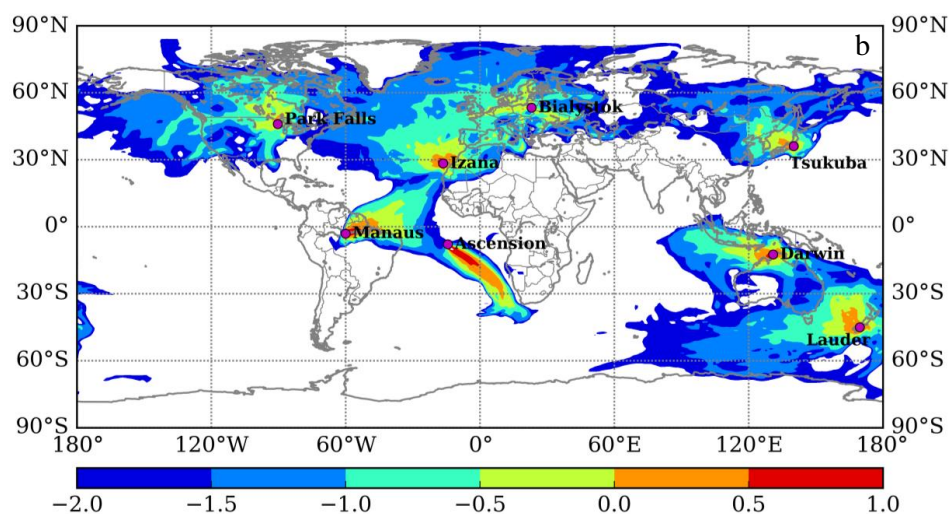
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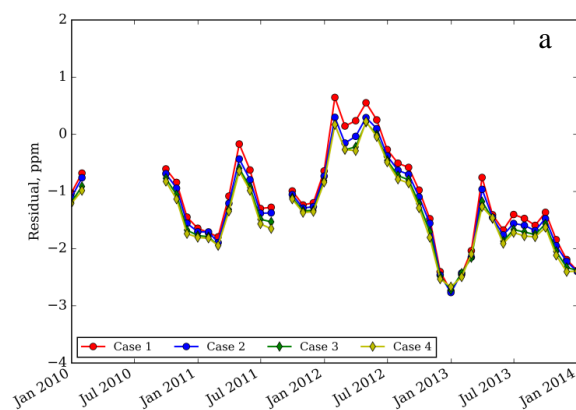
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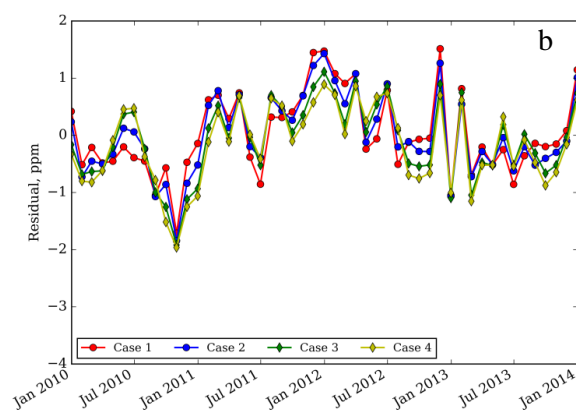
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4 **Fig. 4.** Footprints for different seasons for Ascension Island, Białystok, Darwin, Izaña, Manaus,
 5 Park Falls, and Tsukuba, for a) the summer (June, July, and August) of 2010 and b) the
 6 winter (December, January, February) of 2010–2011.
 7



1



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Fig. 5. Monthly average residuals of modeled XCO_2 compared with TCCON ground-based FTS for methods C1, C4, C5 and C8, for a) Darwin and b) Garmisch.

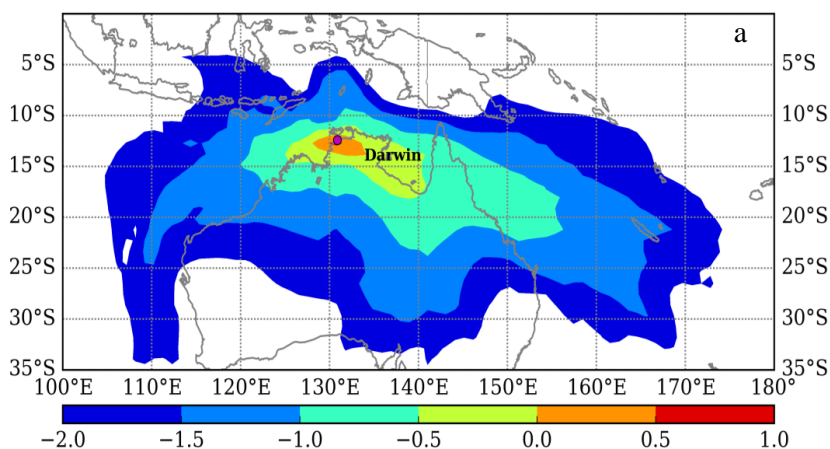
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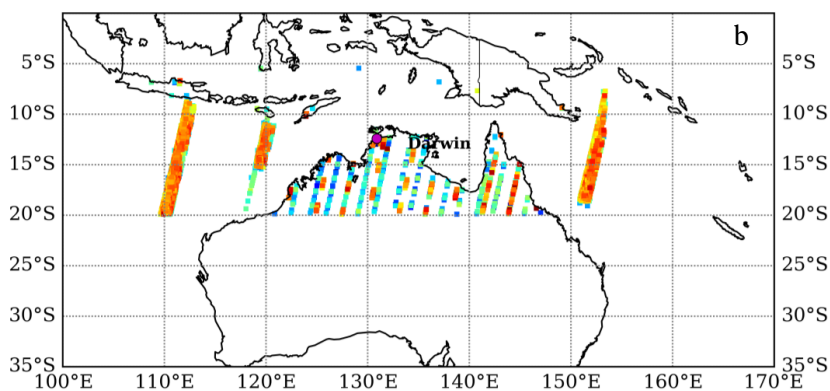
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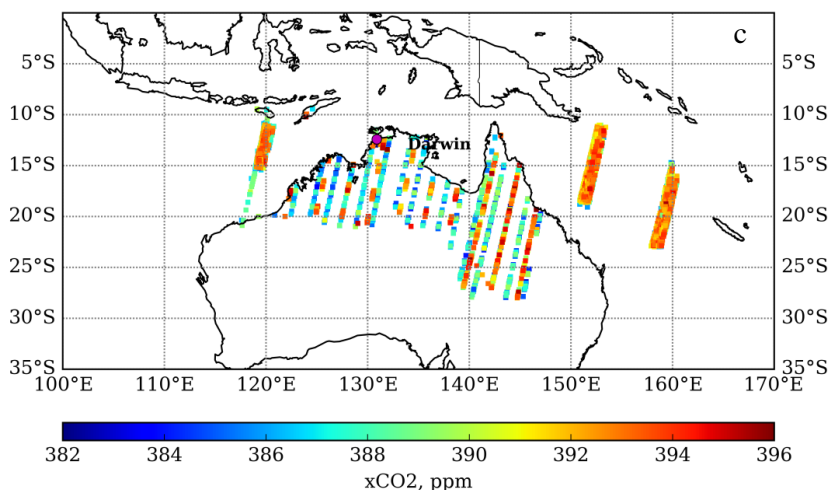
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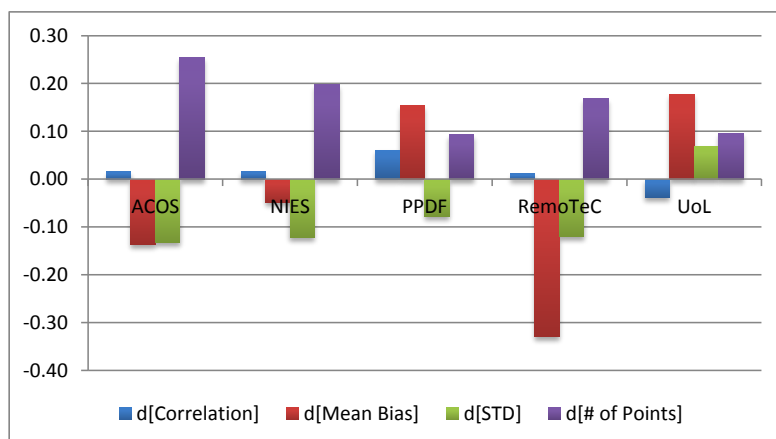
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5 **Fig. 6.** a) Annual average footprint for the Darwin TCCON observation site; ACOS GOSAT XCO₂
 6 observations selected using b) the geostatistical method within an area of $\pm 7.5^\circ \times \pm 22.5^\circ$,
 7 and c) the footprint-based method with the limit $\log_{10}(x) = -2.0$.
 8



1
 2 **Fig. 7.** Difference (denoted as d[]) in correlation coefficients, mean bias (ppm), STD (ppm) and
 3 number of observational points between methods C4 and C8 using ACOS, NIES, PPDF,
 4 RemoTeC, and UoL GOSAT products near the Darwin site. Please note scale of number of
 5 observational points is 10^5 .
 6

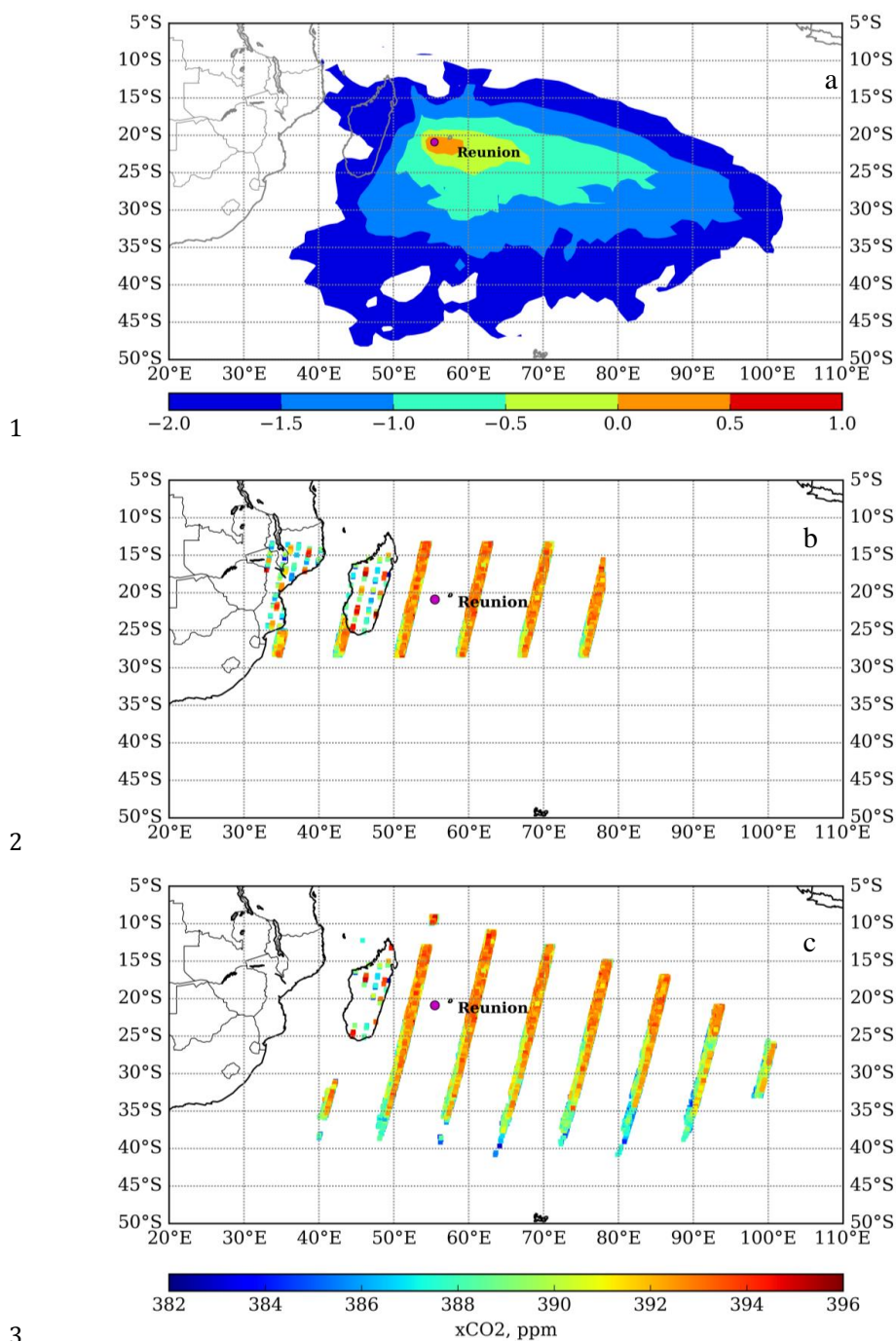
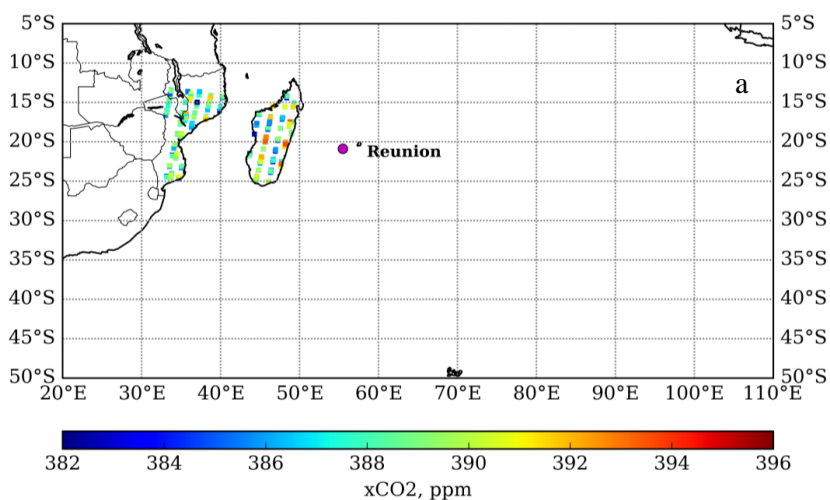


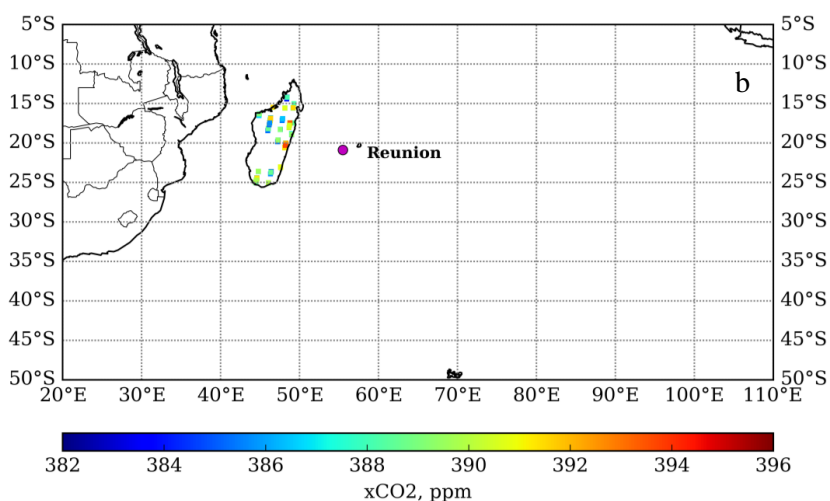
Fig. 8. a) Annual average footprint for the La Réunion TCCON observation site; ACOS GOSAT XCO₂ observations selected using b) the geostatistical method within an area of $\pm 7.5^\circ \times \pm 22.5^\circ$, and c) the footprint-based method with the limit $\log_{10}(x) = -2.0$.



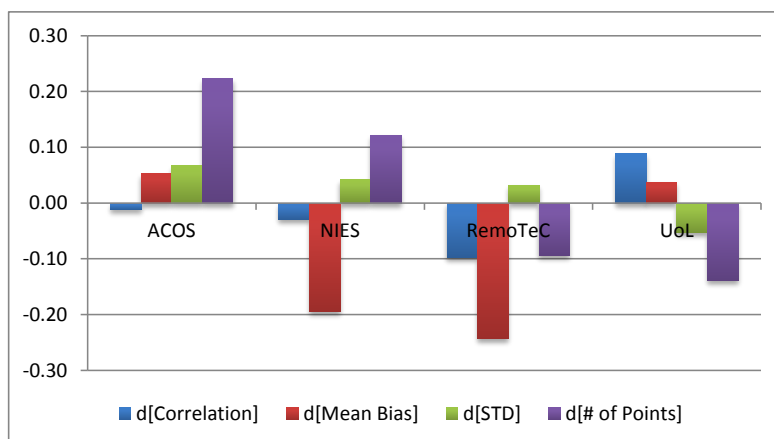
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2



3 **Fig. 9.** UoL-FP GOSAT XCO₂ observations selected using a) the geostatistical method within an
 4 area of $\pm 7.5^\circ \times \pm 22.5^\circ$, and b) the footprint-based method with the limit $\log_{10}(x) = -2.0$.
 5



1

2 **Fig. 10.** Difference (denoted as d[]) in correlation coefficients, mean bias (ppm), STD (ppm)
 3 and number of observational points between methods C4 and C8 using ACOS, NIES,
 4 RemoTeC, and UoL GOSAT products near the La Réunion site. Please note scale of number
 5 of observational points is 10^4 .
 6