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Consistent evaluation of GOSAT, SCIAMACHY, CarbonTracker, and MACC through comparisons to TCCON

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Abstract

Consistent validation of satellite CO₂ estimates is a prerequisite for using multiple satellite CO₂ measurements for joint flux inversion, and for establishing an accurate long-term atmospheric CO₂ data record. We focus on validating model and satellite observation attributes that impact flux estimates and CO₂ assimilation, including accurate error estimates, correlated and random errors, overall biases, biases by season and latitude, the impact of coincidence criteria, validation of seasonal cycle phase and amplitude, yearly growth, and daily variability. We evaluate dry air mole fraction (X_{CO_2}) for GOSAT (ACOS b3.5) and SCIAMACHY (BESD v2.00.08) as well as the CarbonTracker (CT2013b) simulated CO₂ mole fraction fields and the MACC CO₂ inversion system (v13.1) and compare these to TCCON observations (GGG2014). We find standard deviations of 0.9 ppm, 0.9, 1.7, and 2.1 ppm versus TCCON for CT2013b, MACC, GOSAT, and SCIAMACHY, respectively, with the single target errors 1.9 and 0.9 times the predicted errors for GOSAT and SCIAMACHY, respectively. When satellite data are averaged and interpreted according to $\text{error}^2 = a^2 + b^2/n$ (where n are the number of observations averaged, a are the systematic (correlated) errors, and b are the random (uncorrelated) errors), we find that the correlated error term $a = 0.6$ ppm and the uncorrelated error term $b = 1.7$ ppm for GOSAT and $a = 1.0$ ppm, $b = 1.4$ ppm for SCIAMACHY regional averages. Biases at individual stations have year-to-year variability of ~ 0.3 ppm, with biases larger than the TCCON predicted bias uncertainty of 0.4 ppm at many stations. Using fitting software, we find that GOSAT underpredicts the seasonal cycle amplitude in the Northern Hemisphere (NH) between 46–53° N. In the Southern Hemisphere (SH), CT2013b underestimates the seasonal cycle amplitude. Biases are calculated for 3-month intervals and indicate the months that contribute to the observed amplitude differences. The seasonal cycle phase indicates whether a dataset or model lags another dataset in time. We calculate this at a subset of stations where there is adequate satellite data, and find that the GOSAT retrieved phase improves substantially over the prior and the SCIAMACHY retrieved phase improves substantially for

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2 of 7 sites. The models reproduce the measured seasonal cycle phase well except for at Lauder125 (CT2013b), Darwin (MACC), and Izana (+ 10 days, CT2013b), as for Bremen and Four Corners, which are highly influenced by local effects. We compare the variability within one day between TCCON and models in JJA; there is correlation
 5 between 0.2 and 0.8 in the NH, with models showing 10–100 % the variability of TCCON at different stations (except Bremen and Four Corners which have no variability compared to TCCON) and CT2013b showing more variability than MACC. This paper highlights findings that provide inputs to estimate flux errors in model assimilations, and places where models and satellites need further investigation, e.g. the SH for models
 10 and 45–67° N for GOSAT.

1 Introduction

Carbon-climate feedbacks are a major uncertainty in predicting the climate response to anthropogenic forcing (Friedlingstein et al., 2006). Currently, about 9 Gigatons (Gt) of carbon are emitted per year from human activity (e.g. fossil fuel burning, deforestation), of which about 5 Gt stays in the atmosphere, causing an annual CO₂ increase of approximately 2 ppm yr⁻¹. The yearly increase is quite variable, estimated at 1.99 ± 0.43 ppm yr⁻¹ (<http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html>), however always positive (Houghton et al., 2007). The remaining 4Gt of carbon is taken up by the ocean and the terrestrial biosphere, however there are uncertainties in the location and mechanism of these sinks, e.g. the distribution of land sinks between the Northern Hemisphere and the tropics (e.g. Stephens et al., 2007), and the localization of sources and sinks on regional scales (Canadell et al., 2011; Baker et al., 2006). The uncertainties in top-down source and sink estimates are a consequence of uncertainties in model transport and dynamics (e.g. Prather et al., 2008; Stephens et al., 2007) and sparseness of available surface-based CO₂ observations (Hungershoefer et al., 2010; Chevallier et al., 2010). Satellites offer a much denser and spatially contiguous
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dataset for top-down estimates, but are much more susceptible to biases as compared to ground-based measurements (e.g. see summary in Sect. 3.3.2 of Ciais et al., 2014).

This paper tests different characteristics of model and satellite CO₂ (e.g. seasonal cycle amplitude and phase, regional and seasonal biases, effects of averaging, and diurnal variations) through a series of specialized comparisons to the Total Carbon Column Observing Network (TCCON). The findings from this work can be propagated into assimilation systems to determine the influence of various findings on top-down flux estimates (e.g. see Miller et al., 2007; Deng et al., 2013; Chevallier and O'Dell, 2013; Chevallier et al., 2014). For example, this paper characterizes biases by latitude and season; these biases can be assimilated to determine their effects on flux estimates (e.g. Kulawik et al., 2013). These findings also apply to bottom-up flux estimates, for example, updates should be made in inventories or transport to correct the model fields at the TCCON stations showing seasonal cycle phase differences.

2 Data and models used

The characteristics of the sets of carbon dioxide that will be compared to TCCON are summarized in Table 1. The following sections contain detailed descriptions of the dataset versions and characteristics.

2.1 GOSAT CO₂

The Greenhouse gases Observing SATellite (GOSAT) takes measurements of reflected sunlight in three short-wave bands with a footprint of approximately 10.5 km at nadir (Yokota et al., 2009; Crisp et al, 2012). The first useable science measurements were made in April 2009, but due to changing observational modes in the early months, we use data beginning in July 2009. In this work, we use column averaged dry air mole fraction (X_{CO₂}) retrievals produced by NASA's Atmospheric CO₂ Observations from Space (ACOS) project, version 3.5 (see O'Dell et al., 2012, for retrieval details).

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For each sounding, the retrieval produces an estimate of X_{CO_2} , the vertical sensitivity of the measurement (i.e., the averaging kernel), and the posterior uncertainty in X_{CO_2} . It also produces a number of other retrieval variables, such as surface pressure and aerosols, which are used in both filtering and bias-correction. Post-retrieval filter is employed based on a number of variables associated with the retrieval. In addition to filtering, a revised bias-correction scheme has been developed for the v3.5 retrievals. This scheme is similar to the approach described in Wunch et al. (2011), which characterized the errors in earlier versions of the ACOS retrieval using a simple spatial uniformity assumption of X_{CO_2} in the Southern Hemisphere (sometimes referred to as the “Southern Hemisphere Approximation”) to assess errors and biases in the retrievals. V3.5 has corrections of GOSAT High (H) and Medium (M) gain data over land, as well as glint-mode data over the ocean, by using not only the “Southern Hemisphere Approximation”, but also TCCON observations, and comparisons to an ensemble mean of multiple transport model output. Details of the post-retrieval filter and the bias-correction scheme can be found in the ACOS v3.5 user’s guide which will soon be at <https://co2.jpl.nasa.gov/>.

2.2 SCIAMACHY CO₂

The following description of the SCanning Imaging Absorption SpectroMeter for Atmospheric Chartography (SCIAMACHY) CO₂ retrieval algorithm summarizes important aspects of Reuter et al. (2010, 2011) and is adopted in parts from the algorithm theoretical basis document (Reuter et al., 2012b).

The Bremen Optimal Estimation DOAS (BESD) algorithm is designed to analyze SCIAMACHY sun normalized radiance measurements to retrieve the column-average dry-air mole fraction of atmospheric carbon dioxide (X_{CO_2}). BESD is a so-called full physics algorithm, which uses measurements in the O₂-A absorption band to retrieve scattering information of clouds and aerosols. This information is transferred to the CO₂ absorption band at 1580nm by simultaneously fitting the spectra measured in both spectral regions. Similar to the ACOS three-band retrieval for GOSAT, the explicit

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Tracker uses the Transport Model 5 (TM5) offline atmospheric tracer transport model (Krol et al., 2005) driven by meteorology from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational forecast model and from the ERA-interim re-analysis (Dee et al., 2011) to propagate surface emissions. TM5 runs at a global $3^\circ \times 2^\circ$ resolution and at a $1^\circ \times 1^\circ$ resolution over North American. CarbonTracker separately propagates signals from fossil fuel emissions, air-sea CO_2 exchange, and terrestrial fluxes from wildfire emissions and non-fire net ecosystem exchange. Similar to other existing CO_2 inverse models, oceanic and terrestrial biosphere surface fluxes are optimized to agree with atmospheric CO_2 observations, while fossil fuel and wildfire emissions are specified. First-guess fluxes from terrestrial biosphere models and surface ocean carbon analyses are modified by applying weekly multiplicative scaling factors estimated for 126 land and 30 ocean regions using an ensemble Kalman filter optimization method. The CT2013b release of CarbonTracker assimilates in situ observations between 2000 and 2012 from 103 datasets around the world, including time series from NOAA observatories, tall towers, and flasks sampled by the NOAA Cooperative Air Sampling Network, and flask and continuous measurements from partners including Environment Canada, the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO), the National Center for Atmospheric Research (NCAR), the Lawrence Berkeley National Laboratory, and the Brazilian Instituto de Pesquisas Energéticas e Nucleares.

In order to explicitly quantify the impact of transport uncertainty and prior flux model bias on inverse flux estimates from CarbonTracker, the CT2013b release is composed of a suite of inversions, each using a different combination of prior flux models and parent meteorological model. Sixteen independent inversions were conducted, using two terrestrial biosphere flux priors, two air-sea CO_2 exchange flux priors, two estimates of imposed fossil fuel emissions, and two transport estimates in a factorial design. CT2013b results are presented as the performance-weighted mean of the inversion suite, with uncertainties including a component of across-model differences.

All CarbonTracker results and complete documentation can be accessed online at <http://carbontracker.noaa.gov>.

For model-data comparisons at selected sites, CT2013b is sampled at 90-minute intervals on the model's native vertical grid of 34 levels. Quantities are laterally interpolated from grid points to the location of the site using the sub-grid tracer distribution model of the Russel and Lerner (1981) advection scheme. This "column" output includes CO₂ tracers and meteorological conditions, and is available online at <ftp://aftp.cmdl.noaa.gov/products/carbontracker/co2/CT2013/column/>.

2.5 MACC

Monitoring Atmospheric Composition and Climate (MACC, <http://www.gmes-atmosphere.eu/>) is the European Union-funded project responsible for the development of the pre-operational Copernicus atmosphere monitoring service. MACC monitors the global distributions of greenhouse gases, aerosols, and reactive gases, and estimates some of their sources and sinks. Since 2010, it has been delivering every year an analysis of the carbon dioxide in the atmosphere and of its surface fluxes, based on the assimilation of air sample mole fraction measurements (Chevallier et al., 2010). It relies on a variational inversion formulation, developed by LSCE, that estimates 8-day grid-point daytime/nighttime CO₂ fluxes and the grid point total columns of CO₂ at the initial time step of the inversion window. The Bayesian error statistics of the estimate are computed by a robust randomization approach. The MACC inversion scheme relies on the global tracer transport model LMDZ (Hourdin et al., 2006), driven by the wind analyses from the ECMWF. For release v13.1 of the MACC inversion, used here, LMDZ was run at a horizontal resolution 3.75° longitude × 1.9° latitude with 39 vertical layers. The other elements of the inversion configuration follow Chevallier et al. (2011), with climatological (i.e. not interannually-varying) terrestrial and ocean prior fluxes and interannually-varying fossil-fuel and biomass-burning emissions. The variational formulation of the inversion allowed the 1979–2013 period to be processed in a single assimilation window, therefore ensuring

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the physical and statistical consistency of the inversion over the full 35-year period. Mole fraction records from 131 measurement sites have been used from the NOAA Earth System Research Laboratory archive, the World Data Centre for Greenhouse Gases (WDCGG) archive and the Réseau Atmosphérique de Mesure des Composés à Effet de Serre (RAMCES) database (see the list in the Supplement of Peylin et al., 2013).

3 Direct comparisons to TCCON

We show comparisons between satellite X_{CO_2} , model simulated mole fraction fields and TCCON X_{CO_2} at 17 different TCCON sites, shown in Fig. 1. These sites span the Northern and Southern Hemispheres and cover a wide range of latitudes and longitudes, though not covering South America, and Africa, or Asia excepting Japan. Newer sites are not used as the coverage of SCIAMACHY dataset ends in mid-2012 and our version of CarbonTracker (CT2013b) ends at the end of 2012. We show representative time series for CT2013b, MACC, GOSAT, SCIAMACHY for a Northern Hemisphere site (Lamont, OK, US at 37° N) and two Southern Hemisphere sites (Lauder, NZ at 45° S or Wollongong, New South Wales, Australia at 35° S) in Fig. 2. These plots show matches using the geometric coincidence criteria described in Table 2 below (for satellites) and give an idea of the number of coincidences for each dataset using these criterion. These sites were chosen as they have the most coincidences in the Northern and Southern Hemisphere, respectively, for satellites. All sets compare well; the 30-day moving averages show differences most easily; such as a repeating blip in CT2013b comparisons at the summer drawdown at Lamont and a seasonal mismatches in CT2013b comparisons to Lauder, which will be discussed later in the paper.

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3.1 Coincidence criteria and other matching details

The SCIAMACHY and GOSAT comparisons in this paper are based on two different definitions of coincidence criteria between TCCON and satellite data. Satellite measurements, which satisfy the so-called geometric criteria, are within ± 1 h, $\pm 5^\circ$ latitude and longitude of the mean time of a 90-min TCCON average. The dynamical criteria (Wunch et al., 2011; Keppel-Aleks et al., 2011, 2012) are designed to exploit information about the dynamical origin of an air parcel through a constraint on the free-tropospheric temperature. This allows us to relax the geometric constraints and find more coincident satellite soundings per TCCON measurement. Briefly, a match is found when the measurements are within 5 days and the following is satisfied:

$$\left(\left(\frac{\Delta \text{Latitude}}{10} \right)^2 + \left(\frac{\Delta \text{Longitude}}{30} \right)^2 + \left(\frac{\Delta \text{Temperature}}{2} \right)^2 \right) < 1, \quad (1)$$

where $\Delta \text{Temperature}$ is the co-located NCEP temperature difference at 700 hPa (Kalnay et al., 1996). Table 2 summarizes the coincidence criteria and data versions that are used. Other matching schemes not included in this paper include a method implemented by S. Basu described in Guerlet et al. (2013), which utilizes model CO_2 fields to determine coincidences and Nguyen et al. (2013) which uses a weighted average of distance, time, and mid-Tropospheric temperature. Dynamic and geometric coincidence criteria are compared in Sect. 3.3 and geometric coincidence criteria are used to spot-check dynamic coincidence criteria results.

The choices used in this paper regarding model/TCCON matchups are: linearly interpolating to the TCCON latitude, longitude, and time for MACC, interpolating to the TCCON time from the special CarbonTracker output that has been interpolated to the TCCON locations, and using the TCCON surface pressure for calculating X_{CO_2} . In the cases where the TCCON surface pressure is greater than the model surface pressure, the model surface CO_2 value is replicated to the missing pressure values.

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3.2 Bias and standard deviation for individual matches

Figure 3 shows a summary of the comparisons for geometric criteria where satellite matches are not averaged. Averaging and the effects of coincidence criteria and satellite averaging are addressed in Sect. 3.4. The black box shows 5 European stations which are very close, geographically, yet have different biases. The gray bars labeled “TCCON Bias Uncertainty” in Fig. 3 are estimated to be 0.4, the overall calibration uncertainty in TCCON (Wunch et al., 2010, 2011). When the measured biases are larger than the gray box, they are considered significantly different than TCCON. For GOSAT, biases larger than the TCCON bias uncertainty occur at stations north of 67° N (Eureka, Sodankyla), Garmisch, Four Corners, Tsukuba, and Lauder. Stations which have special circumstances regarding validation are: Garmisch which is in the midst of complicated terrain that is difficult to model local atmospheric transport and to measure from space; Four Corners (4C), which is located in the vicinity of two power plants with large CO₂ emissions (Lindenmaier et al., 2014). The meteorology is such that 4C regularly samples large localized plumes with column CO₂ increases of several ppm that last hours in the late morning. Therefore, the low bias in models and satellite data relative to the 4C TCCON is attributed to the smaller scale enhancements from the power plants measured in TCCON which are significantly diluted in the model and satellite results; Bremen is also affected by local urban sources, and satellites and models would be expected to be biased low; which is a finding, though it is similar to adjacent stations; and JPL is in a megacity with complex adjacent terrain. SCIAMACHY has the same outliers as GOSAT with an additional low bias at Karlsruhe. The models show similar biases to GOSAT and SCIAMACHY at stations north of 67° N (Eureka, Ny Alesund, Sodankyla), Garmisch, Four Corners, but not at Tsukuba or Lauder. MACC additionally shows a low bias at JPL where the model scale does not allow resolution of this site. The standard deviation is shown in the right panel of Fig. 3. For unaveraged results, model standard deviations are lower than either satellite as satellite differences result from both systematic and random measurement error, the latter which does not

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occur for models. The standard deviations show some variability from station to station which are investigated below. The effects of averaging and coincident criteria are investigated in Sect. 3.3.

Figure 4 shows the biases and standard deviations grouped globally and over the northern and Southern Hemispheres. To estimate the overall bias and standard deviations for single observations, we take out the outliers as follows. For the models, we take out JPL, Four Corners, Bremen, and Garmisch, with the caveat that models are unable to resolve variations with complex orography (Garmisch) or strongly influenced by local sources (JPL, Four Corners, Bremen) due to resolution, and Tsukuba for the standard deviation, as the TCCON instrument at Tsukuba has higher standard deviation. For satellites, we remove the above plus Tsukuba and Lauder due to limited numbers of comparisons for SCIAMACHY. For the bias we take out stations poleward of 60° N, which have large positive biases for GOSAT and SCIAMACHY, which we note as an issue. There is an overall bias versus TCCON on the order of 0.7 ppm for CT2013b, and 0.2–0.3 ppm for the other 3 sets. The overall bias is less of a concern than the bias variability in satellite data which indicates regional errors that will translate to regional errors in flux estimates. The bias variability is 0.4, 0.4, 0.5, and 0.3 ppm for CT2013b, MACC, SCIAMACHY, and GOSAT respectively. Note SCIAMACHY data are corrected to have an average zero bias with respect to TCCON GGG2012 which is 0.3 ppm higher than GGG2014 (https://tcon-wiki.caltech.edu/Network_Policy/Data_Use_Policy/Data_Description#CORRECTIONS_AND_CALIBRATIONS). When stations north of 67° N and other large outliers are excluded, the bias variability is on the order of the TCCON bias uncertainty of 0.4 ppm. The overall standard deviations are 0.9 ppm for CT2013b, 0.9 ppm for MACC, 2.1 ppm for SCIAMACHY, and 1.7 ppm for GOSAT. These values represent the overall performance of CT2013b, MACC, and single soundings from SCIAMACHY and GOSAT. The standard deviations are somewhat lower for the SH stations used, with values of 0.8, 0.8, 2.0, and 1.6 for CT2013b, MACC, SCIAMACHY, and GOSAT, respectively. Reuter et al. (2013) validated earlier retrieval versions of BESD-SCIAMACHY and ACOS-GOSAT with TCCON and found

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2.1 ppm (BESD) and 2.3 ppm (ACOS) for the single sounding precision and 0.9 ppm for the station-to-station biases. Their findings for BESD are consistent with the findings of Dils et al. (2014). The station-to-station biases are lower in our analysis due to corrections in TCCON, improvements in satellite estimates, and removal of several stations from the estimates.

We test whether the biases seen in Figs. 3 and 4 are persistent from year to year. When at least two full-year averages exist for a station, the standard deviation of the yearly bias is calculated. The average over all stations of the yearly bias standard deviation is 0.3 ppm for all sets (CT2013b, MACC, SCIAMACHY, GOSAT). The year-to-year variability in the bias could be partly attributed to the distribution of data seasonally. Stations which have absolute biases more than 0.3 ppm different than the mean bias therefore have biases that are persistent from year to year. The stations which do not show biases are: GOSAT: Bialystok, Karlsruhe, Lamont, Izana. SCIAMACHY: Lamont. CT2013b: Ny Alesund, Orleans, Izana, Darwin, Wollongong, Lauder (both). MACC: Ny Alesund, Orleans, Park Falls, Lamont, Izana, Darwin, Wollongong, Lauder (both).

Another important comparison is of the predicted and actual errors. The predicted error (also referred to as the a posteriori error) is reported for each satellite product and the actual error we take to be the standard deviation of the satellite observation versus TCCON. These two quantities should agree if the TCCON error is much smaller than the a posteriori error and the coincidence criteria does not degrade the agreement. The predicted and actual errors vary from site to site, e.g. from variations in albedo, aerosol composition, solar zenith angle, etc. We calculate the correlation between the standard deviation vs. TCCON and the predicted error for each site as follows: the standard deviation of the satellite vs. TCCON is calculated at each TCCON station. The correlation of the vectors of standard deviation and predicted errors by station are calculated. ACOS-GOSAT has a 0.6 correlation and BESD-SCIAMACHY has a 0.5 correlation. This indicates that the predicted error should be utilized, e.g. when assimilating ACOS-GOSAT, as the variability in the predicted error represents variability in the actual error, though not perfectly. A scale factor should also be applied to the

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predicted errors. For ACOS-GOSAT the predicted error averaged over all TCCON sites is 0.9 ppm, as compared to the actual error of 1.7 ppm and can be corrected by applying a factor 1.9 to the reported GOSAT errors. For BESD-SCIAMACHY, the prediction error of 2.3 ppm multiplied by 0.9° with the 2.1 ppm actual error.

3.3 Errors as a function of coincidence criteria and averaging

We now directly compare performance of geometric and dynamic coincidence criteria and averaging in terms of error. Figure 5 shows SCIAMACHY and GOSAT standard deviations versus TCCON for geometric and dynamical coincidence criteria. The stations used were those that had entries for all comparisons, listed in the Fig. 5 caption. For $n = 1$ no averaging is done and the dynamic coincidence criteria performs similarly to the geometric criteria, though the dynamic error is ~ 0.2 ppm higher for SCIAMACHY. For $n = 2$, exactly two satellite observations were averaged for each coincidence. The error drops substantially, but not as $1/\sqrt{2}$, which would be expected if the error were uncorrelated. For $n = 4$, the error again drops but it is not half the $n = 1$ error, which is shown by the dotted line. At $n = 4$, the dynamic coincidence criteria is the same as the geometric error, likely because dynamic coincidence involves averaging observations farther apart in location and time, which are less likely to have correlated errors. The last bar is the maximum n , which has results for all stations included. The dynamic criteria allows far more coincidences, resulting in significantly lower average errors. The dynamic criteria is used for the remainder of the paper but with checks using the geometric criteria to ensure that artifacts are not added by the dynamic criteria. Note that all averaged satellite observations match to one particular TCCON observation.

3.4 Errors versus averaging: random and correlated error

To test the effects of spatial averaging, we calculate station by station standard deviations of satellite – TCCON matched pairs as a function of n , where n is the number of satellite observations that are averaged, which are chosen randomly from available

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matches (so there should be no difference in the characteristics of chosen points for larger vs. smaller n). Figure 6 shows plots from Lamont for SCIAMACHY and GOSAT for standard deviation difference to TCCON versus n . Initially the error drops down rapidly with n , however the decrease slows with larger n . The curve fits well to the theoretically expected form:

$$\text{error}^2 = a^2 + b^2/n, \quad (2)$$

where a represents correlated errors which do not decrease with averaging for similar cases (including smoothing errors, errors from interferences such as aerosols, TCCON error, and co-location error), b represents uncorrelated errors which decrease with averaging, and n represents the number of satellite observations that are averaged. The purple dashed line represents the standard deviation of CT2013b at the satellite time and location vs. CT2013b at the TCCON time and location. The purple dashed line represents spatio-temporal mismatch error and as expected, this value is much smaller for geometric than for dynamic coincidence criteria.

We calculate a and b by station in Table 3 with average values for northern hemispheric stations of $a = 1.5 \pm 0.3$ ppm, $b = 1.6 \pm 0.2$ ppm for SCIAMACHY geometric, $a = 1.1 \pm 0.2$ ppm, $b = 1.4 \pm 0.4$ ppm for SCIAMACHY dynamic, $a = 0.9 \pm 0.2$ ppm, $b = 1.7 \pm 0.3$ ppm for GOSAT dynamic. These values indicate the expected error when averaging GOSAT or SCIAMACHY observations matching to a single TCCON observation. There is more correlated error, a , for SCIAMACHY geometric versus dynamic matches in 4/7 stations in the Northern Hemisphere, indicating that averaging is more effective when it is over a larger spatial/temporal area, probably due to variability in the source of the correlated errors. GOSAT only has two stations, Lamont and Park Falls, which have enough co-locations to directly compare dynamic and geometric coincidence criteria but these stations have smaller correlated error for geometric matches, which is true in all seasons. This could be due to the smaller GOSAT footprint allowing more variability from observation to observation. The co-locations error are ~ 0.3 , 0.7, and 0.7 ppm, for SCIAMACHY geometric, SCIAMACHY dynamic, and GOSAT dy-

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In the Southern Hemisphere (SH), CT2013b underestimates the seasonal cycle. Figure 10 shows a map of fits of the seasonal cycle amplitude of SCIAMACHY, GOSAT, CT2013b, and MACC with TCCON having at least 2 years of matches shown as circles. This map shows how the results of Table 4 fits into the global pattern (with the model fields matched to GOSAT locations and times). Interestingly, the seasonal cycle amplitude varies longitudinally; this pattern is seen in both satellite datasets and both models. Since the amplitude is taken from the sampled harmonic there is no extrapolation although the seasonal cycle could be underpredicted at high latitudes where there are data gaps. This map is consistent with Lindqvist et al. (2015), Fig. 8 which also finds high values in the 45–50° N, 120–180° E range.

4.2 CO₂ yearly growth rate

The same fitting program in the above section, CCGCRV, also calculates a yearly increase. In Table 5 we compare the fitted yearly increase for TCCON to each of the datasets. Comparisons to TCCON are within the predicted error except the SH where SCIAMACHY is low compared to TCCON and in the 46–53° N range where GOSAT is low compared to TCCON. The yearly increase for TCCON varies from 1.9 to 2.3 ppm yr⁻¹ for the different locations and time ranges. To see how much of the observed variability in the growth rate is temporal vs. spatial variability in the growth rate, we compare to the global annual increase (growth rate) from surface measurements (<http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html>) shown in Table 6. The average global yearly increase predicted from Table 6 using the time periods in Table 5 are shown in the last column of Table 5. The correlation r value between “Yearly incr. TCCON” and “global” (Table 6) columns is 0.84 (similarly the correlation to Mauna Loa calculated average annual increase is 0.82), whereas the correlation r value between “Yearly incr. TCCON” and “Yearly incr.” columns is 0.60. Therefore, the variability of the seen in Table 5 is primarily explained by the time-range of the comparisons.

Reuter et al. (2011, JGR, Table 2) found agreement within the calculated errors at Park Falls and Darwin for BESD-SCIAMACHY and CT2009 vs. TCCON. However, older

datasets were used for this result. Looking specifically at Park Falls, we see 1.80 ± 0.14 and 2.10 ± 0.22 for SCIAMACHY and TCCON, respectively and at Darwin 1.67 ± 0.08 and 2.16 ± 0.05 for SCIAMACHY and TCCON, respectively, where the errors represent the standard deviation of SCIAMACHY fits for similar latitudes.

4.3 Seasonal cycle phase

This section looks at the time-offset correlation and standard deviation between the test datasets and TCCON. This checks whether, for example, a seasonal cycle is delayed or ahead of the TCCON seasonal cycle, which has important implications for flux estimates (Keppel-Aleks, 2012), whether there are seasonally dependent biases that are affecting the seasonal cycle, and whether the datasets are seeing the “same” seasonal cycle.

To compare seasonal cycle amplitudes, all datasets have 2 ppm yr^{-1} subtracted off to approximately remove secular increases (over the ± 60 days offset this has a very small effect). For a 0 day offset, the datasets are matched as usual. For a 1 day offset, TCCON is moved forward by 1 day and compared to the dataset. This is repeated for all offset times. Correlations are fit to a 2nd order polynomial to determine the phase minimum difference. As TCCON is moved forward or backward in time, different points will match up, particularly when there are data gaps in either dataset. This can cause difficulties in interpretation. The maximum correlation is limited by the ratio of the error to the variability. It follows from the definition of correlation that:

$$\text{corr_max} = \text{corr}_o \frac{1}{\sqrt{1 + (\varepsilon_x/\sigma_x)^2} \sqrt{1 + (\varepsilon_y/\sigma_y)^2}}, \quad (3)$$

where corr_o is the noise-free correlation, ε_x is the error on x and σ_x is the true variability for x , ε_y is the error on y and σ_y is the true variability for y . Because we are estimating σ and ε , there is uncertainty on the correlation maximum. In our case σ_y is taken to be the TCCON variability and ε_y is estimated using Table 3 with 10 SCIAMACHY and

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4 GOSAT averages. The error bars on the correlations are calculated from the fisher's z test. (Fisher, 1915, 1921). Figure 11 shows SCIAMACHY and GOSAT results at Park Falls. Although the prior performs well in regards to the standard deviation vs. TCCON Fig. 11 shows the prior has a clear seasonal cycle phase error which is corrected by the satellite retrievals for both SCIAMACHY and GOSAT at Park Falls.

Results of the seasonal cycle phase error are tabulated in Table 8, columns "GOSAT prior" and "GOSAT retrieved", "SCIA prior" and "SCIA retrieved". Stations not shown have either too few match-ups (e.g. Sodankyla) or too little variability compared to the noise (e.g. Wollongong) to have useful comparisons. The GOSAT retrieval markedly improves the seasonal cycle phase versus TCCON all stations where there is adequate data. The SCIAMACHY retrieval clearly improves over the prior for Park Falls and Four Corners, mildly improves in 3 and stays the same in 2 cases. Mismatches in SCIAMACHY phase could be from mismatches in vertical sensitivity (as higher altitudes have lagged seasonal cycles), effects of coincidence criteria, or seasonal-dependent biases. To check the coincidence criteria, cross-correlations were done for the geometric coincidence criteria which had significantly fewer matchups. Similar results for geometric coincidence criteria were found for GOSAT and SCIAMACHY for Lamont and Park Falls; the other stations are too noisy to draw conclusions.

Table 7 also shows the phase differences for the models, which have closer spatial/temporal matches and lower single-matchup errors. Model-TCCON phase differences could result from errors in model flux distributions, seasonal timing, or transport errors. Table 7 shows the phase differences, which vary from -20 to +10 days. Phase differences more than 10 days are noticeable by eye and occur in the NH at: Bremen and Four Corners (negative) (these stations are influenced by local effects), and Orleans and Izaña (positive, CT2013b only). Larger phase differences occur at some stations in the Southern Hemisphere. Although the seasonal cycle is weaker in the Southern Hemisphere, it can be clearly seen in, e.g. the Lauder_125HR data in Fig. 2. The correlations versus offset days show a phase difference of -20 days for CT2013b and +0 days for MACC at LAUDER_125HR, as seen in Fig. 12. Note that the fits of

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the seasonal cycle in the SH display more complexity, such as multiple local maximum, than fits in the NH and “phase lag” could also be an indication of an issues with the fit shape. Figure 12 shows correlations and standard deviations versus day offset for 3 stations that have the seasonal cycle peak within ± 10 days for CT2013b and MACC (top panels), and for stations which have a larger phase lag compared to TCCON (bottom panels). There is often a small peak within ± 3 days, which indicates the models’ capability of picking up variations that occur day to day (i.e., synoptic scale variability), which indicates the strength of synoptic activity and matching between models and TCCON. This peak is not seen in satellite data for dynamic coincidence criteria likely due to matching, or geometric coincidence criteria likely due to the noise. Not that this synoptic peak occurs at 0 even when the seasonal cycle has a phase lag (e.g. MACC model at Bremen, in the lower right panel, or Lauder_125HR comparisons). The synoptic scale correlation varies between 0 and 0.17, as seen in Table 7.

A brief discussion on Izana. The TCCON station is on Tenerife Island, a small island (about 50×90 km) with complex topography located about 300 km west of southern Morocco. The TCCON station is located at 2.37 km (about 770 mb). The MACC and CT2013b models at $\sim 2^\circ \times 3^\circ$ resolution do not resolve topography at these scales and consequently have mean surface pressure at sea level, about 1000 hPa at this location. Our standard treatment is to interpolate the model to the TCCON pressure grid, then calculate X_{CO_2} using the TCCON pressure weighting function. At Izaña this has the effect of chopping off the lower atmosphere. The CT2013b result for this treatment has a $\sim +10$ day seasonal cycle phase difference at Izaña; whereas MACC has no phase difference at Izaña. If, however, the model surface pressure is used to calculate X_{CO_2} , MACC goes from a 0 to a -10 day phase lag, and CT2013b has 0 phase difference. An argument for using the model surface pressure would be if the upslope winds at Izaña (Sancho et al., 1991; Bergamaschi et al., 2000) shifted the profile upwards rather than chopping it off, which would occur if the air instead deviated around the island. This finding has important implications on the choice of the comparison methodology and the ideal location for validation sites. Validation sites within complex geographical terrain

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portant as the column diurnal variability better represents the amount of CO₂ emitted or absorbed by surface processes as compared to surface measurements, which are impacted by boundary layer height. To our knowledge this is the first comparison of model fields to TCCON to compare the diurnal cycle. As TCCON itself has not been validated at multiple times in one day, this is considered a comparison not a validation. We compare the difference between morning and afternoon in models and TCCON. To minimize potential TCCON biases that depend on the solar zenith angle (through the air mass factor), we compare at two points in each day separated by the largest time with the same solar zenith angle (SZA). The methodology is to (1) identify two points, t_1 and t_2 , from the same day with the largest time difference but with the same SZA. As the TCCON data used in this paper has been averaged over 90 min, t_1 or t_2 may be interpolated between two time points. (2) We compare TCCON at t_2 minus TCCON at t_1 and the same times for each model. We look at the variability within one day for one season (JJA). Looking at different seasons for the Northern Hemisphere at the bottom of Table 8, both models showed clearly higher correlations and slopes in MAM and JJA vs. DJF and SON. In the SH for other seasons, there was less consistency between model findings. For CT2013b, correlations were seen in MAM, JJA, and SON at Lauder-125HR, and JJA and SON at Darwin (0.3–0.7), but not the other seasons, and correlations only in SON at Wollongong (0.22). MACC did not show correlations with Darwin in any season, but showed the best correlations with Wollongong in JJA and SON (0.3–0.4), and correlations with Lauder-125HR in all seasons (0.24–0.6), peaking in DJF.

Table 8 show correlations between CT2013b or MACC vs. TCCON in the daily variability. The correlations are about 2/3 as large as could be expected, given the relative sizes of the variability and errors (see text around Eq. 3). When correlations are present the models have about 1/3 to 1/2 the variability of TCCON (as seen from the smaller slopes). In the far north (Ny Alesund, Sodanklya), the correlations indicate agreement but the model daily variability is less than 1/4 TCCON. In the mid-latitudes there is the highest correlation ($\sim 0.3\text{--}\sim 0.7$) with model daily variability $\sim 0.2\text{--}0.6$ that of TC-

differences) should be tested using an OSSE to determine its effect on flux biases and flux distribution errors. For example, Kulawik et al. (2013) tested the effect of a NH bias of 0.3–0.5 ppm in JJA, finding flux biases comparable to GOSAT updates in some regions.

We find standard deviations of 0.9, 0.9, 1.7, and 2.1 ppm versus TCCON for CarbonTracker, MACC, GOSAT, and SCIAMACHY, respectively. GOSAT predicted error should be multiplied by 1.9 and SCIAMACHY predicted error should be multiplied by 0.9 to represent the actual single target error. There is a correlation r value of 0.5 for SCIAMACHY and 0.6 for GOSAT for the actual and predicted errors grouped by station. Equation (2) and Table 3 show how errors decrease when satellite results are averaged and estimate the magnitude of the correlated and random error components for averaged satellite results, where random error components decrease with increasing number of averaged observations. When satellite data are averaged and interpreted according to the model $\text{error}^2 = a^2 + b^2/n$ (where n are the number of observations averaged, a are the systematic (correlated) errors, and b are the random (uncorrelated) errors), $a = 0.6 \pm 0.3$ ppm and $b = 1.7 \pm 0.3$ ppm for GOSAT, and $a = 1.0 \pm 0.3$ ppm, $b = 1.4 \pm 0.4$ ppm for SCIAMACHY regional averages (dynamic coincidence criteria) in the Northern Hemisphere, correcting for coincidence errors and TCCON errors. SCIAMACHY averaging results in the lowest correlated errors when using dynamic coincidence criteria where values are averaged from a larger spatio-temporal region, whereas GOSAT, in the two stations where sufficient data exists (Lamont, Park Falls), geometric criteria performs better than dynamic coincidence criteria. These data represent averaging of satellite data which matches a single TCCON value. The above error model should help assigning realistic retrieval error correlations in assimilation systems in place of current ad hoc hypotheses (see, e.g., Sect. 2.2 in Basu et al., 2013, for an example of such hypotheses).

Biases vary by station (see Fig. 3); the station-dependent biases have a standard deviation of ~ 0.3 ppm from year to year. Biases larger than ~ 0.3 ppm likely represent persistent biases. Biases of this magnitude are seen in many stations for all datasets,

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particularly Eureka, Ny Alesund, Sodankyla in the far north, Garmisch, Four Corners, JPL (MACC only), Tsukuba (satellites only), and Lauder (satellites only). Biases also vary by time. Looking seasonally, and subtracting the overall bias, there are also persistent biases affecting the seasonal cycle amplitudes on the order of -0.8 to 0.8 ppm.

5 However, note that the TCCON bias uncertainty is on the order of 0.4 ppm; the TCCON team is working to improve this. The persistent seasonal biases were that SCIAMACHY for $0-45^\circ$ N is high in MAM, low in JJA, on the order of 1.2 ppm total spread; poleward of 45° N GOSAT and SCIAMACHY are low in DJF and high in JJA on the order of $0.3-0.5$ ppm, and MACC is high in DJF and low in SON on the order of 0.3 ppm.

10 Related to the seasonal biases, we validate the seasonal cycle amplitudes, which are important for biospheric flux attribution. All sets show the same general patterns for the different latitude bands (SH, $28-37^\circ$ N, $46-53^\circ$ N, $67-79^\circ$ N). The discrepancies versus TCCON which are statistically significant are that GOSAT has too small a seasonal amplitude in the $46-53^\circ$ N range by 0.9 ppm, SCIAMACHY overestimates $28-37^\circ$ N (which includes only Lamont) by 0.8 ppm, and CT2013b is too small in the SH by 0.5 ppm. A preliminary study of how a seasonal bias in JJA in GOSAT of 0.5 ppm in the NH would affect fluxes using a global assimilation showed that the effect was not minor (Kulawik et al., 2013).

20 The seasonal cycle phase can detect seasonally dependent biases in satellite data and issues with model fluxes or transport errors. We investigate the alignment of the seasonal cycles by offsetting each CO_2 set versus TCCON by -60 to $+60$ days. For satellites, the following stations had adequate data and high enough signal/error to estimate a result: Bialstok, Karlsruhe, Orleans, Garmisch, Park Falls, Four Corners, Lamont, and Izaña (GOSAT only). The GOSAT r.m.s. phase difference versus TCCON is 16.9 days for the prior and 4.7 days for the GOSAT retrieved X_{CO_2} , a marked improvement. SCIAMACHY improved substantially at 2 of 7 sites, and SCIAMACHY r.m.s. phase difference versus TCCON is 16.3 days for the prior and improves to 13.4 days for the SCIAMACHY retrieved X_{CO_2} . Model comparisons to TCCON are much less noisy as there are many more matches. Most NH stations show the expected seasonal

dropoff (e.g. see Fig. 12), with the peak correlation near 0 days, and an additional spike within ± 3 days indicating the capture of synoptic variability. Stations that showed phase differences larger than 10 days are Four Corners (both models), Bremen (both models), Izana (CT2013b only), Darwin (Macc only), and Lauder 125HR (CT2013b only).

In studying the variability through a single day, both models show correlation to the variability within a day versus TCCON, on the order of 0.2–0.8 correlation for NH stations, about 2/3 of the possible correlation given the errors (except at Bremen and Four Corners which had little correlation and no slope). The amplitude of the variability is higher in TCCON versus the models, with CT2013b closer to TCCON than MACC. However, TCCON daily variability has not been validated (there are plans to validate TCCON throughout the day in the near future). Diurnal pattern will not be constrained by satellite observations, except as preserved in transported air coincident with satellite measurements downwind, and therefore may be important to independently verify the diurnal cycle in models to ensure accurate satellite assimilation results. The importance of the diurnal cycle on flux estimates would need to be tested.

In our analysis a clear picture has emerged of two TCCON stations (Bremen, Four Corners) most influenced by local sources, seen in phase differences versus models, daily variability, and large overall biases. Caution should be used when using these stations for validation. Spatial and seasonal-dependent biases are obstacles to accurate and better resolved CO₂ flux estimates. This paper highlights findings that provide inputs to estimate flux errors in model assimilations, and places where models and satellites need additional validation or improvement. Some of the issues which need further investigation are: the GOSAT seasonal cycle in 46–53° N latitude range (which is 0.9 ppm smaller than TCCON), SCIAMACHY over-predicting the seasonal cycle at Lamont, both models with seasonal cycle differences at the different SH stations, differences in the diurnal cycle amplitude between models and TCCON, and high biases for GOSAT and SCIAMACHY north of 67° N.

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Author contributions. S. Kulawik set the direction of the research and did much of the analysis. The following authors were involved with discussions of results with specific knowledge in the listed areas: Debra Wunch, TCCON, Christopher O'Dell, ACOS-GOSAT, Christian Frankenberg, ACOS-GOSAT, Maximilian Reuter, BESD-SCIAMACHY, Tomohiro Oda, CarbonTracker, Frederic Chevallier, MACC, Vanessa Sherlock, TCCON, Michael Buchwitz, BESD-SCIAMACHY, Greg Osterman, ACOS-GOSAT, Charles Miller, CO₂ data records, The TCCON data providers, who also provide expertise regarding TCCON sites are Paul Wennberg, David Griffith, Isamu Morino, Manvendra Dubey, Nicholas M. Deutscher, Justus Notholt, Frank Hase, Thorsten Warneke, Ralf Sussmann, John Robinson, Kimberly Strong, and Matthias Schneider. Joyce Wolf is a science programmer and provided technical expertise.

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Table 1. Summary of the CO₂ datasets and models we are using showing the coverage for several different CO₂ products. The obs/day are the approximate number of CO₂ observations which pass quality screening.

Satellite/TCCON	Dates available	day/ night	land/ ocn	latitude	obs/ day	footprint
SCIAMACHY v2.00.08	Jan 2003–Apr 2012	day	land	80° S–80° N	~ 800	60 × 30 km
GOSAT ACOS-v3.5	Jun 2009–Apr 2014	day	both	80° S–80° N	~ 360	10.5 km cir.
TCCON GGG2012	see Fig. 1	day	both	45° S–80° N	–	–
Model	Dates available			Time res.		Spatial res. (lat × lon)
CT2013b	2000–2012			3 h		2 × 3° global, 1 × 1° US
MACC 13.1	1979–2013 (used 2007–2013)			3 h		1.9 × 3.75°

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Table 2. Coincidence criteria, data versions, and terminology used in our analysis.

Coincidence criteria	
Geometric Dynamical	5° in lat/lon, ± 1 h from Wunch et al. (2011). Considers free-tropospheric temperature, ± 10° lat, ± 30° lon and 5 days (see Sect. 3.1)
Datasets	
GOSAT	ACOS-GOSAT version 3.5 with corrections and quality flags from the user's guide
SCIAMACHY	BESD-SCIAMACHY v02.00.08
TCCON	GGG2014 when available, GGG2012 data from Four Corners, Tsukuba, and Bremen with GGG2012 bias corrections applied as described in Sect. 2.3
CarbonTracker MACC	CT2013b MACC v13.1
Averaging: All averaging is done by station first and then averaging over station results.	
Model choices: MACC is interpolated to TCCON latitude, longitude, and time. CT2013b special output is interpolated to TCCON time. Model XCO ₂ uses TCCON surface pressure.	

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Table 3. Fit of a and b in Eq. (2), with stations having data out to at least $n = 50$ for dynamic coincidence criteria, $n = 20$ (GOSAT) or $n = 40$ (SCIAMACHY) for geometric coincidence criteria. The CT-CT column describes the standard deviation of CT@satellite vs. CT@TCCON at the largest n for that station, providing a lower bound on the satellite/TCCON differences. The “subtr co-location error” row estimates the correlated error for satellites only, subtracting in quadrature TCCON error (0.44 ppm) and co-location error (0.3 or 0.7 ppm). The GOSAT geometric averages are $a = 0.7 \pm 0.1$, $b = 1.5 \pm 0.1$, a “subtr co-location error” = 0.5 ± 0.1 .

Station	Geometric			Dynamic			Dynamic/Geometric		
	SCIAMACHY		CT-CT	SCIAMACHY		CT-CT	GOSAT		CT-CT
	a	b	a	a	b	a	a	b	a
Bialystok	1.7	1.5	0.2	1.2	2.1	0.8	0.8	1.8	0.8
Bremen*	1.1	1.6	0.2	1.3	2.0	0.7	1.6	1.8	0.7
Karlsruhe	1.6	1.9	0.4	1.3	1.1	0.8	1.0	1.8	0.9
Orleans	1.5	1.7	0.2	1.1	1.2	0.5	0.9	1.9	0.4
Garmisch	1.9	1.4	0.7	1.3	1.1	1.0	0.9	1.9	1.0
Park Falls	1.2	1.6	0.2	1.2	1.5	0.8	1.1/0.7	1.8/1.5	0.8/0.3
Lamont	1.2	1.5	0.3	1.2	2.0	0.6	1.1/0.8	1.6/1.4	0.6/0.3
Izaña	–	–	–	0.7	1.1	0.4	0.6	1.3	0.4
Mean NH	1.5 ± 0.3	1.6 ± 0.2	0.3 ± 0.2	1.1 ± 0.2	1.4 ± 0.4	0.7 ± 0.2	0.9 ± 0.2	1.7 ± 0.3	0.7 ± 0.2
Mean NH: subtr co-location error	1.4 ± 0.4	–	–	1.0 ± 0.3	–	–	0.6 ± 0.3	–	–
Darwin	1.4	1.5	0.1	1.3	1.2	0.1	0.7	1.1	0.2
Wollongong	1.0	1.8	0.2	1.2	1.8	0.2	0.8	1.3	0.2
Mean SH	1.2 ± 0.3	1.6 ± 0.2	0.2 ± 0.1	1.3 ± 0.1	1.5 ± 0.4	0.2 ± 0.1	0.8 ± 0.1	1.2 ± 0.1	0.2 ± 0.0

* Bremen is influenced by local effects and is not included in averages.

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Table 4. Seasonal cycle amplitudes. Each comparison to TCCON uses a time period based on the available matchups (see Table 1), stations, observations which have at least 2 years of data for comparisons. Stations included for satellites are: Bialystok, Bremen, Karlsruhe (GOSAT), Orleans, Garmisch, Park Falls, Four Corners (GOSAT), Lamont, Izaña (Gosat), Darwin, and Wollongong. Stations included for satellites are: Bialystok, Bremen, Karlsruhe (GOSAT), Orleans, Garmisch, Park Falls, Four Corners (GOSAT), Lamont, Izaña (GOSAT), Darwin (GOSAT), and Wollongong, Lauder_120HR, and Lauder_125HR. Bold shows entries with differences larger than the predicted error which is the greater of: the bootstrap error (Rubin, 1981) (on the order of 0.1 ppm), variability within the latitude bin (the dominant error).

Comparison	Region	Seasonal amp. (ppm)	Seasonal amp. TCCON (ppm)	Seasonal amp. difference ppm)
CT2013b	67–79° N ($n = 2$)	10.1 ± 0.1	10.0 ± 0.5	0.1 ± 0.6
	46–53° N ($n = 4$)	7.6 ± 0.3	7.9 ± 0.4	–0.4 ± 0.5
	28–37° N ($n = 2$)	4.7 ± 0.9	5.5 ± 0.5	0.8 ± 1.0
	SH ($n = 4$)	0.9 ± 0.3	1.4 ± 0.4	–0.5 ± 0.5
MACC	67–79° N ($n = 3$)	11.0 ± 0.3	10.7 ± 0.3	0.3 ± 0.4
	46–53° N ($n = 4$)	8.2 ± 0.3	8.0 ± 0.5	0.1 ± 0.6
	28–37° N ($n = 2$)	5.5 ± 0.1	5.4 ± 0.4	0.1 ± 0.3
	SH ($n = 4$)	1.1 ± 0.3	1.3 ± 0.1	–0.2 ± 0.4
GOSAT (v3.5)	46–53° N ($n = 6$)	7.2 ± 0.5	8.1 ± 0.4	–0.9 ± 0.6
	28–37° N ($n = 3$)	5.3 ± 0.3	5.1 ± 0.1	0.2 ± 0.3
	SH ($n = 2$)	1.6 ± 0.5	1.8 ± 0.8	–0.2 ± 0.9
SCIAMACHY (BESD- v02.00.08)	46–53° N ($n = 4$)	7.7 ± 0.5	7.4 ± 0.9	0.3 ± 1.2
	28–37° N ($n = 1$)	7.2 ± 0.1	6.4 ± 0.1	0.8 ± 0.2
	SH ($n = 1$)	2.6 ± 0.3	1.8 ± 0.7	0.8 ± 0.8

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Table 5. Yearly increases. Each comparison uses matched pairs with TCCON using locations which have at least 2 years of data for comparisons. See Table 4 for stations included. The start date and end date are averaged for the stations in each bin and are shown in the next to last column. Bold text shows one difference larger than predicted errors. The last column shows the average global yearly increase for the time period using Table 6.

Comparison	Region	Yearly incr. (ppm yr ⁻¹)	Yearly incr. TCCON (ppm yr ⁻¹)	Yearly incr. Difference (ppm yr ⁻¹)	Period (year fract)	global (Table 6) (ppm yr ⁻¹)
CT2013b	67–79° N (<i>n</i> = 2)	2.05 ± 0.23	2.03 ± 0.21	0.0 ± 0.3	2007.7–2012.8	1.99
	46–53° N (<i>n</i> = 6)	2.11 ± 0.09	2.12 ± 0.12	–0.0 ± 0.2	2008.1–2013.1	2.02
	28–37° N (<i>n</i> = 2)	2.05 ± 0.07	2.00 ± 0.09	–0.0 ± 0.1	2007.9–2013.1	2.01
	SH (<i>n</i> = 4)	1.96 ± 0.04	1.98 ± 0.20	0.0 ± 0.1	2007.7–2012.6	1.97
MACC v13.1	67–79° N (<i>n</i> = 2)	2.10 ± 0.17	2.20 ± 0.06	0.1 ± 0.2	2009.1–2013.4	2.11
	46–53° N (<i>n</i> = 6)	2.22 ± 0.10	2.21 ± 0.11	0.0 ± 0.1	2008.5–2013.9	2.11
	28–37° N (<i>n</i> = 2)	2.20 ± 0.04	2.08 ± 0.12	0.1 ± 0.1	2008.0–2013.9	2.08
	SH (<i>n</i> = 4)	2.10 ± 0.08	2.08 ± 0.06	0.0 ± 0.1	2008.0–2013.9	2.08
GOSAT v3.5	46–53° N (<i>n</i> = 6)	2.04 ± 0.02	2.27 ± 0.06	–0.2 ± 0.1	2009.4–2013.9	2.11
	28–37° N (<i>n</i> = 2)	2.24 ± 0.02	2.29 ± 0.20	–0.0 ± 0.2	2009.3–2013.9	2.20
	SH (<i>n</i> = 3)	2.10 ± 0.03	2.10 ± 0.09	0.0 ± 0.1	2009.4–2012.9	2.23
SCIAMACHY BESD-V2	46–53° N (<i>n</i> = 5)	2.00 ± 0.15	1.99 ± 0.07	0.0 ± 0.1	2007.8–2012.2	1.93
	28–37° N (<i>n</i> = 1)	2.11 ± 0.14	2.15 ± 0.22	–0.0 ± 0.3	2008.5–2012.2	1.92
	SH (<i>n</i> = 1)	1.79 ± 0.09	1.94 ± 0.05	–0.1 ± 0.1	2008.5–2012.2	1.92

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Table 6. Annual increase globally and at Mauna Loa from ESRL website (<http://www.esrl.noaa.gov/gmd/ccgg/trends/global.html>).

Year	Global (ppm yr ⁻¹)	Mauna Loa (ppm yr ⁻¹)
2006	1.74 ± 0.06	1.76 ± 0.11
2007	2.10 ± 0.07	2.22 ± 0.11
2008	1.78 ± 0.05	1.60 ± 0.11
2009	1.65 ± 0.10	1.88 ± 0.11
2010	2.44 ± 0.06	2.45 ± 0.11
2011	1.71 ± 0.09	1.84 ± 0.11
2012	2.43 ± 0.09	2.66 ± 0.11
2013	2.53 ± 0.09	2.05 ± 0.11
2014	1.86 ± 0.09	2.13 ± 0.11

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Table 8. Diurnal variability of CT2013b and MACC13.1 versus TCCON in JJA arranged by latitude. TCCON variability and maximum theoretical correlation are shown, as well as actual correlation and slope for both models. The slope is the mode vs. TCCON fit to a straight line. Max corr. is calculated using Eq.(3), TCCON stdev, and the lower of the model-TCCON standard deviations from Appendix A. TCCON range, std shows the range of the values seen for the daily variability for TCCON, as well as the standard deviation of the TCCON daily differences. The Average row is for all entries above it. The AverageDJF, etc., rows are for stations Karlsruhe, Orleans, Garmisch, Park Falls, and Lamont.

Station	Lat (°)	TCCON		Max Corr. (Eq. 3)	CT2013b		MACC 13.1	
		range (ppm)	stdev (ppm)		Correlation	Slope	Correlation	Slope
Nyalesund	79	−2 to +2	0.6	0.6	0.22	0.14	0.27	0.04
Sodankylä	67	−1.5 to +1.5	0.5	0.6	0.63	0.32	0.40	0.19
Bialystok	53	−2 to +1	0.5	0.6	0.59	0.60	0.64	0.35
Bremen*	53	−2 to +1	0.7	0.5	0.48	0.09	−0.02	0.00
Karlsruhe	49	−2 to 0	0.7	0.6	0.58	1.04	0.62	0.56
Orleans	48	−1 to +0.5	0.7	0.7	0.75	0.43	0.70	0.31
Garmisch	47	−3 to 0	0.8	0.6	0.58	0.56	0.69	0.46
Park Falls	46	−3.5 to +2	1.0	0.8	0.77	0.32	0.54	0.23
Four Corners*	37	−4.5 to +0.5	1.8	0.9	0.85	0.04	0.22	0.02
Lamont	37	−3.0 to +1.0	0.8	0.7	0.70	0.23	0.32	0.14
Tsukuba	36	−2 to +1.5	0.8	0.6	0.59	0.58	0.64	0.24
Izaña	28	−0.5 to +0.5	0.1	0.2	0.20	0.16	0.45	0.04
Darwin	−12	−0.5 to +0.5	0.2	0.3	0.27	0.02	0.10	0.03
Wollongong	−34	−1.5 to +1.0	0.4	0.5	0.48	0.18	0.26	0.14
Lauder120HR	−45	−0.5 to +0.5	0.3	0.3	0.34	0.02	0.20	0.02
Lauder125HR	−45	−0.5 to +0.5	0.2	0.4	0.44	0.51	0.31	0.06
Average JJA for all stations				0.6	0.44	0.33	0.40	0.18
Average DJF (see caption for station list)				0.6	0.36	0.15	0.33	0.08
Average MAM (see caption for station list)				0.6	0.54	0.35	0.51	0.23
Average JJA (see caption for station list)				0.6	0.45	0.46	0.52	0.29
Average SON (see caption for station list)				0.6	0.39	0.22	0.22	0.09

* Sites expected to be strongly influenced by local sources.

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Table A1. We estimate the 90-min average TCCON standard deviation error by calculating the standard deviation (SD) of adjacent time points and model standard deviation of CT2013b and MACC13.1 versus TCCON by station. These values are used to estimate theoretical maximum correlations for seasonal cycle and diurnal correlations using Eq. (3).

Station	TCCON adjacent SD (ppm)	CT2013b SD (ppm)	MACC SD (ppm)
Eureka	0.2	0.8	0.9
Ny Alesund	0.8	0.8	0.8
Sodankyla	0.3	0.7	0.8
Bialystok	0.3	0.7	0.7
Bremen ^a	0.5	1.3	1.4
Karlsruhe	0.4	0.9	0.9
Orleans	0.3	0.7	0.7
Garmisch	0.3	0.9	0.9
Park Falls	0.4	0.8	0.8
Four Corners ^a	0.7	1.1	1.1
Lamont	0.3	0.8	0.8
Tsukuba ^b	0.9	1.0	1.1
JPL2007 ^a	0.6	1.3	1.1
Izaña	0.2	0.8	0.6
<hr/>			
NH average	0.44	0.91	0.92
NH average (subset)	0.35	0.79	0.79
<hr/>			
Darwin	0.4	0.9	1.0
Wollongong	0.4	0.8	0.7
Lauder	0.4	0.8	0.8
Lauder125	0.3	0.6	0.5
<hr/>			
SH average	0.38	0.78	0.75

^a Stations strongly influenced by local effects; ^b higher TCCON error. These stations have been removed in the “NH average (subset)” row.

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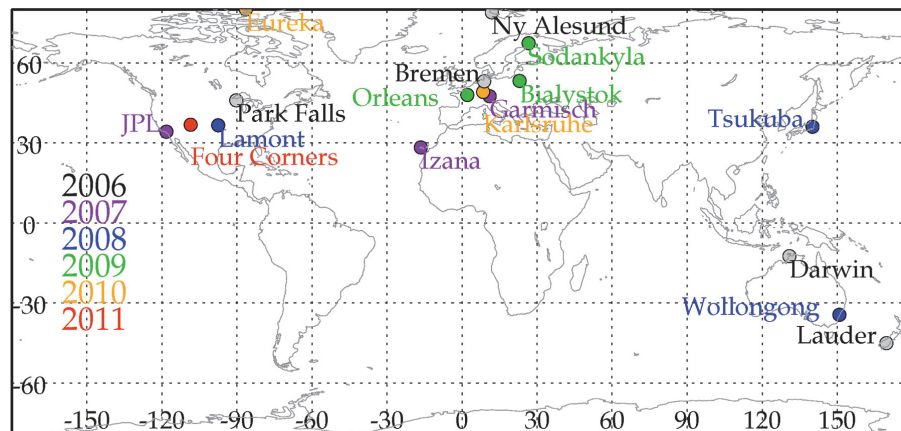


Figure 1. TCCON site locations used for this work. The color indicates the year when each station started collecting data.

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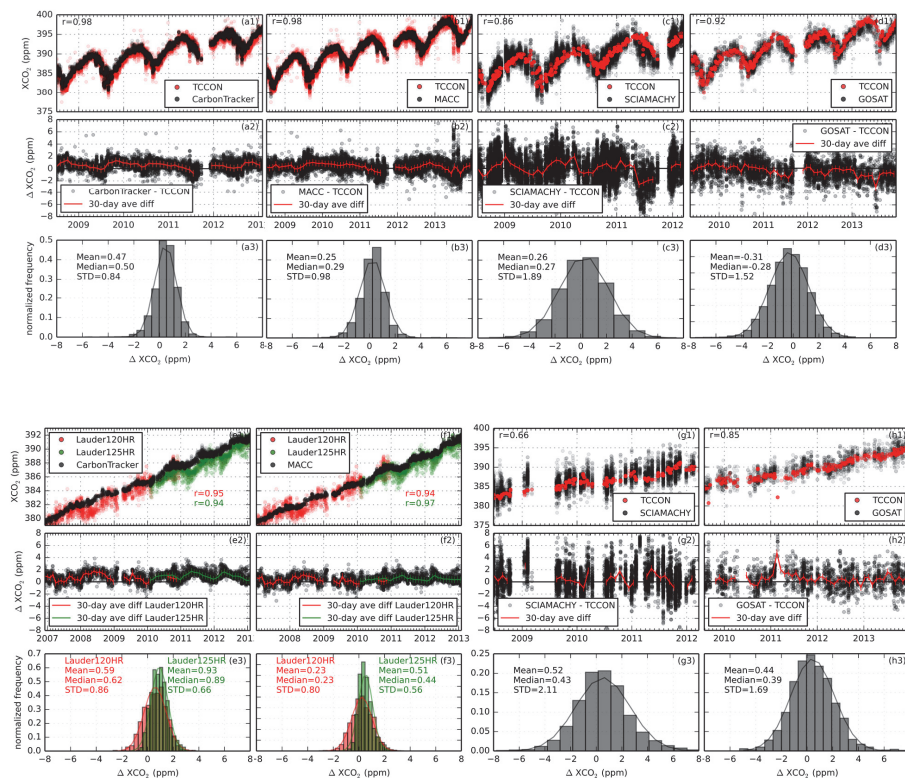


Figure 2. CarbonTracker (CT2013b), MACC, SCIAMACHY, and GOSAT versus TCCON at Laumont (top) and Lauder125 (for models) or Wollongong (for satellites) (bottom). The top plot of each set shows a time series of all geometric matching pairs. The middle plot shows the difference versus TCCON, with the blue line the 30-day average difference. The bottom plot shows a histogram of the differences, indicating an approximate error and bias.

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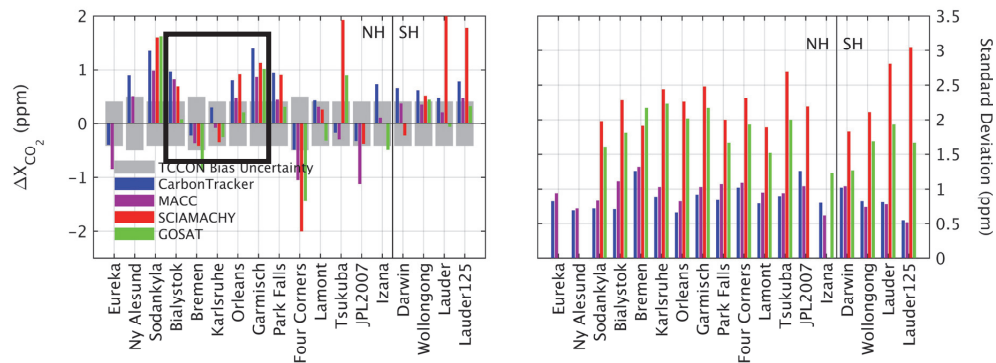


Figure 3. Bias (left) and standard deviation (right) for CT2013b, MACC, BESD-SCIAMACHY, and ACOS-GOSAT versus TCCON stations, arranged from high to low latitude. Comparisons which have a particularly low number of matches are TSUKUBA and LAUDER for SCIAMACHY and LAUDER for GOSAT.

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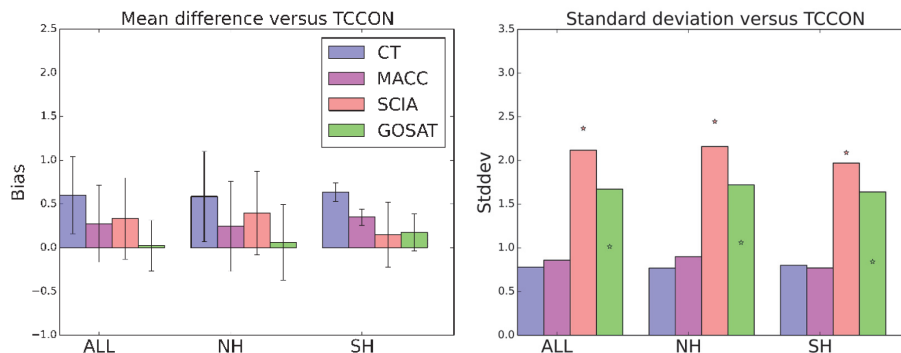


Figure 4. Overall bias (left, with error bars showing the standard deviation of the bias) and standard deviation (right, with stars showing the predicted error for satellites) for most stations (some stations removed, see text).

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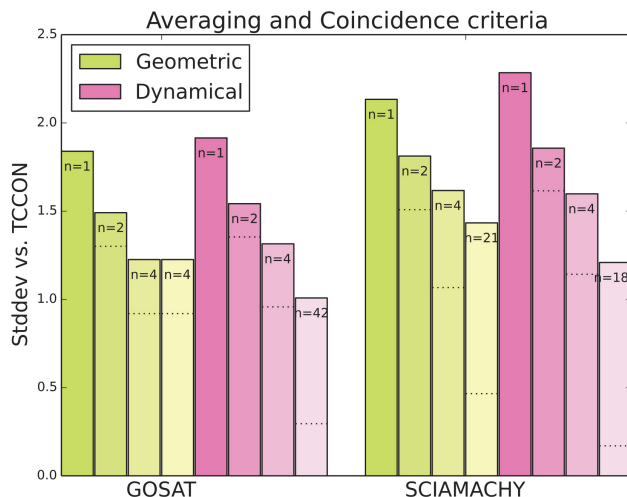


Figure 5. SCIAMACHY and GOSAT standard deviation versus TCCON for different coincidence criteria and # of satellite observations averaged, n , in the Northern Hemisphere. The following consistent set of stations was used for all comparisons: Bialystok, Bremen, Karlsruhe, Orleans, Garmisch, Park Falls, Lamont, Darwin, and Wollongong. The dotted line shows the error if it scaled as the inverse square root of the number of averaged observations. The far right case for each of the categories contains the maximum n that has results for all stations.

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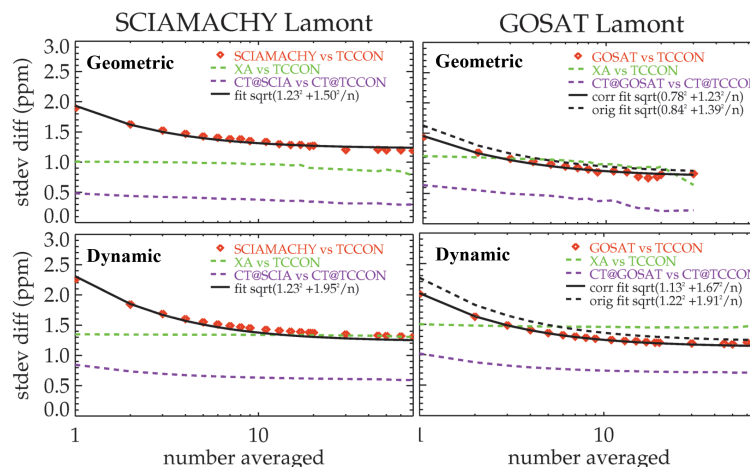


Figure 6. Averaging matches of satellite data versus TCCON at Lamont. As the number averaged increases, the standard deviation versus TCCON decreases. CT2013b at the satellite versus at CT2013b at TCCON (purple) is used to quantitate spatio-temporal mismatch error. The points are fit to Eq. (2) (black). For GOSAT the uncorrected data is also fit (black dashed). We see that in this case, for GOSAT at Lamont, averaging more than about 4 observations improves over the initial guess.

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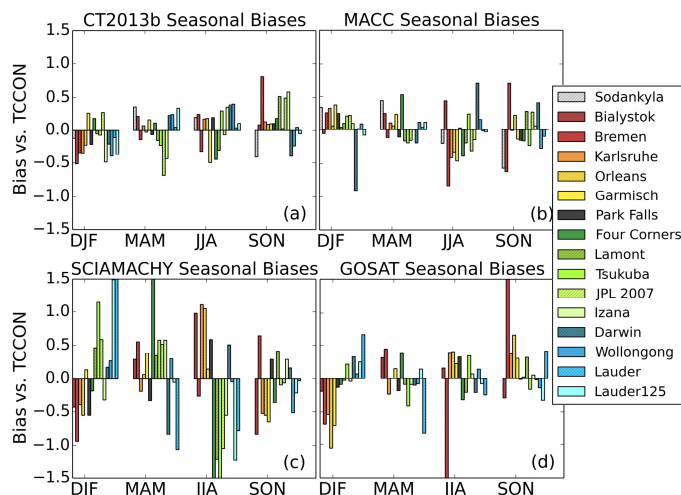


Figure 7. Bias for 3 month groups for each station, where each station is normalized to have 0 yearly bias. For satellites, stations are included when at least 20 matches are found in each season. Dynamic coincidence criteria are used. The station colors are coded by location: far NH gray, European read/yellow, mid-latitude green, SH blue.

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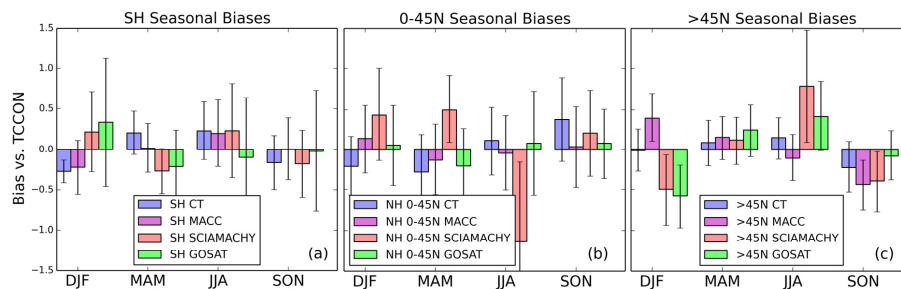


Figure 8. Bias for 3 month groups for Southern Hemisphere (left), 0–45° N (middle), and poleward of 45° N (right). Each group is normalized to have zero average over the year. The Southern Hemisphere (left, Lauder (except SCIAMACHY), Wollongong, and Darwin) has relatively small biases. The results that are significant are that for 0–45° N (Lamont, Tsukuba, Izana), SCIAMACHY is high for MAM, low for JJA; for > 45° N (Bialystok, Karlsruhe, Orleans, Garmisch, Park Falls, Eureka (models), Ny Alesund (models), and Sodankyla (models)), MACC is high, and GOSAT and SCIAMACHY are low in DJF; GOSAT and SCIAMACHY are high in JJA (reducing the seasonal cycle).

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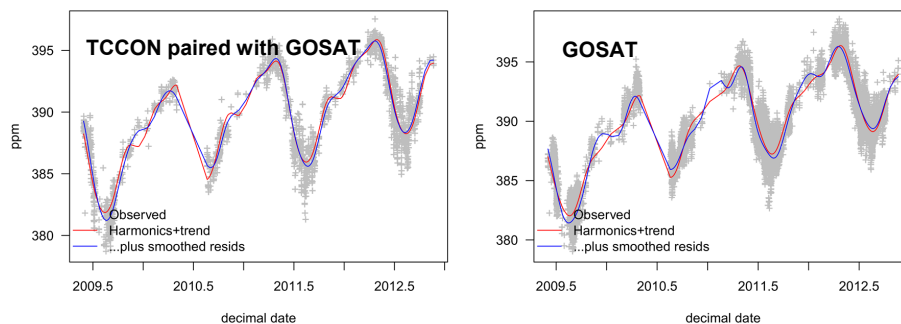


Figure 9. Time series of matches at Park Falls, WI, USA using the dynamic criteria for TCCON and GOSAT with fits by the NOAA CCGCRV program.

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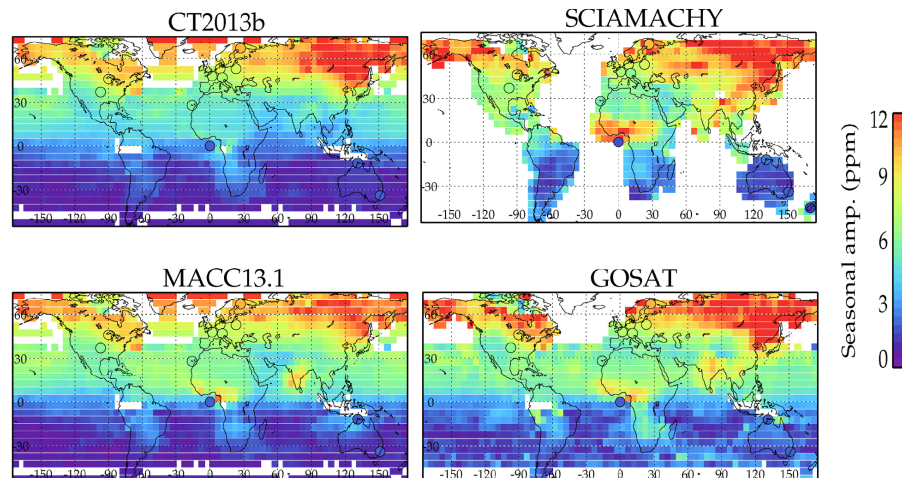


Figure 10. Seasonal Cycle amplitude. The TCCON values are shown in the circles. The averaging is done over $10 \times 10^\circ$ bins every 5° . Comparisons vs. TCCON may be different than Table 4, since Table 4 has very close criteria for models and dynamic coincidence criteria for satellite data. The models are sampled at GOSAT observations.

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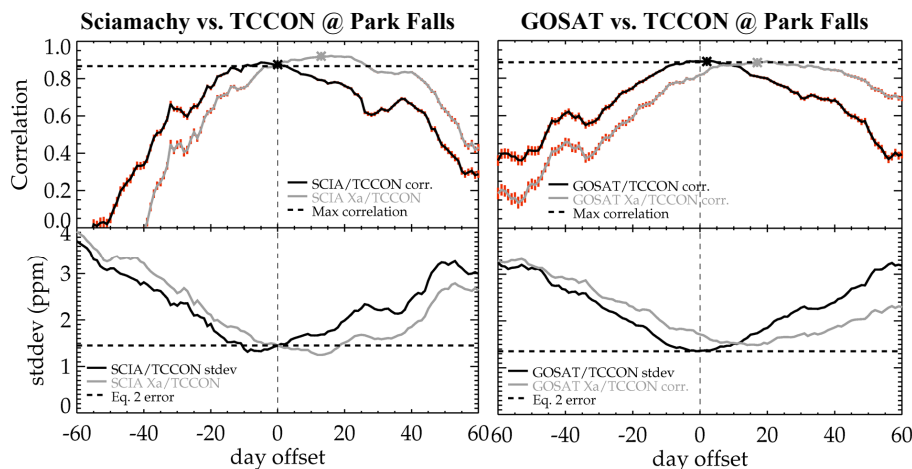


Figure 11. Top: Cross correlation between TCCON and SCIAMACHY (top, left) and GOSAT (top, right) with matches using dynamic criteria at Park Falls. The x axis shows results when satellite data is offset in days versus TCCON. The dashed line shows the expected maximum correlation based on the error (see Eqs. 2, 3). The gray line is the correlation for the satellite priors, which are each out of phase by at least > 10 days. The * is the peak of a polynomial fit of the correlation between -25 and $+25$ days. Bottom: standard deviation between TCCON and SCIAMACHY (bottom, left) and GOSAT (bottom, right). The dashed line shows the Eq. (2) predicted error.

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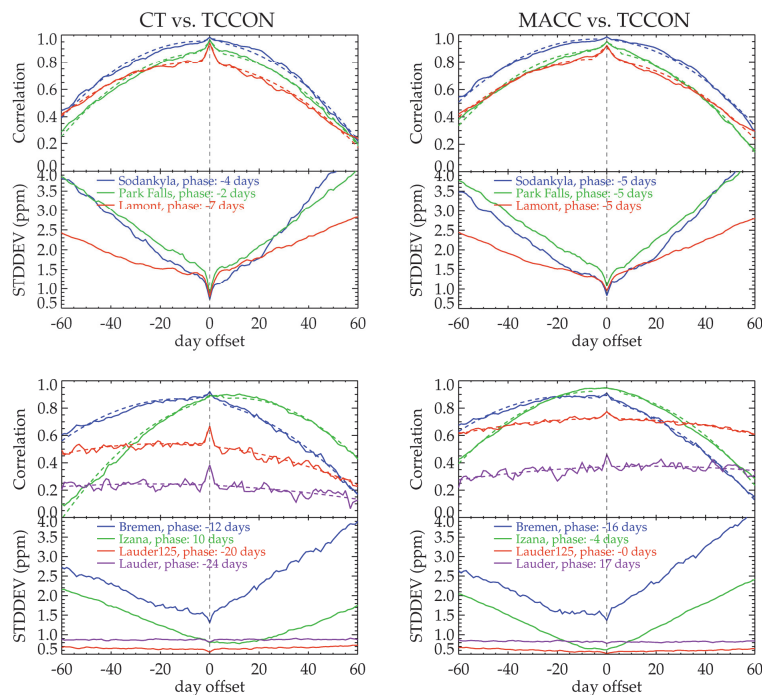


Figure 12. Top: Cross correlation examples between TCCON and CT2013b (left) or MACC (right). Each panel shows the correlation and 2nd order polynomial fits (top) and standard deviation (bottom) versus offset in days of TCCON versus satellite data. The correlation should be at a maximum and standard deviation at a minimum at days offset = 0. The top panels shows examples of stations in with phase less than 10 days. The bottom set shows example stations which have phase differences of at least 10 days for one or both of the models.

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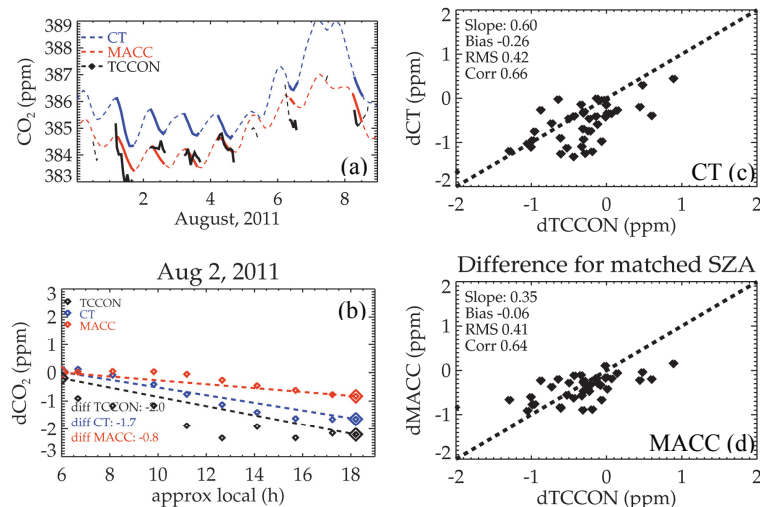


Figure 13. (a) Time series for models and TCCON from 1–8 August 2011 at Bialystok. The end-points of the solid lines show the time points used for comparing daily variability; both diurnal and synoptic variations are seen. (b) Change throughout the day at Bialystok for 2 August 2011. The large diamonds at 6 a.m. and 6 p.m. show the two times with largest difference that have the same solar zenith angle that are used in the analysis. The difference between these times are -2 , -1.7 , and -0.7 ppm for TCCON, CT2013b, and MACC, respectively. Right: CarbonTracker (c) and MACC (d) daily trends versus TCCON daily trends for BIALYSTOK in JJA, from compiling differences like shown in (b). Correlation is seen in the daily trends as compared to TCCON with the daily amplitude for the models smaller than TCCON.