Long-term Trends and Inter-annual Variability of Carbon Dioxide and its Surface Fluxes from the OCO and GOSAT Missions

Abstract

Observing and analyzing the long-term trends and inter-annual variability of carbon dioxide (CO_2) and its surface fluxes are essential if we hope to understand the response of the Earth's climate and carbon cycle to human emissions and mitigation efforts. The Goddard Earth Observing System (GEOS) analysis of column CO_2 (XCO_2) observations from the Orbiting Carbon Observatory 2 (OCO-2) was the first system of its kind to successfully identify and quantify the impact on atmospheric CO_2 due to decreases in human activity meant to slow the spread of the Coronavirus Disease 2019 (COVID-19) pandemic. That signal was the greatest short-term anomaly in atmospheric CO_2 due to human activity since at least the Great Depression, and was still at the very limit of our current observational capabilities. Yearly changes in CO_2 due to emissions mitigation (or increases) are expected to be even smaller, only becoming apparent in the observational record after several years. The Greenhouse Gases Observing Satellite (GOSAT) has been in operation for over 11 years, since 2009, 6 years longer than OCO-2. We propose to extend the GEOS/OCO analysis to GOSAT data to better understand the long-term trends and inter-annual variability of human emissions and the carbon cycle. This goal will require updating the Atmospheric CO_2 Observations from Space (ACOS) GOSAT XCO_2 retrievals to the current Build 10 (B10) of the OCO-2 algorithm. Several updates in the OCO-2 algorithm from B9 to B10 made the GEOS/OCO analysis possible, most notably the improvement in ocean glint retrievals, and this project will investigate whether they have a similar impact on ACOS-GOSAT retrievals. While other GOSAT retrievals are available, using the ACOS-GOSAT retrieval in this analysis has the added benefit of allowing us to develop a record as consistent with the OCO-2 data as possible, minimizing the impact of jumps in the data record. As future missions come online, e.g., the Geostationary Carbon Observatory (GeoCarb), we expect this ability to be absolutely essential in the interpretation of long-term trends and inter-annual variability.

Long-term Trends and Inter-annual Variability of Carbon Dioxide and its Surface Fluxes from the OCO and GOSAT Missions

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Science/Technical/Management

1. Motivation

Observing and quantifying long-term trends of anthropogenic carbon emissions and the response of the terrestrial biosphere and ocean exchange to those emissions (and the resultant climate change) are essential for understanding the trajectory of greenhouse gas concentrations in coming decades. Reducing the uncertainty in the mechanisms behind the terrestrial and oceanic responses to future climate projections has been a long term goal of carbon cycle research, but achieving that goal has proved to be notoriously difficult even after more than a decade of effort (Friedlingstein et al., 2006; 2014). One way to understand these mechanisms is to study the impact of weather and climate anomalies on the inter-annual variability (IAV) of the carbon cycle in the recent past. The success of this effort depends on the availability of observations to accurately quantify the carbon cycle response to anomalies such as heat waves, droughts, and the El Niño/Southern Oscillation (ENSO) cycle. The advent of observations of atmospheric carbon dioxide (CO_2) from satellites such as the Orbiting Carbon Observatory 2 (OCO-2) in the past two decades has provided a powerful complement to existing measurements, yielding new insights in under-sampled regions that are subject to rapid change and strongly influenced by interannual variability.

The current era of satellite-based observations of column CO_2 (XCO_2) began in 2003 with the launch of Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY; Buchwitz et al., 2005), and has continued to the present day with the Greenhouse Gases Observing Satellite (GOSAT; Kuze et al., 2009), OCO-2 (Crisp et al., 2017) and OCO-3 (Eldering et al., 2019) instruments, among others. Compared to the surface-based CO_2-sensing network, CO_2 satellites afford broader spatial coverage and measurements over areas under-sampled by the surface network. However, satellite missions have nominal lifetimes of 2–5 years, and rarely last more than a decade without degradation. This necessitates integrating multiple satellite records to study carbon cycle phenomena that take multiple years or even decades to unfold.

Satellites that are co-operational over the same time period can provide additional information (compared to a single satellite) but require a careful combination of multiple CO_2 products to produce a consistent atmospheric picture. The need to combine satellite CO_2 products into a single consistent dataset will only increase in the near future as the number and kind of CO_2-sensing satellites increase (see Crisp et al., 2019 for an overview). This is an especially challenging problem because individual (different) satellite CO_2 sensors cannot be calibrated (cross-calibrated) by measuring a known (common) air mass. An individual satellite sensor can have regional biases (Wu et al., 2018) and drift over time (Yu et al., 2020), and multiple satellite sensors can have different drifts and biases (Kulawik et al., 2016). Differences between satellite CO_2 estimates—even sampling the same air mass—can arise from several different factors, including different instrument characteristics, different retrieval algorithms and choices made therein, and different validation strategies (Kataoka et al., 2017). Validating satellite CO_2, either regionally or over long times, is therefore a crucial step before using it for scientific studies.

In this project, we will improve the consistency and inter-comparison of the OCO-2 and GOSAT records by applying the same Level 2 (L2) XCO_2 retrieval algorithm, Level 3 (L3) atmospheric CO_2 state estimation, and Level 4 (L4) surface flux inversion to GOSAT as we apply to the current OCO-2 product. This effort builds on the long legacy of collaboration between the OCO and GOSAT teams and will enable the scientific community to use the GOSAT and OCO-2 XCO_2 records simultaneously by porting the latest innovations implemented in OCO-

2 retrievals back to the longer GOSAT record. We believe the availability of a compatible GOSAT data product from 2009 on will enable researchers to tackle carbon cycle questions that require a decade or more of continuous observation. As part of this project, we will also deliver surface CO_2 fluxes over more than a decade from an atmospheric inversion of the newly derived GOSAT XCO_2 retrievals, as well as surface CO_2 fluxes from a more traditional inversion of in situ CO_2 data. This will allow us to assess the added value of a satellite CO_2 instrument over a decade compared to the information provided by the existing surface network and will complement ongoing OCO-2 based surface flux estimates.

While originally supported directly by the OCO project, recent applications of OCO's Atmospheric CO_2 Observations from Space (ACOS) retrieval algorithm to GOSAT have been supported only as a project of opportunity. With the recent launch of OCO-3, continued ACOS-GOSAT processing and its update to the current ACOS version, Build 10 (B10), is beyond the resources of the core OCO project and there is no plan to continue it there. The work proposed here provides a pathway toward continued production of these widely used datasets.

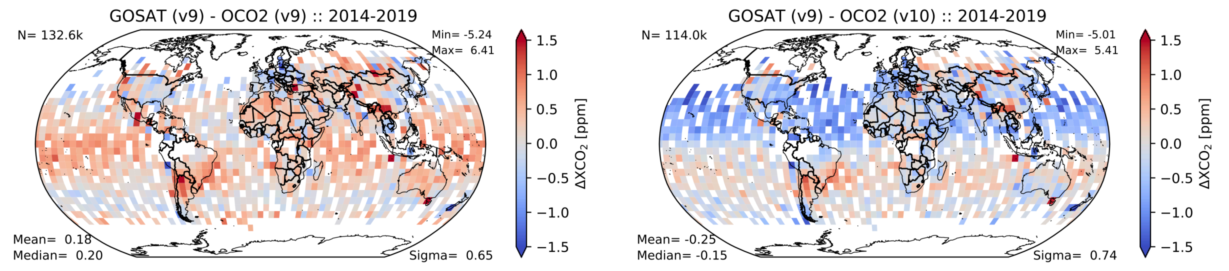


Figure 1. **Comparisons of GOSAT with two different versions of OCO-2 data highlights the importance of understanding differences between satellites and expanding the tools used by the OCOST for validation.** When a similar retrieval algorithm is applied to both GOSAT and OCO-2 (left), GOSAT data are on average a few tenths of a ppm greater than OCO-2. When compared with the most recent version of OCO-2 data (right), the sign of this difference is reversed. The main goals of this proposal are to increase consistency between GOSAT and OCO data products, to better understand the factors that cause differences in their XCO_2 estimates, and to quantify how such differences influence atmospheric concentrations and surface flux estimates.

Even with the presence of multi-year, dense satellite CO_2 datasets, their difference in sampling methods can pose a challenge to using them together to study the carbon cycle (**Figure 1**). The retrievals over an area of interest might be episodic, or different across years, the former (latter) posing challenges to determining the seasonal (interannual) variation in the carbon cycle. We have developed a unique L3 state estimation system using the GEOS general circulation model (GCM) to provide a time varying estimate of the atmospheric CO_2 state at high spatiotemporal resolution consistent with multiple CO_2 data sources (such as multiple CO_2 satellites) and atmospheric transport. This has allowed us, essentially, to use the GCM as an interpolator between different observational datasets and overcome satellite sampling limitations over areas of interest. Our data product—the atmospheric CO_2 state—has been used to cross-validate airborne CO_2 lidars and OCO-2 with aircraft CO_2 data (Bell et al., 2020), and detect the reduction in fossil CO_2 emissions due to the COVID-19 lockdown in 2020 (Weir et al., *in review: b*). In this project, in additional to L2 retrievals, we will deliver i) L3 atmospheric CO_2 state estimates by jointly assimilating OCO-2 and GOSAT XCO_2 retrieved with the same ACOS B10 algorithm, whereas previous efforts combined OCO-2 and GOSAT data using different builds of the ACOS algorithm, and ii) L4 CO_2 surface fluxes over the ACOS B10 period from an atmospheric inversion of our newly derived GOSAT XCO_2 retrievals within the Transport Model 5 - 4-Dimensional Variational (TM5-4DVar) system (fluxes from OCO-2 retrievals are already funded through a separate project). We believe our CO_2 state and flux products will enable broader use of the OCO-2 and GOSAT data in research endeavors within the community.

2. Previous Contributions to the OCO Science Team

Our team, based at NASA's Global Modeling and Assimilation Office (GMAO), Colorado State University (CSU), and JPL, includes a unique mix of experience in data assimilation and greenhouse gas retrievals with a long legacy of contributions to the OCO Science Team (OCOST) including the OCO Model Intercomparison Project (OCOMIP; Crowell et al., 2019). The GMAO has contributed to the OCOST since 2014 in proposals led by Co-I Ott. Accomplishments from the previous funding cycle demonstrate our team's unique capability to create products that broaden the user base of OCO data, support the science goals of the OCO mission, and enhance the OCOST's ability to monitor data quality.

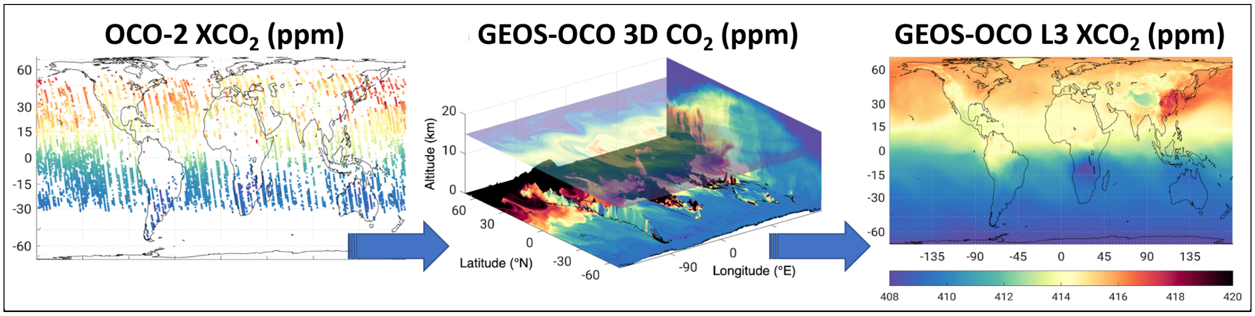
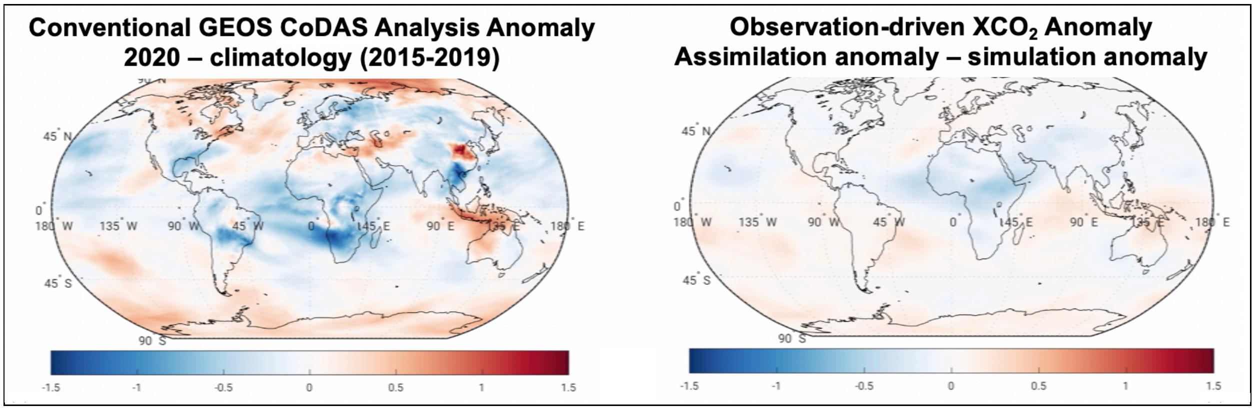


Figure 2. The GEOS CoDAS has previously supported the OCOST by providing L3 products that combine OCO observations with a high-quality, data driven background field. When OCO data are unavailable because of clouds, darkness, or gaps between swaths, the GEOS-OCO leverages millions of meteorological and land surface observations to fill gaps and provides additional information about the vertical structure of CO_2, supporting validation efforts.

A major focus of our previous Ott/OCO-17 proposal was the creation of L3 OCO data products using the GEOS Constituent Data Assimilation System (CoDAS). The GEOS CoDAS creates high quality global maps of CO_2 by combining OCO L2 column XCO_2 retrievals with a background field produced by the GEOS GCM (**Figure 2**, more details in Section 5). In May 2020, we updated our GEOS/OCO products to make use of newly available B10 retrieval products several months before they were publicly released, an effort that was expedited to support the OCOST's response to the COVID-19 pandemic and the inclusion of OCO L3 data on national (https://earthdata.nasa.gov/covid19/) and international (https://eodashboard.org/) dashboards tracking environmental impacts. The timing of the pandemic presented a unique problem to the OCOST. Processing of the previous B9 products had ended in late 2019 in anticipation of a planned transition to B10, which was originally to be completed by the fall of 2020. However, the unprecedented public demand for timely information on changes in air pollutant and greenhouse gas concentrations during the pandemic required a change in strategy to expedite analysis of B10 data. We coordinated with the team at JPL to revise their reprocessing schedule, which would prioritize most recent months as well as the corresponding months in previous years to create a baseline for detecting anomalies related to emissions. Our team then changed from our typical sequential processing strategy to run in 6 streams that started in November of each year from 2014 to 2020. We then coordinated with the NASA Center for Climate Simulation (NCCS) to run all 6 streams in parallel, which required a higher prioritization of OCO related jobs. As a result, our

GEOS/OCO B10 assimilated products began to be delivered to the OCOST in July 2020, less than two months from the beginning of this effort. This was a significant technical achievement made possible through close coordination with the operational processing team at JPL, senior leadership within the OCOST, and the NCCS. The adoption of B10 data also marked the first successful assimilation of land and ocean retrievals in the GEOS CoDAS, which allowed for detection of emissions related anomalies downwind of key regions in China and the Eastern U.S.


Conventional GEOS CoDAS Analysis Anomaly 2020 – climatology (2015-2019)

Observation-driven XCO_2 Anomaly Assimilation anomaly – simulation anomaly

Figure 3. Calculating a meaningful anomaly for detecting challenges in XCO_2 is challenging because conventional methods reveal a strong imprint of year specific circulation changes. The example from January 1–15 (left) seems to indicate a strong change in concentrations over Asia, which could easily be misinterpreted. Our anomaly estimation method separates changes due to circulation from those due to fluxes (right). Careful consideration of weather effects is needed to properly interpret OCO anomalies. This is the technique currently used to identify flux-driven XCO_2 changes on COVID-19 dashboards.

In addition to the generation of new L3 products, our team developed new techniques to detect anomalies related to changes in carbon flux. These methods were first presented at the OCOST meeting in October 2018 and were refined for inclusion in the COVID-19 dashboards. Simple methods of calculating trace gas anomalies (e.g., 2020 monthly mean minus multi-year mean) are ill-suited to XCO_2 because they reveal a strong imprint of year specific circulation anomalies (**Figure 3**). Our method for separating circulation and flux anomalies involves running a separate reference simulation of GEOS which is identical to the CoDAS runs used to produce GEOS/OCO products except that OCO data are not assimilated. In both runs, fluxes for the current year are derived from an extrapolation of previous year's fluxes (Weir et al., *in review: a*). An anomaly calculated from the reference run represents the circulation anomaly that can be subtracted from the anomaly calculated from the GEOS/OCO products to reveal the flux driven component of the XCO_2 anomaly observed by OCO. Our team began regularly producing these anomaly maps in July 2020 and have since updated them monthly. They have documented COVID-19 emissions decreases over the world's largest economies and provided some of the first indications of climate-driven land flux anomalies over Africa and India associated with a record-breaking 2019–2020 Indian Ocean Dipole (Weir et al., *in review: b*). This anomaly detection method was critical in detecting the imprint of COVID-19 related emissions decreases, which occurred over relatively short time periods (weeks to months) and regional to country-level spatial scales. This effort also highlights several advantages of the GEOS/OCO L3 system for helping the OCOST track recent changes in CO_2: the ability to handle discontinuous datasets because of the relatively short 6-hour assimilation window, the ability to run in near real time even when many land and ocean flux input datasets are not yet available, and the ability to provide global results at relatively high (50-km) spatial resolution.

The GEOS CoDAS has also been used by the OCOST in support of validation efforts. In this example, CoDAS was used to assimilate aircraft data collected during the Atmospheric Carbon and Transport - America (ACT-America) field campaign instead of OCO retrievals. Between 2016 and 2018, ACT-America performed a series of coordinated underflights to support OCO, but direct comparison of aircraft observations and column-integrated retrievals is challenging because aircraft only sample a portion of the column. In this configuration, the CoDAS leverages high quality information about stratospheric circulation in the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2; Gelaro et al., 2017) to fill in regions not observed by the campaign's research aircraft and produces data constrained "curtains" of profiles that can be integrated for comparison with OCO retrievals (Bell et al., 2020, **Figure 4**). As part of our previous funded work, we produced curtains for all ACT-America underflights and used them to evaluate improvement in retrieval versions over time demonstrating a reduction in mean absolute error of 0.4 ppm in OCO's transition from the B7.3 to B9 retrievals.

Co-I's Basu and O'Dell are currently involved in a retrieval-related activity that may prove crucial to future use of OCO-2 data. The retrieved XCO_2 from OCO-2 has regional biases that are corrected by a post-retrieval bias correction of the form

$$XCO_2(bias\ corrected) = XCO_2(retrieved) + \sum\nolimits_i \alpha_i P_i$$

where P_i are covariates that influence regional biases (such as the change in surface pressure, the albedo, or the aerosol loading) and α_i are scalar coefficients derived from comparing the retrievals to various truth metrics. If the P_i is retrieved along with CO_2, this post-retrieval bias correction changes the column averaging kernel of the final, bias-corrected CO_2, which in turn affects model comparisons to OCO-2 XCO_2. This correction can exceed 0.25 ppm, which is a significant adjustment given the high accuracy requirement on XCO_2. Co-I's Basu and O'Dell are currently investigating this further, including how to validate OCO-2 XCO_2 in the presence of this correction, how to derive a consistent post-retrieval bias correction, and the impact this correction might have on flux products assimilating OCO-2 XCO_2. Once it has been thoroughly studied, it is likely that the OCO-2 XCO_2 distributed to the community will include this adjustment to the averaging kernel and a bias correction calculated consistently.

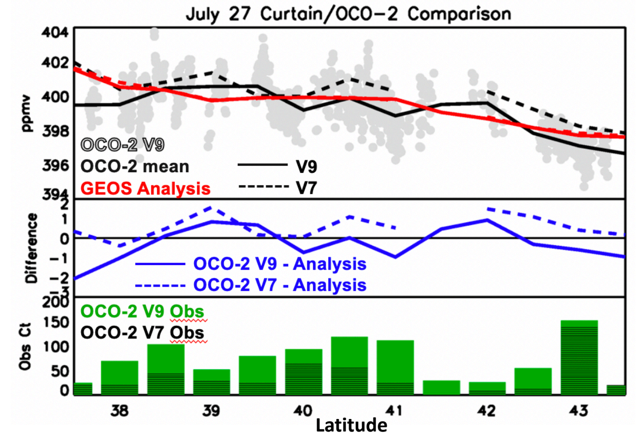


Figure 4. In addition to assimilating OCO data, the GEOS CoDAS has supported the OCOST's validation efforts by assimilating independent aircraft data. In this example from a July ACT-America flight, GEOS CoDAS aircraft curtains (red) are compared against OCO B9 (solid) and B7 (dashed) retrievals. Differences (middle panel) show that the mean absolute error was reduced from 0.5 to 0.3 ppm by improvements in the retrieval algorithm. This analysis helped the OCOST quantify improvements in data quality over time. Refinements in the quality control process also increased the number of good soundings available for science investigations (bottom).

Our team also includes extensive experience in greenhouse gas retrievals and operational retrieval processing, most notably from Co-Is O'Dell, Taylor, and Dang, necessary for the development, interpretation, and production of XCO_2 retrieval algorithms. Co-I O'Dell is the lead developer of the ACOS L2 full-physics (L2FP) algorithm, quality filtering, and bias correction for both OCO and ACOS-GOSAT products (O'Dell et al., 2012, 2018). Co-I Taylor has extensive experience in ACOS algorithm development including developing the primary cloud screening and pre-filtering tools (Taylor et al., 2012, 2016), the application of the ACOS algorithm to OCO-3 data (Eldering et al., 2019) and cross-calibration of GOSAT and OCO data (Kataoka et al., 2017). In addition, Co-Is O'Dell and Taylor have demonstrated the ability to provide a full assessment of ACOS retrieval products to verify and validate the results (O'Dell et al., 2018; Taylor et al., 2020). Co-I Dang is an expert in science data systems operations and has previously led processing of ACOS-GOSAT projects at JPL. Furthermore, the work described below performed under an OCOST funded project led by Co-I Basu has served as a bridge to better understand technical aspects of the retrieval and bias correction methodology and their impacts on surface flux estimates.

Collaborator Kuze is the GOSAT and GOSAT-2 project team lead at JAXA and an expert in remote sensing of greenhouse gases. His input on the mission and instrument status and operations of GOSAT will be absolutely essential to the success of this project. Collaborator Wargan is an expert in the assimilation of trace gases having developed the ozone assimilation code of which GEOS CoDAS is a generalization. Likewise, his ozone trend analysis (Wargan et al., 2018) will serve as the starting point of our CO_2 trend analysis.

3. Relevance to the OCO Missions and NASA

Currently, the opportunity to compare OCO and GOSAT is limited by the availability of GOSAT products. The scientific community strongly prefers to use ACOS retrievals in combination with OCO data because of consistency in the retrieval algorithm. This dataset will not be regularly updated because of the need for the operational processing team at JPL to prioritize production of OCO-2 and OCO-3 products, which poses several challenges to users. First, the current ACOS-GOSAT dataset, which ends in early 2020, uses an older algorithm build (B9) than the current OCO build (B10). While other retrievals of GOSAT do exist from Europe and Japan, these products can differ substantially from ACOS retrievals in terms of data quality, spatial coverage, and bias correction (Nöel et al., *in review*). Second, latencies of more than a year limit the ability of our team and others to provide timely feedback on data quality. For the broader scientific community, the lack of timely data can delay research studies that seek to quantify interannual variations in carbon flux and attribute it to underlying processes because most of these studies rely on the combination of ACOS-GOSAT and OCO products to provide a longer time record. Extending the ACOS-GOSAT record facilitates comparisons between OCO and ACOS-GOSAT, will provide valuable combined datasets to the scientific community, and continues an important scientific collaboration between NASA and JAXA on greenhouse gas remote sensing.

The proposed research is specifically responsive to several aspects of the solicitations. The focus of this effort is enabling, "*[n]ew research and innovative analyses using OCO-2 and OCO-3 data combined with other sensors (e.g., GOSAT [...]) to advance OCO-2 and OCO-3 science goals and significantly advance our understanding of carbon cycle processes (oceanic and terrestrial) and/or anthropogenic emissions*." Extension of the ACOS-GOSAT record and updating the algorithm to the current version also provides a valuable tool for assessing, "*retrieval biases, errors, and covariances in the OCO-3 (primarily) and OCO-2 (secondarily) Level 2 products*." As documented in our previous work, the GEOS CoDAS provides a unique tool in support of validation activities and is particularly useful in, "*under-sampled regions of the globe*." Finally, our TM5-4DVar system will provide, "*[f]lux inversion analysis using OCO-2/3 data*

(GOSAT data may also be included as appropriate), including assessment of retrieval errors on flux inversions."

Establishing a new pathway to more regular processing of ACOS-GOSAT retrievals would support users of XCO_2 data at GMAO and beyond, helping to advance the OCO mission. Additionally, while not proposed here, such collaboration could eventually help support wider use of GOSAT-2 and GOSAT-3 data by building capacity at other institutions to process similar retrievals.

4. The ACOS Software Suite

Originally developed through funding for OCO, NASA's ACOS software suite, was first used to retrieve XCO_2 from GOSAT measurements in 2009 when, following the launch failure of OCO, the GOSAT team graciously invited the OCO team to join in the analysis of GOSAT data (Crisp et al., 2012; O'Dell et al., 2012). Since that time the ACOS software suite has been continually developed and improved, while maintaining the flexibility to be applied to both OCO and GOSAT measurements (B8 in O'Dell et al., 2018; B9 in Kiel et al., 2019). While a publication detailing the changes to the B10 algorithm is still in progress, they include:

- Upgrading to version 5.1 gas absorption coefficients (ABSCO; Payne et al., 2020)
- An improved solar continuum model derived from the Total and Spectral solar Irradiance Sensor (TSIS)
- Improved aerosol priors from GEOS Forward Processing: Instrument Teams (FPIT) plus a tighter a priori aerosol constraint (Nelson et al., 2019)
- New CO_2 priors to match the Total Carbon Column Observing Network (TCCON) GGG2020 prior
- Implementation of a quadratic fit to the spectral variation in retrieved albedo over land (replaces a linear fit)
- Loosened Solar Induced Fluorescence (SIF) prior constraint over land

Algorithm settings that are specific to the satellite sensor, i.e., OCO or GOSAT, include i) the setting of the surface pressure prior constraint, ii) the development of Empirical Orthogonal Functions (EOFs) fit in each spectral band (see Section 3.3 in O'Dell et al., 2018 for a full discussion of ACOS EOFs), and iii) a zero level offset (ZLO) fit in the state vector. The ZLO has always been implemented for ACOS-GOSAT to account for non-linearity in the O_2 A-Band signal chain of GOSAT (Crisp et al., 2012), whereas it has not been needed for OCO-2.

A step in the processing pipeline that is critical to ACOS GOSAT is the Level 1b (L1b) file resampler. The raw L1b are first obtained directly from JAXA and then repackaged into a format consistent with use in the ACOS L2 L2FP retrieval. Another required step is running a meteorological resampler code to generate files that correspond to the repackaged L1b on a sounding by sounding basis. This provides a set of inputs (L1b and meteorological) that are of the proper format to serve as input to the L2FP code.

Prior to running the computationally expensive L2FP retrieval algorithm, a prefiltering step is normally implemented. The retrieval of carbon dioxide from space using the short-wave CO_2 absorption channels (1.6 and 2.0 microns) is highly sensitive to contamination by clouds and aerosols. A computationally fast algorithm has been developed (Taylor et al., 2012, 2016) that uses the A-band radiances to retrieve an effective surface pressure. Scenes that contain aerosols and clouds will have effective surface pressures that differ significantly from the a priori meteorological values, allowing these soundings to be flagged and removed from L2FP processing. The A-Band Preprocessor (ABP), which serves as the primary sounding selection for GOSAT, generally flags between 50 and 70% of the full data volume as too cloudy to process.

As was done for previous GOSAT XCO_2 versions, the XCO_2 retrieved from the ACOS B10 L2FP code will need to be filtered for "good quality" retrievals and bias corrected. The quality filtering will consider several pre-existing metrics such as the degree of convergence, aerosol loading, and adherence of certain co-retrieved non-CO_2 parameters to judiciously choose ranges of values (Crisp et al., 2012; O'Dell et al., 2012). The bias correction step is required to tie GOSAT XCO_2 retrievals to the World Meteorological Organization (WMO) CO_2 scale. This involves evaluation of quality filtered XCO_2 against several different truth metrics, such as ground-based XCO_2 retrievals from the TCCON (Wunch et al., 2011), and the assumption that XCO_2 in the deep southern hemisphere is relatively homogenous within some tolerance (Nguyen et al., 2014). In recent years, a careful selection of CO_2 inverse models assimilating in situ CO_2 data has also been added as a truth metric (O'Dell et al., 2018). Typically, the retrieved XCO_2 has regional biases due to interference from co-retrieved quantities (such as aerosol and albedo parameters; Connor et al., 2016), which is estimated and corrected by correlating those co-retrieved quantities with deviations of retrieved XCO_2 from the truth metrics (Guerlet et al., 2013; Crisp et al., 2012). Often this evaluation against the truth metrics yields additional quality filtering criteria—such as cutoffs on aerosol parameters and surface pressure changes—that need to be applied. For GOSAT XCO_2 retrievals with ACOS B10, we will perform the same evaluation, quality filtering, validation and bias correction procedure as for previous GOSAT ACOS versions. Our final, released product will be bias corrected GOSAT XCO_2 and statistical evaluation against various truth metrics, along with a documentation of the steps taken.

Although no results have yet been published on the OCO-2 B10 L2FP retrieval, internal analysis indicates that there are demonstrable improvements in the OCO-2 XCO_2 results compared to B9. One of the most promising results is that there appears to be a significant reduction in the regional low bias in tropical ocean glint soundings compared to carbon inversion models that featured so prominently in the B9 (and earlier) products (see Figure 1). In addition, low biases in some land regions have been reduced, as well as an overall increase in good quality throughput. Furthermore, the OCO-2 B10 XCO_2 product is in better agreement with collocated measurements from TCCON for both land and ocean soundings. There is every reason to believe that similar improvements will occur in the GOSAT record when processed via the ACOS B10 algorithm.

5. Modeling and Assimilation Capabilities

5a. The NASA GEOS Constituent Data Assimilation System

NASA's GEOS is an integrated family of Earth system models with a broad range of possible configurations and the capability to assimilate atmospheric measurements developed primarily at NASA's GMAO. It is the basis of the widely used MERRA-2 meteorological reanalysis and the GEOS Forward Processing (FP) weather forecast and analysis. It can be run both as a GCM and chemical transport model (CTM) at horizontal resolutions as fine as 7 km (e.g., the GEOS Nature Run) and is able to simulate meteorological variables (e.g., wind, pressure, temperature, geopotential height), surface conditions (e.g., soil temperature and moisture), alongside a variety of atmospheric constituents (e.g., aerosols and trace gases).

The ability to assimilate observations of trace gases into the GEOS model follows from an extension of the meteorological assimilation system. This functionality began as an approach for estimating atmospheric mixing ratios of ozone in the GEOS framework (see Wargan et al., 2015 for an overview). Tangborn et al. (2009, 2013) first demonstrated its potential to assimilate measurements of carbon monoxide (CO) and CO_2. Since then, PI Weir has led the extension and generalization of this functionality into the GEOS Constituent Data Assimilation System (CoDAS). This work was completed under NASA funding from the Carbon Monitoring System (CMS) project, the Orbiting Carbon Observatory 2 (OCO-2) science team, a Modeling, Analysis, and Prediction (MAP) 2016 project led by Collaborator Wargan, and core GMAO funding from MAP. GEOS CoDAS is a flexible system that can produce an analysis of any collection of trace gases in the model and is able to assimilate most satellite retrievals. It has been used by PI Weir to assimilate retrievals of CO_2 from OCO-2 (**Figure 5**; Eldering et al., 2017) and CO from the Measurements of Pollution in the Troposphere (MOPITT) instrument and by PI Weir and Collaborator Wargan to assimilate measurements of water vapor (H_2O), nitrous oxide (N_2O), and nitric acid (HNO_3) from the Microwave Limb Sounder (MLS; Wargan et al., 2020). Currently, GEOS CoDAS is used by PI Weir with OCO-2 data to produce the CO_2 analysis for the COVID-19 dashboards as described in Section 2.

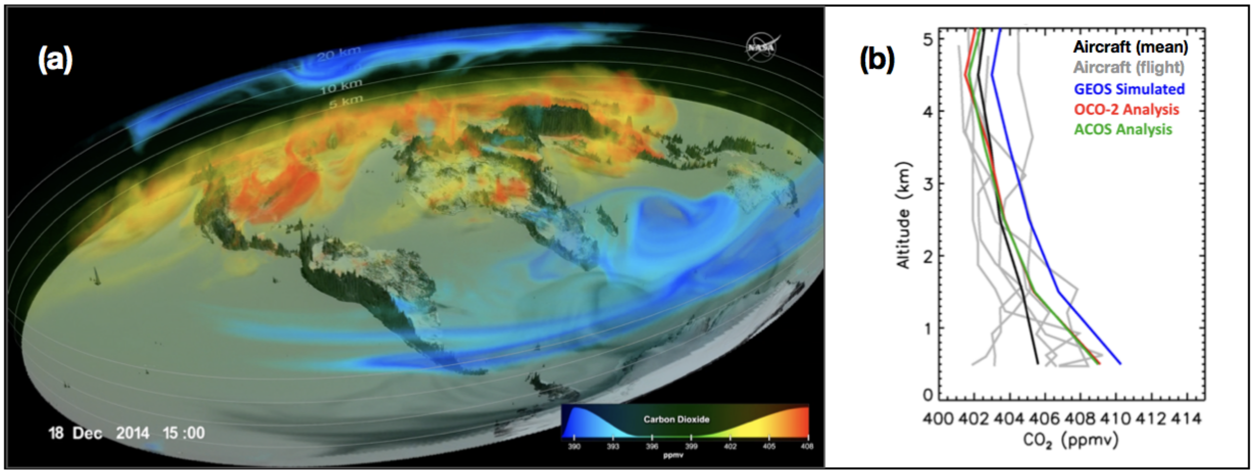


Figure 5. GEOS CoDAS combines satellite data and scientific models to infer three-dimensional, time-varying analyses and improve agreement with independent data. A major benefit of data assimilation is that it infers three-dimensional constituents that vary in time (a). This allows for uncertainty quantification through comparison to independent data, e.g., suborbital campaigns and ground-based networks. Frame (b) compares NOAA aircraft profiles over Oklahoma in March 2015 (flights in grey, mean in black) to results of a free running control simulation (blue), assimilated OCO-2 data (red), and assimilated ACOS-GOSAT data (green). Both assimilations show improved agreement with aircraft data, indicating the satellite data captures the onset of the Spring–Summer sink of CO_2 better than the model (Eldering et al., 2017).

5b. The TM5-4DVar Atmospheric Inversion System

Atmospheric inversions infer surface fluxes of a constituent from its observed spatiotemporal gradients, using a chemistry transport model to connect surface fluxes with atmospheric concentrations (Bennett, 2005). For the CO_2 flux estimation proposed in this project, we will use the TM5-4DVar inversion framework, which is a state-of-the-art variational inversion system that has been used to estimate fluxes of CO_2 (Babenhauserheide et al., 2015; Basu et al., 2013), methane (CH_4; Houweling et al., 2014; Monteil et al., 2013) and CO (Basu et al., 2014; Hooghiemstra et al., 2011; Krol et al., 2013; Nechita-Banda et al., 2018), using both in situ and remotely sensed atmospheric measurements. At the heart of this system is the offline TM5 global atmospheric transport model, driven by European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis - Interim (ERA-Interim) or ERA-5 meteorology, and capable of high resolution nested grids over regions of interest (Krol et al., 2005). The variational inversion approach uses the "adjoint" of TM5 (Meirink et al., 2008), which allows for the calculation of the sensitivity of atmospheric observations to surface fluxes. The assimilation of GOSAT (Basu et al., 2013, 2014) and OCO-2 (Crowell et al., 2019) XCO_2 in TM5-4DVar is a mature capability. For the proposed work, we will perform decadal and multi-year flux estimations with GOSAT and OCO-2 XCO_2 respectively, as appropriate given the time spans of those two records. The inversions to be performed are described in Task 3B in Section 7. All inversions will simulate TM5 atmospheric transport at 3°×2° globally, with the option of going to higher resolutions (up to 1°×1°) should need and interest arise.

For a linear problem such as CO_2 flux estimation, the TM5-4DVar system provides an approximation to the posterior flux uncertainty, which is however an overestimate of the exact posterior uncertainty (Meirink et al., 2008). Therefore, we will employ a Monte Carlo approach to accurately estimate the posterior covariance of the fluxes, performing an ensemble of independent inversions with prior fluxes and measurements perturbed according to their respective covariance matrices (Bousserez and Henze, 2018; Chevallier et al., 2007). This is a well-tested procedure within the TM5-4DVar framework (Basu et al., 2016, 2020), and an ensemble of ~100 inversions is expected to yield uncertainty estimates accurate to 10% (Bousserez and Henze, 2018). Our requested computing budget includes resources for estimating flux uncertainties.

6. Proposed Work

The proposed work is divided into three tasks that build upon each other. In the first task, personnel at GMAO (Weir, Balashov, and Basu) will work with personnel at JPL (Dang) to take over production of ACOS-GOSAT B9 on the JPL cluster and its delivery to Goddard Earth Sciences Data and Information Services Center (GES DISC; Ott, Balashov). This will be essential training for the next task, which will port the ACOS B10 software suite, as deployed for OCO-2, to run on GOSAT measurements, thus producing ACOS-GOSAT B10 L2 XCO_2 retrievals at NCCS. The third and final task will ingest the ACOS-GOSAT B10 L2 retrievals to produce analyses of atmospheric mixing ratios, i.e., L3 CO_2 fields, and L4 surface fluxes. These analyses will be used to study similarities and differences in the long-term trends and IAV of GOSAT and OCO-2 data (**Figure 6**). Results of initial test runs of the L3 and L4 analyses in Task 3 will feed back into the development of the L2 product in Task 2. While the proposed work focuses entirely on XCO_2 from GOSAT, this effort will build capacity for future work that could extend to XCH_4, XCO, and SIF from GOSAT 2 and 3 and their comparison to retrievals from other missions like the Tropospheric Monitoring Instrument (TROPOMI) and the Geostationary Carbon Observatory (GeoCarb).

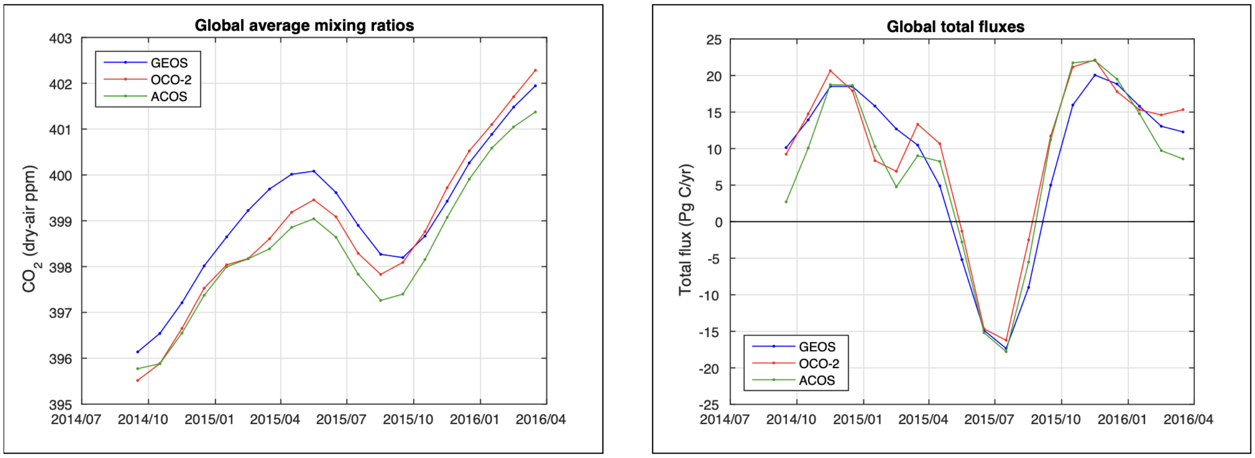


Figure 6. Assimilation provides a valuable approach for cross-validating satellite retrievals. Comparisons of global total mixing ratios (left) and surface fluxes (right) for a free-running simulation (blue), OCO-2 B7b assimilation

(red), and ACOS-GOSAT B7.3 assimilation (green) show how the assimilated products can detect global biases (offset between green and red in left panel), while also demonstrating robustness in estimated monthly fluxes from the two sensors (similarity between green and red in right panel).

Task 1: Regular delivery of ACOS-GOSAT B9 retrievals

Deliverable(s)	Continuation of ACOS-GOSAT B9 L2 XCO_2 retrievals at a 3 month latency
Staff	Weir, Balashov, Basu, Dang, Ott

This task ensures continued processing and delivery of the ACOS-GOSAT B9 L2 XCO_2 retrievals that currently end in April 2020. The ACOS-GOSAT B9 products are considered to be mature and already validated. The processing of these retrievals at JPL is led by Co-I Dang and the scientific development by Co-Is O'Dell and Taylor at Colorado State University (CSU). As part of previous OCOST work with this goal in mind, PI Weir has already set up an SDOS account on the JPL servers. However, training on the processing of the ACOS-GOSAT retrievals was delayed because of the COVID-19 pandemic. This task will complete that process by PI Weir with Co-Is Balashov and Basu at GMAO learning the data processing workflow from Co-I Dang (specific steps detailed below in the next section). Once the GMAO personnel is able to process and deliver ACOS-GOSAT B9 data on the JPL servers without direct assistance, they will continue delivering products with a 3 month latency. This processing will stop once the next task develops a B10 product ready for delivery or if there is a reprocessing of GOSAT L1 data that would necessitate any changes to the retrieval algorithm. In the latter case, production would end and all effort would transition to the next task.

Task 2: Implement, evaluate, and process ACOS-GOSAT B10

Deliverable(s)	ACOS-GOSAT B10 L2 XCO_2 retrievals at a 3 month latency
Staff	Weir, Balashov, Basu, O'Dell, Taylor

This task will begin by making the necessary (relatively minor) changes to the ACOS B10 software suite to run on the GOSAT measurements, led by Co-Is O'Dell and Taylor at CSU. Next, the ACOS B10 code base will be deployed on the NASA High-End Computing (HEC) systems, to allow for reprocessing of the full GOSAT data record at NCCS, led by PI Weir and Co-Is Balashov and Basu at GMAO. All personnel will contribute to the development, testing, and evaluation of the B10 quality filtering and bias correction. The steps of this task are listed below.

The ACOS software suite follows a number of steps, outlined here and described in detail by Crisp et al. (2012) and O'Dell et al. (2012), for converting radiance measurements into quality-flagged and bias-corrected retrievals of XCO_2. These steps include first running a quick test set (QTS) of pre-selected sample soundings to train empirical orthogonal functions (EOFs) to remove persistent errors due to deficiencies in the spectroscopy and other parts of the retrieval. After the algorithm outputs "raw" XCO_2 retrievals, it applies post hoc quality filtering and bias correction to correct persistent errors, and aggregated into daily files referred to as the "lite" product (see Section 4 above for more details).

<u>*Processing steps*</u>

1) Port the JPL B9 workflow to NCCS and ensure the two produce equivalent results. This step will coincide with the GMAO team learning how to operate the JPL workflow in Task 1
2) Verify that the JAXA to ACOS L1b converter produces B10 compatible products

3) Compile an L2 QTS for GOSAT
4) Run the preprocessors and evaluate the results, in particular the sounding selection. The ABP has been updated from B9 to B10, so the sounding selection might change slightly. We will also investigate using Generic Algorithm for Single Band Acquisition of Gases (GASBAG) instead of the Iterative Maximum A Posteriori - Differential Optical Absorption Spectroscopy Preprocessor (IDP) as the former is more widely supported at this point
5) Implement and verify the GOSAT instrument model in the B10 algorithm
6) Run the QTS using the B10 algorithm, fix any bugs that we encounter, make sure the time record is complete as possible for the next step, and validate the results
7) Train the new EOFs from the clearest scenes in the QTS, which do not have EOFs applied. Since the spectroscopy and solar model have changed from B9 to B10, we expect the EOFs to change as well
8) Re-run the QTS with the new EOFs and create the new quality filtering and bias correction schemes
9) Quality filter and bias correct retrieved XCO_2 as outlined in Section 4
10) Create daily "lite" files to distribute the filtered and bias corrected GOSAT XCO_2 from ACOS B10

L2 data products will be evaluated following the established procedures used for OCO-2 and described in Section 4. Products will be documented with an updated User's Guide as has been done for previous ACOS-GOSAT data releases.

Task 3: Trend and IAV analysis of ACOS-GOSAT & OCO data

Deliverable(s)	L3 and L4 analyses using ACOS-GOSAT retrievals
Staff	Weir, Balashov, Basu, Ott

This task will use the ACOS-GOSAT B10 retrievals from Task 2 to produce analyses of atmospheric mixing ratios (L3) and surface fluxes (L4) and compare them to the same methods applied to OCO-2 data. This work will pay special attention to the quantification of the spatial and temporal extents over which the two sensors provide consistent trends and inter-annual variability in atmospheric CO_2 and its surface fluxes.

Task 3A: Joint ACOS-GOSAT/OCO-2 B10 atmospheric mixing ratio (L3) analysis

This subtask will produce a joint L3 analysis of ACOS-GOSAT and OCO-2 B10 retrievals using the same GEOS CoDAS framework as the existing GEOS/OCO-2 product. In particular, we will compare the trends from the product before (2009–2014) and after (2015–onwards) the launch of OCO-2. While the goal of assimilated products is to make an estimate consistent with all sensors, including a new sensor often introduces an artificial jump in the analysis (citation). One of our goals in Task 2 is to develop a product that minimizes such jumps. To analyze this difference, we will follow an approach similar to that outlined for ozone in Wargan et al. (2018). In that work, the authors used a free-running simulation and piecewise trends fit using a multi-linear regression of environmental, e.g., phases of ENSO, and other factors to quantify and remove the jump due to observing system changes. In the proposed work, we'll modify that formulation, designed for ozone, to reflect the factors affecting the carbon cycle and thus quantify and remove the jump due to the introduction of OCO-2 into the analysis in 2015. This effort will be complicated by the coincidence of the exceptional 2015–2016 El Niño. To best separate the natural variability from the jump due to the observing system change, we will continue a GOSAT-only analysis as a separate stream through 2017 for comparison. The infrastructure development needed for this work was supported by CMS and MAP projects and is already completed. This project supports the individual GOSAT B10 run, and the joint GOSAT/OCO analysis, which will add GOSAT to our best available system, whether that is OCO-2 only as exists now or a more complex system supported in pending proposals.

Another major focus of this work will be a comparison of the COVID-19 anomaly calculated from the existing OCO-2 product (Weir et al., *in review: a*) to that calculated from the joint ACOS-GOSAT/OCO-2 product. In particular, we will investigate to what extent both the estimated anomalies and their uncertainties change with the inclusion of GOSAT data and by doubling the length of the baseline period to 12 years. Our hope is that the additional data and longer period will provide a meaningful reduction in uncertainty. While GOSAT returns far fewer soundings than OCO-2, cross-sounding correlations and the narrow swath-width of OCO-2 likely reduce its effective degrees of freedom in a global L3 analysis.

An additional benefit of assimilated products that ingest data streams from multiple sensors is that they can quickly identify sensor degradations through monitoring the statistics of the observations minus model differences (OMFs). This approach is widely used in nonlinear weather prediction for identifying instrument drifts and calibration errors. As we regularly update the L2 product in Task 2, we will continue to update the joint L3 product here, and notify the OCOST if there is any suggestion of sensor problems in the OMFs. We expect this to be a valuable resource as OCO-2 and GOSAT have long exceeded their nominal lifetimes.

Task 3B: ACOS-GOSAT B10 surface flux (L4) analysis

XCO_2 retrievals from GOSAT between 2009 and 2023 will represent the first such long term satellite-based atmospheric CO_2 time series, affording the possibility of inferring 15-year trends and shorter-term anomalies in regional CO_2 surface fluxes. Using the TM5-4DVar inversion framework, we will estimate CO_2 surface fluxes between 2010 and 2023 from GOSAT XCO_2 retrievals. In parallel, we will also estimate CO_2 surface fluxes from a global network of in situ CO_2 samples by multiple laboratories, available from NOAA in a convenient "ObsPack" format. The latter has been the traditional source of atmospheric data in long-term CO_2 inversions (Chevallier et al., 2010; Peylin et al., 2013), and our flux estimates from in situ data will serve as a baseline against which we can evaluate the information content of our GOSAT inversion. The TM5-4DVar inversion framework has already been developed and applied to GOSAT and in situ data (Basu et al., 2013, 2014). The effort in this task will be applying it to the new ACOS-GOSAT B10 data and tuning/evaluating the results: land M-gain retrievals, for example, were missing from ACOS-GOSAT B7.3. Co-I Basu is funded by an existing OCO-2 ST grant (80NSSC20K0818) to perform flux inversions with OCO-2 XCO_2 at least till the end of 2021, and possibly beyond depending on the results. We will compare our GOSAT-derived surface fluxes with those derived from OCO-2 as a way of assessing differences between OCO-2 and GOSAT data processed through the same retrieval and validation process.

While the in situ CO_2 sampling network is dense over large parts of North America and Europe, it is fairly sparse over Asia, South America and Africa. Over these sparsely covered regions, satellite XCO_2 can "see" behavior of the terrestrial carbon cycle and its response to weather and climate anomalies that are not otherwise visible to the existing in situ network (Detmers et al., 2015; Guerlet et al., 2013; Liu et al., 2017; Palmer et al., 2019). Therefore, it is highly likely that our GOSAT-based flux estimates will yield different anomalies and interannual variabilities, especially over regions not well covered by in situ samples, compared to our flux estimates from in situ CO_2 data. We will assess the quality of our in situ and GOSAT CO_2 inversions by comparing to validation data withheld from either inversion, and will investigate the additional carbon cycle knowledge provided by GOSAT XCO_2 over regions sparsely sampled by in situ CO_2 data.

7. Science Team Membership

PI Weir is the lead developer of the GEOS CoDAS for carbon species and has extensive experience assimilating OCO and GOSAT data. He has been a member of the OCOST since 2014 and in this time he has 1) spearheaded the development of GEOS/OCO L3 products and coordination with COVID-19 dashboards, 2) developed new methods for assimilating aircraft data in support of OCO validation, and 3) contributed to OCOMIP activities. He also initiated the collaboration with the operational processing team at JPL to extend ACOS-GOSAT processing that forms the basis for much of this proposal. He will continue to contribute to validation, development and delivery of new data products that support the OCOST, and scientific analysis of carbon flux processes.

Co-I Ott leads GMAO's carbon modeling and assimilation group. She is currently involved in a number of relevant efforts. Under support from NASA Headquarters, she leads a multi-institution initiative designed to improve the quality of carbon cycle modeling in support of future mission planning. She has led GMAO's efforts in CO_2 validation and uncertainty quantification giving her experience with satellite, aircraft, surface, and ground-based remote sensing observations of CO_2. She also leads GMAO's contributions to NASA's Carbon Monitoring System and its implementation of experimental seasonal carbon cycle forecasts. She has previously contributed to planning for NASA's future Active Sensing of CO_2 Emissions Over Nights, Days, Seasons (ASCENDS) mission, focusing on characterization of meteorological errors in reanalyses and their influence on XCO_2 products and has been a member of the OCO-2 Science Team since 2011. As part of the proposed work, she will continue to coordinate with the science team and GEOS system development and contribute to experiment design, analysis, and product delivery.

Co-I Basu is currently a member of the OCOST by virtue of an existing OCO-2 grant. As enumerated above, he has contributed in numerous ways to the OCOST besides working on his own project. If this proposal is funded, Co-I Basu is expected to continue to be a part of the OCOST and contribute for the next three years. He will attend both in-person and remote meetings and conferences as required for this.

Co-Is Dang, O'Dell, Taylor are members of the OCOST through their involvement in the OCO Science Implementation team.

8. Project Management

Our team combines expertise in remote sensing algorithms, global modeling and data assimilation and is well suited to the challenges of processing large satellite datasets to create new products in support of the OCOST. Despite the broad scope of delivering new L2 through L4 products that incorporate GOSAT data, this team consists of several distinct tasks that are each led by scientists with extensive experience. PI Weir will have the overall responsibility for project coordination and will be responsible for coordinating across the team with biweekly telecons and in-person meetings at the OCOST Meetings. He will also participate in regular coordination meetings between the GOSAT and OCO teams. The team will use a variety of existing computer systems to share code and datasets. These include CSU's ocomaster, NASA's NCCS, and for B9 processing, JPL's SDOS systems. Our plan for sharing deliverables from this proposal are described in detail in the data management plan that follows the Science/Technical/Management section. Individual team member contributions are summarized in **Table 1** and an expected timeline of progress in **Table 2**.

Table 1. Summary of team member primary responsibilities. All team members will contribute to the interpretation of the scientific results.

Team member	Responsibilities
B. Weir (PI)	Project coordination; lead all tasks
N. Balashov	Model and data analysis and comparisons to independent datasets, e.g., those from NASA's ACT-America aircraft campaign
S. Basu	Expertise developing bias corrections and column CO_2 retrievals (Tasks 1–2); surface flux inversions
L. Ott	Overall project guidance, oversight of evaluation and product delivery, and scientific analysis
C. O'Dell	Expertise on the development and production of previous ACOS-GOSAT products (Tasks 1–2)
T. Taylor	Expertise on the development and production of previous ACOS-GOSAT products (Tasks 1–2)
L. Dang	Train GMAO staff on ACOS-GOSAT production and delivery workflow
A. Kuze	Communicate updates and status of GOSAT mission and L1 processing
K. Wargan	Collaborate on trend analysis of trace gas reanalyses

Table 2. Expected timeline of progress for the steps in each task.

	PY1 (2021-2022)				PY2 (2022-2023)				PY3 (2023-2024)			
Task	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1A. Continue B9 ACOS processing (Weir, Balashov, Basu, Dang)	■	■	■	■								
1B. Evaluation and delivery of updated B9 products to GES DISC (Ott, Balashov)		■	■	■	■							
2A. Port the B10 workflow to NCCS and produce test dataset (Weir, Balashov, Basu)			■	■	■	■	■					
2B. Update EOFs, quality filtering, and bias correction (O'Dell, Taylor)			■	■	■	■	■	■				
2C. Production of B10 lite files (Weir, Balashov, Basu, O'Dell, Taylor)							■	■	■	■	■	■
3A. L3 state estimation using ACOS-GOSAT B10 data (Weir, Balashov, Ott)							■	■	■	■	■	■
3B. L4 surface flux estimate using ACOS-GOSAT B10 data (Basu, Weir)									■	■	■	■

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Data Management Plan

Our team will continue to comply with NASA Earth Science data policy as we have demonstrated in our past work. This includes providing open access to publications and data used to generate figures and tables through NASA's PubSpace. Our data products (deliverables) listed in the Task Tables throughout the proposal will leverage GMAO resources and HEC systems to distribute all netCDF products. We plan to continue delivering ACOS-GOSAT B9 products to the GES DISC as is currently done. B10 products will be publicly available from the NCCS data portal and will also be available for redistribution from other sources (e.g., GES DISC, JPL's CO_2 Virtual Science Data Environment) as deemed fit by OCO and headquarters management. We will also update the ACOS-GOSAT User's Guide to include any changes made in this project. GMAO is well versed in data distribution and has systems in place to distribute NRT meteorological analyses and forecasts to users with a need for rapid delivery including instrument teams and field missions. In addition, retrospective analysis products, including MERRA-2, the GEOS-CF, and the 7-km GEOS Nature Run, are currently distributed to a wide array of users for a variety of applications. GMAO has ample storage capacity to host and distribute the proposed products. We will leverage GMAO core funding to continue development of visualization capabilities built upon GMAO's Framework for Live User-Invoked Data (FLUID, https://fluid.nccs.nasa.gov/carbon/) focusing on addition on assimilation statistics that can help the OCOST monitor data quality.

List of Acronyms

4D	Four-Dimensional
ABSCO	Absorption Coefficient
ACOS	Atmospheric CO_2 Observations from Space
ACT-America	Atmospheric Carbon and Transport - America
B#	Build #
CMS	Carbon Monitoring System
CoDAS	Constituent Data Assimilation System
COVID-19	Coronavirus Disease 2019
EOF	Empirical Orthogonal Function
GASBAG	Generic Algorithm for Single Band Acquisition of Gases
GCM	General Circulation Model
GeoCarb	Geostationary Carbon Observatory
GEOS	Goddard Earth Observing System
GES DISC	Goddard Earth Sciences Data and Information Services Center
GMAO	Global Modeling and Assimilation Office
GOSAT	Greenhouse Gases Observing Satellite
HEC	High-End Computing
IAV	Inter-Annual Variability
IDP	Iterative Maximum A Posteriori - Differential Optical Absorption Spectroscopy Preprocessor
L#	Level #
MAP	Modeling, Analysis, and Prediction
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, Version 2
NCCS	NASA Center for Climate Simulation
OCO-2	Orbiting Carbon Observatory 2
OCOMIP	OCO Model Intercomparison Project
OCOST	OCO Science Team
OMF	Observation Minus Forecast
QTS	Quick Test Set
SDOS	Science Data Operation Systems
SIF	Solar Induced Fluorescence
TCCON	Total Carbon Column Observing Network
TM5	Transport Model 5
TROPOMI	Tropospheric Monitoring Instrument
TSIS	Total and Spectral solar Irradiance Sensor
ZLO	Zero Level Offset

Biographical Sketches

Brad Weir

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Brief bio

Dr. Brad Weir is the lead developer of NASA's Goddard Earth Observing System (GEOS) Constituent Data Assimilation System (CoDAS) — a state-of-the-art statistical method for estimating atmospheric trace gas abundances based on satellite observations. He has over 10 years of experience developing and applying mathematical and statistical methods to address questions about the physics, chemistry, and biology of the Earth's atmosphere, ocean, and land surface. His work has appeared in Science Magazine, the websites of National Geographic and the BBC, and the NASA/ESA/JAXA trilateral COVID-19 dashboard.

Positions

2013 – present	Scientist. Global Modeling and Assimilation Office (GMAO), NASA Goddard Space Flight Center contract through Universities Space Research Association (USRA).
2010 – 2013	Post-doctoral Research Associate. College of Earth, Ocean, and Atmospheric Sciences, Oregon State University.

Education

2003 – 2010	Ph.D., Mathematics, University of Arizona.
1999 – 2003	B.A. with honors, Mathematics, New York University.

Publications

- Sweeney et al. (2020). "Atmospheric carbon cycle dynamics over the ABoVE domain: an integrated analysis using aircraft observations (Arctic-CAP) and model simulations (GEOS)" *Atmos. Chem. Phys. Discuss.*, in review, doi:10.5194/acp-2020-609.
- Wargan et al. (2020). "The anomalously small 2019 Antarctic ozone hole in an assimilation of MLS observations with the GEOS Constituent Data Assimilation System." *J. Geophys. Res.: Atmos.*, in review, doi:10.1002/essoar.10503445.1.
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- Lee et al. (2020). "Impact of a Regional US Drought on Land and Atmospheric Carbon." *J. Geophys. Res.: Biogeosci.*, in press, doi:10.1029/2019jg005599.
- Bell et al. (2020). "Evaluation of OCO−2 XCO2 Variability at Local and Synoptic Scales using Lidar and In Situ Observations from the ACT−America Campaigns." *J. Geophys. Res.: Atmos.*, 125, doi:10.1029/2019jd031400.

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- Schuh et al. (2019). "Quantifying the impact of atmospheric transport uncertainty on CO2 surface flux estimates." *Global Biogeochem. Cycles*, 33, 484-500, doi:10.1029/2018GB006086.
- Lee et al. (2018). "The impact of spatiotemporal variability in atmospheric CO2 concentration on global terrestrial carbon fluxes." *Biogeosci.*, 15, 5635-5652, doi:10.5194/bg-15-5635-2018.
- Eldering et al. (2017). "The Orbiting Carbon Observatory-2 early science investigations of regional carbon dioxide fluxes." *Science*, 358, doi:10.1126/science.aam5745.
- Weir et al. (2013). "A potential implicit particle smoother for high-dimensional systems." *Nonlin. Processes Geophys.*, 20, 1047-1060, doi:10.5194/npg-20-1047-2013.
- Weir et al. (2013). "Implicit estimation of ecological model parameters." *Bull. Math. Biol.*, 75, 223-257, doi:10.1007/s11538-012-9801-6.
- Weir et al. (2011). "A vortex force analysis of the interaction of rip currents and surface gravity waves." *J. Geophys. Res.: Oceans*, 116, C05001, doi:10.1029/2010JC006232.

Selected Invited Presentations

- Weir, B., L.E. Ott, A. Chatterjee, K. Wargan, and S. Pawson (2017). The GEOS-Carb reanalysis of atmospheric carbon dioxide. GMAO Seminar Series on Earth System Sceince, Global Modeling and Assimilation Office, Greenbelt, Maryland, 5 April.
- Weir, B., R.N. Miller, and Y.H. Spitz (2013). Implicit assimilation of satellite-based observations of ocean color. New Pathways to Understanding and Managing Marine Ecosystems: Quantifying Uncertainty and Risk Using Biophysical-Statistical Models of the Marine Environment, CSIRO Marine and Atmospheric Research, Hobart, Australia, 27-30 May.
- Weir, B., R.N. Miller, and Y.H. Spitz (2013). Implicit parameter estimation. Probabilistic Approaches to Data Assimilation for Earth Systems, Banff International Research Station, Banff, Alberta, Canada, 17-22 Feb.
- Weir, B., R.N. Miller, and Y.H. Spitz (2013). Implicit sampling: theory and implementation. International Workshop on Particle Filters for Data Assimilation, Institute for Statistical Mathematics, Tachikawa, Tokyo, Japan, 7 Feb.
- Weir, B., R.N. Miller, and Y.H. Spitz (2012). Implicit assimilation for marine ecological models. Abstract NG41D-02 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., USA, 3-7 Dec.

Awards & Fellowships

2015	Outstanding Scientific Contribution by a New GMAO Member. GMAO, NASA.
2013	Early Career Travel Award. CSIRO Marine and Atmospheric Research.
2003	Graduate VIGRE Fellowship. Department of Mathematics, University of Arizona.
2003	Perley Lenwood Thorne Medal. Department of Mathematics, New York University.

Dr. Nikolay V. Balashov

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NASA Goddard Space Flight Center, Global Modeling and Assimilation Office (GMAO),
Greenbelt, MD, 20771, USA
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Research Interests:

- Quantification of methane and carbon dioxide emissions, carbon cycle, model evaluation
- Air quality prediction, effects of meteorology on surface ozone
- Relationships between climate oscillations and air pollution, tropospheric ozone trends
- Time series analysis, data mining, applied statistics

Education:

The Pennsylvania State University; PhD in Meteorology; December 2016
The Pennsylvania State University; MS in Meteorology; December 2012
The Pennsylvania State University; BS in Meteorology; BM in Music Composition; December 2012

Publications (Selected):

- **Balashov, N. V.**, Davis, K. J., Miles, N. L., Lauvaux, T., Richardson, S. J., Barkley, Z. R., and Bonin, T. A. (2020), Background heterogeneity and other uncertainties in estimating urban methane flux: results from the Indianapolis Flux Experiment (INFLUX), *Atmos. Chem. Phys.*, 20, 4545–4559, https://doi.org/10.5194/acp-20-4545-2020.
- Barkley, Z. R., Davis, K. J., Feng, S., **Balashov, N.,** Fried, A., DiGangi, J., et al. (2019), Forward modeling and optimization of methane emissions in the South Central United States using aircraft transects across frontal boundaries. *Geophysical Research Letters*, 43. https://doi.org/10.1029/2019GL084495
- Miles, N.L., Richardson, S.J., Lauvaux, T., Davis, K.J., **Balashov, N.V.,** Deng, A., Turnbull, J.C., Sweeney, C., Gurney, K.R., Patarasuk, R. and Razlivanov, I. (2017), Quantification of urban atmospheric boundary layer greenhouse gas dry mole fraction enhancements in the dormant season: Results from the Indianapolis Flux Experiment (INFLUX). *Elem Sci Anth*, 5: 27, doi: https://doi.org/10.1525/elementa.127.
- **Balashov, N. V.***,* A. M. Thompson*, and* G. S. Young *(2016),* Probabilistic surface ozone forecasts with a novel statistical approach, *J. Appl. Meteor. Climo.*, 56(2), 297-316, doi: 10.1175/JAMC-D-16-0110.1.
- **Balashov, N. V.***,* A. M. Thompson*,* S. J. Piketh*, and* K. E. Langerman (2014*),* Surface ozone variability and trends over the South African Highveld from 1990 to 2007*, J. Geophys. Res. Atmos.,* 119*,* 4323–4342*, doi: 10.1002/2013JD020555.*

Manuscripts in Preparation:

Balashov, N. V.*,* A. M. Thompson, A. K. Huff (2020), Interpretation of Probabilistic Surface Ozone Forecasts: A Case Study for Philadelphia.

Balashov N. V., L. E. Ott, B. Weir, K. E. Knowland, K. J. Davis, C. A. Keller, A. Chatterjee, Novel Application of NASA's GEOS-CF Forecasting System to ACT-America Airborne Campaign.

Balashov N.V., L. E. Ott, B. Weir, K. J. Davis, A. M. Thompson, R. M. Stauffer, N. L. Miles, Short Term Effects of 2019 Early Summer Floods on Atmospheric CO2 in the Midwestern and Southern Regions of the United States.

Professional Experience:

NASA Postdoctoral Program, NASA GSFC, GMAO, Greenbelt, MD (2019-present)
Evaluation of CO_2 and CO in NASA's GEOS models using airborne observations from ACT-America campaign
Postdoctoral Researcher, Pennsylvania State University (2016-2019)
Worked on quantifying CH_4 urban emissions and on understanding the corresponding uncertainty; evaluated WRF-Chem CH_4 simulations on urban and regional scales; used towers to analyze CO_2 emissions signals from urban sources
Participant, NASA ACT-America Campaign, Wallops Island, VA (Fall 2017, Spring 2018, and Summer 2019)
Helped with weather forecasting and flight planning, served as a research scientist on the project flights, analyzed data
Participant, NASA DISCOVER-AQ Field Research Deployment, Platteville, Colorado (Summer 2014)
Assisted with preparing and lunching ozonesondes, assisted in collection of air quality data from trace gas instruments, with calibrations, and data archiving
Participant, NASA SEAC4RS Campaign, Houston, Texas (Summer 2013)
Assisted with preparing and lunching ozonesondes and cryogenic frost point hygrometer sondes, analyzed measured data

Sourish Basu

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Education

Ph.D.	2009	Physics	Cornell University, Ithaca NY
M.S.	2006	Physics	Cornell University, Ithaca NY
B.Tech.	2003	Engineering Physics	Indian Institute of Technology Bombay, Mumbai, India

Professional Employment History

2019 –	Assistant Research Scientist, University of Maryland, College Park
2014 – 2019	Research Scientist II, CIRES, University of Colorado, Boulder
2013 – 2014	National Research Council Post-doctoral Fellow, NOAA/ESRL
2009 – 2013	Scientist C, SRON Netherlands Institute for Space Research

Relevant Expertise

Sourish Basu is a carbon cycle scientist with expertise in assimilating in situ and satellite CO, CO_2 and CH_4 measurements and their isotope ratios in surface flux inversions. He has extensive experience in flux inversions and atmospheric modeling. Basu is a key developer of the TM5 4DVAR modeling system to be used in this proposal.

Selected Publications

1. Schuh, A. E., Jacobson, A. R., Basu, S., Weir, B., Baker, D., Bowman, K., Chevallier, F., Crowell, S., Davis, K. J., Deng, F., Denning, S., Feng, L., Jones, D., Liu, J. and Palmer, P. I.: Quantifying the Impact of Atmospheric Transport Uncertainty on CO_2 Surface Flux Estimates, *Global Biogeochemical Cycles*, 33(4), 484–500, doi:10.1029/2018GB006086, 2019.
2. Crowell, S., Baker, D., Schuh, A., Basu, S., Jacobson, A. R., Chevallier, F., Liu, J., Deng, F., Feng, L., McKain, K., Chatterjee, A., Miller, J. B., Stephens, B. B., Eldering, A., Crisp, D., Schimel, D., Nassar, R., O'Dell, C. W., Oda, T., Sweeney, C., Palmer, P. I. and Jones, D. B. A.: The 2015–2016 carbon cycle as seen from OCO-2 and the global in situ network, *Atmos. Chem. Phys.*, 19(15), 9797–9831, doi:10.5194/acp-19-9797-2019, 2019.
3. Basu, S., Baker, D. F., Chevallier, F., Patra, P. K., Liu, J. and Miller, J. B.: The impact of transport model differences on CO_2 surface flux estimates from OCO-2 retrievals of column average CO_2, *Atmos. Chem. Phys.*, 18(10), 7189–7215, doi:10.5194/acp-18-7189-2018, 2018.
4. Basu, S., and Coauthors, 2014: The seasonal variation of the CO_2 flux over Tropical Asia estimated from GOSAT, CONTRAIL, and IASI. *Geophys. Res. Lett.*, 41, 1809–1815, https://doi.org/10.1002/2013GL059105.
5. Basu, S, S Guerlet, A Butz, S Houweling, O Hasekamp, I Aben, P Krummel, et al. 2013: Global CO_2 Fluxes Estimated from GOSAT Retrievals of Total Column CO_2. *Atmos. Chem. Phys.* 13: 8695–8717. https://doi.org/10.5194/acpd-13-4535-2013.

Dr. Lesley Ott
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8800 Greenbelt Road,
Greenbelt, MD 20771, USA

Current Position

- Research Meteorologist, NASA GSFC Global Modeling and Assimilation Office

Relevant Experience

Dr. Ott's research focuses on understanding how small-scale physical processes affect atmospheric composition, climate variability, and understanding of the global carbon cycle. She has used a combination of satellite and in situ trace gas observations to clarify the roles of different transport processes and improve their representation in global models. This has led to a new carbon data assimilation techniques and characterization of the role of transport uncertainty in top-down flux estimates. She currently leads the carbon cycle modeling group in NASA's Global Modeling and Assimilation Office including projects that aim to i) integrate land, ocean, and atmospheric models to better understand carbon flux, ii) support NASA's OCO and GeoCarb missions, and iv) use models to evaluate the benefit of future space-based CO_2 and CH_4 missions.

Education

- Ph.D., M.S., Univ. of Maryland, College Park (2000-2006), Dept. of Atmospheric and Oceanic Science
- B.S., Univ. of Maryland, College Park (2000), College of Computer, Mathematical and Physical Sciences

Selected Professional Service

- Guest Editor of Environmental Research Letters Special Collection on Carbon Monitoring Systems
- Member of Earth Science and Applications from Space 2017 Decadal Survey – Marine and Terrestrial Ecosystems and Natural Resource Management Panel
- Member of NASA's Carbon Monitoring System, OCO, and GeoCarb Science Teams

Selected Publications

- Weir, B., **L.E. Ott**, G.J. Collatz, S.R. Kawa, B. Poulter, A. Chatterjee, T. Oda, and S. Pawson, Calibrating satellite-derived carbon fluxes for retrospective and near real-time assimilation systems, *Atmos. Chem. Phys. Discuss.*, doi:10.5194/acp-2020-496, in review, 2020.
- Lee, E., F.-W. Zeng, R.D. Koster, **L.E. Ott**, S. Mahanama, B. Weir, B. Poulter, and T. Oda, Impact of a regional U.S. drought on land and atmospheric carbon, *Journal of Geophysical Research: Biogeosciences*, 125, e2019JG005599. doi:10.1029/2019JG005599, 2020.
- Chen, Y., J.T. Randerson, S.R. Coffield, E. Foufoula-Georgiou, P. Smyth, C.A. Graff. D.C. Morton, N. Andela, G.R. van der Werf, and **L.E. Ott**: Forecasting global fire emissions on sub-seasonal-to-seasonal (S2S) timescales, *Journal of Advances in Modeling the Earth System*, doi:10.1029/2019MS001955, 2020.
- Duncan, B. N., **L. E. Ott**, et al., Space-Based Observations for Understanding Changes in the Arctic-Boreal Zone, *Reviews of Geophysics*, 58 (1): 2019RG000652, doi:10.1029/2019rg000652, 2019.
- **Ott, L. E.**, et al., Assessing the Observability of CO_2 Flux Uncertainty in Atmospheric CO_2 Records: Application using Products from NASA's Carbon Monitoring Flux Pilot Project, *Journal of Geophysical Research,* 120, doi: 10.1002/2014JD022411, 2015.
- Tangborn, A., L. L. Strow, B. Imbiriba, **L. Ott**, and S. Pawson, Evaluation of a new middle-lower tropospheric CO_2 product using data assimilation, *Atmospheric Chemistry and Physics*, 13, 4487-4500, doi:10.5194/acp-13-4487-2013, 2013.
- **Ott, L. E.**, B. N. Duncan, S. Pawson, P. R. Colarco, M. Chin, C. Randles, T. Diehl, and J. E. Nielsen, The influence of the 2006 Indonesian biomass burning aerosols on tropical dynamics studied with the GEOS-5 AGCM, *Journal of Geophysical Research*, 115, D14121, doi:10.1029/2009JD013181, 2010.

Christopher O'Dell

Cooperative Institute for Research in the Atmosphere
Colorado State University

RELEVANT EXPERIENCE

PI for CSU-based GOSAT, OCO-2, and OCO-3 Algorithm Teams, as well as GeoCarb Lead for the Level-2 algorithms. Chris has significant experience in assessing systematic errors in satellite-based CO_2 retrievals and their validation, designing cloud-screening methods, assessing impact of calibration-induced biases, developing and validating filtering and bias correction techniques for satellite retrievals, and facilitating the use of satellite-based GHG measurements in inversion frameworks.

EDUCATION:

Ph. D. (summa cum laude), Physics, University of Wisconsin-Madison, 2001.

CURRENT POSITION:

2015 – present: Senior Research Scientist, CIRA, Colorado State University.

PREVIOUS POSITIONS:

2012 – 2015: Assistant Professor, Dept. of Atmospheric Science, Colorado State University
2010 – 2012: Research Scientist III, CIRA, Colorado State University
2007 – 2009: Research Scientist II, Dept. of Atmospheric Science, Colorado State University.
2006 – 2007: EUMETSAT Hydrology SAF Visiting Fellow, European Centre for Medium-Range Weather Forecasting, Reading, UK.
2003 – 2006: Research Scientist, Atmospheric and Oceanic Sciences Dept., University of Wisconsin-Madison, Madison, WI.

SELECTED PUBLICATIONS

O'Dell, C. W., Eldering, A., Wennberg, P. O., Crisp, D., Gunson, M. R., et al., 2018: Improved retrievals of carbon dioxide from Orbiting Carbon Observatory-2 with the version 8 ACOS algorithm, *Atmos. Meas. Tech.*, 11, 6539-6576, https://doi.org/10.5194/amt-11-6539-2018.

Liu, J., Bowman, K.W., Schimel, D.S., Parazoo, N.C., Jiang, Z., Lee, M., Bloom, A.A., Wunch, D., Frankenberg, C., Sun, Y. and **O'Dell, C.W.**, 2017. Contrasting carbon cycle responses of the tropical continents to the 2015–2016 El Niño. *Science*, 358 (6360), p.eaam5690.

Taylor, T. E., **O'Dell, C. W.**, Frankenberg, C., et al., 2016: Orbiting Carbon Observatory-2 (OCO-2) cloud screening algorithms: validation against collocated MODIS and CALIOP data, *Atmos. Meas. Tech.*, 9, 973-989.

Lindqvist, H., **O'Dell, C.W**., Basu, S., Boesch, H., Chevallier, F., Deutscher, N., Feng, L., Fisher, B., Hase, F., Inoue, M. and Kivi, R., 2015. Does GOSAT capture the true seasonal cycle of carbon dioxide? *Atmos. Chem. Phys.*, *15*, pp.13023-13040.

O'Dell, C.W., et al., 2012: The ACOS CO_2 retrieval algorithm, Part I: Description and validation against synthetic observations. *Atmos. Meas. Tech.*, 5, 99-121.

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Education

B.S. Physics, University of Georgia, 1997.

M.S. Atmospheric Science, Colorado State University, 2006.

Research Experience

1997 - 2003; Department of Physics and Astronomy, University of Georgia, Research Coordinator, National Ultra-Violet Monitoring Center.

2004 - 2005; Department of Atmospheric Science, Colorado State University, Graduate Student Research Assistant under Prof. Graeme Stephens.

2006 - current; Cooperative Institute for Research in the Atmosphere, Colorado State University, Research Associate III.

Recent Relevant Publications

1. **Thomas E. Taylor**, Annmarie Eldering, Aronne Merrelli, Matthäus Kiel, Peter Somkuti, et al., OCO-3 early mission operations and initial (vEarly) XCO_2 and SIF retrievals, *Remote Sensing of Environment*, Vol 251, 15, 2020.
2. A. Eldering, **T.E. Taylor**, C.W. O'Dell, R. Pavlick, The OCO-3 mission; measurement objectives and expected performance based on one year of simulated data, *Atmos. Meas. Tech.*, Vol 12, No 4, pp 2341–2370, doi: 10.5194/amt-12-2341-2019, 2019.
3. C.W. O'Dell, et al., **T.E. Taylor**, Improved retrievals of carbon dioxide from the Orbiting Carbon Observatory-2 with the version 8 ACOS algorithm, *Atmos. Meas. Tech.*, 11, 6539-6576, doi: 10.5194/amt-11-6539-2018, 2018.
4. A. Eldering, P.O. Wennberg, D. Crisp, D.S. Schimel, M.R. Gunson, A. Chatterjee, J. Liu, F.M. Schwandner, Y. Sun, C.W. O'Dell, C. Frankenberg, **T. Taylor**, B. Fisher, G.B. Osterman, D. Wunch, J. Hakkarainen, J. Tamminen, B. Weir, The Orbiting Carbon Observatory-2 early science investigations of regional carbon dioxide fluxes, *Science*, **358**, 6360, doi: 10.1126/science.aam5745, 2017.
5. **T.E. Taylor et. al.**, Orbiting Carbon Observatory-2 (OCO-2) cloud screening algorithms: validation against collocated MODIS and CALIOP data, *Atmos. Meas. Tech.*, 9, 1-17, doi: 10.5194/amt-9-1-2016, 2016.
6. O'Dell, C.W., Connor, B., Bosch, H., O'Brien, D., Frankenburg, C., Castano, R., Christi, M. Eldering, D, Fisher, B., Gunson, M., McDuffie, J., Miller, C.E., Natraj, V., Oyafuso, F, Polonsky, I., Smyth, M., **Taylor, T.**, Toon, G.C., Wennberg, P.O., and Wunch, D., The ACOS CO_2 retrieval algorithm - Part 1: Description and validation against synthetic observations, *Atmos. Meas. Tech.*, 5, 99-121, doi:10.5194/amt-5-99-2012, 2012.

Last updated: January 7, 2021

Lan Dang

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Proposed Role in the Investigation

Provide hands-on training, mature existing written documentation for an external audience, and be available on an as-needed basis to answer questions regarding current GOSAT processing system.

Experience Related to the Investigation

Over 12 years of experience developing and leading science data system (SDS) operations for various Earth Science missions like Orbiting Observatory-2 (OCO-2), Orbiting Observatory-3 (OCO-3), Soil Moisture Active Passive (SMAP), in both the role of Operations Lead and Science Data System Manager. As Operations Engineer on OCO-2, successfully developed and operated the science data system to process and reprocess the GOSAT data through the ACOS retrieval algorithm. As Operations lead and later SDS Manager, successfully trained and guided an Operations team of 4-5 engineers to support SDSD processing for GOSAT, OCO-2, and OCO-3 data. Broad experience in science data system operations and development for earth science missions like OCO-2/3, SMAP, and NISAR.

7/2020 – present	Manager, Science Data Operations System, OCO-2/3
1/2018 – present	Operations Lead, Science Data Operations System, OCO-3
10/2020 – present	Operations Lead, Science Data System, NISAR
1/2018 – present	Operations Lead, Science Data System, SMAP
7/2015-1/2018	Operations Engineer, ARIA
7/2011-7/2020	Operations Engineer/Operations Lead, OCO-2
3/2009 – 10/2012	Operations Engineer, Science Operational System, Diviner Lunar Radiometer Experiment

Education

B.Sc, Computer Science, California Polytechnic University, Pomona, CA (2008)

TABLE OF WORK EFFORT

		Commitment (months per year)													
				Year 1			***Year 2***			***Year 3***			***Sum***		
				This Project		*Other Projects*	*This Project*		*Other Projects*	*This Project*		*Other Projects*	*This Project*		*Other Projects*
Name	**Role**	*Institution Support*	*Institution Research Time*	*NASA Support*	*Total*		*NASA Support*	*Total*		*NASA Support*	*Total*		*NASA Support*	*Total*	
Brad Weir	PI	12	12	3.6	3.6	2.4	3.6	3.6	2.4	3.6	3.6	2.4	10.8	10.8	7.2
Nikolay Balashov	Co-I	12	12	2.4	2.4	0	2.4	2.4	0	2.4	2.4	0	7.2	7.2	0
Sourish Basu	Co-I	12	12	2.4	2.4	3	2.4	2.4	3	2.4	2.4	1	7.2	7.2	7
Lesley Ott	Co-I	12	12	1.2	1.2	4.8	1.2	1.2	5.7	1.2	1.2	4.8	3.6	3.6	15.3
Christopher O’Dell	Co-I	12	12	1	1	7.75	1	1	6	1	1	6	3	3	19.75
Thomas Taylor	Co-I	12	12	1	1	5.35	1	1	4	1	1	4	3	3	13.35
Lan Dang	Co-I	12	12	1.2	1.2	0	0	0	0	0	0	0	1.2	1.2	0
Natalie Tourville	Support	12	12	0.1	0.1	11.5	0.1	0.1	11.5	0.1	0.1	11.5	0.3	0.3	34.5
Akihkio Kuze	Collaborator	-	-	0*	0*	-	0*	0*	-	0*	0*	-	0*	0*	-
Krzysztof Wargan	Collaborator	-	-	0*	0*	-	0*	0*	-	0*	0*	-	0*	0*	-
Sum of work effort:		**96**	**96**	**12.9**	**12.9**	**34.8**	**11.7**	**11.7**	**32.6**	**11.7**	**11.7**	**29.7**	**11.7**	**11.7**	**97.1**
Comments:															

Institution Support – The total number of months this individual is supported by their institution (for all tasks, not just this project).
Institution Research Time – The number of months institution support is allocated toward all research (less than or equal to *Institution Support*).
Total - The total number of months that will be committed to this project by the team member (including time not funded by this proposal and time funded by this proposal).
NASA Support - The number of months committed to this project that will actually be funded by this proposal.
Other Projects - The number of months that are committed to other currently funded proposals.
** De minimis*

Current and Pending Support

Brad Weir

Support: ☒ Current ☐ Pending
Project/Proposal Title: GEOS Modeling and Assimilation Products in Support of the OCO Missions
Source of Support: Science Team for the OCO Missions
Total Award Period Covered: 04/18-04/21
Person-Months Per Year Committed to the Project: 3.6

Support: ☐ Current ☒ Pending
Project/Proposal Title: Toward a space-based constraint on the hydroxyl radical: combining the assimilation of ozone, and carbon constituents
Source of Support: Modeling, Analysis, and Prediction
Total Award Period Covered: 01/21-01/25
Person-Months Per Year Committed to the Project: 6

Support: ☐ Current ☒ Pending
Project/Proposal Title: Understanding forced trends and variability of radiatively active constituents in the lower stratosphere through model simulations and data assimilation
Source of Support: Modeling, Analysis, and Prediction
Total Award Period Covered: 01/21-01/25
Person-Months Per Year Committed to the Project: 1.2

Support: ☐ Current ☒ Pending
Project/Proposal Title: Using NASA's airborne campaigns and data assimilation to improve satellite retrievals of and NO2 and evaluate their ability to constrain emissions
Source of Support: Atmospheric Composition Campaign Data Analysis and Modeling
Total Award Period Covered: 01/21-01/24
Person-Months Per Year Committed to the Project: 2.4

Support: ☐ Current ☒ Pending
Project/Proposal Title: A Global, Sectorally Disaggregated Methane Budget and Atmospheric State Consistent with 13CH4 Measurements and TROPOMI CH4 Data
Source of Support: Carbon Monitoring System
Total Award Period Covered: 12/20-12/23
Person-Months Per Year Committed to the Project: 3

Support: ☒ Current ☐ Pending
Project/Proposal Title: NASA GSFC contributions to the GeoCarb Science Team
Source of Support: GeoCarb/NASA
Total Award Period Covered: 10/19-10/26
Person-Months Per Year Committed to the Project: 2.4

Support: ☐ Current ☒ Pending
Project/Proposal Title: GEOS-Carb IV: Delivering low-latency carbon flux and concentration datasets in support of NASANASA's Carbon Monitoring System
Source of Support: Carbon Monitoring System
Total Award Period Covered: 12/20-12/23

Person-Months Per Year Committed to the Project: 3.6

Support: ☐ Current ☒ Pending

Project/Proposal Title: Bridging the SAGE data gap: Toward a climate data product with ozone and water vapor NASA SAGE and Aura missions and NASA reanalyses

Source of Support: SAGE Science Team

Total Award Period Covered: 05/21-05/24

Person-Months Per Year Committed to the Project: 1.2

Nikolay Balashov

Support: ☐ Current ☒ Pending

Project/Proposal Title: Take flight through NASA's high-resolution composition forecasting system: A quantitative assessment of ozone forecast skill

Source of Support: Atmospheric Composition Campaign Data Analysis and Modeling

Total Award Period Covered: 04/21-04/24

Person-Months Per Year Committed to the Project: 6

Support: ☐ Current ☒ Pending

Project/Proposal Title: GEOS-Carb IV: Delivering low-latency carbon flux and concentration datasets in support NASA's Carbon Monitoring System

Source of Support: Carbon Monitoring System

Total Award Period Covered: 12/20-12/23

Person-Months Per Year Committed to the Project: 6

Sourish Basu

Support: ☒ Current ☐ Pending

Project/Proposal Title: Reducing the impact of model transport error on flux estimates using CO_2 profile information from OCO2 in concert with an online bias correction

Source of Support: NASA/OCO2 Science Team

Total Award Period Covered: Jun 2020 – May 2023

Person-Months Per Year Committed to the Project: 3

Support: ☒ Current ☐ Pending

Project/Proposal Title: Process-level investigation of revised global methane budget based on in situ and remote sensing of atmospheric composition and the land surface

Source of Support: NASA ROSES/IDS

Total Award Period Covered: Jun 2017 – Mar 2021

Person-Months Per Year Committed to the Project: 3

Support: ☐ Current ☒ Pending

Project/Proposal Title: A Global, Sectorally Disaggregated Methane Budget and Atmospheric State Consistent with $\delta^{13}CH_4$ Measurements and TROPOMI CH_4 Data

Source of Support: NASA/Carbon Monitoring System

Total Award Period Covered: Pending (originally proposed Dec 2020 – Nov 2023)

Person-Months Per Year Committed to the Project: 4

Support: ☐ Current ☒ Pending

Project/Proposal Title: Detection of US National and Regional CO_2 emission changes related to COVID 19; Testing the fidelity and resolution of the GGGRN and CarbonTracker over North America

Source of Support: NOAA/AC4 & COM

Total Award Period Covered: Pending (originally proposed Sep 2021 – Aug 2023)

Person-Months Per Year Committed to the Project: 2.5

Support: ☐ Current ☒ Pending

Project/Proposal Title: Improving Terrestrial Biosphere Carbon Fluxes with a Dual Tracer Flux Estimation System Assimilating Satellite Retrievals of CO_2 and In Situ Measurements of ^{14}C in CO_2

Source of Support: NASA/Carbon Cycle Science

Total Award Period Covered: Pending (originally proposed Aug 2021 – Jul 2024)

Person-Months Per Year Committed to the Project: 3

Lesley Ott

Support: ☒ Current ☐ Pending

Project/Proposal Title**:** GEOS Modeling and Assimilation Products in Support of the OCO Missions

Source of Support: Science Team for the OCO Missions

Total Award Period Covered: 04/18-04/21

Person-Months Per Year Committed to the Project: 2.4

Support: ☒ Current ☐ Pending

Project/Proposal Title: High-resolution atmospheric carbon dioxide simulations in support of the OCO-3 map-mode

Source of Support: Science Team for the OCO Missions

Total Award Period Covered: 04/18-04/21

Person-Months Per Year Committed to the Project: 1.2

Support: ☒ Current ☐ Pending

Project/Proposal Title: Synthesis, reconciliation and assessment of CMS prototype products

Source of Support: Carbon Monitoring System: Continuing Prototype Product Development, A.49

Total Award Period Covered: 09/19-09/22

Person-Months Per Year Committed to the Project: 1.2

Support: ☒ Current ☐ Pending

Project/Proposal Title: Towards Conceptualization and Predictability: A Multi-scalar Analysis of Urban-Influenced Hydrometeorological Processes

Source of Support: Interdisciplinary Science in Earth Science

Total Award Period Covered: 06/20-06/23

Person-Months Per Year Committed to the Project: 1.2

Support: ☐ Current ☒ Pending

Project/Proposal Title: Improving prediction of fire extremes in the GEOS forecasting system on daily and seasonal timescales

Source of Support: Modeling, Analysis and Prediction

Total Award Period Covered: 01/21-01/25

Person-Months Per Year Committed to the Project: 1.2

Support: ☐ Current ☒ Pending
Project/Proposal Title: Improving the Representation of Lightning and its Production of NOx in the GEOS Suite of Models using Machine Learning and Observational Analysis
Source of Support: Modeling, Analysis and Prediction
Total Award Period Covered: 01/21-01/25
Person-Months Per Year Committed to the Project: 1.2

Support: ☐ Current ☒ Pending
Project/Proposal Title**:** Stratospheric Intrusion Investigation using Lidar, Ozonesondes, and SAGE (SIILOS)

Source of Support: Atmospheric Composition: Upper Atmospheric Composition Observations
Total Award Period Covered: 05/21-05/25
Person-Months Per Year Committed to the Project: 1.2 in PY1 only (5/21-5/22)

Support: ☐ Current ☒ Pending
Project/Proposal Title: Using NASA's airborne campaigns and data assimilation to improve satellite retrievals of and NO2 and evaluate their ability to constrain emissions
Source of Support: Atmospheric Composition Campaign Data Analysis and Modeling
Total Award Period Covered: 04/21-04/24
Person-Months Per Year Committed to the Project: 1.2

Support: ☐ Current ☒ Pending
Project/Proposal Title: Take flight through NASA's high-resolution composition forecasting system: A quantitative assessment of ozone forecast skill
Source of Support: Atmospheric Composition Campaign Data Analysis and Modeling
Total Award Period Covered: 04/21-04/24
Person-Months Per Year Committed to the Project:1.2

Support: ☒ Current ☐ Pending
Project/Proposal Title: Global Modeling and Assimilation Office: Proposed Core Activities, FY2020-2024

Source of Support: Modeling, Analysis, and Prediction
Total Award Period Covered: 10/20-10/24
Person-Months Per Year Committed to the Project: 2.4

Support: ☒ Current ☐ Pending
Project/Proposal Title: NASA GSFC contributions to the GeoCarb Science Team

Source of Support: GeoCarb/NASA
Total Award Period Covered: 10/19-10/26
Person-Months Per Year Committed to the Project: 1.2 until FY23, then 2.4

Support: ☐ Current ☒ Pending
Project/Proposal Title: GEOS-Carb IV: Delivering low-latency carbon flux and concentration datasets in support NASA's Carbon Monitoring System
Source of Support:
Total Award Period Covered: 12/20-12/23
Person-Months Per Year Committed to the Project: 3.6

Support: ☐ Current ☒ Pending

Project/Proposal Title**:** Volcanic perturbations of the Global Carbon Cycle

Source of Support: Carbon Cycle Science
Total Award Period Covered: 07/21-07/24
Person-Months Per Year Committed to the Project: 1.1

Support: ☐ Current ☒ Pending
Project/Proposal Title: Diagnosing and attributing Arctic-Boreal carbon fluxes using in situ and satellite CO2 network
Source of Support: Science Team for the OCO Missions
Total Award Period Covered: 07/21-07/24
Person-Months Per Year Committed to the Project: 1.2

Support: ☐ Current ☒ Pending
Project/Proposal Title: Revealing the mystery of African carbon cycle

Source of Support: Science Team for the OCO Missions
Total Award Period Covered: 07/21-07/24
Person-Months Per Year Committed to the Project:1.2

Christopher O'Dell

CURRENT SUPPORT

Proposer Name	Award/Project Title	Program Name/ Sponsoring Agency/ Point of Contact telephone and email	Period of Performance/ Total Budget	Commitment (Person-Months per Year)
Chris O'Dell (CSU)	OCO-2 Task	NASA JPL; Michael Gunson (818.354.2124, Michael.R.Gunson@jpl.nasa.gov)	10/1/2019 – 9/30/2021; $750K	2.5
Chris O'Dell (CSU)	OCO-3 Task	NASA JPL; Annmarie Eldering (818-354-4941, Annmarie.Eldering@jpl.nasa.gov)	10/01/2016 – 09/30/21; $300K	2.5
Lesley Ott (NASA GSFC)	Greenhouse Gases Observing System Simulation Experiments (OSSEs)	NASA; Kenneth W. Jucks (202-358-0476, Kenneth.W.Jucks@nasa.gov)	10/1/2020 – 9/30/2021; $194K §	1.0
Chris O'Dell (CSU)	GeoCarb Level-2 Algorithms	Univ of Oklahoma; Andrea Deaton (adeaton@ou.edu, 405-325-4757)	3/1/2017 – 5/10/2026; $4330K	6.0

§ *Colorado State University Funding Only*

PENDING SUPPORT

Proposer Name	Award/Project Title	Program Name/ Sponsoring Agency/ Point of Contact telephone and email	Period of Performance/ Total Budget	Commitment (Person-Months per Year)
Chris O'Dell (CSU)	OCO-2 Extended Mission Task	NASA JPL; Michael Gunson (818.354.2124, Michael.R.Gunson@jpl.nasa.gov)	10/1/2021 – 9/30/2023*; $500K*	1.0*

Proposer Name	Award/Project Title	Program Name/ Sponsoring Agency/ Point of Contact telephone and email	Period of Performance/ Total Budget	Commitment (Person-Months per Year)
Chris O'Dell (CSU)	OCO-3 Phase E Task	NASA JPL; Annmarie Eldering (818-354-4941, Annmarie.Eldering@jpl.nasa.gov)	10/1/2021 – 12/31/2023*; $600K*	2.4*
Susan Kulawik (NASA Ames)	Reducing OCO-2 regional biases through novel 3d-cloud and meteorology retrievals.	NASA (ROSES 2020); Kenneth W. Jucks (202-358-0476, Kenneth.W.Jucks@nasa.gov)	10/1/2021 – 9/30/2024; $99K §	1.2
Abhishek Chatterjee (NASA GSFC/USRA)	Diagnosing and attributing Arctic-Boreal carbon fluxes using in situ and satellite CO2 monitoring network	NASA (ROSES 2020); Kenneth W. Jucks (202-358-0476, Kenneth.W.Jucks@nasa.gov)	08/02/2021 – 7/31/2024; $255K §	1 YR1 & 0.75 YR2/YR3
Junjie Liu (JPL)	Revealing the mystery of the African carbon cycle	NASA (ROSES 2020); Kenneth W. Jucks (202-358-0476, Kenneth.W.Jucks@nasa.gov)	8/1/2021 – 7/31/2023; $51K §	0.9
Chris O'Dell (CSU)	Reducing geometry-dependent OCO XCO2 biases to better inform SAM-based fossil fuel flux inversions	NASA (ROSES 2020); Kenneth W. Jucks (202-358-0476, Kenneth.W.Jucks@nasa.gov)	10/1/2021 – 9/30/2024; $326K §	1.0

**These numbers not fixed as of this writing*
§ Colorado State University Funding Only

Thomas Taylor

CURRENT SUPPORT

Proposer Name	Award/Project Title	Program Name/ Sponsoring Agency/ Point of Contact telephone and email	Period of Performance/ Total Budget	Commitment (Person-Months per Year)
Chris O'Dell (CSU)	OCO-2 Task	NASA JPL; Michael Gunson (818.354.2124, Michael.R.Gunson@jpl.nasa.gov)	10/1/2019 – 9/30/2021; $750K	2.7
Chris O'Dell (CSU)	OCO-3 Task	NASA JPL; Annmarie Eldering (818-354-4941, Annmarie.Eldering@jpl.nasa.gov)	10/01/2016 – 09/30/21; $300K	2.7
Chris O'Dell (CSU)	GeoCarb Level-2 Algorithms	Univ of Oklahoma; Andrea Deaton (adeaton@ou.edu, 405-325-4757)	3/1/2017 – 5/10/2026; $433K	4

§ Colorado State University Funding Only

PENDING SUPPORT

Proposer Name	Award/Project Title	Program Name/ Sponsoring Agency/ Point of Contact telephone and email	Period of Performance/ Total Budget	Commitment (Person-Months per Year)
Chris O'Dell (CSU)	Reducing geometry-dependent OCO XCO2 biases to better inform SAM-based fossil fuel flux inversions	NASA (ROSES 2020); Kenneth W. Jucks (202-358-0476, Kenneth.W.Jucks@nasa.gov)	10/1/2021 – 9/30/2024; $326K* §	0.75 YR1/YR2 & 0.50 YR3
Chris O'Dell (CSU)	OCO-2 Extended Mission Task	NASA JPL; Michael Gunson (818.354.2124, Michael.R.Gunson@jpl.nasa.gov)	10/1/2021 – 9/30/2023*; $500K*	2.4
Chris O'Dell (CSU)	OCO-3 Phase E Task	NASA JPL; Annmarie Eldering (818-354-4941, Annmarie.Eldering@jpl.nasa.gov)	10/1/2021 – 12/31/2023*; $600K*	2.4
Ian Baker (CSU)	Assessing Drivers of Tropical Carbon Flux Variability across Spatial and Temporal Scales with Space-based Observations	NASA (ROSES 2020); Kenneth W. Jucks (202-358-0476, Kenneth.W.Jucks@nasa.gov)	04/01/2021 – 03/31/2024 $293,099	3

**These numbers not fixed as of this writing*
§ *Colorado State University Funding Only*

Lan Dang

Lan Dang is supported through JPL project funds and is not a Co-I on any current or pending proposals.

UNIVERSITIES SPACE RESEARCH ASSOCIATION

Title: Long-term trends and inter-annual variability of carbon dioxide and its surface fluxes from the OCO and GOSAT missions

P.I: Dr. Brad Weir

USRA Proposal # OPP-21-0065

Summary of Cost and Fee

	7/1/2021-6/30/2022 Year 1	7/1/2022-6/30/2023 Year 2	7/1/2023-6/30/2024 Year 3	Grand Total
Total Direct Labor Research Hours	558	558	558	1,674
Travel	$1,505	$1,543	$4,772	$7,820
Other Direct Costs (under $3k)	$0	$2,563	$2,627	$5,190
ODC Procurements (over $3k)	$0	$0	$0	$0
Total Other Direct Costs	**$1,505**	**$4,106**	**$7,399**	**$13,010**
USRA Total Redacted Cost	**$1,505**	**$4,106**	**$7,399**	**$13,010**
JPL Redacted Cost:	$1,684	$910	$910	$3,504
GSFC Redacted Cost:	$16,803	$17,624	$18,550	$52,977
Grand Total - Redacted	**$19,992**	**$22,640**	**$26,859**	**$69,491**

Reviewed by Business Manager: Russell Berard 1/12/2021

Signature **Date**

Approved by Contracts: Carine Nourieh Digitally signed by Carine Nourieh Date: 2021.01.12 14:22:58 -05'00' 1/12/2021

Signature **Date**

Universities Space Research Association
Budget Narrative

Proposal Title: ***Long-term trends and inter-annual variability of carbon dioxide and its surface fluxes from the OCO and GOSAT missions***

USRA Proposal No.: OPP-21-0065

Investigator: P.I - Dr. Brad Weir, Universities Space Research Association (USRA)

Period of Performance:
July 1, 2021 to June 30, 2024

Personnel:

The Principal Investigator, Dr. Brad Weir is a Research Scientist with The Universities Space Research Association's GESTAR program (Goddard Earth Sciences Technology and Research). Dr. Brad Weir will spend 30% of his time during the proposed three-year period of performance on this work.

Fringe Benefits:

Fringe benefits for the USRA Investigator are estimated based on historical actual rates. However, only actual fringe benefits will be charged to the Prime. The USRA fringe benefit rate is applied, per USRA's approved disclosure statement, to staff direct labor costs, not annual salary.

Travel:

It is proposed that Dr. Weir will attend the American Geophysical Union meeting in San Francisco, CA in year three. Dr. Weir also plans to attend an annual teaming meeting in Pasadena, CA. Estimated costs are based upon currently available rates and escalated by 2.5% for each out-year. Estimates include airfare, lodging, meals, transportation to and from the site and incidental expenses. GSA Per Diem rates are used for lodging and meals. Estimated cost for this travel is being proposed based on the below breakout in **Figure A.**

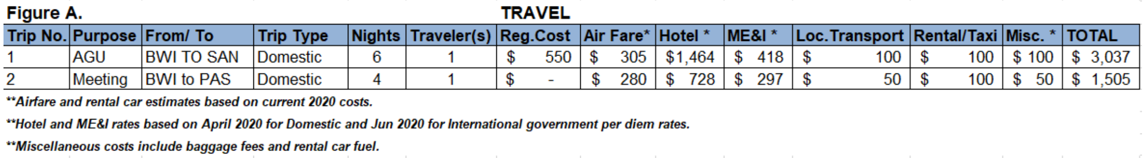

Figure A. **TRAVEL**

Trip No.	Purpose	From/ To	Trip Type	Nights	Traveler(s)	Reg.Cost	Air Fare*	Hotel *	ME&I *	Loc.Transport	Rental/Taxi	Misc. *	TOTAL
1	AGU	BWI TO SAN	Domestic	6	1	$ 550	$ 305	$1,464	$ 418	$ 100	$ 100	$ 100	$ 3,037
2	Meeting	BWI to PAS	Domestic	4	1	$ -	$ 280	$ 728	$ 297	$ 50	$ 100	$ 50	$ 1,505

*****Airfare and rental car estimates based on current 2020 costs.***

*****Hotel and ME&I rates based on April 2020 for Domestic and Jun 2020 for International government per diem rates.***

*****Miscellaneous costs include baggage fees and rental car fuel.***

Other Direct Costs:

The proposed budget includes funding for a publication in years two and three of the proposal. Cost is based on currently available rates from peer-reviewed publications ($250/page; 10 pages per publication). Estimated costs are based upon currently available rates and escalated by 2.5% for each out-year.

Subcontract Cost:

Included in this proposal is cost on behalf of the Colorado State University (CSU) for the three years of the proposal. USRA will engage with the CSU team members as subcontractors and therefore, their costs will be managed closely to ensure budget goals are met as defined in their budget justification.

Indirect Rates:

Universities Space Research Association has approved provisional rates for fringe benefits, R&D business sector overhead, subcontract and procurement rate, and G&A. Rates proposed herein are based on NASA's review of the USRA business plan and associated indirect rates. NASA approved these indirect rates for provisional billing on June 5, 2020. These rates are utilized for forward pricing and provisional billing. The USRA fiscal year is not concurrent with the award year

JPL Cost:

Jet Propulsion Laboratory (JPL) Civil Servant total cost is budgeted separately without being burdened following Government procedures.

GSFC Cost:

Goddard Space Flight Center (GSFC), Civil Servant total cost is budgeted separately without being burdened following Government procedures.

Escalation Rate:

The proposed escalation rate of 3% for all labor and 2.5% for materials.

Colorado State University

Budget Justification
Science Team for the OCO Missions

Proposal Title:
Long-term trends and inter-annual variability of carbon dioxide and its surface fluxes from the OCO and GOSAT missions

	Year 1			Year 2			Year 3			Total
	Rate			Rate		3%	Rate		3%	
DOMESTIC TRAVEL:			**1,285**			**1,324**			**1,363**	**3,972**
OTHER DIRECT COSTS										
Other:			**470**			**484**			**499**	**1,452**
TOTAL OTHER DIRECT:			**470**			**484**			**499**	**1,452**
TOTAL DIRECT COSTS:			**$1,755**			**$1,808**			**$1,862**	**$5,424**

<u>DOMESTIC TRAVEL – $3,972</u>

Funds are being requested for the PI on this project to travel to Greenbelt, MD for the purpose of attending Annual Project Meetings. (*A 3% inflation factor is included in YR2 & YR3)*.

<u>OTHER DIRECT - $1,452</u>

Funds are requested for computer support associated with this project. The Computer Infrastructure hourly rate is determined by the department and depends on the actual cost of the network/printing, consultation, data, and materials.

<u>Total: $5,424</u>

Statement of Work for the JPL participation in the proposal

Long-term trends and inter-annual variability of carbon dioxide and its surface fluxes from the OCO and GOSAT missions

submitted to the NASA funding opportunity NNH20ZDA001N-OCOSTby

Dr. Brad Weir

(Principal Investigator)

Universities Space Research Association

NASA Goddard Space Flight Center

brad.weir@nasa.gov

Lan Dang

(JPL Lead Co-Investigator)

398N – Science Data System Operations Engineering

Lan.B.Dang@jpl.nasa.gov

RESTRICTION ON USE AND DISCLOSURE OF PROPOSAL INFORMATION

The information (data) contained in document constitutes information that is financial and confidential or privileged. It is furnished to the Principal Investigator and to the Government in confidence with the understanding that it will not, without permission of the offeror, be used or disclosed other than for evaluation purposes; provided, however, that in the event a contract (or other agreement) is awarded on the basis of this proposal, the Government shall have the right to use and disclose this information (data) to the extent provided in the contract (or other agreement).

Proposal Overview

Observing and analyzing the long-term trends and inter-annual variability of carbon dioxide (CO2) and its surface fluxes are essential if we hope to understand the response of the Earth's climate and carbon cycle to human emissions and mitigation efforts. The Goddard Earth Observing System (GEOS) analysis of column CO2 (XCO2) observations from the Orbiting Carbon Observatory 2 (OCO-2) was the first system of its kind to successfully identify and quantify the impact on atmospheric CO2 due to decreases in human activity meant to slow the spread of the Coronavirus Disease 2019 (COVID-19) pandemic. That signal was the greatest short-term anomaly in atmospheric CO2 due to human activity since at least the Great Depression, and was still at the very limit of our current observational capabilities. Yearly changes in CO2 due to emissions mitigation (or increases) are expected to be even smaller, only becoming apparent in the observational record after several years. The Greenhouse Gases Observing Satellite (GOSAT) has been in operation for over 11 years, since 2009, 6 years longer than OCO-2. We propose to extend the GEOS/OCO-2 analysis to GOSAT data to better understand the long-term trends and inter-annual variability of human emissions and the carbon cycle. This goal will require updating the Atmospheric CO2 Observations from Space (ACOS) GOSAT XCO2 retrievals to the current Build 10 (B10) of the OCO-2 algorithm. Several updates in the OCO-2 algorithm from B9 to B10 made the GEOS/OCO-2 analysis possible, most notably the improvement in ocean glint retrievals, and this project will investigate whether they have a similar impact on ACOS-GOSAT retrievals. While other GOSAT retrievals are available, using the ACOS-GOSAT retrieval in this analysis has the added benefit of allowing us to develop a record as consistent with the OCO-2 data as possible, minimizing the impact of jumps in the data record. As future missions come online, e.g., the Geostationary Carbon Observatory (GeoCarb), we expect this ability to be absolutely essential in the interpretation of long-term trends and inter-annual variability.

Statement of Work

The processing of the ACOS-GOSAT retrievals has traditionally been handled on a best-effort basis by the Science Data Operations System (SDOS) team on the OCO-2 project. However, as this work is not part of the project task plan, there is no commitment to develop or rework the GOSAT retrieval algorithm for B10. The efforts to update the algorithm and continue producing the ACOS-GOSAT retrieval will necessarily need to build on the software, tools, and processes developed by the SDOS team. Lan Dang leads the SDOS team and has supported GOSAT processing for the past 11 years. The expected level of effort for Lan Dang is 0.1 FTE in year 1. Lan Dang will be an active participant in providing hands-on training, maturing existing written documentation for an external audience, and being available on an as-needed basis to answer questions. The duration of this effort is one year, after which the PI and team will be responsible for processing. A year at 4 hours a week (on average) is sufficient, based on past experience onboarding new operations engineers and transferring responsibility.

Main Proposal Budget Narrative – JPL

Budget Justification: Details – Year 1

JPL Direct Labor:

- Lan Dang is the Lead JPL Co-Investigator for this proposal and will manage the JPL budget and provide the training and knowledge transfer for the SDOS software and pipeline. Time commitment is 0.1 FTE for the first year.

Other Direct Costs:

Subcontracts/Subawards/Caltech Transfers:

- Desktop Network Chargebacks: All JPL computers are subject to a monthly service charge that includes hardware, software, and technical support. ($964)

Consultants:

- There are no consultants required for this task.

Equipment:

- There are no major equipment purchases necessary.

JPL Services:

- JPL NFS Storage, estimated at $10/TB/month with 4 TB for first month, growing to 6 TB by end of the year. ($720)

Supplies and Publications:

- There are no supplies and publications required for this task.

Travel:

- There is no travel required for this task.

Budget Justification: Details – Year 2

JPL Direct Labor:

- There is no JPL direct labor.

Other Direct Costs:

Subcontracts/Subawards/Caltech Transfers:

- There are no chargebacks.

Consultants:

- There are no consultants required for this task.

Equipment:

- There are no major equipment purchases necessary.

JPL Services:

- JPL NFS Storage, estimated at $10/TB/month for 6 TB. ($910)

Supplies and Publications:

- There are no supplies and publications required for this task.

Travel:

- There is no travel required for this task.

Budget Justification: Details – Year 3

JPL Direct Labor:

- There is no JPL direct labor.

Other Direct Costs:

Subcontracts/Subawards/Caltech Transfers:

- There are no chargebacks.

Consultants:

- There are no consultants required for this task.

Equipment:

- There are no major equipment purchases necessary.

JPL Services:

- JPL NFS Storage, estimated at $10/TB/month for 6 TB. ($910)

Supplies and Publications:

- There are no supplies and publications required for this task.

Travel:

- There is no travel required for this task.

Redacted Budget Estimate – JPL

Long-term trends and inter-annual variability of carbon dioxide and its surface fluxes from the OCO and GOSAT missions

Timephased Cost Estimate Sheet
Dollars (Does not include Gov't Co-I's)

	Jul 2021 - Jun 2022	Jul 2022 - Jun 2023	Jul 2023 - Jun 2024	Total Program	
Hours / (FTEs)					
L. Dang (CO-I)	177 (0.10 FTE)	0 (0.00 FTE)	0 (0.00 FTE)	177 (0.10 FTE)	Hours / (FTEs)
Total Hours:	177 (0.10 FTE)	0 (0.00 FTE)	0 (0.00 FTE)	177 (0.10 FTE)	Subtotal
Travel	$0	$0	$0	$0	Direct Travel Cost
JPL Services	$720	$910	$910	$2,540	Direct Services Cost
Procurements					
Chargebacks	$964	$0	$0	$964	Direct Chargebacks cost
Subcontracts	$0	$0	$0	$0	Direct PS cost
Procurement RSA	$0	$0	$0	$0	Direct RSA cost
Purchase Orders	$0	$0	$0	$0	Direct PM cost
Total Direct Costs	**$1,684**	**$910**	**$910**	**$3,504**	Subtotal
Reserves (Burdened)	$0	$0	$0	$0	
Total Redacted JPL Costs	**$1,684**	**$910**	**$910**	**$3,504**	Subtotal
Total Redacted Costs	**$1,684**	**$910**	**$910**	**$3,504**	Subtotal

JPL Cost Accumulation System

Introduction

All costs incurred at the Laboratory, including JPL applied burdens, are billed to the Government as direct charges at the rates in effect at the time the work is accomplished.

Allocated Direct Costs

Allocated Direct Cost (ADC) rates contain cost elements benefiting multiple work efforts, including Project Direct, MPS, and Support and Services activities. Rate applications for cost estimates are specific to the given category as stated below:

1) Engineering and Science (E&S)
2) Procurement: Purchase Order, Subcontract, Research Support Agreement (RSA)
3) General and Administrative (G&A): Basic, RSA
4) Specialized G&A applications: Remote Site

The accounting process fully distributes these costs to the respective project/task(s).

Multiple Program Support

The Multiple Program Support (MPS) rate applies costs for program management and technical infrastructure. Cost estimates and system application tools will apply the composite rate to all project direct hours charged to projects managed by JPL.

Employee Benefits

All costs of employee benefits are collected in a single intermediate cost pool, which is then redistributed to all cost objectives as a percentage of JPL labor costs, including both straight-time and overtime. Functions and activities covered by this rate include paid leave, vacations, and other benefits including retirement plans, group insurance plans, and tuition reimbursements.

For this proposal the estimated costs have been derived in the same manner as stated above. However, presentation of the estimated costs in the required tables has been adapted in the following ways:

1. The costs for Employee Benefits are included in the Direct Labor costs stated in this proposal.
2. Engineering and Science ADC and Procurement ADC along with MPS costs are displayed in the “Other” category in the Other Direct Costs section.
3. G&A is shown in the Facilities and Administrative Costs section.
4. JPL’s forecasted labor rates equal an hourly laboratory-wide average for each job family and are further broken down by career level within the job family. Labor cost estimates apply the family average or family average career level rate to the estimated work hours. An actual individual’s labor is considered discrete and confidential information and is only released on an exception basis and only if a statement of work identifies that specific individual as the only one able to perform a task. The use of family average or family average career level rates is consistent with the JPL CAS disclosure statement and the Cost Estimating Rates and Factors CDRL published in response to a requirement in NASA Prime Contract 80NM0018D0004.

The proposed budget of the NRA proposal also covers labor costs for serving on NASA peer-review panels and advisory committee at the request of NASA discipline scientists or program managers.

Title: Long-term trends and inter-annual variability of carbon dioxide and its surface fluxes from the OCO and GOSAT missions
GSFC Co-I Name: LESLEY OTT
Non-NASA PI Name: Brad Weir, GESTAR/USRA
Submitted in response to NNH20ZDA001N-OCOST, Science Team for the OCO Missions

Summary of Personnel and Work Effort

The following table reflects the level of support required of all personnel necessary to perform the proposed investigation, regardless of whether these individuals require funding from this proposal.

Name and/or Position Title	Role	Institution	PY 1 FTEs	PY 2 FTEs	PY 3 FTEs	Total
NASA-Funded Work Effort						
LESLEY OTT	Co-I	NASA/GSFC	0.10	0.10	0.10	0.30
SOURISH BASU	Co-I	ESSIC/University of Maryland	0.20	0.20	0.20	0.60
NIKOLAY BALASHOV	Co-I	ESSIC/University of Maryland	0.30	0.30	0.30	0.90
Total:			0.60	0.60	0.60	1.80

The proposed work level is appropriate to perform the investigation on the basis of the co-I Dr. Ott's previous experience leading successful OCO Science Team investigations.

Budget Justification: Narrative and Details

Notice of Restriction on Use and Disclosure of Proposal Information
The information (data) contained in this section of the proposal constitutes information that is financial and confidential or privileged. It is furnished to the Government in confidence with the understanding that it will not, without permission of the offeror, be used or disclosed other than for evaluation purposes; provided, however, that in the event a contract (or other agreement) is awarded on the basis of this proposal, the Government shall have the right to use and disclose this information (data) to the extent provided in the contract (or other agreement).

Budget Justification: Narrative

NASA Center Funding

Labor Redacted Costs Only

Per ROSES solicitation instructions, all labor dollars are redacted from budgets in Proposal Documents.

NASA Center Funding By Program Year

	PY 1 Cost	PY 2 Cost	PY 3 Cost	Total Cost
NASA/GSFC	16,803	17,624	18,550	52,977
Total:	16,803	17,624	18,550	52,977

GSFC Civil Servant Roles and Cost Basis:

LESLEY OTT, Co-I, will oversee evaluation of GOSAT retrievals and joint assimilated products. She will also contribute to the analysis of trends and interannual variability.

The civil servants included in this budget are proposed at the following skill levels:

GSFC Civil Servant Name	Budgeted Skill Title
LESLEY OTT	Scientist-Tier 2

GSFC proposal budgets are based on four Scientist skill levels with Scientist-Tier 1 reflecting the experience level equivalent to GS-13 and Scientist Tier-4 the experience level of GS-15 Step 8-10.

The cost of the labor (salary and fringe) is based on GSFC's established salary rates for the skill levels shown in the above table. GSFC fringe dollars are based on a percent applied to salary dollars using GSFC established rates per year.

GSFC On-Site/Near-Site Contractor Roles and Cost Basis:

The following on-site contractors are needed. The cost estimates are based on currently established loaded rates for the contracts that already exist at GSFC. However, no separate budget/budget justification is required from on-site/near-site contractors.

Sourish Basu, Co-I, will lead evaluation of data products against TCCON. He will also be responsible for providing flux estimates using both GOSAT and OCO data.

Nikolay Balashov, Co-I, will perform evaluation of data products using independent aircraft data.

<u>Other Direct Costs</u>

Travel

The budget includes travel as shown below based on the following cost assumptions:

- Estimated airfare and auto rental costs were obtained from either NASA's customary source or from other airfare estimating search engines (ie, Travelocity, etc.); also, per diem costs were obtained from http://www.gsa.gov/
- Inflation of 3% per year is applied for annual occurrences.
- Prior to international travel, NASA civil servants are expected to have physical exams and vaccinations. The associated medical costs are treated as research expenses and included, if applicable, under Other costs below.

Cost Details

Trip 1

	Lodging	**MI&E or Per Diem**	**Airfare**	**Ground Trans**	**Auto Rental**	**Conf Fee**	**Fuel**	**Parking**	**Tolls**	**Other**	**Total**	
Rate	182	66	600	100	0	0	0	0	0	0		
Nbr of People	1	1	1	1								
Nbr of Days	3	3			3							
Total	546	198	600	100	0	0	0	0	0	0	1,568	PY 1
											1,615	PY 2
											1,663	PY 3
											4,846	Total

Purpose of Trip: Attend OCO-2 Science Team Meeting
Depart From: Washington, D.C.
Arrive To: Pasadena, CA

Summary of Travel Budget Requirements

Domestic/Foreign; Purpose	**PY 1**	**PY 2**	**PY 3**	**Total**
Domestic; Attend OCO-2 Science Team Meeting	1,568	1,615	1,663	4,846
Total:	1,568	1,615	1,663	4,846

Other

Other Direct Costs, SED - These costs are applied to the PI's total budget because the PI will perform the work on-site at GSFC. These costs, as discussed in NASA financial regulations, are for services to support the research effort that go beyond the standard costs considered under Center Management and Operations (Center Overhead), and are not incurred elsewhere within GSFC. Within the Sciences and Exploration Directorate these costs cover system administration for the complex information technology services required to support the proposed research activities, administrative and resource analysis support, and supplies to support the research effort.

Facilities and Administrative (F&A) Costs, GSFC

NASA CM&O (Center Management and Operations) is managed from Headquarters and is therefore excluded from this proposal.

Description of Required Facilities and Equipment

Existing Facilities and Equipment for Which Funding is Not Requested

The existing facilities and equipment needed to carry out the proposed research are available at the proposer's institution, NASA/Goddard Space Flight Center. These include: These include: office space, computers, high-speed network connection, software, and data storage in the Global Modeling and Assimilation Office (Code 610.1) of the Earth Sciences Division, in the Science & Exploration Directorate. Use will be made of NASA’s HEC resources, which are available to all NASA funded projects.

Budget Justification: Details

Below is the total budget for the items described in the Budget Narrative. Also below are any supporting budgets.

Per ROSES solicitation instructions, all labor dollars are redacted from budgets in Proposal Documents.

COMPETITION SENSITIVE - FOR PROPOSAL SUBMISSION & PANEL REVIEW ONLY
Budget by Program Year

Solicitation: NNH20ZDA001N-OCOST, Science Team for the OCO Missions
GSFC Proposer Name: LESLEY OTT

Proposal Title: Long-term trends and inter-annual variability of carbon dioxide and its surface fluxes from the OCO and GOSAT missions

Total Excluding Labor Dollars and Indirect Costs: $52,977
Proposal Start Date: 07/01/2021
Proposal End Date: 06/30/2024

Description	PY 1 FTE	PY 1 Cost	PY 2 FTE	PY 2 Cost	PY 3 FTE	PY 3 Cost	Total FTE	Total Cost
A. Senior / Key Personnel (CS Only)								
Scientist-Tier 2	0.10		0.10		0.10		0.30	
Subtotal	0.10		0.10		0.10		0.30	
B.1.a-c Other Personnel (Civil Servants Not Named as Co-I in Proposal)								
Subtotal								
Subtotal GSFC Civil Servants	0.10		0.10		0.10		0.30	
Other Personnel (Non-Civil Servants)								
B.2s.1 On-Site Contractors and Cooperative Agreements	0.50		0.50		0.50		1.50	
B.2a.2 On-Site, Test & Fab Pool								
C. Off-Site Subawards / Subcontracts								
Subtotal Other Personnel	0.50		0.50		0.50		1.50	
Subtotal Labor-Redacted Cost	0.60		0.60		0.60		1.80	
Travel Total		1,568		1,615		1,663		4,846
Other Costs								
Other Direct Costs, SED		15,235		16,009		16,887		48,131
Subtotal Other Cost		15,235		16,009		16,887		48,131
Indirect CM&O								
Total Labor-Redacted Proposal Costs	0.60	16,803	0.60	17,624	0.60	18,550	1.80	52,977

Summary

	PY 1 FTE	PY 1 Cost	PY 2 FTE	PY 2 Cost	PY 3 FTE	PY 3 Cost	Total FTE	Total Cost
Civil Servant, GSFC	0.10		0.10		0.10		0.30	
Contractor, On-Site	0.50		0.50		0.50		1.50	
Subawards / Off-Site								
Other Costs, Direct		16,803		17,624		18,550		52,977
Other Costs, CM&O								
Total Labor-Redacted Proposal Costs	0.60	16,803	0.60	17,624	0.60	18,550	1.80	52,977

Funds Distribution

	PY 1 FTE	PY 1 Cost	PY 2 FTE	PY 2 Cost	PY 3 FTE	PY 3 Cost	Total FTE	Total Cost
Other NASA Centers and JPL								
GSFC	0.60	16,803	0.60	17,624	0.60	18,550	1.80	52,977
Total Labor-Redacted Proposal Costs	0.60	16,803	0.60	17,624	0.60	18,550	1.80	52,977

(Labor Dollars Redacted)

CS Labor Distribution by FY

	FY 2021 FTE		FY 2022 FTE		FY 2023 FTE		FY 2024 FTE	
Civil Servant, GSFC	0.03		0.10		0.10		0.08	