DIRECT ASSIMILATION OF SATELLITE-BASED MEASUREMENTS OF THE NEAR INFRARED RADIANCES OF GREENHOUSE GASES

Abstract

The goal of this proposal is to demonstrate the potential for improving atmospheric analyses by assimilating radiance measurements of near infrared (NIR) wavelengths into the Goddard Earth Observing System, Version 5 (GEOS-5) model without an intermediate retrieval step. Currently, the GEOS-5 analysis treats NIR measurements separately from those in the thermal infrared (TIR). TIR radiances are used to correct temperature and water vapor, but keep radiatively active trace gases like carbon dioxide (CO_2) fixed at a given value. NIR radiances, on the other hand, are never used directly. Instead, the system assimilates CO_2 mixing ratios produced by a retrieval algorithm that uses different vertical levels and prior profiles than those in GEOS-5. At a minimum, the direct assimilation of both NIR and TIR radiances has at least two possible advantages over the existing approach. The first is that combining NIR measurements in the weak and strong CO_2 bands from the Orbiting Carbon Observatory 2 (OCO-2) and Greenhouse Gases Observing Satellite (GOSAT) with TIR measurements sensitive to CO_2 from the Atmospheric Infrared Sounder (AIRS) constrains surface CO_2 better than NIR measurements alone, thus leading to improved surface flux inversions. The second is that the NIR radiances provide an independent source of information about the vertical variability of water vapor that is not present in the TIR radiances, thus leading to an improved representation of the water cycle. The proposed work will produce reanalyses of water vapor, 3D fields of CO_2 mixing ratios, and CO_2 surface fluxes and compare them with the existing GEOS-5 products: the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) and the GEOS-5 Carbon (GEOS-Carb) reanalysis. Such comparisons will indicate the benefit of our proposed approach in integrating individual pieces of information from existing remote-sensing missions. With the advent of future remote-sensing missions in the next decade, we expect this work to lay out a framework for combining radiances into an integrated Earth system analysis that can be used by the science community to understand the connections between the carbon, water, and energy cycles on timescales from hours to decades.

DIRECT ASSIMILATION OF SATELLITE-BASED MEASUREMENTS OF THE NEAR INFRARED RADIANCES OF GREENHOUSE GASES

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Submitted in Response to NNH16ZDA001N-MAP

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1. BACKGROUND AND OVERVIEW

Water vapor and carbon dioxide (CO_2) are the two strongest greenhouse gases, combining to make up roughly 75% of the total greenhouse effect (Kiehl and Trenberth, 1997; Schmidt et al., 2010). They are both expected to have a significant impact on the future climate of the Earth as anthropogenic levels of CO_2 increase, with their relative contributions to the greenhouse effect remaining roughly unchanged (Schmidt et al., 2010). Accurate, long-term retrospective analyses (reanalyses) of water vapor and CO_2 are thus essential to determine the processes that regulate the climate of the Earth and to improve the skill of medium-range to seasonal forecasts.

While water vapor is expected to play an important role in global warming, there remains considerable uncertainty about its variability in space and time. This uncertainty can have a significant impact on climate projections, e.g., Minschwaner and Dessler (2004) and Soden et al. (2005) show that the rise in temperature in climate models doubles when assuming a constant relative humidity compared to when the water vapor feedback is forced to be zero. Water vapor is also thought to be responsible for most of the upward and nearly half of the poleward heat transfer (Sherwood et al., 2010), yet previous studies show a large discrepancy between current water vapor datasets including both measurements and reanalyses. For instance, Moradi et al. (2013) reported more than a 50% bias in mid and upper-tropospheric radiosonde humidity measurements, and Vergados et al. (2015) reported a large difference among water vapor simulations in different reanalyses including the Modern-Era Retrospective Analysis for Research and Applications (MERRA) and Era-Interim.

For carbon dioxide, there are significant uncertainties about the mechanisms driving the interannual trends and variability and regional distribution of the carbon fluxes of the terrestrial and marine biospheres. As the anthropogenic burning of fossil fuels has increased since the Industrial Age, so too has the natural biospheric uptake. Even though the magnitude of this increasing uptake is well understood on the global scale, it is unclear how it is partitioned between the tropics and extratropics (Stephens et al., 2007; Schimel et al., 2015). One explanation with growing evidence is that semi-arid ecosystems play a dominant role in the interannual trends and variability of land-atmosphere fluxes (Poulter et al., 2014; Ahlstrom et al., 2015). Since these ecosystems are primarily water limited, a thorough analysis of their changes requires a fundamental understanding of the global water cycle and its connection to the carbon cycle.

a. THE ATMOSPHERIC INFRARED SOUNDER

A significant advancement in the capability to observe the Earth's water and energy cycles came in 2002 with the launch of the NASA EOS Aqua satellite carrying the Atmospheric Infrared Sounder (AIRS), a hyperspectral grating spectrometer measuring the thermal infrared (TIR) spectrum (Aumann et al., 2003). AIRS represents the modernization of infrared (IR) atmospheric sounding, moving from tens to thousands of measurements in an observed footprint and is part of a full suite of sounding instruments along with the Advanced Microwave Sounding Unit A (AMSU-A) and Humidity Sounder for Brazil (HSB). AIRS observes 2378 channels over a spectral range of 650 – 2675 cm^{-1} and has a nominal spatial resolution of 13 km at nadir (Pagano et al., 2003; Susskind et al., 2003). This was a technical and scientific step forward in infrared sounding, as it measured two orders of magnitude more channels from its multispectral predecessors, including the High-resolution Infrared Radiation Sounder (HIRS) instruments which have flown on NASA Nimbus, NOAA Polar-orbiting Operational Environmental Satellites (POES) and EUMETSAT Metop satellites. These observations have provided improved characterization of atmospheric temperature, water vapor, and clouds, both in terms of data assimilation (Collard, 2004; McNally et al., 2004 and 2006; Le Marshall et al., 2006; McCarty et al., 2009) and atmospheric profile retrievals (Susskind et al., 2003). Additionally, the increase in spectral resolution and coverage of AIRS provides sensitivity to trace gases (Chahine et al., 2005 and 2006), including ozone (O_3), CO_2, and carbon monoxide (CO).

AIRS radiances have been assimilated into the Goddard Earth Observing System, Version 5 (GEOS-5; Molod et al., 2012) Data Assimilation System (GEOS DAS) routinely since MERRA (Rienecker et al., 2011) and continue through the current MERRA-2 reanalysis (Bosilovich et al., 2015) and forward processing system at the Global Modeling and Assimilation Office (GMAO). Additionally, these observations have been routinely assimilated in most major operational numerical weather prediction (NWP) systems globally (Collard, 2004; McNally et al., 2004; Le Marshall et al. 2006).

While shortwave infrared (SWIR[1]; 2100 – 2675 cm^{-1}) channels contain valuable information that can complement that from long-wave infrared (LWIR; 650 – 2100 cm^{-1}) channels, shortwave channels are not currently assimilated by the GMAO and most operational NWP centers. There are two main advantages to the shortwave channels, as compared with the long-wave channels: (1) the temperature weighting functions of the channels operating at the shortwave part of the infrared spectrum are sharper than the weighting functions for the long-wave channels providing an opportunity for resolving smaller scale vertical features (McNally et al., 2006 and 2011), and (2) many of the shortwave channels are free from any water vapor effect, which is not the case for the lower-tropospheric or surface sensitive channels in the other parts of the IR spectrum (McNally et al., 2011). However, assimilation of shortwave infrared channels is limited by factors such as sensitivity to solar radiation including scattering of solar radiation by aerosols as well as non-local thermodynamic equilibrium (NLTE). Previous studies conducted by ECMWF show very large biases for the AIRS stratospheric channels operating around 4.3 um and shorter wavelengths (McNally et al., 2006). These studies have focused on the assimilation of nighttime data from tropospheric channels to avoid the aforementioned limitations. Since near infrared (NIR; 2675 – 13300 cm^{-1}) channels are sensitive to solar effects and NLTE, the joint retrieval of NIR and TIR radiances has the potential to advance the use of SWIR channels in assimilation systems.

Beyond their use for temperature and moisture, the LWIR channels of AIRS are also sensitive to CO_2, and it is possible to retrieve the average-column carbon dioxide (XCO_2) seen in a sounding (Chahine et al., 2005). Unfortunately, AIRS CO_2 retrievals have not yet proven useful to estimate surface carbon fluxes at regional and seasonal scales. This has not been for a lack of effort. The primary limitation is that the sensitivity of the AIRS retrieval peaks in the mid to upper troposphere, which makes it difficult to relate the measured variations in CO_2 mixing ratios to the spatial and

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[1] The definitions of NIR, SWIR, and LWIR used here are selected for simplicity and may not perfectly match conventions from other sources.

temporal variation of surface fluxes. Chevallier et al. (2009) show that an inversion using AIRS observations gives worse agreement with aircraft measurements than an inversion using in situ measurements from surface flasks. Furthermore, while the reported AIRS retrieval errors are approximately 2 ppm, their variability within a model grid box can be significantly larger (Ott et al., 2015), suggesting a source of uncertainty in model-data comparisons that is not yet fully understood.

b. The Orbiting Carbon Observatory 2

The primary goal of the NASA's Orbiting Carbon Observatory 2 (OCO-2) satellite mission is to reduce the uncertainty about the regional distribution of the terrestrial and marine carbon source-sink distribution (Crisp et al., 2004 and 2012; O'Dell et al., 2012). Launched in July 2014, OCO-2 flies just ahead of the EOS Aqua platform in the Afternoon Constellation (A-train). It is a dedicated mission whose sole instrument incorporates three diffraction grating spectrometers that measure sunlight in the 0.76 um O_2 A-band, 1.61 um weak CO_2 band, and 2.06 um strong CO_2 band. Currently, the only other satellite instrument that measures in these bands is the Thermal and Near-infrared Sensor for Carbon Observation Fourier Transform Spectrometer (TANSO-FTS) onboard JAXA's Greenhouse Gases Observing Satellite (GOSAT), launched five years earlier in 2009 (Kuze et al., 2009; Yokota et al., 2009). After the failure of the original OCO mission in February 2009, the NASA OCO team started processing GOSAT data under the auspices of Atmospheric CO_2 Observations from Space (GOSAT-ACOS) task. Unlike the TIR channels of AIRS, the CO_2 averaging kernels of the NIR channels of OCO-2 and GOSAT are roughly constant through the troposphere. This makes them better suited to the inference of surface fluxes because their measurements are less susceptible to transport error.

However, flux inversions using satellite retrievals of XCO_2 from OCO-2 and GOSAT have faced many hurdles. In an intercomparison of eight inverse models, Houweling et al. (2015) found that assimilating GOSAT data consistently increased the North African source and the European sink and that this degraded the agreement of the models with background aircraft and surface observations. As a possible reason for these difficulties, both Chevallier et al. (2014) and Reuter et al. (2014) suggested that using XCO_2, as opposed to in situ data, amplifies the effect of regional transport and retrieval biases and that these biases are aliased onto the flux inversion results

One approach that could improve the performance of flux inversions is to directly assimilate both AIRS TIR channels and OCO-2 NIR channels at the same time and generate an integrated analysis product. Since the averaging kernel of the AIRS TIR channels peaks in the mid to upper-troposphere and the averaging kernel of the OCO-2 NIR channels is nearly constant, their combination has the potential to constrain surface CO_2 more precisely than either measurement treated separately and also contain more information content throughout the total column. A stronger constraint on surface values could further reduce the effect of transport error on flux inversions.

In additional to CO_2, there is also evidence that the NIR measurements of OCO-2 contain additional information about water vapor that is not present in current data assimilation systems. Figure 1 shows the results of a comparison against SuomiNet of OCO-2 soundings and the ECMWF IFS data used as its prior. The OCO-2 soundings show an uncertainty reduction greater than 50%, suggesting that the NIR channels it is observing have some information beyond the TIR channels that ECMWF uses in its IFS system.

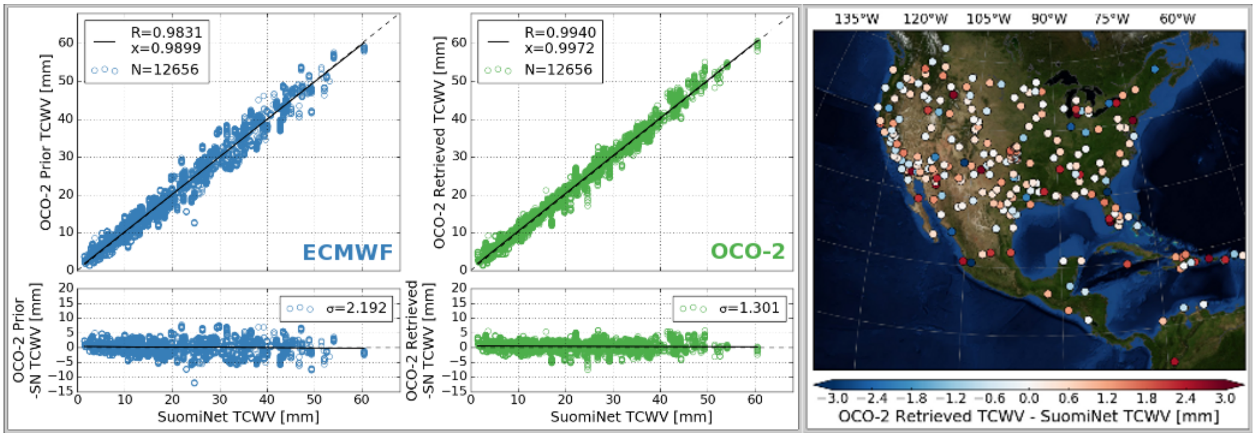

Figure 1. Total-column water vapor (TCWV) retrieved by OCO-2 compared to SuomiNet. The OCO-2 retrieval (green) shows better agreement with SuomiNet than the ECMWF IFS data (blue) used as its prior. Uncertainty reductions are greater than 50%.

c. THE GEOS DATA ASSIMILATION SYSTEM

A fundamental part of the GEOS DAS is the Gridpoint Statistical Interpolation (GSI) analysis algorithm. The GSI is used routinely at the GMAO to blend short-term forecasts (nominally 6 hourly) and observations of the atmosphere to determine the initial model state used in the forecast. The system is capable of assimilating a wide range of data, including conventional, remotely-sensed retrieved atmospheric parameters, including trace gases like O_3, CO, and CO_2 (Tangborn et al., 2009; Tangborn et al., 2013; Wargan et al., 2015), and remotely-sensed radiance observations.

Integral to the atmospheric DAS, the Community Radiative Transfer Model (CRTM; Han et al., 2006) is the basis of radiance assimilation within the GSI variational analysis (co-Is McCarty and Moradi are two of the lead developers of CRTM and GSI at the GMAO). Specifically, the CRTM is used to perform forward radiative transfer calculations and to determine the radiance Jacobians as a function of the background state. The forward calculations are necessary to determine the difference between the measurements and the background states in radiance space, and the radiance Jacobians are necessary for the variational solution. All radiative transfer calculations are performed using an Optical Depth in Pressure Space (ODPS; Chen et al., 2012) transmittance algorithm. This method allows for the calculation of Jacobians as a function of many absorbers, including the greenhouse gases that are the focus of this proposal.

Operational assimilation of NIR channels requires careful implementation of solar effects and NLTE into models such as CRTM. However, such developments require several years and significant resources to be implemented, thus we propose to implement a state-of-the-art model developed at Colorado State University and JPL for OCO-2 instrument product retrievals. This model has been extensively validated and is currently used for the operational Level 2 (L2) retrieval of XCO_2 from OCO-2 observations (co-I O'Dell is the OCO-2 Algorithm Development Team lead and the original developer, and collaborator Payne is the OCO-2 ABSCO Team lead and maintains the spectroscopic absorption coefficient lookup tables). The complete retrieval package is publicly known as the RT Retrieval Framework, is open source software, and is available for public download along with extensive documentation at the NASA GitHub repository (https://github.com/nasa/RtRetrievalFramework/).

d. PROJECT OBJECTIVES

The goal of this proposal is to demonstrate the potential for improving atmospheric analyses by assimilating radiance measurements of NIR wavelengths into the GEOS-5 model without an intermediate retrieval step. The proposed work contributes a new perspective to questions about the drivers of interannual variability of the Earth's water and carbon cycles and their connection to one another through two major advancements:

1. **Incorporating water vapor information from NIR channels into the GEOS DAS.**
2. **Constraining the vertical profile of CO_2 by combining NIR and TIR measurements.**

The work is divided into three separate tasks, which seek to answer the following questions:

1. Do Level 2 (L2) OCO-2 and GOSAT-ACOS retrievals improve the GEOS-5 atmospheric analysis in a measureable way?
2. Is the GEOS-5 atmospheric analysis improved further by directly assimilating Level 1b (L1b) NIR radiances from OCO-2 and GOSAT?
3. Does direct assimilation of L1b radiances from OCO-2, GOSAT, and AIRS constrain surface CO_2 analyses to the extent that surface flux estimates are measurably improved?

The immediate impact of this study would be that any measureable improvements seen from these tasks would be a strong justification to include their functionality in the official GEOS DAS products. In the long run, it would provide valuable insights into observing strategies for future carbon satellite missions, which addresses NASA's Earth Sciences Division's core directives (see also Section 6).

2. TASK 1 – ASSIMILATION OF OCO-2 AND GOSAT-ACOS LEVEL 2 RETRIEVALS

Developments	Preliminary evaluation of the impact of NIR radiances on the GEOS DAS from three sources: (a) inclusion of OCO-2 & GOSAT-ACOS L2 surface pressure retrievals; (b) inclusion of L2 total-column water vapor (TCWV) retrievals; (c) using a Level 3 (L3) CO_2 analysis in the TIR radiance assimilation
Deliverables	Reanalysis comparable to MERRA-2 covering the period 2014/09 – 2017/12 with OCO-2 & GOSAT-ACOS L2 surface pressure, TCWV, and XCO_2 included in the observations and variable CO_2 used in TIR radiance assimilation
Timeline	PY1: initial development and implementation; PY2: reanalysis run and evaluation; PY3 – PY4: maintenance, evaluation, and improvements
Staff	Chattopadhyay, McCarty, O'Dell, and Weir

This task will be an initial test of the impact of NIR radiances from OCO-2 and GOSAT on a retrospective analysis like MERRA-2. It will recreate as closely as possible the direct assimilation of L1b NIR radiances, but will assimilate only L2 retrievals, leaving the direct assimilation of NIR radiances to the next task. The work will be divided into four subtasks, each involving the implementation and evaluation of new functionality: (a) assimilation of surface pressure retrievals, (b) assimilation of TCWV retrievals, (c) using a L3 CO_2 analysis in the TIR radiance assimilation, (d) doing subtasks (a—c) all at once. Since OCO-2 and GOSAT-ACOS L2 retrievals are delivered approximately 2 days or more behind real time, this approach is only appropriate in a reanalysis setting.

Evaluation of reanalysis deliverables: All reanalysis products will be evaluated using standard analysis and forecast metrics, e.g., anomaly correlations, fits to observations, monthly mean values, and monthly mean RMS. Analyzed and forecasted CO_2 concentrations will also be evaluated against independent data including in situ measurements from flasks, profilers, towers, and aircraft from NOAA ObsPack (Masarie, et al., 2014) and total-column measurements from stations in the Total Column Carbon Observing Network (TCCON; Wunch et al., 2010 and 2011).

a. SURFACE PRESSURE

The assessment of assimilated surface pressure retrieved from OCO-2 in the GOES-5 modeling and assimilation system is currently underway. This is work by support scientist Chattopadhyay as part of a separately funded project, and we are not requesting funding for it here. The surface pressure retrievals are considered in three classes: nadir-viewing over land (land/nadir), glint-viewing over land (land/glint), and glint-viewing over ocean (ocean/glint). Two forms of observation filtering are applied prior to the assimilation of these data. First, only observations with a reported warn level (an indication from 0 to 19 of data quality) less than or equal to 15 are considered. Second, a gross error check is applied within the GSI to eliminate outliers. After the correction, although the mode of each distribution moves closer to zero (Figure 2, right), each distribution is still non-Gaussian compared to the expected distribution based on the mean and standard deviation of each. The spatial distribution of all surface pressure observations and the OCO-2 retrievals are shown for 18:00 UTC on 12 July 2015 in Figure 3. The spaceborne OCO-2 retrievals have the potential to fill in data void regions away from the existing observing system. Further investigation is ongoing to assess the impact of the OCO-2 retrievals on the atmospheric data assimilation system – specifically how they interact with the existing conventional surface pressure observations in the assimilation procedure. The impact of the retrievals on numerical weather prediction skill will also be considered.

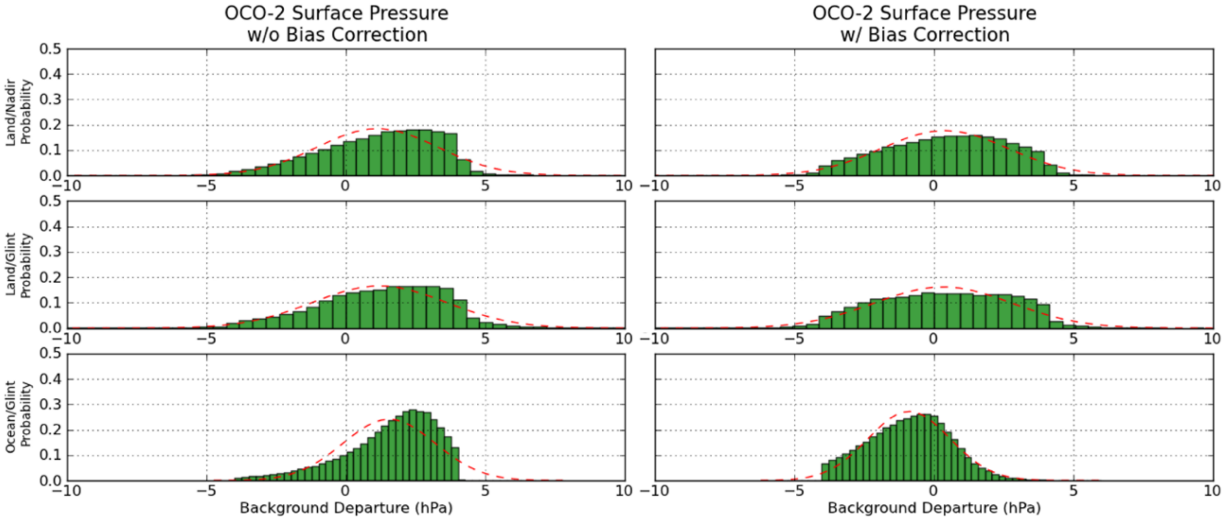

Figure 2. Background departure distributions without (left) and with (right) bias correction for 12—17 July 2015 for the land/nadir (top), land/glint (middle), and ocean/glint (bottom) OCO-2 surface pressure retrievals. The red lines represent the calculated normal distribution.

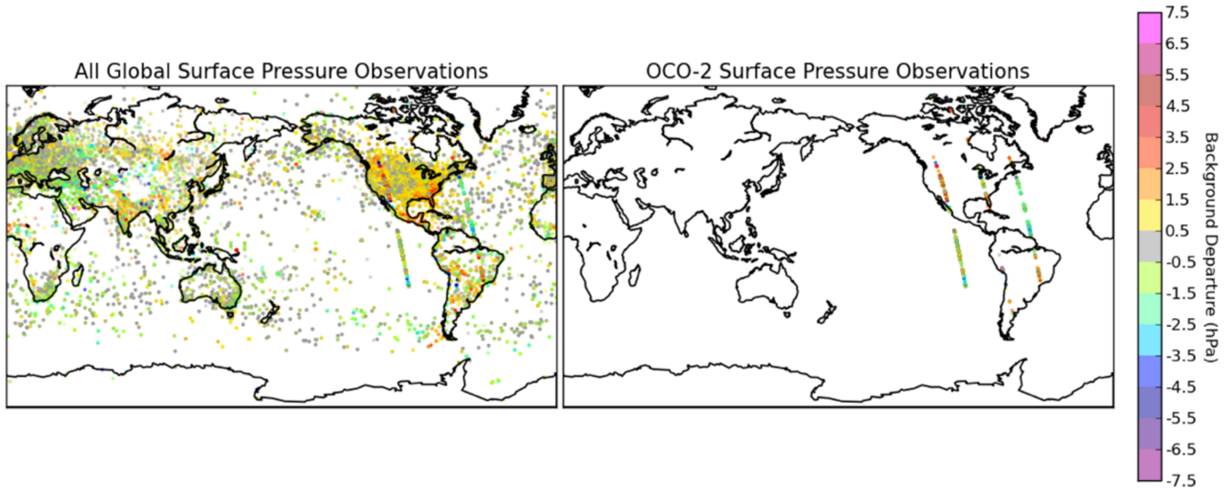

Figure 3. Spatial distribution of background departure for 18:00 UTC on 12 July 2015 for all assimilated surface pressure observations (left) and the assimilated OCO-2 surface pressure retrievals (right).

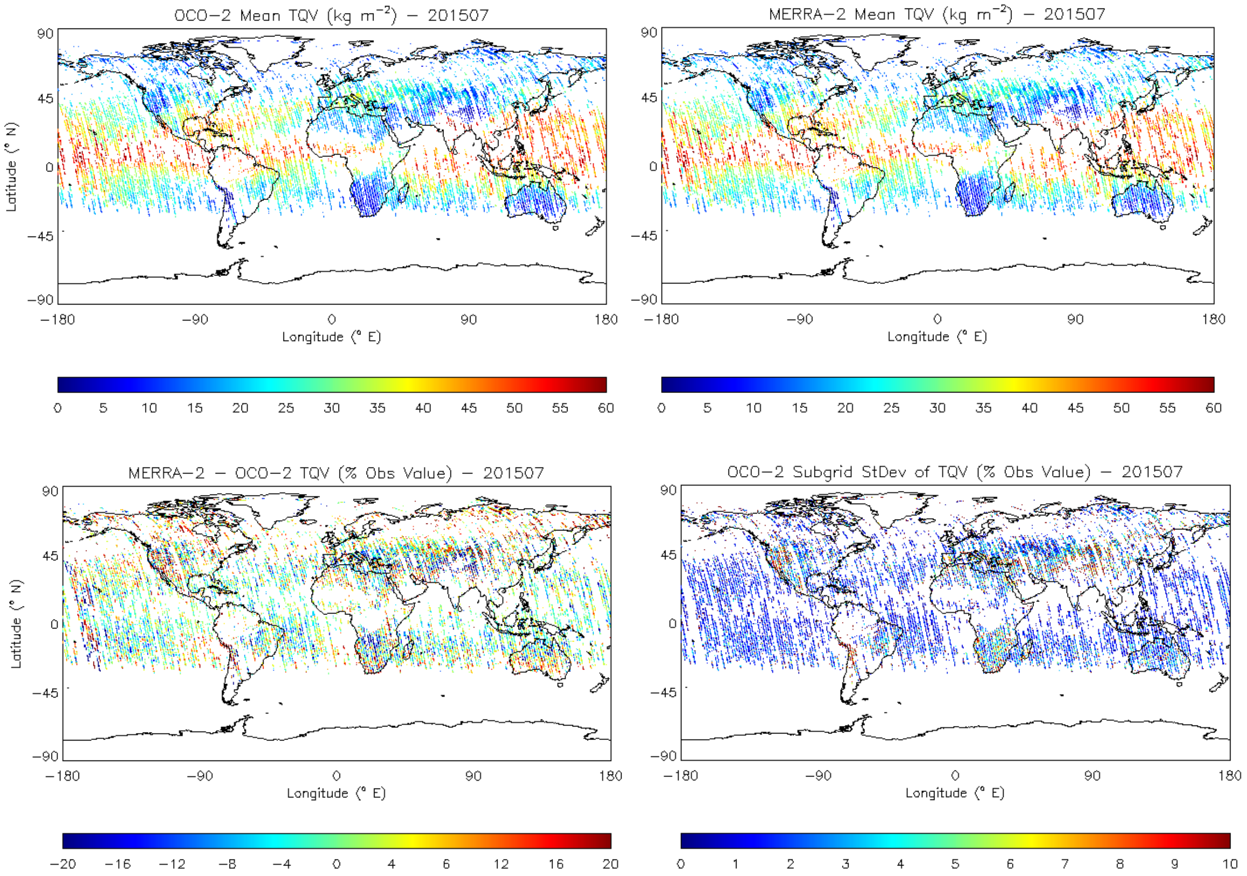

Figure 4. Comparisons of OCO-2 total-column water vapor (here, TQV) soundings with MERRA-2.

b. TOTAL-COLUMN WATER VAPOR

Preliminary evaluations of OCO-2 TCWV retrievals indicate that its NIR measurements may contain significant information about water vapor beyond what is captured by current meteorological analyses. In Figure 1, the OCO-2 TCWV retrievals show better agreement with independent evaluation data than their ECMWF IFS prior. The differences of the retrievals with MERRA-2 are considerable as well (Figure 4), and cannot be attributed to sub-grid variability since they are much greater, especially over the ocean (Figure 4, bottom right panel). While the first result is limited to a specific region, and the second to a specific month, together they suggest that OCO-2 data has the potential to improve upon the current state of meteorological reanalysis. This task will address this question in more detail, covering all space and time scales. Specifically, we will address the questions of whether OCO-2 TCWV data can be used to improve upon the MERRA-2 analysis fields, to what extent the differences are attributable to the ECMWF IFS prior, and what we might expect in the direct assimilation setting.

c. LEVEL 3 CO_2 FOR TIR RADIANCE CALCULATION

The GEOS DAS uses a zonal and monthly mean CO_2 field to calculate TIR radiances in CRTM. This assumption or zonal and monthly mean or the alternate assumption that the CO_2 field is constant, which are both quite common, can introduce errors in retrieved temperature profiles up to 0.35 K and 0.85 K respectively (Engelen et al., 2001). While these errors are reduced further by variational bias correction, there is some evidence that a fully variable CO_2 field can improve forecast skill in the stratosphere and tropics (Engelen and Bauer, 2014).

This subtask will analyze the effect of replacing the zonal and monthly mean CO_2 field used in CRTM with the GEOS-Carb L3 analysis of OCO-2 and GOSAT-ACOS retrievals of XCO_2. The GEOS-Carb CO_2 analysis is developed and maintained by PI Weir and is fully funded as part of the GEOS-Carb I & II Carbon Monitoring System (CMS) projects (Part I, PI: Steven Pawson and Part II, PI: Lesley Ott). GEOS-Carb computes 3D fields of CO_2 mixing ratios at a time resolution of 6 hours, horizontal resolution of 0.5 degrees, on 72-level sigma vertical coordinate system, can generate NRT forecasts, and its analysis lags real time only due to availability of L2 data. The transport in GEOS-Carb NRT is computed online using GEOS-5 forward processing (FP) replay mode: the GCM makes a 6 hour forecast, computes its difference with the corresponding FP analysis, then applies this increment in the same way the full DAS would while re-computing unresolved processes like convection.

Figure 5 shows GEOS-Carb NRT forecasts for two days during the recent Fort McMurray fires. The surface fluxes due to fires are taken from the Quick Fire Emissions Dataset NRT v2.4r6 (QFED; Darmenov and da Silva, 2015). QFED is a daily fire product based on MODIS Fire Radiative Power (FRP) observations. From the comparisons to the smoke plumes visible in the MODIS True Color images (Figure 5, top row), the NRT forecasted XCO_2 (Figure 5, bottom row) appears to be accurately capturing the enhancement in smoke plumes. Unofficial OCO-2 L2 retrievals of XCO_2, plotted on the top row of Figure 5, also appear to detect the enhancement at the fire source on May 15th.

The results of the GEOS-Carb NRT forecast and analysis have been extensively validated against the same datasets that will be used for the evaluation of the reanalysis (see Page 6). Figure 6 shows that differences with TCCON data are, on average, roughly 2 ppm or less. This level of agreement is encouraging since it is within the 2 ppm requirement suggested by previous studies (Rayner and O'Brien, 2001; Miller et al., 2007) and is far less than the zonal and sub-monthly variations of XCO_2, which can exceed 10 ppm. Currently, the GEOS-Carb L3 analysis does not assimilate AIRS L2 CO_2 retrievals. This functionality will be added in the future to facilitate the comparisons with the reanalyses in this proposal. No funding for this work is requested here since it is already covered as a GMAO core activity.

As a first step, the subtask will replace the zonal and monthly mean CO_2 fields used in CRTM with the GEOS-Carb NRT forecast which is not based on any satellite XCO_2 retrievals. The second step of the subtask will be to replace the GEOS-Carb NRT forecast with the L3 analysis. This way, we may isolate the effect of adding in zonal and sub-monthly variability from the effect of the XCO_2 retrievals on the analysis. Since the functionality to make the necessary changes to CRTM is already in place, the funding for this subtask will be solely for the evaluation of replacing the zonal and monthly mean CO_2 field with the GEOS-Carb L3 analysis.

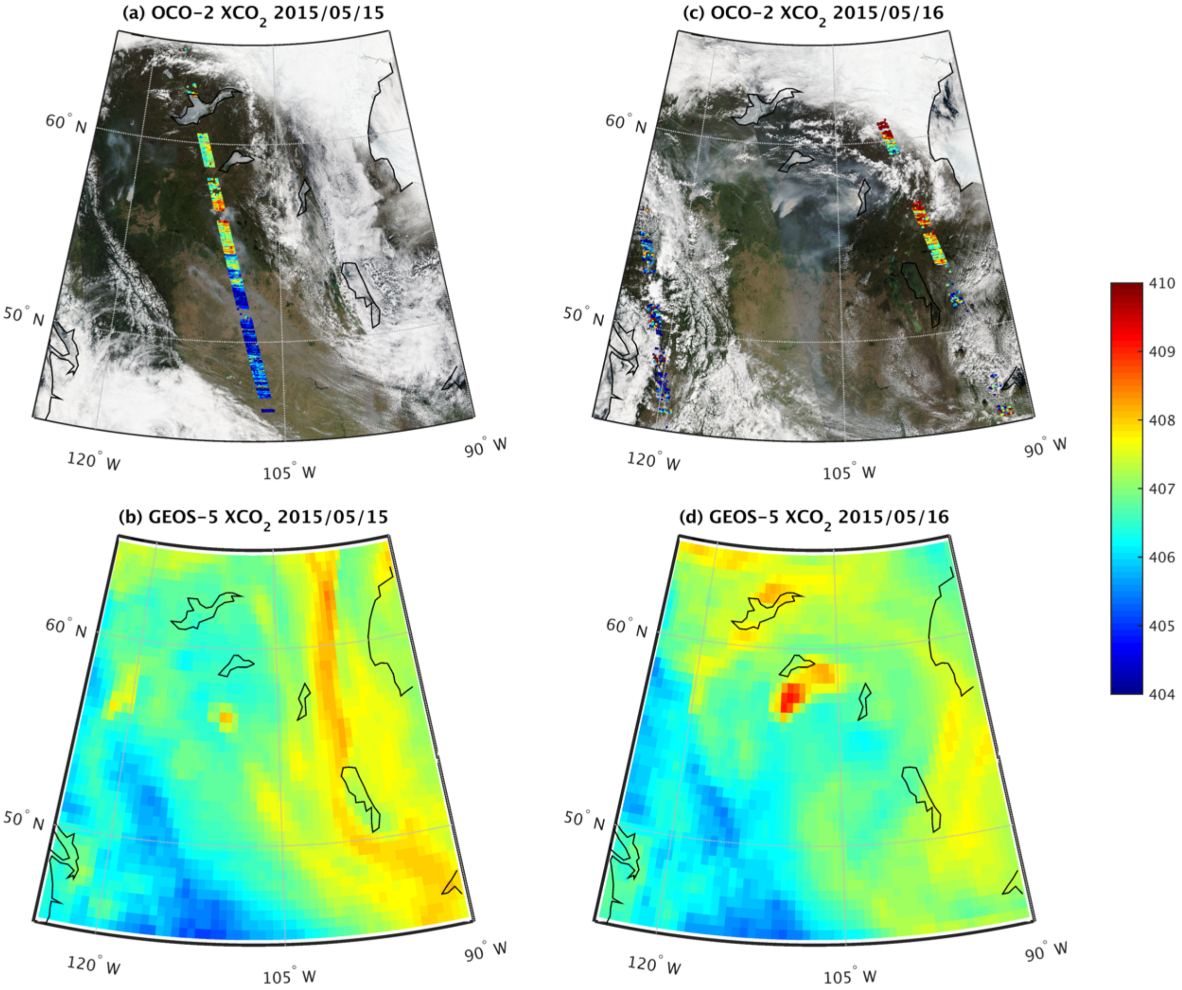

Figure 5. Snapshots of two days during the Fort McMurray fires. Top row: Unofficial OCO-2 v7b XCO_2 retrievals overlaid on the Aqua/MODIS True Color image. Bottom row: GEOS-5 model XCO_2 at 21:00 UTC from a 0.5 degree run with meteorology replayed to GEOS-5 FP and biomass burning emissions from QFED v2.4r6 NRT.

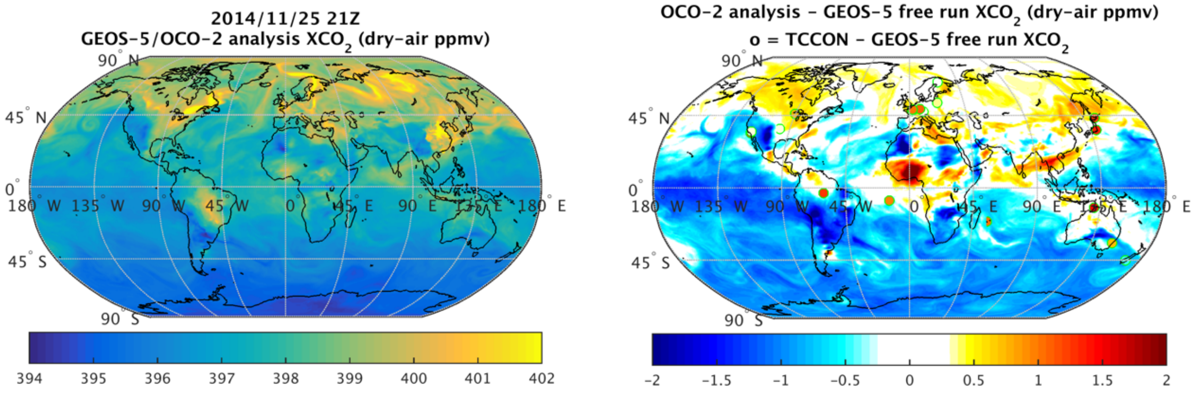

Figure 6. Results of GEOS-Carb assimilation of OCO-2 after ingesting roughly 2.5 months of data. Left: Analysis XCO$_2$. Right: Difference between analysis and free running model XCO$_2$ and (circles) difference between TCCON, taken here as an approximation of the truth, and the free running model.

d. ALL RETRIEVED VARIABLES TOGETHER

The last subtask will be to enable the changes from all the previous subtasks. By turning each function on and off, we will be isolate effects of one subtask from another. Any improvement to the reanalysis from the work in this task would suggest that an assimilation of Level 1b NIR radiances should have a similar or greater impact. Furthermore, these developments would help inform the core mission of GMAO and suggest possible future approaches to the treatment of atmospheric constituents in an integrated Earth system analysis.

3. TASK 2 – ASSIMILATION OF OCO-2, GOSAT, AND AIRS LEVEL 1B NIR/TIR RADIANCES

Developments	Ability to simulate and assimilate NIR radiances in scenes with low cloud and aerosol levels; analysis of the effect of direct assimilation of NIR radiances on (1) an atmospheric CO$_2$ reanalysis and (2) meteorological variables, viz. water vapor
Deliverables	Reanalysis comparable to MERRA-2 & GEOS-Carb covering the period 2014/09 – 2017/12 for (1) meteorological variables and (2) atmospheric CO$_2$ mixing ratios with NIR/TIR radiances from OCO-2, GOSAT, and AIRS included in the observations
Timeline	PY1: evaluation of forward models; PY2 – PY3: development and implementation of the assimilation system, including integrating a new NIR radiative transfer model into GSI; PY4: reanalysis run and evaluation
Staff	McCarty, Moradi, O'Dell, and Weir

While Task 1 will assimilate the JPL operational L2 retrievals, this task will directly assimilate L1b NIR/TIR radiances from OCO-2, GOSAT, and AIRS. As noted above, we will implement the forward operator used in the JPL operational L2 retrieval of XCO$_2$ into GSI to handle NIR radiance measurements from OCO-2 and GOSAT. As work progresses, we will evaluate CRTM simulations of SWIR radiance measurements from AIRS, keeping open the possibility of assimilating these channels.

The development of the retrievals within the GSI framework will focus on three important questions: (a) what AIRS channels are retrieved, (b) how is bias removed, (c) what a priori assumptions are made about the CO_2 profile and aerosols. Each of these points is addressed in detail below. The reanalysis will be evaluated the same way as was done for Task 1 (see Page 6), with **the primary goal of understanding what improvement in skill a direction assimilation of L1b radiances gives over an assimilation of L2 retrievals.**

a. DETERMINING THE RETRIEVED AIRS CHANNELS

Assimilation of all channels from hyper-spectral instruments such as AIRS not only is computational expensive but also unnecessary because many of the AIRS channels provide redundant information. Therefore, alternative techniques such as the assimilation of principal components or channel selection are used to assimilate observations from such instruments. The principal component technique can be used to directly assimilate all the channels by selecting the components that provide maximum information content with least noise (Matricardi and McNally, 2014), but would require a principal component based version of the radiative transfer model (Matricardi, 2010). An alternative that is currently used for the assimilation of AIRS long-wave channels is the assimilation of a subset of the channels that are selected to maximize the vertical coverage as well as the information content of the observations (Collard, 2007; Fourri'e and Thépaut, 2003). The selection criteria can vary based on the application. For instance, McNally et al. (2011) selected a subset of short-wave channels to be sensitive to the entire troposphere, and Crevoisier et al. (2003) use the optimal sensitivity profile method to select a global set of 43 channels for CO_2 retrievals. Generally, it is desirable to select a subset of channels with sharper weighting functions, that can be used both in day and night, are most sensitive to temperature, humidity, and ozone, then other gas species such as CO_2 and CO. It is also preferred if the selected channels are primarily sensitive to one element, e.g., either temperature or humidity, but this is not always possible as many of the channels are sensitive to more than one variable. The current channel selections are based on the technique developed by Rodgers (1996 and 2000) and can be outlined as follows (Collard, 2007):

1. Exclude the channels with large forward operator error.
2. Employ CO_2 channels with relatively constant temperature Jacobians to perform an initial analysis for temperature.
3. After selection of temperature channels, perform the analysis with the channels sensitive to water vapor.
4. Repeat the same for the trace gasses such as CO_2, O_3, CO, etc. if required.
5. Selection of solar and NLTE channels.
6. Manual selection of channels that can be used to determine the clouds and surface emissivity.

b. BIAS CORRECTION

After the operational OCO-2 L2 XCO_2 retrieval is performed, a post-hoc bias correction is applied to reduce their systematic error. This bias correction, which is developed in large part by co-I O'Dell, involves comparing retrievals to TCCON and analyzing their variability in small areas and over the Southern Hemisphere. The GSI also performs bias correction on satellite radiance measurements. The current system employs a two-step correction process. First, a variational bias correction (VarBC; Dee, 2004; Zhu et al., 2014) is applied and updated within the assimilation routine. In the infrared, four correction terms are applied via VarBC and are a function of: a constant correction, the cosine of the viewing angle, and two air mass predictors (lapse rate scaled by the weighting function and its square). Second, an in-line bias correction is applied to all satellite measurements as a function of its scan position. Both bias corrections are applied channel-by-channel and instrument-by-instrument prior to assimilation, and are updated via a separate routine after the analysis procedure. This step will investigate different bias correction techniques within the GSI.

c. A PRIORI ASSUMPTIONS: CO_2 PROFILE AND AEROSOLS

Further complicating matters, satellite retrievals of XCO_2 appear to have non-negligible error correlations, which are difficult to quantify and to implement in inversion systems (Chevallier, 2007; Basu et al., 2013). Kulawik et al. (2016) estimate the error correlations of GOSAT retrievals by using overpass criteria for the satellite track with TCCON stations. Independent of the station and overpass criterion selected, they show that the evaluation of GOSAT retrievals against TCCON measurements has a correlated error component compared to its random error.

To try to understand their effect on large-scale horizontal error correlation patterns, we will test changes to two a priori assumptions in the XCO_2 retrieval: the form of the CO_2 profile and the aerosol model. The first test will involve using the GEOS-Carb NRT forecast as a prior (see Page 8) versus the GLOBALVIEW-based prior used in the JPL operational OCO-2 retrievals. The second test will involve experimenting with different prior assumptions about aerosol types.

4. TASK 3 – ANALYSIS OF INFERRED CO_2 SURFACE FLUXES

Developments	Derivation of estimates of surface fluxes of CO_2 from the results of Tasks 1 and 2; analysis of the effect of direct NIR radiance assimilation on
Deliverables	(a) CO_2 surface flux inversions and (b) interactive prognostic model emissions inferred from the GEOS-5 assimilation of NIR/TIR radiances from OCO-2, GOSAT, and AIRS
Timeline	PY4
Staff	Chatterjee and Weir

The goal of the final task will be to understand the effect of the reanalyses of Tasks 1 and 2 on inferred surface fluxes of CO_2. The primary justification for combining the NIR channels from OCO-2 and GOSAT with the TIR channels from AIRS was to better constrain surface CO_2, thus reducing the effect of transport errors on inversion results. This task will test to what extent that effort was successful and what, if any, conclusions about the carbon cycle can be drawn from the results. In particular, we will post-aggregate the fluxes to coarser spatial and temporal resolutions (as necessary) and attempt to answer the following science questions: (a) at what spatial and temporal scales can flux estimates based on the results from Task 1 and Task 2 be considered consistent? (b) can we identify specific regions and seasons where the flux estimates based on Task 2 are superior to those obtained from Task 1? **If there are indeed such regions and seasons, this would be a strong justification to further develop the ability of CRTM to simulate NIR radiances and include their assimilation in the official GEOS DAS products.**

This task will be divided into two subtasks that derive surface fluxes in different ways: (a) using a top-down inverse modeling/data assimilation framework and (b) running a Dynamic Global Vegetation Model (DGVM) offline with prescribed meteorology and CO_2 mixing ratios. For both subtasks, flux estimates will be derived using three different prescribed meteorology and CO_2 fields for 2014/09 – 2017/12: (1) the MERRA-2 and GEOS-Carb reanalyses, (2) the results of Task 1, and (3) the results of Task 2. The three sets of flux estimates will be compared to other inversion products, like CarbonTracker (Peters et al., 2007) and MACC (Chevallier et al., 2011), as they become available for the given time period. In addition, the flux estimates will be rerun through GEOS-5 and the posterior CO_2 mixing ratios from will be evaluated using the same independent data used for evaluation in the previous tasks (see Page 6).

a. SURFACE FLUX INVERSION

As part of Co-I Chatterjee's participation in the OCO-2 Science Team, a top-down inverse modeling/data assimilation framework has already been developed and implemented. We are not requesting funding for the development of this inverse modeling system as part of this proposal; instead the requested funding is necessary to test the relative constraint provided by the retrieved GEOS-5 CO_2 mixing ratios on surface flux estimates, especially when compared to that provided by the JPL operational OCO-2 L2 XCO_2 observations.

The inverse modeling system that will be used is based on an ensemble Kalman Filter formulation (Chatterjee et al., 2013) where the retrieved XCO_2 observations along with other CO_2 measurements (e.g., in situ sites) are assimilated to estimate surface carbon fluxes at nominal 0.5° and daily time scales. Note that this system is specifically designed to: (a) estimate fluxes at extremely high spatial and temporal resolution, thus reducing the impact of aggregation and representation error sources, which may otherwise bias the inferred flux estimates, and (b) provide a rigorous characterization of the uncertainties associated with the flux estimates.

b. DYNAMIC GLOBAL VEGETATION MODEL ANALYSIS

We'll run the analyzed fields through Catchment-CN as well to get a diagnostic estimate of CO_2 surface fluxes. Catchment-CN (Koster et al., 2014; Koster and Walker, 2015) is a DGVM developed at the GMAO that is an extension of the Catchment Land Surface Model component of GEOS-5 (Koster et al., 2000) to include the carbon physics (i.e., prognostic biogeochemistry) of the NCAR/DOE Community Land Model, Version 4 (CLM4; Oleson et al., 2010). Land surface fluxes will be estimated by running Catchment-CN offline with three different prescribed meteorology and CO_2 fields. Although it is possible to run Catchment-CN with two-way coupling between the DGVM and atmosphere, we will limit ourselves to offline runs, leaving the two-way coupling as a direction for further research if the results are promising. While Koster and Walker (2015) did show some effect of the two-way coupling on the quality of seasonal forecasts, it was small compared to the feedback from soil moisture (Koster et al., 2004).

5. PROJECT MANAGEMENT

This project will take place at GMAO and Colorado State University (CSU) under the supervision of Steven Pawson (GMAO) and Chris O'Dell (CSU). Co-I O'Dell is the lead of the OCO-2 L2 Algorithm Development team, making this collaboration a unique opportunity for the GMAO to expand the capability of the GEOS DAS to simulate and assimilate NIR radiances and potentially gaining far more insight from OCO-2 measurements than was originally expected.

The work plan is divided into two parts (Tasks 1 and 2) that can proceed independently, yet whose progress will inform each other, and a third part (Task 3) that applies existing capabilities of the GMAO to the results obtained from the first two tasks. Although Task 3 depends on the results of Tasks 1 and 2, it requires no additional development, only the interpretation of scientific results. A summary of each team member, his/her relevant experience and expertise, and expected responsibilities is given in Table 1. Co-Is McCarty, O'Dell, and Pawson (the GMAO Chief) will provide invaluable oversight and guidance for all tasks, while collaborator Koster will do the same for the DGVM subtask of Task 3 and collaborator Payne will provide updates to the ACOS/OCO-2 Absorption Coefficient (ABSCO) tables needed for Task 2. Throughout the project, the PI will coordinate communication between the tasks and organize a bi-weekly teleconference.

The only non-GMAO based members of the team, co-I O'Dell and a postdoctoral researcher at CSU, will both travel to GMAO once per year to collaborate in person with the entire team. The postdoc will spend a week at GMAO each of the last 3 years learning about and working with the GEOS DAS and CRTM to help foster the development and use of the systems outside of GMAO.

Table 1. Summary of team members, relevant experience expertise, and expected responsibilities.

Team member	Relevant experience and expertise	Responsibilities
Weir (PI)	Data assimilation; carbon cycle and surface flux parameterization	Project coordination; interpretation of scientific results (Tasks 1—3)
Moradi (Co-I)	Calibration and validation of satellite retrievals; radiative transfer modeling; OSSEs and data assimilation	Implementation of the JPL operational NIR retrieval algorithm and interpretation of scientific results (Task 2)
Chattopadhyay (Support)	Cloudy radiance assimilation and satellite retrievals; model development, large-scale climate data analysis	Assimilate surface pressure and TCWV retrievals from NIR radiances into GEOS-5 (Task 1)
O'Dell (Co-I)	OCO-2 and ACOS Level 2 Algorithm Development Team lead; satellite retrievals; carbon cycle	Guidance on implementation of JPL radiation code, and assimilation of OCO-2 and GOSAT data (Tasks 1 & 2); Scientific analysis and supervision of post-doctoral researcher (Tasks 1—3)
McCarty (Co-I)	Leads GMAO assimilation of cloudy and precipitating radiance measurement assimilation	Guidance and interpretation of results in assimilation of surface pressure and TCWV retrievals (Task 1) and direct assimilation of NIR radiances (Task 2)
Chatterjee (Co-I)	CO_2 surface flux inversion; error covariance tuning and estimation; terrestrial biosphere carbon fluxes	Use CO_2 reanalysis product from Tasks 1 & 2 to estimate corresponding surface fluxes (Task 3)
Pawson (Co-I)	Atmospheric transport, composition, and reanalyses; Chief of the GMAO	Overall project guidance, oversight, and scientific analysis (Tasks 1—3)

Koster (Collaborator)	Land surface modeling, climate variability, and sub-seasonal prediction	Guidance in running and interpreting results of Catchment-CN (Task 3)
Payne (Collaborator)	OCO-2 and ACOS ABSCO Team lead; atmospheric remote sensing; molecular spectroscopy	Guidance and updates about the OCO-2 and ACOS ABSCO tables (Task 2)

6. SUMMARY AND EXPECTED IMPACTS

This proposal is relevant to the A.13 ROSES-2016 Modeling, Analysis, and Prediction (MAP) call because it seeks to fully utilize NIR radiance measurements to study the role of the two strongest greenhouse gases: water vapor and CO_2, in the global water, energy, and carbon cycles. The period of study (2014/09 — 2017/12), while short, covers three years and includes one of the strongest El Niño/Southern Oscillations of recent history (2015). It is thus well suited to address changes in the magnitude and trends of these cycles within the Earth system. In particular, the proposed work directly applies to the "Constituents in the Climate System" and "Assimilation" themes of the MAP call in the following ways:

1. It "expand[s] our understanding of the role of atmospheric constituents […] in the context of the climate system."
2. It utilizes "constituent observations to better understand global processes and their model representation."
3. By directly assimilating NIR radiances and using all NIR/TIR radiances to constrain water vapor and CO_2, it is an essential step in "the development of an Integrated Earth System Analysis (IESA) capability."

This work will build upon the existing meteorological analyses (FP and MERRA-2) that are funded as part of the core mission of GMAO and the GEOS-Carb CO_2 analysis that was funded through the Carbon Monitoring System (CMS) calls. In this way, it is an important first step that addresses possible approaches to extending the core capabilities of the GMAO, the potential benefit of improving the ability of CRTM to simulate NIR radiances, and maximizing the impact of measurements from OCO-2 on Earth system analyses.

Any quantifiable improvement of the direct radiance assimilation of NIR measurements over the assimilation of retrievals of surface pressure, TCWV, and XCO_2, would also serve as motivation to explore the direct assimilation radiance measurements of other atmospheric constituents, e.g., incorporating NIR and TIR channels from GOSAT that are sensitive to methane.

This is an ideal time for this research since considerable international and domestic resources are planned for space-based CO_2 observations over the next decade, for example, GOSAT-2 (http://www.gosat-2.nies.go.jp/), OCO-3 (http://science.nasa.gov/missions/oco-3/), MicroCarb (https://microcarb.cnes.fr/en/), and TanSat are all expected to launch. Developing this assimilation capability will help facilitate getting the most out of the observations from these missions.

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TABLE OF ACRONYMS

ABSCO	ACOS/OCO-2 ABSorption COefficient
AIRS	Atmospheric InfraRed Sounder
CRTM	Community Radiative Transfer Model
FP	Forward Processing
DAS	Data Assimilation System
GEOS	Goddard Earth Observing System
GMAO	Global Modeling and Assimilation Office
GOSAT	Greenhouse gas Observing SATellite
IR	InfraRed
LWIR	Long-Wave InfraRed (650 – 2100 cm^{-1}; 15.4 – 4.76 um)
MERRA-2	Modern-Era Retrospective analysis for Research and Applications, version 2
NIR	Near InfraRed (2675 – 13300 cm^{-1}; 3.74 – 0.75 um)
NLTE	Non-Local Thermodynamic Equilibrium
NRT	Near Real Time
L1b	Level 1b
L2	Level 2
OCO-2	Orbiting Carbon Observatory 2
SWIR	ShortWave InfraRed (2100 – 2675 cm^{-1}; 4.76 – 3.74 um)
TCCON	Total Carbon Column Observing Network
TCWV	Total-Column Water Vapor
TIR	Thermal InfraRed (650 – 2675 cm^{-1}; 15.4 – 3.74 um)
XCO_2	Average-column carbon dioxide

BIOGRAPHICAL SKETCHES

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Research Interests

Dr. Weir's research focuses on developing data assimilation methodologies for the analysis of high-dimensional questions about the Earth system, especially for non-linear and non-Gaussian problems. He has contributed to the development of assimilation systems for (1) atmospheric mixing ratios of trace gases like carbon dioxide and carbon monoxide based on measurements from OCO-2, GOSAT, MOPITT, and IASI, (2) parameter estimation for a marine ecological model based on in situ data and ocean color measurements from SeaWiFS, MODIS/Aqua, and VIIRS, (3) observing system simulation experiments for non-linear models of nearshore ocean circulation. Broadly, his interests include the carbon cycle, wave-current interaction, modeling wave breaking, and air-sea transfer.

Experience

Oct. 2013 – present	Research Scientist I. Global Modeling and Assimilation Office (GMAO), NASA Goddard Space Flight Center employed through Universities Space Research Association (USRA), Goddard Earth Sciences Technology and Research (GESTAR) award.
Sept. 2010 – Sept. 2013	Post-doctoral Research Associate. College of Earth, Ocean, and Atmospheric Sciences, Oregon State University.
Aug. 2004 – July 2010	Graduate Research Assistant and Teaching Instructor. Department of Mathematics, University of Arizona.
June & July 2006	Summer Intern. Mathematical Modeling and Analysis Division (T-MMA), Los Alamos National Laboratory.

Education

Aug. 2003 – July 2010	Ph.D. in Mathematics, University of Arizona. ○ Thesis title: "The transfer of momentum from waves to currents due to wave breaking." ○ Adviser: Juan M. Restrepo.
Aug. 1999 – May 2003	B.A. (cum laude) in Mathematics, New York University.

Selected Publications

1. Weir, B., R.N. Miller, and Y.H. Spitz (2013). A potential implicit particle smoother for high-dimensional systems. *Nonlin. Processes Geophys.*, 20, 1047-1060, doi:10.5194/npg-20-1047-2013.
2. ——, ——, and —— (2013). Implicit estimation of ecological model parameters. *Bull. Math. Biol.*, 75, 223-257, doi:10.1007/s11538-012-9801-6.
3. Weir, B., Y. Uchiyama, E.M. Lane, J.M. Restrepo, and J.C. McWilliams (2011). A vortex force analysis of the interaction of rip currents and surface gravity waves. *J. Geophys. Res.*, 116, C05001, doi:10.1029/2010JC006232.

Selected Invited Presentations

1. 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.
2. ——, ——, and —— (2013). Implicit parameter estimation. Probabilistic Approaches to Data Assimilation for Earth Systems, Banff International Research Station, Banff, Alberta, Canada, 17-22 Feb.
3. ——, ——, and —— (2013). Implicit sampling: theory and implementation. International Workshop on Particle Filters for Data Assimilation, Institute for Statistical Mathematics, Tachikawa, Tokyo, Japan, 7 Feb.
4. ——, ——, and —— (2013). Implicit sampling: data assimilation in geosciences. Magnetosphere-Ionosphere Modeling and Data Assimilation, Institute for Statistical Mathematics, Tachikawa, Tokyo, Japan, 4-5 Feb.
5. ——, ——, and —— (2012). Implicit assimilation for marine ecological models. Abstract NG41D-02 presented at 2012 Fall Meeting, AGU, San Francisco, Calif., USA, 3-7 Dec.

Funded Projects

Sept. 2014 – Aug. 2017	GEOS-Carb II: Delivering Carbon Flux and Concentration Products Based on the GEOS Modeling System, (in response to NNH14ZDA001N-CMS, Carbon Monitoring System, A.7), PI: Lesley Ott, Total award: $500k/year, Co-Investigator at 0.3 FTE.

Awards & Fellowships

Feb. 2015	Outstanding Scientific Contribution by a New GMAO Member. GMAO, NASA.
May 2013	Early Career Travel Award. CSIRO Marine and Atmospheric Research.
Aug. 2003 – July 2004	Graduate VIGRE Fellowship. Department of Mathematics, University of Arizona.
May 2003	Perley Lenwood Thorne Medal. Department of Mathematics, New York University.

Dr. Isaac Moradi - *Associate Research Scientist* GMAO/GSFC/NASA
ESSIC, University of Maryland Greenbelt, MD 20771

Professional Preparation

Institution	**Degree**	**Field**
Chalmers University of Technology	PhD	Radio and Space Science
Kharazmi University of Tehran	PhD	Climatology and Environmental Planning
University of Tehran	M.Sc.	Meteorology
University of Ahvaz	B.Sc.	Agricultural Engineering

Appointments

- Research Scientist, ESSIC, University of Maryland, MD, U.S., 2011 present
- Department of Computer Science, Electrical and Space Engineering, Luleå University of Technology, Sweden, 2008-2011
- University of Tehran and Renewable Energy Organization of Iran, 2003 to 2008

Selected publications

1. S. Boukabara, I. Moradi, B. Atlas, R. Hoffman, et al. Community Global Observing System Simulation Experiment (OSSE) Package :: CGOP. Description and Usage. J. of Atmos. Oceanic Tech., 2016, doi: 10.1175/JTECH-D-16-0012.1.
2. I. Moradi et al. Diurnal Variation of Tropospheric Relative Humidity in Tropical Region, Atmos. Chem. Phys., 16, 6913-6929, 2016, doi: 10.5194/acp-16-6913-2016
3. I. Moradi, R. Ferraro. Inter-calibration and validation of observations from ATMS and SAPHIR microwave sounders. IEEE TGRS, 2015, doi: 10.1109/TGRS.2015.2427165
4. I. Moradi, R. Ferraro, B. Soden, and P. Eriksson. Retrieving layer-averaged tropospheric humidity from Advanced Technology Microwave Sounder (ATMS) water vapor channels. IEEE TGRS, 2015, doi: 10.1109/TGRS.2015.2445832
5. I. Moradi, H. Meng, and R. Ferraro. Correcting geolocation errors for microwave instruments aboard NOAA satellites. IEEE TGRS, 2013. doi:10.1109/TGRS.2012.2225840.
6. I. Moradi, B. Soden, R. Ferraro, Ph. Arkin, and H. Vomel. Assessing the quality of humidity measurements from global operational radiosonde sensors. Journal of Geophysical Research, 118:80408053, 2013. doi:10.1002/jgrd.50589.
7. W. Yang, H. Meng, R. Ferraro, I. Moradi, and C. Devaraj. Cross-scan asymmetry of amsu-a window channels: Characterization, correction and verification. IEEE TGRS, 51:15141530, 2013. doi:10.1109/TGRS.2012.2211884.
8. I. Moradi, S. Buehler, and V. John. Comparing upper tropospheric humidity data from microwave satellite instruments and tropical radiosondes. Journal of Geophysical Research, 115(D24310), 2010. doi:10.1029/2010JD013962.

Related Awards and Professional Experiences

1. 12/2012 ESSIC Best Research Faculty Paper Award for developing a state-of-the-art geolocation correction technique and package for the microwave instruments aboard NOAA satellites.
2. 04/2014, 12/2014, 04/2015, 12/2015 Convener of the scientific sessions at EGU and AGU
3. Associate Editor of Atmospheric Measurement Techniques (AMT) and Geoscience Data Journal

Mohar Chattopadhyay, Ph.D.

Biography:

Dr. Mohar Chattopadhyay is an Atmospheric scientist with experience in model development, data assimilation, large-scale climate data analysis and climate variability. She is an experienced numerical modeler with work experience in New Zealand, Australia and USA. Mohar has worked with numerous modeling systems including UKMO's UM, MM5/WRF and Australian Bureau of Meteorology (BoM) models GASP/LAPS and ACCESS model and 4DVAR data assimilation systems. She also has experience in the simulation of CSIRO's Cubic Conformal Model (CCAM). More recently, Mohar has worked at NOAA/NESDIS/STAR/JCSDA on Cloudy Radiance assimilation and Microwave Intergrated Retrieval Systems (MiRS). She is currently working at the NASA/GMAO on assimilation of retrieved surface pressure from OCO2 project. Mohar obtained her doctorate degree in Atmospheric Physics from the University of Canterbury, Christchurch, New Zealand in 2003.

Positions/Employment:

01/2016-present: Senior Research Scientist, SSAI Inc.
07/2014-12/2015: Senior Staff Scientist, AER Inc.
08/ 2009-06/ 2014: Research Scientist, Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia
07/ 2005-07/ 2009: Data Assimilation Scientist, Bureau of Meteorology, Melbourne, Australia
01/2002-12/2004: Meso-scale Modeller, New Zealand Met. Services, Wellington, NZ

Education:

PhD. (2003): Atmospheric Physics, University of Canterbury, Christchurch, NZ
MSc. (1997): Physics, University of Mumbai, India
BSc. (1994): Physics, University of Mumbai, India

Selected Publication:

- Simulating the climate of South Pacific islands using a high resolution model, 2015, **M Chattopadhyay**, J Katzfey, International Journal of Climatology 35 (6), 1157-1171
- Implementation of the initial ACCESS numerical weather prediction system, 2013, K Puri, G Dietachmayer, P Steinle, M Dix, L Rikus, L Logan, M Naughton, C. Tingwell,Y. Xiao,V. Barras, J. Lee, T. Le, G. Roff, A. Sulaiman, H. Sims, X. Sun, Z. Sun, H. Zhu, **M. Chattopadhyay,** C. Engel, Australian Meteorological and Oceanographic Journal, J 63, 265-284
- On the variability of projected tropical cyclone genesis in GCM ensembles, 2012, **M. Chattopadhyay,** D. Abbs, Tellus A 64
- The added value of dynamical downscaling, 2011, J Katzfey, **M Chattopadhyay,** JL McGregor, K Nguyen, M Thatcher, 19th Int. Congress on Modelling and Simulation, 2747-2753
- Impact of using 4D-VAR assimilation of SSM/I data in the ACCESS modelling framework**, 2009,** M Chattopadhyay, P Steinle, Y Xiao, J Le Marshall, T Le, C Tingwell**,** 5th WMO Conference on Data Assimilation, 5-9 October 2009, Melbourne, Victoria; Melbourne, Victoria . 2009: 11.
- Lemus-Deschampers, L.; **Chattopadhyay M.;** Xiao, Y.; Steinle, P.; Sulaiman, A., and Le, T. Ozone and UV index forecast. 5th WMO Conference on Data Assimilation, 5-9 October 2009, Melbourne, Victoria; Melbourne, Victoria. 2009: 49.

Will McCarty, Ph. D.

Global Modeling and Assimilation Office
Mail Code 610.1 Phone: (301) 614-6496
NASA/GSFC E-Mail: Will.McCarty@nasa.gov
8800 Greenbelt Rd.
Greenbelt, MD 20771

Education

University of Alabama in Huntsville

2008 Univ. of Alabama in Huntsville Ph. D., Atmospheric Science
2005 M.S., Atmospheric Science

Valparaiso University

2003 B.S., Meteorlogy

Experience

03/2010- Present

National Aeronautics and Space Administration
Goddard Space Flight Center
Global Modeling and Assimilation Office, Code 610.1
Research Meteorologist

Coordinate efforts among GMAO atmospheric assimilation team management and members focusing on satellite data assimilation development for forward processing and reanalysis systems

Develop the methogolodies for the assimilation of cloud-affected infrared measurements from hyperspectral infrared sounders

01/2009- 03/2010

University of Maryland - Baltimore County
Goddard Earth Sciences and Technology Center
Assistant Research Scientist

05/2003- 01/2009

University of Alabama in Huntsville
Earth System Science Center / Dept. of Atmospheric Science
Research Associate III (08/2008 - 01/2009)
Graduate Research Assistant (05/2003 - 08/2008)

Select Publications

Coy, L., K. Wargan, A. Molod, W. McCarty, and S. Pawson, 2016: Structure and Dynamics of the Quasi-Biennial Oscillation. *J. Climate,* in press. doi:10.1175/JCLI-D-15-0809.1

Norris, P. M., W. McCarty, and R. M. Errico, 2014: Evaluation of the 7-km GEOS-5 Nature Run, Chapter 6: Clouds and Radiation. NASA Technical Memomorandum NASA/TM-2014-104606

Baker, W. E. and others, 2013: Lidar-Measured Wind Profiles - The Missing Link in the Global Observing System. *Bull. Amer. Met. Soc.* 95, 543–564

McCarty, W., R. Errico, and R. Gelaro, 2012: Cloud Coverage in the Joint OSSE Nature Run. *Mon. Wea. Rev.* 140, 1863–1871.

Lee, T., and others, 2010: NPOESS: Next Generation Operational Global Earth Observations. *Bull. Amer. Met. Soc* . 91, 727-740.

McCarty, W., G. J. Jedlovec, and T. L. Miller, 2009: Impact of the Assimilation of Atmospheric Infrared Sounder Radiance Measurements on Short-Term Weather Forecasts. *J. Geophys. Res.* , 114, D18122, doi:10.1029/2008JD011626.

DR. CHRISTOPHER O'DELL **CO- INVESTIGATOR**

CIRA, Colorado State University, Fort Collins, CO

Summary of Professional Achievements

Dr. O'Dell is an expert in microwave and Visible/Near-Infrared radiative transfer, and the remote sensing of clouds and trace gases. He is currently a science team member and algorithm Team Lead for the NASA Orbiting Carbon Observatory-2, responsible for column CO_2 retrieval algorithm development and data assessment. He is skilled in designing hyperspectral cloud-screening methods and assessing the impact of random and systematic error sources in such retrievals, including from calibration, the treatment of atmospheric scattering, and surface effects. He has done extensive work on radiative transfer in the near infrared and microwave, writing fast and accurate algorithms for remote sensing applications. In addition to helping guide the OCO-2 algorithms team, he supervises the research activities of three research scientists and three graduate students at Colorado State University.

Education

- Ph. D. (summa cum laude), Physics, University of Wisconsin-Madison, WI, 2001.
- B.S. (Honors), Physics, University of Dayton, OH, 1995.

Professional Employment History

2015 – Present: Senior Research Scientist, CIRA, Colorado State University

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

- Taylor, T.E., **C.W. O'Dell**, P.T. Partain, H.Q. Cronk, R.R. Nelson, E.J. Rosenthal, A.Y. Chang, G.B. Osterman, R.H. Pollock, and M.R. Gunson, 2016: Orbiting Carbon Observatory-2 (OCO-2) cloud screening algorithms: validation against collocated MODIS and CALIOP data, *Atmos. Meas. Tech.,* 9 (3), 973.
- Merrelli, A., Bennartz, R., **O'Dell, C.W.,** and Taylor, T. E., 2015: Estimating bias in the OCO-2 retrieval algorithm caused by 3-D radiation scattering from unresolved boundary layer clouds, *Atmos. Meas. Tech*., 8, 1641-1656
- **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
- **O'Dell, C.W.** et al., 2010: Acceleration of multiple-scattering, hyperspectral radiative transfer calculations via low-streams interpolation. *J. Geophys. Res*., **115**, D10206**,** doi:10.1029/2009JD012803.
- **C.W. O'Dell**, A.K. Heidinger, T. Greenwald, & R. Bennartz, 2006: The Successive Order of Interaction Radiative Transfer Model, Part II: Model Performance and Applications. *J. Appl. Meteorol. Clim*., 45 (10), pp. 1403-1413.

Dr. Abhishek Chatterjee
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Code 610.1, NASA GSFC
8800 Greenbelt Road,
Greenbelt, MD 20771, USA

Current Position

- Scientist, USRA, NASA GSFC Global Modeling and Assimilation Office

Relevant Experience

Dr. Chatterjee has worked on geophysical data assimilation problems for over 6 years with specific focus on carbon cycle science, Earth system models, and utilization of remote-sensing data. He has developed new data assimilation techniques for estimating carbon sources and sinks at high spatial-temporal resolutions, and is a science team member of both the Orbiting Carbon Observatory-2 (OCO-2) and the Soil Moisture Active Passive (SMAP) missions. At the Global Modeling and Assimilation Office, his primary responsibility is to develop and maintain NASA's GEOS-Carb inversion system for improving carbon flux diagnosis and attribution.

Education

- Ph.D., The University of Michigan, Ann Arbor (2008-2012)
  Environmental Engineering, Department of Civil and Environmental Engineering
- M.S.E., The University of Michigan, Ann Arbor (2007)
  Environmental Engineering, Department of Civil and Environmental Engineering

Selected Professional Service

- North American Carbon Program, Review Committee Member for the NACP Implementation Plan
- Co-organizer and convener:
  - AGU Fall Meeting, Session titled "*Constraining Biosphere-Atmosphere Exchange Processes using Remote Sensing and In Situ Networks*", 2011-present
  - AMS Annual Meeting, Session titled "*Greenhouse Gas Emissions: Measurements, Processes and Impacts*", 2015 –present
  - North American Carbon Program Principal Investigators Meeting, 2017
- Journal Reviewer: *Journal of Geophysical Research – Atmospheres*, *Atmospheric Chemistry and Physics*, *Monthly Weather Review*, *Water Resources Research*

Selected Honors and Awards

- NOAA Postdoctoral Program in Climate and Global Change Fellowship, *UCAR*, 2012 – 2014
- NASA Earth and Space Science Fellowship, *NASA*, 2009-2012
- Rackham International Student Fellowship, *University of Michigan*, 2009
- Distinguished Leadership Award, *College of Engineering*, *University of Michigan*, 2008

Selected Relevant Publications

- Chatterjee, A. and A. Michalak, A scale dependent review of atmospheric CO_2 inversions, *in preparation for submission to Advances in Geosciences*
- Huntzinger, D.N., et al., Future projections and associated climate change in N. America, *in preparation for USGCRP's State of the Carbon Cycle Report-2 (SOCCR-2)*
- Schimel, D., et al., *in review,* Observing the Carbon-Climate System, *Bulletin of the American Meteorological Society*, 2016
- Chatterjee, A., et al. (2013), Technical Note: Comparison of ensemble Kalman filter and variational approaches for CO_2 data assimilation, *Atm. Chem. and Phys.*,13, doi:10.5194/acp-13-11643-2013
- Chatterjee, A., et al. (2012), Towards reliable ensemble Kalman filter estimates of CO_2 fluxes, *J. Geophys. Res.-Atm.*, 117, D22306, doi:10.1029/2012JD018176

Steven Pawson **NASA/GSFC**
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Tel.: 301 614 6159
Global Modeling and Assimilation Office, Code 610.1
NASA GSFC, Greenbelt, MD 20771

Research Interests

Earth system modeling and analysis; interactions between circulation, carbon cycle and chemistry; atmospheric ozone modeling and assimilation; circulation and transport model validation, assessment and development.

Positions Held

Since 2014	Chief of the Global Modeling and Assimilation Office at NASA GSFC
Since 2004	Meteorologist, Global Modeling and Assimilation Office at NASA GSFC
1997-2000	Research Scientist, Universities Space Research Association, based at NASA GSFC
1995	Guest scientist at the PCMDI, Lawrence Livermore National Laboratory, USA
1991-1997	Assistant Professor ('Wissenschaftlicher Assistent') at the FU Berlin, Germany
1988-1991	Research Fellow ('Wissenschaftlicher Mitarbeiter') at the FU Berlin, Germany
1987-1988	Research Fellow at the University of Oxford, UK

Qualifications and Education

1996	'Habilitation' in Meteorology, Faculty of Geo-sciences, FU Berlin, Germany
1987	Ph.D., Department of Meteorology, Univ. of Edinburgh, UK
1984	M.Sc.: Atmospheric Physics and Dynamics, Imperial College, Univ. of London, UK
1982	B.Sc. (honors) 2(i): Mathematics, Univ. of York, York, UK

Professional Activities

- Co-author of Chapter 2 of the WMO-UNEP 2014 Scientific Assessment of Stratospheric Ozone.
- Current or past member of numerous NASA Science Teams.
- Former Editor of The Journal of Geophysical Research, Atmospheres.
- Co-author of more than 125 peer-reviewed publications.
- Reviewer for numerous international journals and funding agencies.
- Former leader of WCRP-SPARC climate modeling activities.
- Convener of workshops and conference sessions.

Selected Recent Publications, From a Total of More Than 125

Zeng, X., S. Ackerman, R. Ferraro, T. Lee, J. Murray, S. Pawson, R. Reynolds, and J. Teixeira, 2016. Challenges and Opportunities in NASA Weather Research. *Bull. Am. Meteorol. Soc*. doi: 10.1175/BAMS-D-15-00195.1

Coy, L., K. Wargan, A. M. Molod, W. R. McCarty, and S. Pawson, 2016. Structure and Dynamics of the Quasi-Biennial Oscillation in MERRA-2. *J. Clim*. doi: 10.1175/JCLI-D-15-0809.1

Li, F., Y. Vikhliaev, P. A. Newman, S. Pawson, J. Perlwitz, D. W. Waugh, and A. R. Douglass, 2016. Impacts of Interactive Stratospheric Chemistry on Antarctic and Southern Ocean Climate Change in GEOS-5. *J. Clim*, **29**, 3199-3218. doi: 10.1175/JCLI-D-15-0572.1

K. Wargan, S. Pawson, M.A. Olsen, J. C. Witte, A.R. Douglass, J.R. Ziemke, S. Strahan, J.E. Nielsen: *The Global Structure of UTLS Ozone in GEOS-5: A Multi-Year Assimilation of EOS-Aura Data*. J. Geophys. Res. (2015).

L.E. Ott, S. Pawson, G.J. Collatz, W.W. Gregg, C. Rousseaux, D. Menemenlis, H. Brix, K. Bowman, J. Liu, A. Eldering, M.R. Gunson, S.R. Kawa: *Quantifying the Observability of CO_2 Flux Uncertainty in Atmospheric CO_2 Records Using Products from NASA's Carbon Monitoring Flux Pilot Project.* J. Geophys. Res. 12/2014; DOI: 10.1002/2014JD022411 (2014).

C.A. Keller, M.S. Long, R.M. Yantosca, A.M. da Silva, S. Pawson, D.J. Jacob: HEMCO v1.0: A Versatile, ESMF-Compliant Component for Calculating Emissions in Atmospheric Models. Geosci. Model Dev., 7, 1409-1417, doi:10.5194/gmd-7-1409-2014 (2014).

SUMMARY OF WORK EFFORT

Investigator	Institution	Role	PY1 FTEs	PY2 FTEs	PY3 FTEs	PY4 FTEs
Brad Weir	USRA/GESTAR	PI	0.5	0.5	0.5	0.5
Isaac Moradi	ESSIC	Co-I	0.5	0.5	0.5	0.5
Mohar Chattopadhyay	SSAI	Support	0.3	0.3	0.1	0.1
William McCarty	NASA/GSFC	Co-I	0.1	0.1	0.2	0.2
Chris O'Dell	Colorado State Univ.	Co-I	0.1	0.1	0.1	0.1
Postdoctoral fellow (supervised by O'Dell)	Colorado State Univ.			0.5	0.5	0.5
Abhishek Chatterjee	USRA/GESTAR	Co-I				0.1
Steven Pawson	NASA/GSFC	Co-I	0.1	0.1	0.1	0.1

CURRENT AND PENDING SUPPORT

Brad Weir – Current support

Title of award: GEOS-Carb II: Delivering Carbon Flux and Concentration Products Based on the GEOS Modeling System
PI: Lesley Ott
Funding agency: NASA (ROSES 2014 A.7, NNH14ZDA001N-CMS, Carbon Monitoring System)
Point of contact: Kenneth W. Jucks, (202) 358-0476, kenneth.w.jucks@nasa.gov
Performance period: 2014/09 – 2017/08
Commitment (months/year): 3.6

Pending Support

Title of award: A new look at stratospheric chemistry with multispecies chemical data assimilation
PI: Krzysztof Wargan
Funding agency: NASA (ROSES 2016 A.13, NNH16ZDA001N-MAP, Modeling, Analysis, and Prediction)
Point of contact: David B. Considine, (202) 358-2277, david.b.considine@nasa.gov
Performance period: 2017/01 – 2020/12
Commitment (months/year): 2.4

Isaac Moradi – Pending support

Title of award: Assimilation of all-weather GMI and ATMS observations into HWRF
PI: Isaac Moradi
Funding agency: NASA (ROSES, NNH16ZDA001N-NDOA, NASA ROSES: NASA Data for Operation and Assessment)
Point of contact: Tsengdar J. Lee, (202) 358-0860, tsengdar.j.lee@nasa.gov

Performance period: 2016/11 – 2018/10
Commitment (months/year): 1.2

Mohar Chattopadhyay – Pending support

Title of award: Re-calibrate water vapor bands from international geostationary satellites for consistency with AIRS
PI: Mathew Gunshor
Funding agency: NASA (ROSES 2015 A.34, NNH15ZDA001N-SCIS, Satellite Calibration Interconsistency Studies)
Point of contact: Lucia S. Tsaoussi, (202) 358-4471, lucia.s.tsaoussi@nasa.gov
Performance period: 2016/06 – 2019/05
Commitment (months/year): 1.8

William McCarty – Current support

Title of award: Global Modeling and Assimilation Office Core Support
PI: Steven Pawson
Funding agency: NASA (ROSES, MAP)
Point of contact: David B. Considine, (202) 358-2277, david.b.considine@nasa.gov
Performance period: 2013/01 – 2017/12
Commitment (months/year): 4.8

Title of award: All-sky GPM Microwave Imager (GMI) Radiance Data Assimilation Global Products from the GEOS-5 System in Support of the GPM Mission
PI: Min-Jeong Kim
Funding agency: NASA (ROSES, NNH15ZDA001N-PMM, Precipitation Measurement Missions Science Team)
Point of contact: Ramesh K. Kakar, (202) 358-0240, ramesh.k.kakar@nasa.gov
Performance period: 2016/01 – 2018/12
Commitment (months/year): 1.2

Title of award: Observing System Simulation Experiments in the Context of MISTiC Winds
PI: William McCarty
Funding agency: NASA
Point of contact: David B. Considine, (202) 358-2277, david.b.considine@nasa.gov
Performance period: 2016/04 – 2017/03
Commitment (months/year): 3.6

Pending Support

Title of award: Re-calibrate water vapor bands from international geostationary satellites for consistency with AIRS
PI: Mathew Gunshor
Funding agency: NASA (ROSES 2015 A.34, NNH15ZDA001N-SCIS, Satellite Calibration Interconsistency Studies)
Point of contact: Lucia S. Tsaoussi, (202) 358-4471, lucia.s.tsaoussi@nasa.gov

Performance period: 2016/06 – 2019/05
Commitment (months/year): 1.2

Title of award: Assimilation of all-weather GMI and ATMS observations into HWRF
PI: Isaac Moradi
Funding agency: NASA (ROSES, NNH16ZDA001N-NDOA, NASA ROSES: NASA Data for Operation and Assessment)
Point of contact: Tsengdar J. Lee, (202) 358-0860, tsengdar.j.lee@nasa.gov
Performance period: 2016/11 – 2018/10
Commitment (months/year): 1.2

Title of award: Assimilation of observations with non-Gaussian error characteristics in GEOS-5
PI: Daniel Holdaway
Funding agency: NASA (ROSES 2016 A.13, NNH16ZDA001N-MAP, Modeling, Analysis, and Prediction)
Point of contact: David B. Considine, (202) 358-2277, david.b.considine@nasa.gov
Performance period: 2017/01 – 2020/12
Commitment (months/year): 1.2

Title of award: Winds from Hyperspectral Infrared Soundings Passive Environmental Radiometer (WHISPER) Mission
PI: David Santek
Funding agency: NASA (NNH15ZDA011O, Earth System Science Pathfinder Program: Earth Venture Mission – 2)
Point of contact: Ramesh K. Kakar, (202) 358-0240, ramesh.k.kakar@nasa.gov
Performance period: 2018/10 – 2024/06
Commitment (months/year): 2.4

Chris O'Dell – Current support

Title of award: A Data Record of the Cloudy Boundary Layer
PI: Joao Texeira (JPL)
Funding agency: NASA (ROSES 2012, MEASURES)
Point of contact: Martha E. Maiden, (202) 358-1078, martha.e.maiden@nasa.gov
Performance period: 2013/01 – 2017/12
Commitment (months/year): 0.5

Title of award: Orbiting Carbon Observatory (OCO-2) Phase E task
PI: Chris O'Dell (Colorado State University)
Funding agency: NASA JPL
Point of contact: Robert A. Granat, (818) 393-5353, robert.a.granat@jpl.nasa.gov
Performance period: 2014/12 – 2016/03
Commitment (months/year): 8

Title of award: Atmospheric Carbon and Transport study: ACT-America
PI: Ken Davis (Penn. State)

Funding agency: NASA (EVS-2)
Point of contact: Hal Maring, (202) 358-1679, hal.maring@nasa.gov
Performance period: 2014/10 – 2019/09
Commitment (months/year): 1

Title of award: Tackling aerosol and CO2 uncertainties through the synergistic use of MODIS and OCO-2 observations
PI: Chris O'Dell (Colorado State University)
Funding agency: NASA (ROSES 2014)
Point of contact: Kenneth W. Jucks, (202) 358-0476, kenneth.w.jucks@nasa.gov
Performance period: 2015/04 – 2018/03
Commitment (months/year): 1

Title of award: Enhancing OCO-2's observational capabilities under partly and fully cloudy conditions
PI: Ralf Bennartz (Univ. of Wisconsin)
Funding agency: NASA (ROSES 2014)
Point of contact: Kenneth W. Jucks, (202) 358-0476, kenneth.w.jucks@nasa.gov
Performance period: 2015/04 – 2018/03
Commitment (months/year): 0.5

Pending Support

Title of award: CIRA Support to Improve GSI Assimilation of All-Sky GPM-GMI Radiances
PI: Lewis Grasso (CIRA-CSU)
Funding agency: NASA (ROSES 2016, A.29)
Point of contact: Tsengdar J. Lee, (202) 358-0860, tsengdar.j.lee@nasa.gov
Performance period: 2016/12 – 2018/11
Commitment (months/year): 0.5

Title of award: Amplification of Arctic/Boreal Carbon Cycle Dynamics and its Impact on the Permafrost Carbon Feedback
PI: Charles Miller (NASA JPL)
Funding agency: NASA (ROSES 2016, A.5, Carbon Cycle Science)
Point of contact: Paula S. Bontempi, (202) 358-1508, paula.s.bontempi@nasa.gov
Performance period: 2017/01 – 2019/12
Commitment (months/year): 1.5

Abhishek Chatterjee – Current support

Title of award: Operations and data products for carbon-climate feedbacks using OCO-2
PI: David Schimel (JPL)
Funding agency: NASA (OCO-2 Science Team)
Point of contact: Kenneth W. Jucks, (202) 358-0476, kenneth.w.jucks@nasa.gov
Performance period: 2015/04 – 2018/03
Commitment (months/year): 3

Title of award: Use of SMAP observations in conjunction with OCO-2 data to improve understanding of coupled carbon and water cycle within the GEOS-5 modeling system
PI: Abhishek Chatterjee
Funding agency: NASA (SMAP Science Team)
Point of contact: Jared K. Entin, (202) 358-0275, jared.k.entin@nasa.gov
Performance period: 2016/08 – 2019/07
Commitment (months/year): 3

Steven Pawson – Current support

Title of award: GMAO leadership function, coming from a combination of internal GSFC/Code 610 resources and GMAO Core project funds
PI: Steven Pawson
Funding agency: NASA
Point of contact: David B. Considine, (202) 358-2277, david.b.considine@nasa.gov
Performance period: 2013/01 – 2017/12
Commitment (months/year): 8.4

Pending Support

Title of award: A comprehensive capability for atmospheric chemistry in the GEOS Earth System Model (ESM) and Data Assimilation System (DAS) at GMAO
PI: Daniel Jacob (Harvard)
Funding agency: NASA (ROSES 2014 A.7, NNH14ZDA001N-CMS, Carbon Monitoring System)
Point of contact: Kenneth W. Jucks, (202) 358-0476, kenneth.w.jucks@nasa.gov
Performance period: 2014/09 – 2017/08
Commitment (months/year): 1.2

Title of award: Subseasonal Predictability Characteristics and Prediction Skill in the NASA GEOS Modeling and Data Assimilation System
PI: Duane Waliser (JPL)
Funding agency: NASA (ROSES 2014 A.7, NNH14ZDA001N-CMS, Carbon Monitoring System)
Point of contact: Kenneth W. Jucks, (202) 358-0476, kenneth.w.jucks@nasa.gov
Performance period: 2014/09 – 2017/08
Commitment (months/year): 1.2

BUDGET JUSTIFICATION

Title: Direct assimilation of satellite-based measurements of near infrared radiances of greenhouse gases
GSFC Co-I Name: William Mccarty
Non-NASA PI Name: Brad Weir , GESTAR/USRA
Submitted in response to NNH16ZDA001N-MAP, Modeling, Analysis, and Prediction, A.13

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	PY 4 FTEs	Total
NASA-Funded Work Effort							
WILLIAM MCCARTY	Co-I	NASA/GSFC	0.10	0.10	0.20	0.20	0.60
STEVEN PAWSON	Co-I	NASA/GSFC	0.10	0.10	0.10	0.10	0.40
ISAAC MORADI	Co-I	ESSIC	0.50	0.50	0.50	0.50	2.00
MOHAR CHATTOPADHYAY	Support	SSAI	0.30	0.30	0.10	0.10	0.80
Total:			1.00	1.00	0.90	0.90	3.80

The proposed work level is appropriate to perform the investigation on the basis of previous investigations with OCO-2 retrievals, atmospheric radiative transfer, and satellite radiance assimilation, all of which are covered by the proposing team.

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
Procurement and Travel Only

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

http://science.nasa.gov/researchers/sara/how-to-guide/nspires-CSlabor/

NASA Center Funding By Program Year

	PY 1 Cost	PY 2 Cost	PY 3 Cost	PY 4 Cost	Total Cost
NASA/GSFC	28,453	30,927	34,015	36,423	129,819
Total:	28,453	30,927	34,015	36,423	129,819

GSFC Civil Servant Roles and Cost Basis:

Co-I William McCarty will provide expertise and help develop techniques in the assimilation of both OCO-2 retrievals and later OCO-2 satellite radiances.

Co-I Steven Pawson will provide oversight as the head of the Global Modeling and Assimilation Office. He will also provide expertise and feedback in the overall assimilation of OCO-2 measurements and retrievals, based on his background in atmospheric chemistry and head of the chemistry group within the GMAO.

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

GSFC Civil Servant Name	Budgeted Skill Title
WILLIAM MCCARTY	Scientist-Tier 1
STEVEN PAWSON	Scientist-Tier 4

GSFC proposal budgets are based on four Scientist skill levels with Scientist-Tier 1 reflecting the experience level equivalent to GS-13-Step 6 and Scientist Tier-4 the experience level of GS-15-Step 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 Contractor Roles and Cost Basis:

Co-I Isaac Moradi provides expertise in radiative transfer modeling and development as well as data assimilation. He will provide feedback and assist in the extension of GMAO assimilation routines to assimilate radiance measurements sensitive to greenhouse gases. His support is needed for 0.5 FTE per year. The cost estimate is based on currently established loaded rates for the contract that already exists at GSFC

Support Scientist Mohar Chattopadhyay will assist in the assimilation of retrieved OCO-2 measurements within GMAO atmospheric data assimilation routines at 0.3 FTE in years 1 and 2 and at 0.10 FTE in years 3 and 4. The cost estimate is based on currently established loaded rates for the contract that already exists at GSFC

Other Direct Costs

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.

Cost Details

Trip 1

	Lodging	**MI&E or Per Diem**	**Airfare**	**Ground Trans**	**Auto Rental**	**Conf Fee**	**Fuel**	**Parking**	**Tolls**	**Other**	**Total**	
Rate	150	45	1,000	25	0	500	0	0	0	0		
Nbr of People	1	1	1	1								
Nbr of Days	5	5			5							
Total	750	225	1,000	25	0	500	0	0	0	0	2,500	PY 1
											0	PY 2
											2,652	PY 3
											2,732	PY 4
											7,884	Total

Purpose of Trip: Present at Scientific Conference
Depart From: Washington, DC
Arrive To: San Francisco, CA

Summary of Travel Budget Requirements

Domestic/Foreign; Purpose	**PY 1**	**PY 2**	**PY 3**	**PY 4**	**Total**
Domestic; Present at Scientific Conference	2,500	0	2,652	2,732	7,884
Total:	2,500	0	2,652	2,732	7,884

Other

Other Direct Costs, SED - 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 computers and information technology support from the Global Modeling and Assimilation Office of the Earth Science Division in the Sciences and Exploration Directorate. Additionally, supercomputing made available by the NASA Center for Climate Simulation at GSFC will be utilized in this study.

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.