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Evaluation of Regional CO_2 Mole Fractions in the ECMWF CAMS Real-Time Atmospheric Analysis and NOAA CarbonTracker Near-Real-Time Reanalysis With Airborne Observations From ACT-America Field Campaigns

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Key Points:
- Two global CO_2 analysis products are compared with airborne in situ data collected during the first two ACT-America field campaigns
- Both analyses agree reasonably well with observations but show considerable biases in CO_2 in the Mid-Atlantic region during summer 2016
- The two independent analysis products can be used to quantify the overall analysis uncertainties in estimated CO_2 mole fractions

Supporting Information:
- Supporting Information S1

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Abstract This study systematically examines the regional uncertainties and biases in carbon dioxide (CO_2) mole fractions from two of the state-of-the-art global CO_2 analysis products, namely, the Copernicus Atmosphere Monitoring Service (CAMS) real-time atmospheric analysis from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the CarbonTracker Near-Real-Time (CT-NRT) reanalysis from the National Oceanic and Atmospheric Administration (NOAA), by evaluation against hundreds of hours of airborne in situ measurements from the summer 2016 and winter 2017 Atmospheric Carbon and Transport (ACT)-America field campaigns. Both the CAMS and CT-NRT analyses agree reasonably well with the independent ACT-America airborne CO_2 measurements in the free troposphere, with root-mean-square deviations (RMSDs) between analyses and observations generally between 1 and 2 ppm but show considerably larger uncertainties in the atmospheric boundary layer where the RMSDs exceed 8 ppm in the lowermost 1 km of the troposphere in summer. There are strong variations in accuracy and bias between seasons, and across three different subregions in the United States (Mid-Atlantic, Midwest, and South), with the largest uncertainties in the Mid-Atlantic region in summer. Overall, the RMSDs of the CAMS and CT-NRT analyses against airborne data are comparable to each other and largely consistent with the differences between the two analyses. The current study provides uncertainty estimates for both analysis products over North America and suggests that these two independent estimates can be used to approximate regional CO_2 analysis uncertainties. Both statistics are important in future studies in quantifying the uncertainties in regional CO_2 mole fraction and flux estimates.

1. Introduction

The capability to monitor atmospheric carbon dioxide (CO_2) using in situ and remote sensing observations combined with numerical models has rapidly evolved to improve our understanding of biogenic CO_2 sources and sinks and to provide independent estimates of anthropogenic CO_2 emissions (Cavallaro et al., 2018; National Research Council, 2010). Changes in atmospheric CO_2 can be used to infer uptake and release of CO_2 from terrestrial ecosystems and the ocean through inverse methods (Enting, 2002), which in turn can help us understand how the natural carbon cycle responds to both natural and human-induced environmental changes including climate disturbances and human land-use management (e.g., Bousquet et al., 2000; Patra et al., 2005; Rdenbeck et al., 2003; Schimel et al., 2001). Moreover, applied at continental to urban scales, inversions may become critical tools in the future to support policies aimed at limiting greenhouse gas

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emissions by providing independent data-driven verification of emissions accounting (e.g., Lauvaux et al., 2013; National Research Council, 2010).

To support these efforts, a wide variety of CO_2 inversion systems have been developed over the past decade. Two state-of-the-art global CO_2 analysis systems are the Copernicus Atmosphere Monitoring Service (CAMS) real-time atmospheric analysis developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the CarbonTracker Near-Real-Time (CT-NRT) reanalysis developed by the National Oceanic and Atmospheric Administration (NOAA). These two systems provide global gridded estimates of atmospheric CO_2 mole fractions by combining CO_2 observations with modeled CO_2 from atmospheric transport models. Although the end goal is similar, CAMS and CT-NRT have different focuses and differ in their approaches to estimating the four-dimensional state of atmospheric CO_2. CT-NRT is based on the CarbonTracker system, which is designed to keep track of the carbon budget by estimating the sources and sinks of CO_2. CT-NRT optimizes weekly CO_2 surface fluxes by assimilating mainly in situ measurements of CO_2. A long assimilation window of 12 weeks is used to account for long-distance transport of CO_2. The atmospheric transport model used by CT-NRT is an offline tracer transport model driven by winds from a reanalysis data set. To update the atmospheric CO_2 state, the transport model is rerun for the last 2 weeks with the optimized surface CO_2 fluxes for every assimilation cycle. CAMS, on the other hand, aims at providing near-real-time analyses and forecasts of the atmospheric composition including CO_2. Because of the time constraint of near-real-time forecasts, CAMS assimilates column-averaged CO_2 (XCO_2) satellite observations and optimizes atmospheric CO_2 mole fractions in a 12-hr assimilation window. The transport of CO_2 is calculated online together with meteorology in a numerical weather prediction model. Biogenic CO_2 surface fluxes are provided by an online biosphere model and biased corrected in real time throughout the forecast. Given these two widely different approaches to estimating the atmospheric CO_2 distribution, it is informative to compare the CO_2 estimates from CAMS and CT-NRT and evaluate the analyses against independent observations.

The spatiotemporal distribution of atmospheric CO_2 was extensively sampled over eastern United States during the Atmospheric Carbon and Transport (ACT)-America field campaigns (see ACT-America's official website, https://act-america.larc.nasa.gov). ACT-America is a National Aeronautics and Space Administration (NASA) Earth Venture Suborbital mission that aims at studying the transport and fluxes of CO_2 by conducting five airborne campaigns over three subregions spanning the eastern United States. Compared with in situ CO_2 observations from the flask and tower network, the airborne observations from ACT-America provide CO_2 measurements at a higher spatial resolution (5-s averaged data set corresponding to an average distance of 500 m) that can capture CO_2 gradients created by varying weather systems and flux gradients with minimal influences from other factors, such as the diurnal cycle of the boundary layer and biogenic CO_2 fluxes (see, e.g., Hurwitz et al., 2004). Satellite XCO_2 observations are useful to provide a global coverage of the atmospheric CO_2 distribution, but at regional scales the current satellites suffer from long revisit times, lack of data in cloudy conditions, and very limited information about the vertical CO_2 distribution. The airborne CO_2 observations from ACT-America therefore provide an ideal verification data set to evaluate CO_2 analysis products in terms of regional CO_2 distributions over eastern United States.

In this study, we provide a first evaluation of the CAMS analysis and CT-NRT reanalysis of CO_2 against ACT-America airborne measurements from the summer 2016 and winter 2017 field campaigns. We present comprehensive statistics from comparisons with hundreds of hours of airborne in situ measurements to assess the reliability of the global analyses. Furthermore, we compare the analyses and observation mismatches with the differences between the two analyses to investigate whether the differences between the two independent CO_2 estimates can be used to quantify the uncertainties in the estimates. Although these two systems have been separately evaluated against observations—see, e.g., Agust-Panareda et al. (2014); Agust-Panareda et al. (2017); Boussetta et al. (2013); Massart et al. (2016); Tang et al. (2018) for CAMS and its predecessors; and Peters et al. (2005, 2007) for CarbonTracker—this study is unique because it provides the first intercomparison with both the CAMS analysis and CT-NRT reanalysis against independent high-resolution in situ airborne observations of CO_2 that cover a large portion of eastern United States.

2. Data and Methodology

2.1. CAMS Analysis and CT-NRT Reanalysis

CAMS is an atmospheric analysis produced by the Copernicus Atmosphere Monitoring Service focusing on atmospheric composition including aerosols, chemical species, and greenhouse gases (Inness et al., 2019; Massart et al., 2016). The CAMS analysis is produced using the ECMWF four-dimensional variational (4DVar) system (Engelen & McNally, 2005) within the Integrated Forecasting System (IFS; version CY42r1 for 2016 and CY43r1 for 2017), which is one of the world's leading operational global weather prediction systems. Transport of tracers such as CO_2 is carried out online by the IFS model concurrently with the meteorological forecast. Because the semi-Lagrangian advection scheme in IFS is not mass conserving, a global mass fixer is applied to restore mass conservation for the global budget (Agust-Panareda et al., 2017). The IFS model used in CAMS has a horizontal resolution corresponding to approximately 40 km and 137 vertical levels. Further information about the IFS model is documented online (https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model/ifs-documentation). In this study, we used CAMS data interpolated to a 0.25° longitude × 0.25° latitude grid, 137 vertical levels, and 6-hourly instantaneous values.

Due to the time constraints of near-real-time forecasts and analyses, CAMS currently assimilates CO_2 observations from only the Greenhouse Gases Observing Satellite, which has a Sun-synchronous orbit with a revisit period of about 2 weeks. The specific Greenhouse Gases Observing Satellite XCO_2 product used in CAMS is the Bremen Optimal Estimation DOAS product (real-time stream; Heymann et al., 2015). A cycling data assimilation system with a 12-hr assimilation window is used for the CO_2 analysis with the background estimate derived from the short-term forecast initialized from the previous analysis cycle, while the meteorological initial conditions at each forecast cycle come from the ECMWF operational analyses. Surface CO_2 fluxes from the terrestrial biosphere are directly modeled within IFS using the CTESSEL carbon module (Boussetta et al., 2013). Other sources and sinks of CO_2 are prescribed from different inventory sources and data sets (Agust-Panareda et al., 2014; Massart et al., 2016). The CO_2 fluxes are not directly updated by the observations assimilated, but an online flux correction scheme is applied to correct for biases in modeled net ecosystem exchange on a 10-day time scale by comparing the modeled biogenic fluxes with a climatology of optimized fluxes (Agust-Panareda et al., 2016). More details about the CAMS analysis products are available online (https://confluence.ecmwf.int/display/CKB/CAMS+Reanalysis+data+documentation).

CT-NRT is an extension of NOAA's CarbonTracker system (Peters et al., 2005, 2007) aimed at providing more timely results than the formal CarbonTracker product. CarbonTracker operates with at least a 1-year delay, limited by the availability of meteorological driving data and CO_2 observations, in particular, in receiving and processing flask samples. To overcome this time limitation, CT-NRT uses real-time meteorological data, a statistical land flux anomaly model to provide prior CO_2 fluxes, and a small subset of provisional CO_2 observations. We note that although NRT stands for near real time, the goal of CT-NRT is not to provide real-time forecasts of CO_2 like CAMS, and there can be a delay of several months before the latest CT-NRT analyses are available. For this reason we will often refer to the CAMS near-real-time product as an analysis and the CT-NRT product as a reanalysis. The transport of CO_2 in CarbonTracker and CT-NRT is simulated by the offline tracer transport model TM5, which is run globally at a resolution of 3° longitude × 2° latitude horizontal resolution and 25 vertical layers and in a nested grid over North America at 1° × 1° resolution. This study used CO_2 mole fractions from CT-NRT v2017 on the regional nested high-resolution grid available as 3-hourly average values.

The observations in CT-NRT include ground-based CO_2 measurements from marine sampling stations and continental tower sites and are assimilated using an ensemble Kalman Filter to scale a set of prior surface CO_2 fluxes to yield an atmospheric CO_2 distribution that matches more closely the observed values. Only land biosphere and ocean fluxes are updated in the assimilation. A long assimilation window of 12 weeks is used to capture remote influences of surface CO_2 fluxes. After finding an optimal set of surface fluxes, CT-NRT updates the atmospheric CO_2 mole fractions by rerunning the atmospheric transport model with the optimized fluxes for two weeks at the beginning of the assimilation window and then shifts the window forward by 2 weeks. CO_2 fluxes and mole fractions that fall outside the assimilation window become the analysis fields. The CT-NRT system is further documented online (https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT-NRT/), and the CarbonTracker documentation is available online (https://www.esrl.noaa.gov/gmd/ccgg/carbontracker/CT2016_doc.php).

2.2. ACT-America Field Campaigns and Data

ACT-America's objectives are as follows: (1) quantify and reduce atmospheric transport uncertainties, (2) improve regional-scale estimates of CO_2 and methane fluxes, and (3) evaluate the sensitivity of Orbiting Carbon Observatory-2 (OCO-2) XCO_2 measurements to regional variability in tropospheric CO_2. To achieve

Table 1
A Brief Overview of the Research Flights Performed by NASA's C-130 and B-200 Over the Three ACT-America Subregions During the Summer 2016 and Winter 2017 Field Campaigns

Description	Summer 2016			Winter 2017		
Summary						
Dates	15 Jul to 28 Aug 2016			1 Feb to 10 Mar 2017		
Research flights	25			25		
Flight hours	225			216		
Straight-level legs	182			157		
Vertical profiles	272			216		
Regions	**Mid-Atlantic**	**Midwest**	**South**	**South**	**Midwest**	**Mid-Atlantic**
Dates	15–30 Jul	1–15 Aug	16–28 Aug	1–12 Feb	13–27 Feb	1–10 Mar
Research flights	7	9	9	8	9	8
Straight-level legs	51	62	69	48	67	42
Vertical profiles	88	98	86	64	86	66

Note. Shown are the dates, number of research flights, flight hours, number of horizontal or straight-level flight legs, and number of vertical profiles. The profiles were obtained via spirals, en route ascents and descents, and during takeoffs and landings. NASA = National Aeronautics and Space Administration; ACT = Atmospheric Carbon and Transport.

these goals, a total of five airborne field campaigns were conducted over three subregions in the eastern United States (Mid-Atlantic, Midwest, and South) during four different seasons. Two coordinated aircraft were deployed during each field campaign over a period of 6 weeks, with 2 weeks spent in each region. In this paper, we report on the findings of the first two field campaigns, which were conducted in the summer of 2016 and winter of 2017. Table 1 provides an overview of the research flights that were performed during these two campaigns.

The aircraft collected a wealth of data from in situ and remote sensing measurements of meteorological variables, greenhouse gases (CO_2 and methane), and other trace gases (e.g., carbon monoxide, ozone, and carbonyl sulfide) in fair weather conditions and across weather systems. The flight patterns were designed on a case-by-case basis to address one or more of the mission objectives and include both long horizontal legs in the boundary layer and free troposphere, often over distances greater than 600 km, as well as several vertical profiles obtained via spirals, en route ascents and descents, and during takeoffs and landings. Three types of research flight patterns were performed: (1) frontal weather research flights to obtain greenhouse gas structures across frontal boundaries, (2) fair weather research flights for measuring greenhouse gas variability over large regions associated with surface fluxes, and (3) OCO-2 underflights to compare airborne CO_2 measurements with XCO_2 retrievals from OCO-2. Figures 1 and 2 show the flight tracks for the summer 2016 and winter 2017 campaigns, respectively, plotted on top of the average CO_2 mole fractions from the CAMS analysis and CT-NRT reanalysis. The two instrumented NASA aircraft, C-130 and B-200, were operated out of NASA Langley Research Center and NASA Wallops Flight Facility for the Mid-Atlantic part of the campaign; Lincoln, Nebraska for Midwest; and Shreveport, Louisiana for South. The B-200 aircraft was mainly equipped with in situ sensors measuring meteorological variables and greenhouse gases, while the C-130 aircraft was equipped with both lidar remote sensing and in situ sensors measuring both trace gases and meteorological variables. Observations were typically conducted between 10 and 17 LST, focusing on mid-day, well-mixed conditions in the atmospheric boundary layer.

This study used the data set "ACT-America: L3 Merged In Situ Atmospheric Trace Gases and Flask Data, eastern USA" (Davis et al., 2018). Observed CO_2 mole fractions were obtained from quality-controlled 5-s averaged PICARRO Cavity Ring Down Spectrometer measurements, which have a precision of 0.15 ppm. Given that the average speeds of the C-130 and B-200 aircraft were 120 and 100 m/s, respectively, the 5-s airborne measurements yield a spatial resolution of about 500 m.

2.3. Evaluation Strategy and Metrics

In our evaluation of the CAMS and CT-NRT analyses of atmospheric CO_2 mole fractions against airborne observations collected during the ACT-America field campaigns, we first excluded observational data points with missing or flagged data in aircraft altitude, barometric pressure, or in situ CO_2 mole fraction. We also

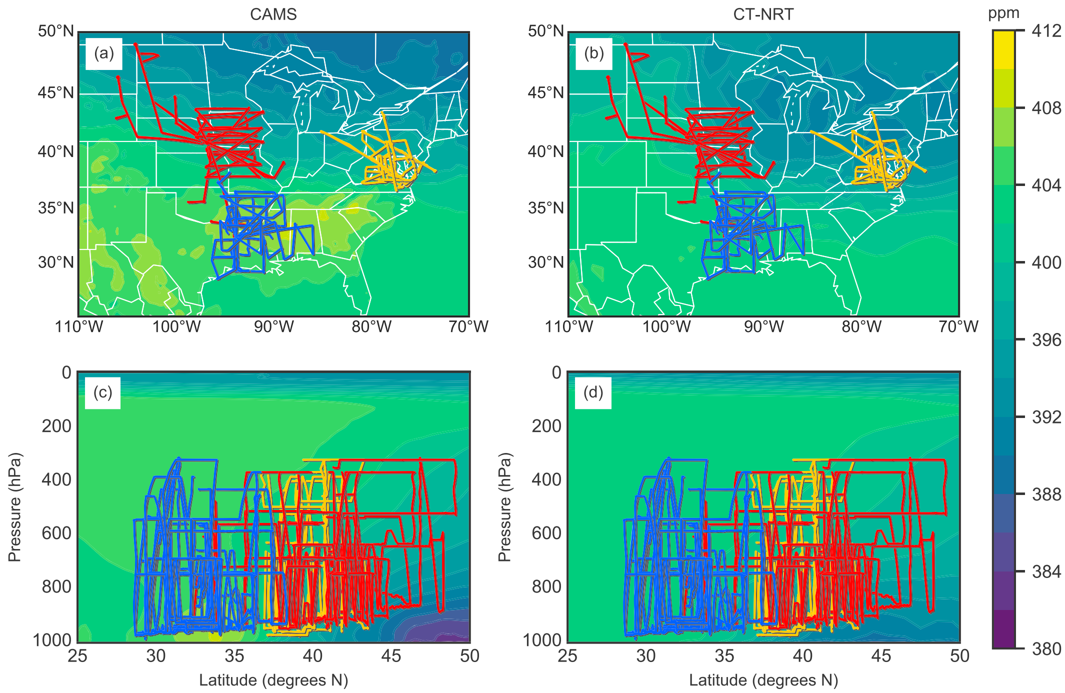

Figure 1. Flight tracks during the ACT-America summer 2016 campaign in Midwest (red lines), Mid-Atlantic (yellow lines), and South (blue lines). (a, b) The flight tracks with respect to longitude and latitude. (c, d) The same tracks with respect to latitude and vertical level in nominal pressure coordinates. The shadings in (a) and (b) show the mean afternoon CO_2 mole fractions for July–August 2016 at around 850 hPa for the CAMS analysis and CT-NRT reanalysis, respectively. Similarly, the shadings in (c) and (d) show the zonally averaged mean afternoon CO_2 mole fractions over the domain for July–August 2016 for the CAMS analysis and CT-NRT reanalysis. CAMS = Copernicus Atmosphere Monitoring Service; CT-NRT = CarbonTracker Near-Real-Time.

excluded data collected during takeoff and landing to limit potential influences of local fossil fuel emissions close to the airports. CO_2 observations during takeoffs in the morning can be especially problematic because the atmospheric boundary layer may still be stable and stratified at this time, which could lead to large horizontal and vertical CO_2 gradients that we do not expect the analyses to accurately capture. Takeoffs and landings as well as straight-level legs and vertical profiles were identified using a new set of maneuver flags (V4.4) which will be provided with the ACT-America data set in future releases (see supporting information Figures S1 to S4).

After identifying which flight data to use, we linearly interpolated in space and time the CO_2 analysis fields from CAMS and CT-NRT to each of the valid ACT-America airborne measurements at the observed time and location. The vertical interpolations were performed using the flight barometric altitude because the CO_2 analyses provide pressure values at each grid point rather than the geometric heights.

Our intercomparison focuses on mainly two metrics. The first metric is the mean difference between modeled values and observations, defined as

$$\mathrm{MD} = \frac{1}{N}\sum_{i=1}^{N}(x_i - y_i),$$

where y_i is a measured CO_2 mole fraction, x_i is the corresponding CO_2 value in the analysis, and N is the total number of observations. Given the high precision of the PICARRO instrument, any systematic mean differences between CAMS or CT-NRT and observations are indicative of biases in the analyses. The second metric is the root-mean-square deviation (RMSD) between analysis CO_2 and observations, calculated as

$$\mathrm{RMSD} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2}.$$

The RMSD is a measure of both systematic and random model-observation differences with a stronger emphasis on larger mismatches. These statistics were calculated in 1-km bins from the surface up to 10 km

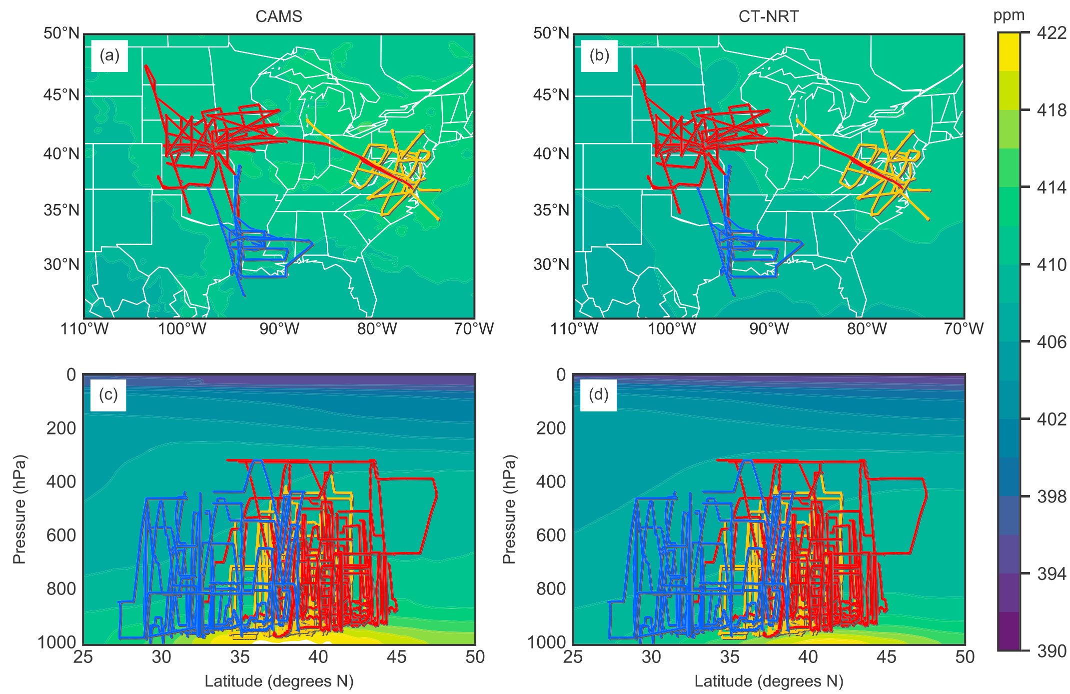

Figure 2. Same as Figure 1 but for the ACT-America winter 2017 campaign. The shadings show the mean afternoon CO_2 mole fractions for January–February 2017.

according to the aircraft altitude above ground level of the airborne observations. All altitudes in this paper are therefore given with respect to local ground level unless otherwise noted. Bins with fewer than 100 data points are not presented. We also calculated the RMSDs between CAMS and CT-NRT to assess whether the differences between these two relatively independent CO_2 analyses can be used to estimate the uncertainties in the CO_2 analysis fields. To summarize our evaluation strategy, our emphasis is on the overall mean differences and RMSDs between CO_2 analyses and observations as a function of altitude in the three subregions and two seasons.

Finally, we provide a summary of the CAMS and CT-NRT analysis performance for all individual research flights visualized using Taylor diagrams (Taylor, 2001). Taylor diagrams illustrate the degree of correspondence between estimated and observed values based on three metrics: the Pearson correlation coefficient, RMSD, and standard deviation. Due to the construct of the diagram, all statistics are based on the centered differences with the differences in the estimated and observed means removed. The Taylor diagrams presented here are thus useful for evaluating the structures of atmospheric CO_2 mole fractions in CAMS and CT-NRT but do not provide information about overall biases in the analyses.

3. Results and Discussion

3.1. Summer 2016

Figure 3 shows a comparison of the mean CO_2 mole fractions profiles averaged over all flight measurements in all three subregions, along with the mean CO_2 profile in each subregion for the 2016 summer phase of the ACT-America field campaign. Averaged over all flights in all subregions, the mean CO_2 profiles simulated by both the CAMS and CT-NRT global analyses interpolated to the flight-level positions show a high level of agreement with the mean profile of the ACT-America measurements. All estimates show much reduced CO_2 mole fractions below 2 km with the lowest values near the surface caused by biogenic uptake of CO_2 through photosynthesis. Mean CO_2 mole fractions increase initially more rapidly in the lower atmosphere to a value of around 400 ppm at 3 km for both analyses and ACT-America measurements and then continue to rise gradually with increasing altitude to between 403 and 405 ppm at the highest level of aircraft measurements. The three subregions display considerable differences in the mean vertical CO_2 profiles which reflect varying regional CO_2 surface fluxes and atmospheric transport dynamics, as well as different aircraft sampling strategies in the different subregions. The South subregion shows the most distinct profile, with

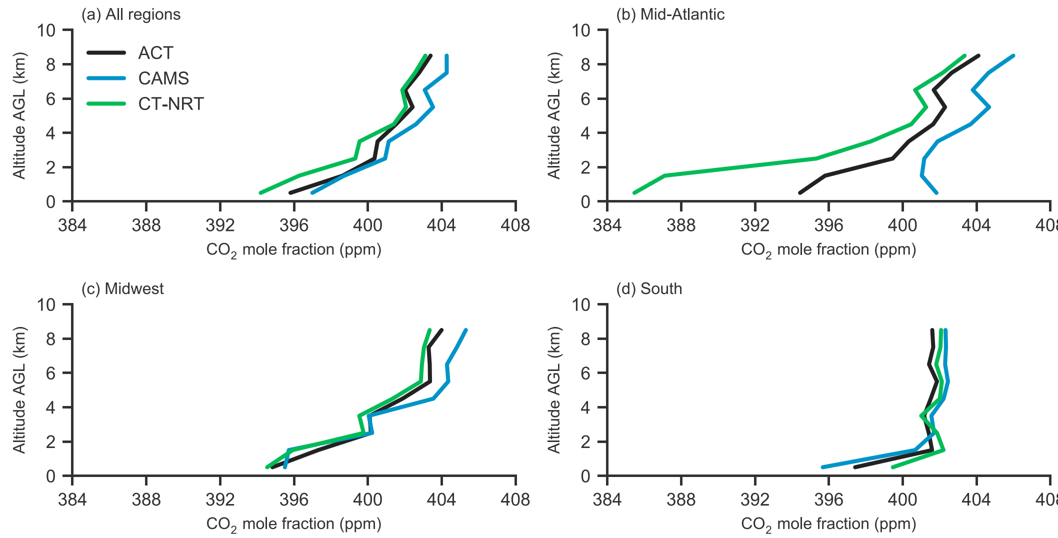

Figure 3. Vertical distribution of CO_2 mole fractions averaged over all flights during the ACT-America summer 2016 campaign in (a) all subregions, (b) Mid-Atlantic, (c) Midwest, and (d) South. The CO_2 profile based on ACT-America airborne observations is shown as a black line. The CAMS and CT-NRT CO_2 products were linearly interpolated in space and time to the ACT-America flight tracks. ACT = Atmospheric Carbon and Transport; CAMS = Copernicus Atmosphere Monitoring Service; CT-NRT = CarbonTracker Near-Real-Time; AGL = above ground level.

a rapid increase in CO_2 mole fractions from the surface to 2 km and then a nearly flat CO_2 profile with CO_2 values around 402 ppm above 2 km. This homogeneous upper-air distribution of CO_2 mole fractions is indicative of a well-mixed air mass, which was likely advected from the Gulf of Mexico considering that several research flights in South were aimed at sampling this Gulf of Mexico inflow of air under prevailing southerly winds.

Figure 4 shows the mean differences between the analyses CO_2 profiles and observed profiles for all flights and when separating the research flights according to the general weather conditions. There are some systematic biases in both analyses, especially near the surface. Averaged over all subregions, the CT-NRT reanalysis has a systematic low bias of about 1.5 ppm below 2 km, while the CAMS analysis has a slight high bias of around 1 ppm above 2 km. Further examination shows that most biases in both the CAMS and CT-NRT analyses originate from the Mid-Atlantic region (Figures 4c and 4d). In the Mid-Atlantic, the CT-NRT analysis has a low bias of as much as 9 ppm below 2 km that reduces to below 0.8 ppm at 3 km and above. The CAMS analysis has a high bias of more than 7 ppm near the surface that drops to around 2 ppm above 2 km. Across the other two subregions, CT-NRT shows a slight low bias in the Midwest of 0.2 ppm above 2 km and a high bias in South of 0.5 ppm above 2 km. In these regions CAMS tends to have a low bias in the range of 0.9–1.8 ppm below 2 km (except for the lowest level in the Midwest) and a high bias of about 1.3 ppm above 4 km in the Midwest and 0.6 ppm above 2 km in South.

The absolute biases in CAMS are larger during stormy weather conditions compared with fair weather conditions in all subregions. In CT-NRT, on the other hand, the absolute biases tend to be larger during fair weather conditions, with the South region being the exception. Both analyses show generally larger CO_2 values near the surface during stormy weather compared with fair weather, which is also seen in the ACT-America airborne observations, especially for the Mid-Atlantic and Midwest regions (not shown). This difference in near-surface CO_2 mole fractions between stormy and fair weather cases is likely to a large part due to reduced photosynthesis during stormy weather caused by increased cloudiness, combined with synoptic-scale transport during frontal passages. Thus, it is plausible that some of the biases in CAMS during stormy weather conditions are associated with systematic errors in the modeled net ecosystem exchange from the online land carbon model, although further analysis is required to confirm whether this is the case or not.

The RMSDs between the analyses and the ACT-America observations are shown in Figure 5. Over all subregions, CAMS and CT-NRT show similar RMSD values below 3 km, which increase to about 8.5 ppm in the lowermost 1 km of the atmosphere. Above 3 km the RMSDs are larger for CAMS (around 1.9 ppm)

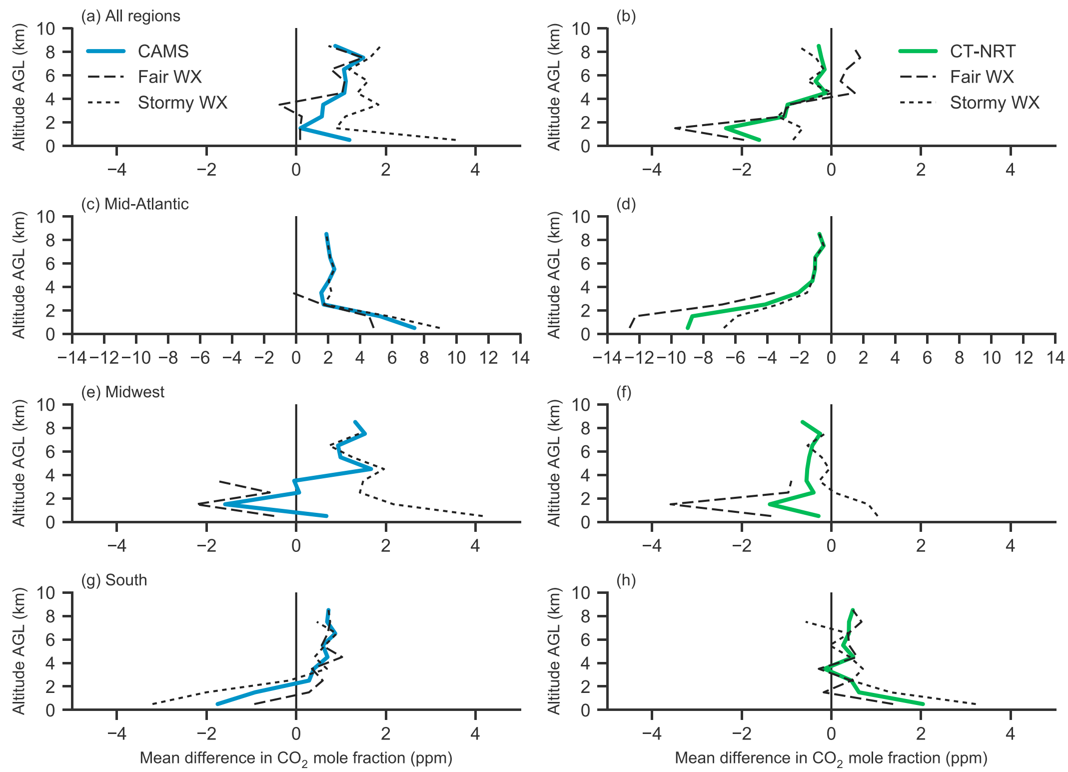

Figure 4. Vertical variation in mean differences of CO_2 mole fractions between CAMS and airborne observations (a, c, e,g) and between CT-NRT and airborne observations (b, d, f, h), for all flights during the ACT-America summer 2016 campaign in (a) all subregions, (b) Mid-Atlantic, (c) Midwest, and (d) South. Solid lines show the mean differences over all flights, dashed lines show the mean differences during fair weather cases, and dotted lines show the mean differences during stormy weather cases. CAMS = Copernicus Atmosphere Monitoring Service; CT-NRT = CarbonTracker Near-Real-Time; AGL = above ground level.

than for CT-NRT (around 1.2 ppm). The RMSDs are smallest in the South region and largest in the Mid-Atlantic region for both analyses, with the Midwest RMSDs lying somewhere in between. The South and Mid-Atlantic regions also display the smallest and largest spatial CO_2 variability, respectively, according to the CO_2 analyses (see Figure 1). We further note that the CAMS and CT-NRT biogenic fluxes show large discrepancies around the Mid-Atlantic region and especially in the U.S. Corn Belt (supporting information Figures S5a and S5b), which is typically upwind of this region. The large biases and RMSDs in the Mid-Atlantic region are therefore likely related to erroneous terrestrial biosphere fluxes. For CAMS, the flux correction scheme based on climatology could lead to large regional biases in this region. Finally, the Mid-Atlantic region is the most highly populated of the three regions and have large spatial and temporal variations in fossil fuel emissions, which can lead not only to biases in the different analyses but also to large RMSDs due to sampling errors. To fully understand why the analyses disagree over the Mid-Atlantic region would require further investigation into the internals of the analysis systems.

To evaluate the RMSDs without the influence of systematic mean differences, we recalculated the RMSDs after first removing the mean differences at each altitude bin for each CO_2 analysis and subregion. The reduction in RMSDs after applying this "bias correction" is illustrated with shading in Figure 5. CAMS benefits the most from the bias correction, especially at higher altitudes above 3 km, with RMSD reductions around 0.4 ppm. The improvement in CAMS in terms of RMSDs is particularly noticeable in the Mid-Atlantic region, where the RMSDs decrease by about 2 ppm in the lowermost 2 km of the atmosphere and 0.8 ppm above 2 km after removing the biases. CT-NRT shows generally only marginal reductions in RMSDs after the bias correction. The removal of biases has the largest effect on CT-NRT in the Mid-Atlantic region near the surface, where the RMSDs below 2 km decrease by 3–4 ppm after the bias correction. This analysis suggests that there is significant room for CAMS to reduce its CO_2 analysis errors by correcting the biases. In contrast, a major part of the uncertainties in the CT-NRT reanalysis are due to unsystematic errors.

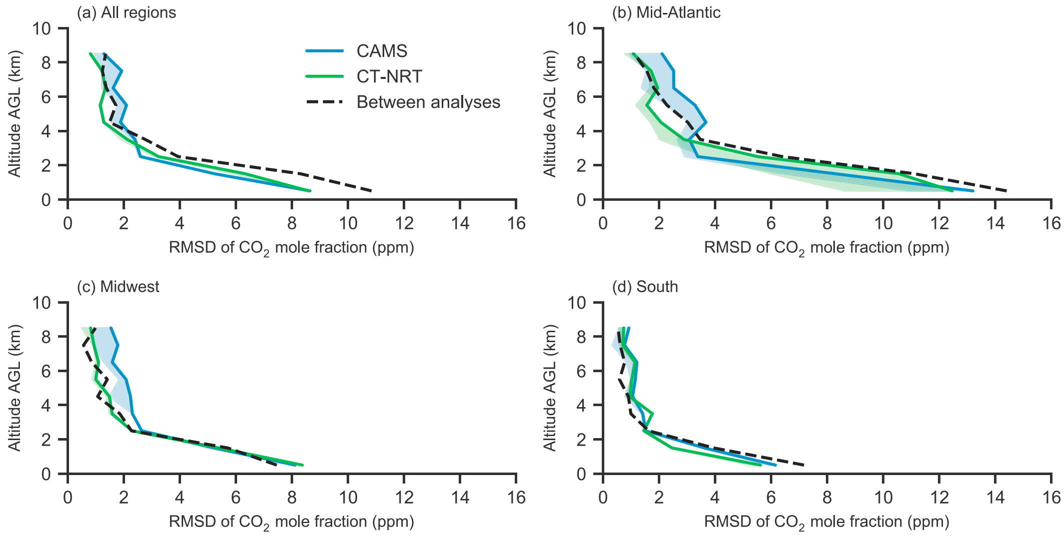

Figure 5. Vertical distribution of RMSDs between CAMS/CT-NRT and observations in terms of CO_2 mole fractions for all flights during the ACT-America summer 2016 campaign in (a) all regions, (b) Mid-Atlantic, (c) Midwest, and (d) South. The blue lines show the RMSDs between CAMS and ACT-America observations, the green lines show the RMSDs between CT-NRT and ACT-America observations, and the black dashed lines show the RMSDs between the two CO_2 analysis products after removing the model-observation mean differences from CAMS. The shading indicates the reduction in RMSDs after subtracting the mean model-observation differences at each altitude bin (see Figure 4) for each region and product. RMSD = root-mean-square deviation; CAMS = Copernicus Atmosphere Monitoring Service; CT-NRT = CarbonTracker Near-Real-Time; AGL = above ground level.

Figure 5 also shows a black dashed line that indicates the RMSDs between CAMS and CT-NRT after removing the biases in CAMS. We chose to exclude the CAMS biases to focus on the random error component of the analyses; the CAMS biases are likely to be addressed and reduced in future iterations of the system. The overall RMSDs between CAMS and CT-NRT show vertical profiles that are highly consistent with the RMSDs between the analyses and ACT-America observations in all subregions. The RMSDs between analyses are slightly larger below 1 km than the RMSDs between either of the analyses and observations and slightly lower above 3 km in the South region. Nevertheless, this result is promising because it suggests that the analysis uncertainties in CO_2 mole fractions from CAMS or CT-NRT can be approximated using the differences between the two analyses, independent of any observations. A key factor behind this result is that the CO_2 analyses from CAMS and CT-NRT are to a large degree independent, and their analysis errors are therefore not highly correlated, which would otherwise result in an underestimation of the analysis uncertainties. Estimations of analysis uncertainties using the differences between CO_2 analysis products can be valuable as a baseline reference for future studies in quantifying the uncertainties of regional CO_2 mole fractions and flux estimates.

Next, we evaluated how the spatial and temporal interpolations of the CO_2 analyses affect the resulting RMSDs. Figure 6 shows the change in RMSDs after excluding the horizontal, vertical, and temporal interpolations and instead choosing the closest grid point, vertical level, and analysis time, respectively. The RMSD changes are shown with respect to the default case when all interpolation methods are used. For CAMS, the temporal interpolation has the largest effect on the results, reducing RMSDs closest to the surface by, on average, 0.4 ppm when considering all regions. The largest RMSD reductions due to temporal interpolation are found in the Mid-Atlantic region. The other interpolation methods have a marginal effect on the RMSDs in CAMS. The CT-NRT reanalysis generally benefits the most from the vertical interpolation, and secondary from horizontal interpolation, especially near the surface in the Mid-Atlantic region. Temporal interpolation has the least effect on the CT-NRT results. These results are consistent with the temporal and spatial resolutions of the CO_2 analysis data that we used. The CAMS analysis has a comparably high horizontal and vertical resolution, but here we used 6-hourly instantaneous CO_2 fields. Based on these results, it is likely that the magnitude of mean differences and RMSDs between CAMS and ACT-America observations in the earlier analyses would decrease further if we used CAMS data with a higher temporal resolution. CT-NRT produces 3-hourly averaged CO_2 mole fractions, which by construct are smoothed in time; thus, it

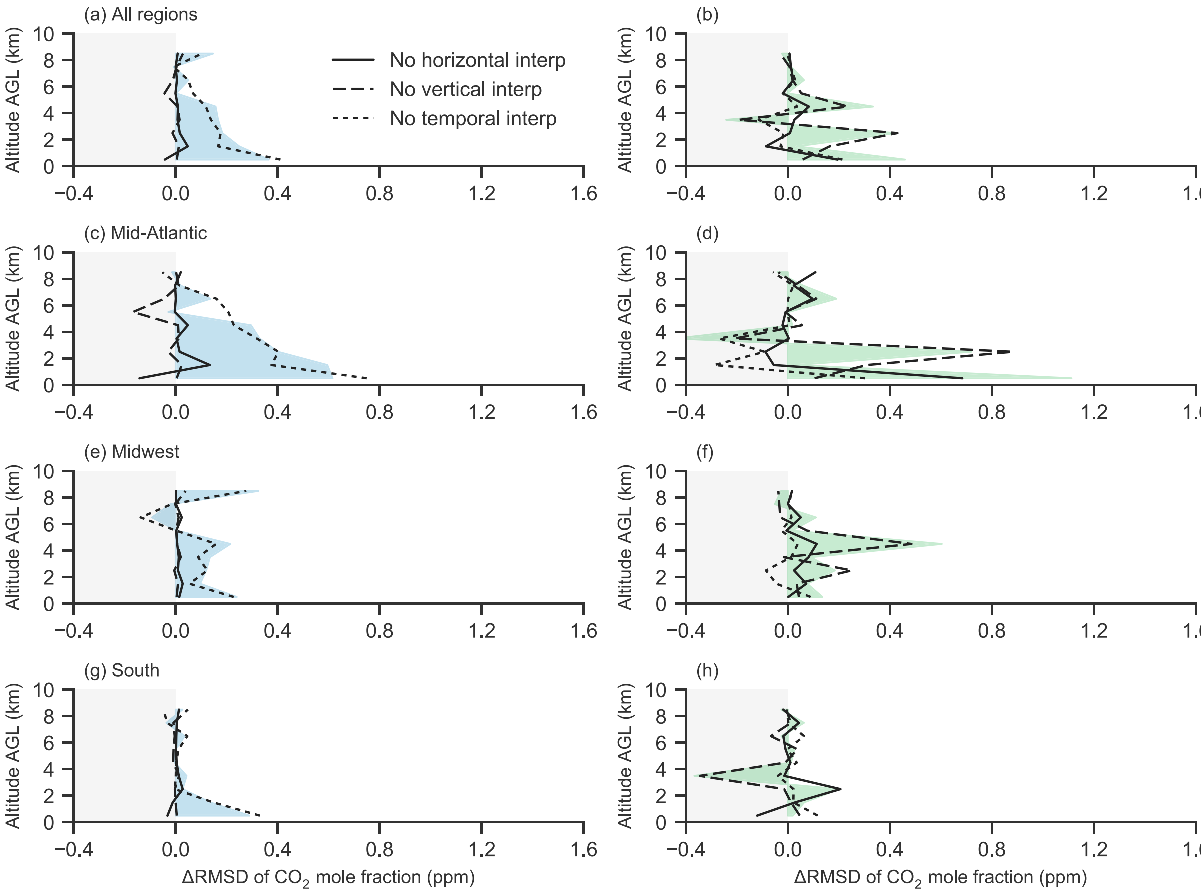

Figure 6. Change in RMSDs (ΔRMSD) of CO_2 mole fractions due to change in interpolation method of model data for all flights during the ACT-America summer 2016 campaign in (a, b) all regions, (c, d) Mid-Atlantic, (e, f) Midwest, and (g, h) South. The results for CAMS are shown in the left column and the results for CT-NRT in the right column. ΔRMSDs are shown with respect to when all interpolation methods (horizontal, vertical, and temporal interpolation) are used. The colored shading indicates the ΔRMSD when no interpolation is performed. Gray shading indicates when RMSDs are reduced when a particular interpolation method is omitted. RMSD = root-mean-square deviation; AGL = above ground level.

is not surprising that CT-NRT does not benefit much from temporal interpolation. However, the relatively course vertical resolution of the atmospheric transport model in CT-NRT (25 vertical layers) appears to lead to some representation errors, and CT-NRT would likely benefit from a higher vertical resolution.

The analyses so far have focused on the overall mean differences and RMSDs between CO_2 analyses and observations for all flights. Figure 7 shows the evaluation of CAMS and CT-NRT against ACT-America airborne observations for each individual research flight, summarized in Taylor diagrams. (For a visualization of the CO_2 mole fractions along the flight tracks in observations and analyses, see supporting information Figures S6 to S13.) The research flights were further separated into straight-level legs, which sample mostly the horizontal CO_2 variations and vertical profiles sampling the vertical CO_2 variations. The Taylor diagram compares the analysis CO_2 mole fractions with observed values in terms of correlation coefficient, standard deviation, and centered RMSD (cRMSD). Here we normalized the analysis standard deviations and cRMSDs by the observed standard deviations to show different research flights in the same graph. Thus, an ideal analysis should have a high correlation, a standard deviation ratio close to 1, and consequently a low normalized cRMSD.

Figure 7 reveals a generally high correspondence between the CO_2 analysis and airborne CO_2 observations from ACT-America. Most of the points in the diagram lie below the 1 ppm normalized cRMSD contour, which indicates that the analysis cRMSDs are smaller than the variability in the observed CO_2. Both analyses show high correlations with the observed CO_2, with a median correlation coefficient of 0.69 for CAMS and 0.71 for CT-NRT when considering all regions and flight legs. CAMS shows a higher number of cases where the correlation coefficient is close to 0 or negative, especially in the South region. The variances of

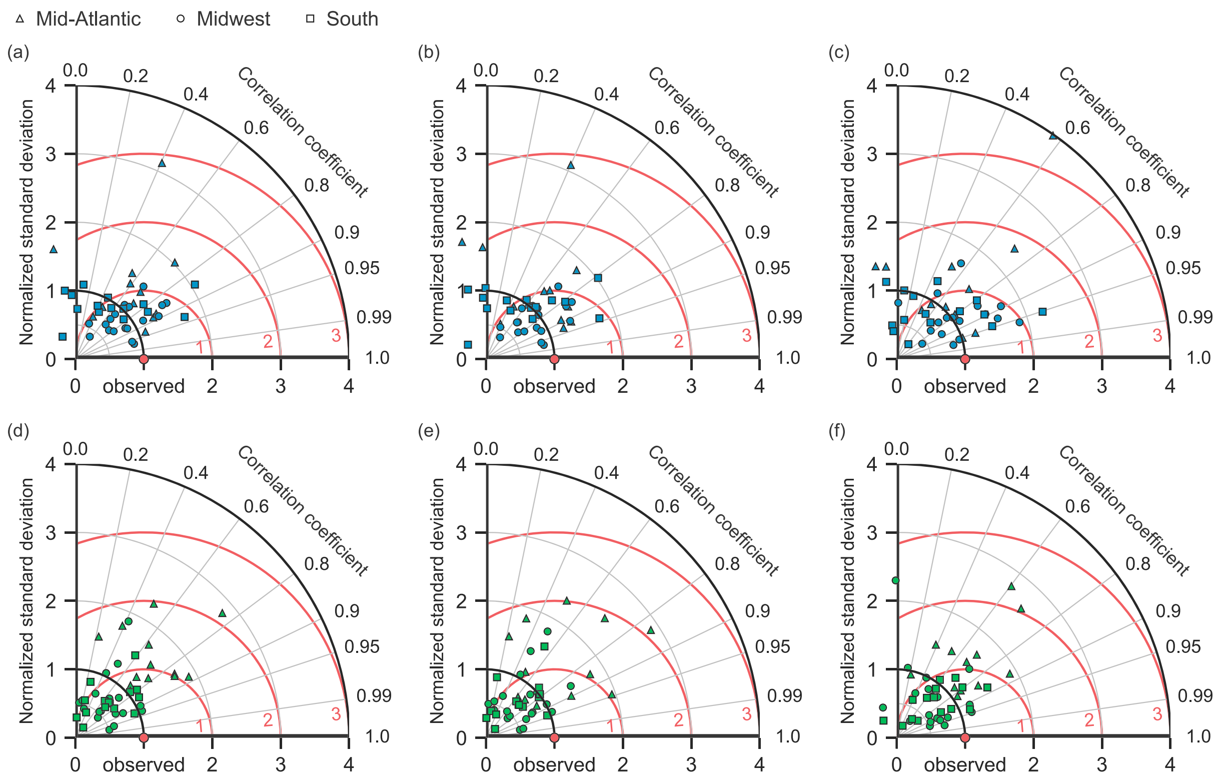

Figure 7. Taylor diagram comparing CO_2 mole fractions in the CO_2 analyses and airborne observations from the summer 2016 ACT-America field campaign for (a–c) Copernicus Atmosphere Monitoring Service and (d–f) CarbonTracker Near-Real-Time. The left column shows the metrics calculated using all flight legs, the middle column for only straight-level legs, and the right column for only vertical profiles. Each point in the diagram depicts the correspondence between analysis CO_2 and observations for a particular research flight. Points closer to the red point labeled "observed" show the closest agreements with observations. The correlation between analysis and observed CO_2 values is shown by the azimuthal angle (gray straight contours), the ratio of the standard deviations in the analysis and observations is proportional to the radial distance from the origin (gray curved contours, with the black contour indicating a ratio of 1), and the centered root-mean-square deviation between the analysis and observations is proportional to the distance from the red circle (red contours, contoured every 1 ppm). Flights with less than 100 data points are omitted.

analysis CO_2 mole fractions along the flight tracks show a reasonable agreement with observations. There is a tendency for CT-NRT to underestimate the CO_2 variability in the Midwest and South regions for both straight-level legs and vertical profiles and overestimate the variability in the Mid-Atlantic. Nevertheless, this analysis of individual research flights shows that the CO_2 analyses can capture realistic structures in the CO_2 distribution over eastern North America in summer.

3.2. Winter 2017

Figure 8 shows the mean CO_2 mole fraction profiles averaged over all flight measurements during the 2017 winter phase of the ACT-America field campaign. First, the mean profiles of both analyses and ACT-America show a reversal of the vertical CO_2 gradient from increasing with altitude during the summer of 2016 to decreasing with altitude during the winter of 2017, as is expected due to the much-reduced photosynthesis in winter and continued CO_2 release from respiration and fossil fuel emissions. The net increase in CO_2 over this 6-month period is about 5 ppm in the free troposphere averaged over all ACT-America flight-level measurements, but the mean net change close to the surface is as high as 10–20 ppm. When comparing the CO_2 analyses to the observed CO_2 mole fractions, we find that the mean CO_2 profiles interpolated from the CT-NRT reanalysis agree exceptionally well with the ACT-America 2017 winter measurements across all subregions except for the lowest 1 km in the Midwest. The CAMS analysis appears to capture the vertical variations well but has a systematic high bias across all subregions throughout the whole atmospheric column, ranging from almost 5 ppm near the surface to a near persistent ~1.9 ppm high bias above 2 km when considering all regions (also see supporting information Figure S13). The South region displays the largest biases close to the surface and smallest biases higher up in the atmosphere compared with the other two regions. We suspect that the biases in CAMS can be attributed to an overestimation of biological respiration given the larger net ecosystem exchange in CAMS compared with CT-NRT during the winter 2017 cam-

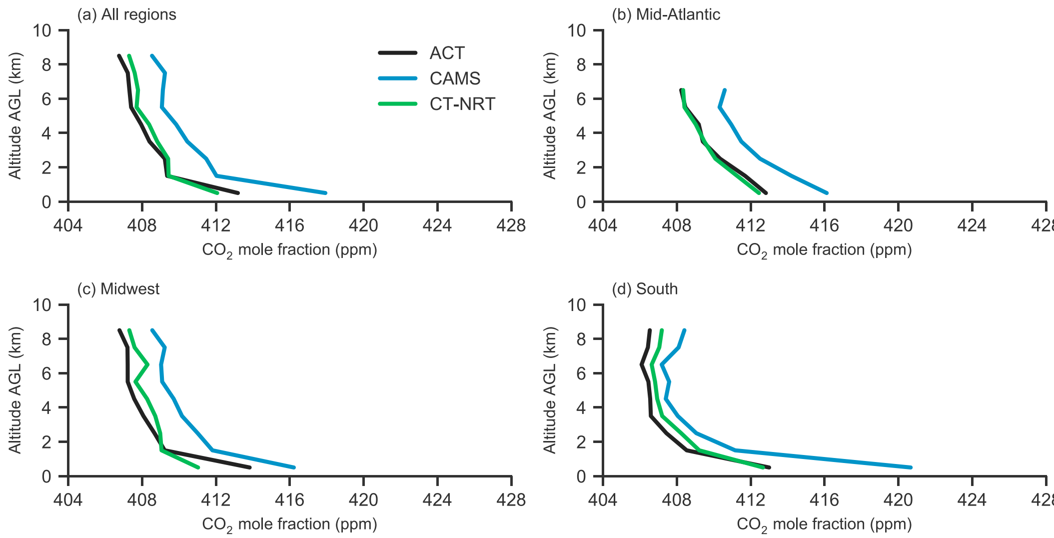

Figure 8. Vertical distribution of CO_2 mole fractions averaged over all flights during the ACT-America winter 2017 campaign in (a) all subregions, (b) Mid-Atlantic, (c) Midwest, and (d) South. The CO_2 profile based on ACT-America airborne observations is shown as a black line. The CAMS and CT-NRT CO_2 products were linearly interpolated in space and time to the ACT-America flight tracks. ACT = Atmospheric Carbon and Transport; CAMS = Copernicus Atmosphere Monitoring Service; CT-NRT = CarbonTracker Near-Real-Time; AGL = above ground level.

paign (supporting information Figures S5c and S5d). Considering that CAMS assimilates only infrequent remote sensing XCO_2 measurements from the polar-orbiting satellite, it is likely that the observations are insufficient to correct for this bias. Furthermore, it is possible that part of the bias is inherited from biases in the satellite retrievals (see Heymann et al., 2015; Massart et al., 2016). Further investigation of the different components of the CAMS system is required to confirm the source of this high bias.

The RMSDs for both analyses are considerably smaller below 2 km during the winter of 2017 (Figure 9) than those during the summer of 2016 (Figure 5) and also slightly smaller but of comparable magnitude above

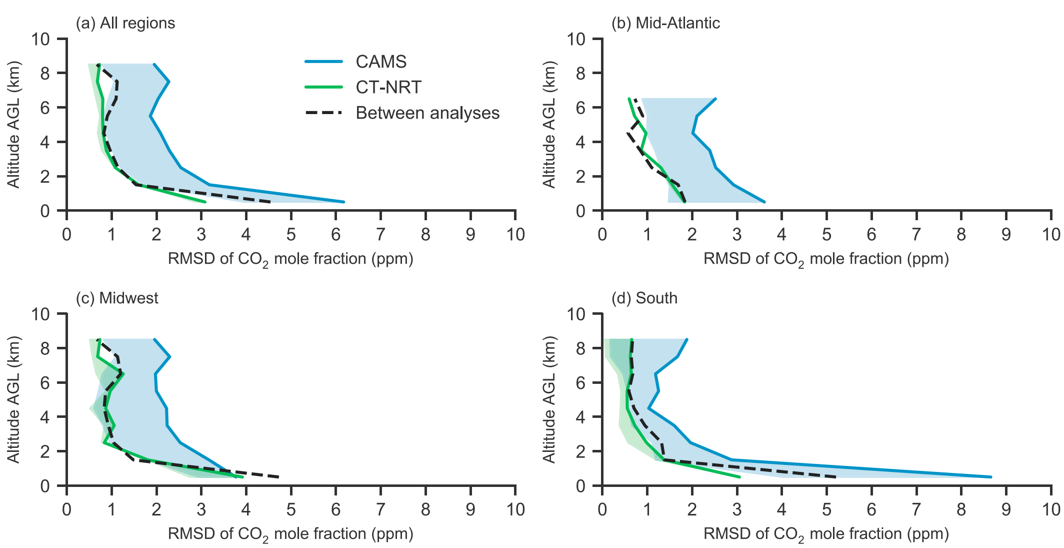

Figure 9. Vertical distribution of RMSD between CAMS/CT-NRT and observations in terms of CO_2 mole fractions for all flights during the ACT-America winter 2017 campaign. The blue lines show the RMSDs between CAMS and ACT-America observations, the green lines show the RMSDs between CT-NRT and ACT-America observations, and the black dashed lines show the RMSDs between the two CO_2 analysis products after removing the model-observation mean differences from CAMS. The shading indicates the reduction in RMSDs after subtracting the mean model-observation differences at each altitude bin for each region and product. CAMS = Copernicus Atmosphere Monitoring Service; CT-NRT = CarbonTracker Near-Real-Time; RMSD = root-mean-square deviation.

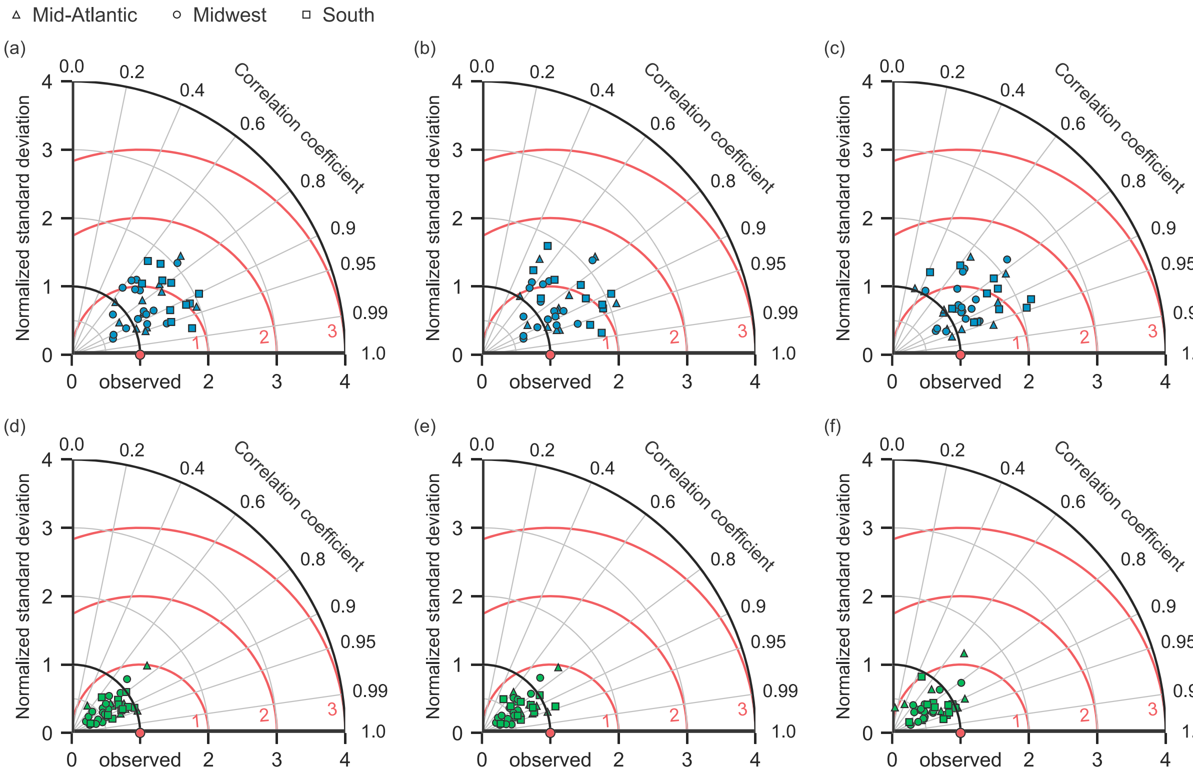

Figure 10. Taylor diagram comparing CO_2 mole fractions in the CO_2 analyses and airborne observations from the summer 2016 Atmospheric Carbon and Transport-America field campaign for (a–c) Copernicus Atmosphere Monitoring Service and (d–f) CarbonTracker Near-Real-Time. The left column shows the metrics calculated using all flight legs, the middle column for only straight-level legs, and the right column for only vertical profiles. The correlation between analysis and observed CO_2 values is shown by the azimuthal angle (gray straight contours), the ratio of the standard deviations in the analysis and observations is proportional to the radial distance from the origin (gray curved contours, with the black contour indicating a ratio of 1), and the centered RMSDs between the analysis and observations is proportional to the distance from the red circle (red contours, contoured every 1 ppm). Flights with less than 100 data points are omitted.

2 km. In winter the RMSDs are rather comparable across the three subregions, except that the Mid-Atlantic does not show a substantial increase in RMSDs near the surface unlike the other two regions. The effects of spatial and temporal interpolations are similar but smaller for winter compared with summer (supporting information Figure S15), with CAMS again benefiting the most from the temporal interpolation, while CT-NRT shows marginal changes in RMSDs due to the vertical interpolation. The RMSDs for the CAMS analysis are noticeably larger in winter than for the CT-NRT reanalysis, which is largely attributable to the systematic biases in CAMS. Removing the bias at each vertical bin prior to the RMSD calculation almost completely closes the gap in RMSDs between CT-NRT and CAMS (Figure 9). CT-NRT does not benefit much from the bias correction, except for CO_2 mole fractions above 2 km in South. We further note that simply subtracting 1.9 ppm from the CO_2 mole fractions in the CAMS analysis for all subregions and vertical levels results in a similar level of RMSD reduction. Thus, there is a real prospect for CAMS to achieve analysis uncertainties in wintertime CO_2 mole fractions comparable to those of the CT-NRT reanalysis if the systematic bias in CAMS is corrected.

The RMSDs between the two analyses after removing the biases in CAMS are again highly consistent with the RMSDs between analyses and observations (see black dashed line in Figure 9). The high correspondence between analysis-analysis RMSDs and analysis-observation RMSDs is robust across all three subregions and all vertical levels, except for a slight overestimation of the analysis uncertainties (analysis-observation RMSDs) at the lowest 1 km in the Midwest and South regions by the analysis-analysis RMSDs. This result suggests that the overall analysis uncertainties in CAMS and CT-NRT can be estimated using the spread between the two analyses, which can be calculated even when observations are absent.

Finally, the performances of the two analyses for each individual research flight during the winter 2017 campaign are summarized in the Taylor diagram in Figure 10. (See supporting information Figures S16 to

S22 for the CO_2 mole fractions in observations and analyses along the flight tracks.) It is evident from this diagram that CT-NRT systematically underestimates the horizontal and vertical variability of CO_2 in winter, while CAMS, in contrast, tends to overestimate the variability. Both analyses show a strong correlation with observed values, with a median correlation coefficient of 0.86 for both CAMS and CT-NRT. The CAMS and CT-NRT analyses of CO_2 thus represent the spatial variations in wintertime CO_2 mole fractions well but could improve in terms of representing the magnitude of the variations.

4. Concluding Remarks

This study systematically examines the regional biases and uncertainties in CO_2 mole fractions from two state-of-the-art global CO_2 analysis products through verifying against hundreds of hours of airborne in situ measurements collected during the summer 2016 and winter 2017 phases of the ACT-America field campaigns. One is the experimental near-real-time global atmospheric analysis produced by ECMWF using a 4DVar data assimilation system as part of the CAMS system, and the other one is the timely carbon reanalysis generated by NOAA's CT-NRT atmospheric inversion system based on the ensemble Kalman filter technique.

It is found that both the CAMS and CT-NRT CO_2 analyses agree reasonably well with the independent ACT-America in situ flight-level measurements, in particular above 3 km. The CAMS analysis exhibit some systematic biases throughout the atmospheric column, which are especially noticeable in winter when CAMS is biased high by about 1.9 ppm. CT-NRT shows some substantial biases close to the surface, especially in the Mid-Atlantic region in summer and in Midwest in winter but much smaller biases higher up in the atmosphere. When controlling for these biases, the uncertainties in CAMS and CT-NRT are comparable to each other, with overall slightly smaller RMSDs in CT-NRT. Both analyses are able to capture realistic variations in the CO_2 distribution along the ACT-America flight tracks. CAMS tends to overestimate the CO_2 variations along the flight tracks in winter, while CT-NRT consistently underestimates the wintertime CO_2 variability. Nevertheless, the correlations between CO_2 mole fractions in the analyses and observations are generally high and are higher in winter than in summer likely owing to weaker uncertain fluxes from the terrestrial biosphere in winter.

An important finding from the evaluation with both CO_2 analyses is that the RMSDs between CAMS and CT-NRT are comparable to the uncertainties in the analyses when verifying against the ACT-America flight measurements. We found that this result holds for all altitudes, all three subregions in the eastern United States where ACT-America field campaigns were conducted, and for both the summer and winter seasons. This finding implies that the spread between the CAMS and CT-NRT analyses can be used to estimate the overall uncertainties in the analyses. Neither of these two analyses currently provide uncertainty estimates, but information about the analysis uncertainties is highly valuable for many uses. As an example, regional CO_2 inversions could use uncertainties from the global CO_2 analyses to estimate background uncertainties due to uncertain CO_2 lateral boundary conditions. Given the limited spatiotemporal coverage of CO_2 observations, the RMSDs between CAMS and CT-NRT could therefore be used as an effective proxy for the real analysis uncertainties.

The current study provides the first uncertainty analysis of the CAMS and CT-NRT CO_2 analysis products verified simultaneously against ACT-America airborne observations and suggests that these two independent estimates can be used to quantify the overall regional CO_2 uncertainties, both of which are important in future studies in quantifying the uncertainties of regional-scale estimates of CO_2 mole fractions and fluxes, as well as in assessing the effect of regional atmospheric transport through more refined regional modeling and analysis systems. We also demonstrate how ACT-America field measurements can be used for evaluating and validating model simulations and CO_2 inversion results. Ultimately, these uncertainty analyses and subsequent modeling experiments will help to address the uncertainties in regional CO_2 flux estimates.

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