Executive Summary

The Atmospheric Carbon and Transport-America (ACT-America) mission will advance society's ability to predict and manage future climate change by enabling policy-relevant quantification of the carbon cycle. Sources and sinks of carbon dioxide (CO_2) and methane (CH_4) are poorly known at regional to continental scales. **ACT-America will enable and demonstrate a new generation of atmospheric inversion systems for quantifying CO_2 and CH_4 sources and sinks. These inversion systems will be the first ever with the precision, accuracy, and resolution needed to 1) evaluate and improve terrestrial carbon cycle models, and 2) monitor carbon fluxes to support climate-change mitigation efforts.** Applications of these inversion systems beyond the conclusion of the mission will improve diagnoses of the carbon cycle across the globe for decades.

The overarching goal described above will be achieved via three mission goals: **1) reduce atmospheric transport uncertainties; 2) improve regional-scale estimates of CO_2 and CH_4 fluxes; and 3) evaluate the sensitivity of Orbiting Carbon Observatory-2 (OCO-2) column CO_2 measurements to regional variability in tropospheric CO_2.** The mission goals and their associated objectives define the baseline mission and address the three primary sources of uncertainty in atmospheric inversions: atmospheric transport, prior flux estimates, and sparse atmospheric CO_2 and CH_4 data. The threshold mission eliminates goal 3, and compromises on the degree of improvement in goals 1 and 2 by reducing the number of flight campaigns.

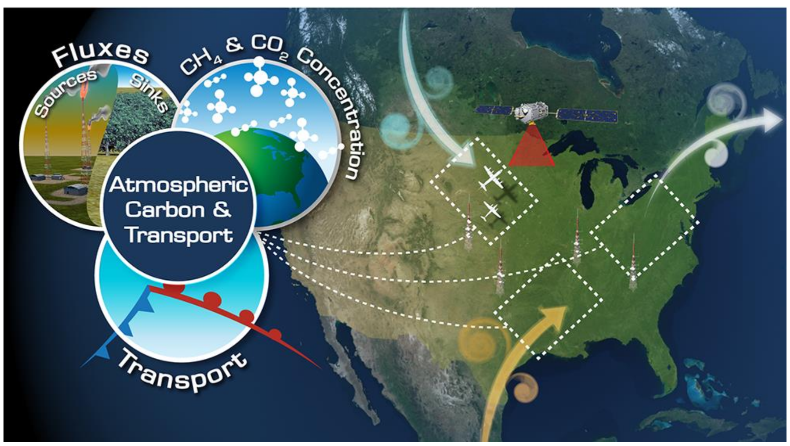

Figure 1. *ACT-America supports NASA's Carbon Cycle and Ecosystems, and Atmospheric Composition missions by improving quantification of CO_2 and CH_4 sources and sinks, enabling detection of changes in the carbon cycle, and enhancing the utility of satellite CO_2 observing systems.*

ACT-America will achieve these goals by deploying airborne and ground-based platforms to obtain data that will be combined with data from existing measurement networks and integrated with an ensemble of atmospheric inversion systems. Aircraft instrumented with remote and in situ sensors will observe how mid-latitude weather systems interact with CO_2 and CH_4 sources and sinks to create atmospheric CO_2/CH_4 distributions. A model ensemble consisting of a mesoscale atmospheric transport model with multiple physics and resolutions options nested within global inversion models and surface CO_2/CH_4 flux ensembles will be used to predict atmospheric CO_2 and CH_4 distributions. We will prune our model ensemble to those members best able to simulate the measured atmospheric CO_2 and CH_4 distributions. **This pruned flux and transport model ensemble will form the basis of the next generation of atmospheric inversion systems, enabling more precise and accurate, regional-scale atmospheric inversions,** and satisfying goals 1 and 2.

The summer 2014 launch of OCO-2 will provide a dramatic expansion of atmospheric CO_2 measurements. ACT-America will collect high-quality column and in situ CO_2 measurements across a variety of continental surfaces and atmospheric conditions directly under OCO-2 overpasses to evaluate the ability of OCO-2 to observe high-resolution atmospheric CO_2 variations. **The improved quantification of OCO-2 observational uncertainties will improve**

the utility of OCO-2 data in atmospheric inversion systems and will satisfy goal 3. The results from goals 1-3 will be integrated in the final year of the mission into an inverse analysis of North American sources and sinks of CO_2 and CH_4 from 2009 through 2018, which we anticipate will show a factor of three reduction in uncertainty relative to current atmospheric inversion results for the continent. *The transport and flux processes, and OCO-2 data characteristics studied will be common across mid-latitudes, thus the results of the mission will improve atmospheric inversions around the globe and over decades*.

The eastern half of the United States, a region that includes a highly productive biosphere, vigorous agricultural activity, extensive gas and oil extraction, dynamic, seasonally varying weather patterns and the most extensive carbon cycle and meteorological observing networks on Earth, serves as an ideal setting for the mission. ACT-America will deploy the NASA P-3B and UC-12 aircraft to measure atmospheric CO_2 and CH_4 in the atmospheric boundary layer (ABL) and free troposphere (FT). The mission proposes a total of 70 science flights, 528 hours for the P-3B and 396 hours for the UC-12, dedicated in a roughly 3:3:1 ratio among fair weather, stormy weather, and OCO-2 underpass flight patterns. For fair and stormy weather flights, the P-3B will fly at 3-8 km above ground, collecting in situ measurements in the lower FT, remotely sensed, column-averaged CO_2 measurements focused on the ABL, and occasional in situ vertical profiles. The UC-12 will primarily sample the ABL. For OCO-2 underflights, the P-3B will fly at 8 km above ground with the UC-12 flying in the ABL, both along the OCO-2 flight track. The existing in situ tower CO_2/CH_4 observing network will be enhanced with five additional tower sites. The mission will deliver 2-3 times more high-quality lower tropospheric CO_2 and CH_4 observations than any previous airborne campaign. **ACT-America will be the first mission ever to focus on improving atmospheric inversions via studying synoptic-scale atmospheric transport.**

The ACT-America schedule includes a 1-year preparation and integration phase, five 6-week campaigns across four different seasons and 3 years, and 1 year dedicated to analyses. Each campaign will yield progress towards the three mission goals, and these results will be integrated to achieve the overall goal in the final year of the project.

ACT-America will deploy high-quality, field-tested (TRL-8 (Technology Readiness Level) or higher) trace gas and meteorological instruments. The mix of remote and in situ sensors enables extensive spatial coverage of key variables. The P-3B instrument complement includes the Multi-Functional Fiber Laser Lidar for CO_2 columns, range to ground and surface reflectance; the High Spectral Resolution Lidar for ABL depths and atmospheric aerosols; Picarro cavity ring-down spectrometers for in situ CH_4, CO_2, water vapor and carbon monoxide (CO); 2B Technologies for in situ ozone; Flasks for CO_2, CH_4, CO, carbonyl sulfide, and $^{14}CO_2$; and an environmental suite for in situ pressure, temperature and winds. The UC-12 has the same in situ sensors save for winds. Towers utilize Picarros for in situ CO_2 and CH_4.

ACT-America brings together world-class science and management teams. Principal Investigator Kenneth Davis (Penn State) leads a Science Team that includes experts in atmospheric measurements, atmospheric inversions, satellite remote sensing, and data management. Project Scientist Syed Ismail (Langley Research Center (LaRC)) leads the instrument investigators on the airborne platforms. Project Manager Byron Meadows (LaRC) leads a mission management team with over 30 years of experience leading airborne campaigns, including the Langley-managed DISCOVER-AQ Earth Venture mission. ACT-America employs proven management processes, high TRL instruments, and reliable aircraft to yield a low-risk, high-return investigation operating from airfields and in airspace within the continental US. The total proposed investigation cost is \$30.8 M (NASA Science Mission Directorate \$30.0 M; Penn State \$0.35M; NASA LaRC \$0.5M).

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1 Science Investigation

1.1 Science Goals and Objectives

Overarching goal: The Atmospheric Carbon and Transport-America (ACT-America) mission will advance society's ability to predict and manage future climate change by enabling policy-relevant quantification of the contemporary carbon cycle. This mission will enable and demonstrate a new generation of atmospheric inversion systems for quantifying regional carbon dioxide (CO_2) and methane (CH_4) sources and sinks. These inversion systems will be the first ever with the precision, accuracy, and resolution needed to 1) evaluate and improve terrestrial carbon cycle models at continental scales, and 2) monitor carbon fluxes to support climate-change mitigation efforts. This will be achieved with an airborne mission that will improve our understanding of regional CO_2 and CH_4 sources and sinks, atmospheric transport, and satellite column CO_2 observations (Figure 1-1). Applications of the inversion systems beyond the conclusion of this mission will improve diagnoses of the contemporary carbon cycle across the globe for decades.

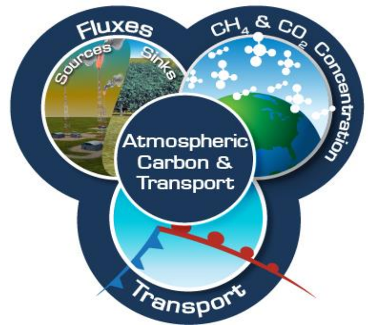


Figure 1-1. *The ACT-America mission addresses the three primary sources of uncertainty in atmospheric inversions: atmospheric transport, sources and sinks of carbon, and atmospheric concentration measurements.*

1.1.1 Needs

Understanding the terrestrial carbon cycle is essential for diagnosing current and predicting future climate change (Marquis and Tans, 2008; Gregory et al., 2009; Michalak *et al.*, 2011). The Earth's terrestrial biosphere has been a strong net sink of atmospheric CO_2 for 3 decades (e.g., LeQuere *et al.*, 2009), substantially slowing the rate of accumulation of CO_2 in the atmosphere from combustion of fossil fuels. CH_4 is accumulating in the atmosphere and is the second largest contributor to anthropogenic climate change (Montzka *et al.*, 2011, Dlugokencky *et al.*, 2011).

The causes of the net biogenic CO_2 sink, its location and magnitude (Peylin *et al.* 2013), and its likely evolution in the future (e.g., Friedlingstein *et al.*, 2006) all remain highly uncertain, contributing substantial uncertainty to our projections of future climate (Stocker *et al.*, 2013). North American biogenic CO_2 fluxes, for example, are known on a 5-year, continentally aggregated basis to an accuracy no better than 50% (SOCCR, 2007; King *et al.*, 2012). Individual annual estimates from biosphere models, biomass inventories, and atmospheric inversions (Hayes *et al.*, 2012; Peylin *et al.*, 2013) often diverge by a factor of 2. U.S. CH_4 inventories (U.S. EPA, 2013a,b; Eur. Comm, 2009) differ from atmospheric estimates by nearly 50% (Bruhwiler *et al.*, submitted; Miller *et al.*, 2013; Kort *et al.*, 2008). The renaissance in oil and gas extraction has raised concerns regarding CH_4 leakage (Howarth *et al.*, 2011; Alvarez *et al.*, 2012) and added uncertainty to the already complex and poorly understood CH_4 budget.

Significant progress quantifying the carbon cycle has been made at the global scale and at the scale of flux tower footprints (~1 km^2), but we lack the ability to diagnose CO_2 and CH_4 sources and sinks with regional (~10^6 km^2) resolution. Regional scales are critically important because they are the scales (biomes, agricultural zones, geopolitical units) over which management activities take place, and over which ecological processes drive terrestrial fluxes. Our inability to diagnose the carbon cycle at regional scales severely restricts our ability to monitor emissions management efforts (Pacala *et al.*, 2010) and to evaluate and improve the accuracy of terrestrial carbon cycle models (Huntzinger *et al.*, 2012). **Accurate and precise diagnoses of CO_2 and**

CH_4 fluxes that are ongoing, possess regional and annual resolution, span the globe, and encompass decades, are needed.

Atmospheric inversions have the potential to provide accurate and precise diagnoses of CO_2 and CH_4 fluxes at the requisite spatial and temporal scales. Atmospheric inversion models (e.g., Baker *et al.*, 2006a) are data analysis systems used to convert measurements of the atmospheric concentration (mole fraction) of CO_2 and CH_4 (hereafter C) into estimates of sources and sinks (fluxes) of these gases. Inversions are performed in two steps. Atmospheric mole fractions are simulated by combining a first guess of fluxes (e.g., a model of ecosystem respiration and photosynthesis), referred to as a prior flux estimate, with a model (actually a reanalysis, or modeled interpolation of meteorological measurements) of atmospheric transport. The prior fluxes are merged with the transport reanalyses to predict space-time distributions of atmospheric C mole fractions. The simulated mole fractions are then compared to mole fraction observations, such as those collected by the global long-term observing network (Conway *et al.*, 1994; Dlugokencky *et al.*, 2011) or satellite platforms (Yokota *et al.*, 2009; Bergamaschi *et al.*, 2007). The prior flux estimates are then adjusted to minimize the difference between the observed and modeled atmospheric mole fractions.

Atmospheric inversions have proven invaluable in determining global to zonal, decadal-scale sources and sinks of C (e.g., Tans *et al.*, 1990; Ciais *et al.*, 1995; Bousquet *et al.*, 2006). At present, however, with the exception of a few focused regional studies with high-density atmospheric observations and high-resolution atmospheric models (Lauvaux et al., 2012a, b), *atmospheric inversions are unable to provide useful constraints on the carbon cycle at the regional, annual scales essential for advancing carbon cycle science*. The fact that inverse flux estimates were not used to evaluate terrestrial carbon models (King et al., 2012) or to assess continental-scale carbon budgets (Stocker et al., 2013) is indicative of this lack of confidence.

Extensive investments have gone into the development of atmospheric inversions; these include new observations, such as the Greenhouse gases Observing Satellite (GOSAT, Yokota et al., 2009) and the Orbiting Carbon Observatory-2 (OCO-2, Crisp et al., 2004; 2008), as well as modeling systems, such as NASA's Carbon Monitoring System (CMS, Liu et al. 2013) and the National Oceanographic and Atmospheric Administration (NOAA)'s Carbon Tracker (CT, Peters et al., 2007). To date, however, these investments have not resulted in clear improvements in the accuracy and precision of atmospheric inversions (Peylin *et al.*, 2013; Chevallier and O'Dell, 2013). Additional observational investments are planned (OCO-3, Eldering *et al.*, 2013; Active Sensing of CO_2 Emissions over Nights, Days, and Seasons (ASCENDS), NRC, 2007). While enhanced observations are necessary to improve inversions (Rayner and O'Brien, 2001), it is unlikely that added observations alone will achieve the desired improvements (Gurney *et al.*, 2002).

The current uncertainty in atmospheric inversions is due to three factors: sparse atmospheric C data, uncertainty in atmospheric transport of these gases, and highly uncertain prior flux estimates. Progress on all three fronts is needed to achieve high accuracy, high precision, and high resolution atmospheric inversions. **This mission addresses the following three unmet needs: 1) A coordinated observational effort to reduce uncertainty in the atmospheric transport reanalyses used in atmospheric inversions**. Uncertainty in atmospheric transport is one of the major sources of uncertainty in inverse flux estimates (Baker *et al.*, 2006a; Stephens *et al.*, 2007; Gerbig *et al.*, 2008; Chevallier *et al.*, 2010a; Lauvaux and Davis, in press). The current atmospheric transport uncertainty in inverse estimates of net biogenic CO_2 fluxes for temperate North America is 0.3-0.5 PgC yr^{-1} (Gurney *et al.*, 2002; Baker *et al.*, 2006a) and has not changed significantly over the past decade (Peylin *et al.*, 2013). Different atmospheric transport models yield N. American annual CO_2 inverse flux estimates that differ by 65% (Peylin *et al.* 2013). Rigorous quantification of transport error in CH_4 flux estimates does not exist. **2) Improved prior estimates of carbon sources and sinks**. The magnitude of seasonal fluxes of CO_2 in biogeochemical models in a N. American synthesis varied by a factor of 2 to 3 (Huntzinger *et al.*, 2012). Comparisons between eddy covariance and modeled CO_2 fluxes show similar ranges of disagreement among models and relatively weak agreement with observations (Raczka *et al.*, 2013; Schaefer *et al.*, 2012; Richardson *et al.*, 2012a). Methane models and observations are less developed than for CO_2, thus broad assessments of model quality are not available. More realistic prior flux estimates improve our ability to use long-term atmospheric data (tower network, OCO-2) for atmospheric inversions. **3) Evaluation of the high-resolution spatial variability in OCO-2 column CO_2 observations.** While there are plans for observational validation of OCO-2 column CO_2 measurements using point-based measurements (e.g., Wunch *et al.*, 2010; 2011), no continuous comparisons along the flight track are planned. The high-resolution, global-scale observations from OCO-2 promise greatly improved atmospheric CO_2 inversions across the globe (Miller *et al.*, 2007), but questions remain concerning the accuracy and precision of these observations (Bréon and Ciais, 2010). In particular, complex surfaces, aerosols, and clouds may cause spatial variations in observed radiances to be misinterpreted as variations in column CO_2. Evaluating the fidelity of the OCO-2 data across space will greatly improve the utility of these data in atmospheric inversions.

1.1.2 Mission Goals

The <u>overarching mission goal</u> will enable a factor of three reduction in uncertainty in regional (~10^6 km^2) to continental scale atmospheric inverse C flux estimates relative to the current state. ACT-America will demonstrate this uncertainty reduction for North America. The overarching goal will be achieved via three synergistic mission goals (Figure 1-2) and associated objectives.

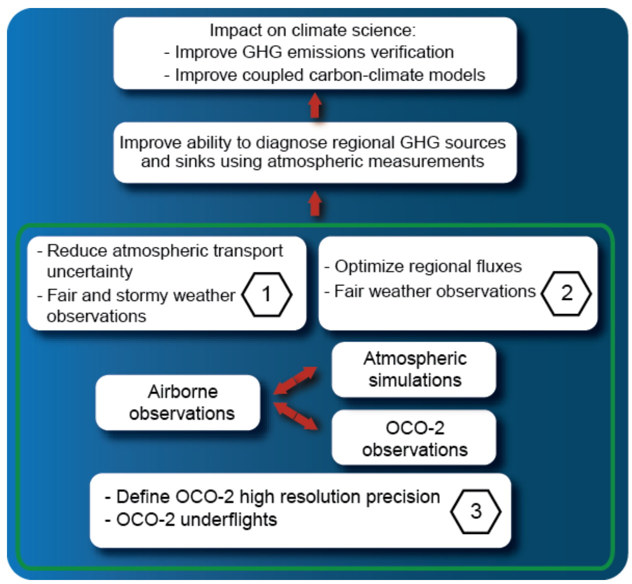


Figure 1-2. *ACT-America will deploy sustained airborne measurements to reduce uncertainty in regional atmospheric inverse estimates of CO_2 and CH_4 sources and sinks by a factor of 3, enabling data-driven understanding of climate management options. The mission builds upon and improves the utility of our nation's investment in long-term carbon cycle observation and analysis systems.*

<u>**Goal 1:** Reduce transport uncertainty for temperate latitude atmospheric inversions</u>. This first-ever sustained airborne study of atmospheric transport of greenhouse gases (GHGs) will greatly reduce transport uncertainty in atmospheric inversions.

<u>**Goal 2:** Provide regional-scale, top-down constraint on seasonal CH_4 emissions and biogenic CO_2 fluxes</u>. Airborne measurements will directly reduce uncertainty in seasonal, regional CH_4 and biogenic CO_2 fluxes.

<u>**Goal 3**: Evaluate the sensitivity of satellite-based passive measurements of CO_2 from OCO-2 to regional variability in tropospheric CO_2</u>.The mission will provide high-resolution, highly calibrated airborne observations under the OCO-2 flight track to document the degree to which OCO-2 observations capture spatial gradients in atmospheric CO_2 caused by regional-scale terrestrial fluxes.

Deliverables associated with these goals address the three primary sources of uncertainty in atmospheric inversions and enable the overarching mission goal of improved regional diagnoses of CO_2 and CH_4 sources and sinks.

1.1.3 Baseline science objectives and expected impacts

Objective 1.1: Reduce transport uncertainty for inverse estimates of net annual biogenic North American CO_2 fluxes to 0.1 PgC yr^{-1} or less. **1.2:** Reduce transport uncertainty in regional (10^6 km^2) net annual biogenic CO_2 flux estimates to 20 TgC yr^{-1} (0.02 PgC yr^{-1}) or less. These uncertainty objectives correspond to roughly 20% uncertainty in net annual fluxes, compared to current net flux uncertainties of 60-100% at the continental scale (Chevallier *et al.*, 2010b; Peylin *et al.*, 2013), and unquantified uncertainties at regional scales. Transport uncertainty in CH_4 inversions will also be reduced, but current quantification of inversion uncertainties is limited. **Impacts:** A continental biogenic CO_2 flux uncertainty of 0.1 PgC yr^{-1} would approach the level of uncertainty in national anthropogenic CO_2 emissions (~ 0.05 PgC yr^{-1}, U.S. EPA, 2013a) and is well below the roughly 0.5 PgC yr^{-1} interannual variability in continental fluxes (Peylin *et al.*, 2013). The regional uncertainty objective yields a flux density uncertainty of 20 gC m^{-2} yr^{-1}, similar to the uncertainty achieved by a ~1 km^2 footprint eddy flux tower (Ricciuto *et al.*, 2008)

Objective 2.1: Determine regional (10^6 km^2) CH_4 emissions and **2.2:** biogenic CO_2 fluxes in our intensive study regions for the period of each flight campaign to 20% uncertainty or less. **Impacts:** The CH_4 uncertainty estimates represent a major improvement over the current 50% discrepancies between emissions estimates and will bridge the gap between short-term, shale basin-scale measurements (Karion *et al.*, 2013a) and national assessments (U.S. EPA, 2013a). The seasonal inverse CO_2 flux estimates will provide benchmarks for discriminating among the factor of 2 differences in regional terrestrial biosphere model estimates (Huntzinger *et al.*, 2012).

Objective 3.1: Quantify and diagnose surface- or aerosol-related biases in OCO-2 column CO_2 measurements greater than 0.5 ppm with 20 km spatial resolution. **Impacts**: The primary OCO-2 validation method (being applied currently to GOSAT observations) is built around spatially fixed column measurements and obtains roughly 0.5-ppm precision (Wunch *et al.*, 2010, 2011). Quantifying how accurately OCO-2 can capture high-resolution (20-km) variations in tropospheric CO_2 along its flight track over the continents and exploring the causes of any biases will improve our confidence in the use of these data to obtain regional-scale fluxes across continents around the globe.

1.1.4 Investigation's value to advancing NASA's Earth Science objectives

The ACT-America mission responds to NASA's Carbon Cycle and Ecosystems, Atmospheric Composition, and Climate Variability and Change mission elements. ACT-America is closely aligned with the Carbon Cycle and Ecosystems (CCE) element of the NASA science plan and addresses the call to "Quantify…terrestrial and marine productivity, and improve carbon cycle and ecosystem models." ACT-America will improve quantification of the northern hemisphere sink of CO_2 and contribute to the CCE objective to "(2) quantify global productivity, biomass, (and) carbon fluxes." ACT-America's long-term legacy will be improved ability to "(1) document and understand how the global carbon cycle, terrestrial and marine ecosystems, … are changing." These objectives will be accomplished by providing "advanced, high-resolution measurements of atmospheric profiles (and horizontal gradients) of CO_2 and CH_4 … needed to further refine our ability to quantify global sources and sinks, providing accuracy sufficient to balance the global carbon budget and monitor carbon-management activities." The project addresses the objectives of the North American Carbon Program (NACP, Denning *et al.*, 2005) and the first question of a U.S. Carbon Cycle Science Plan (Michalak *et al.*, 2011): **"**How do natural processes and human actions affect the carbon cycle on land, in the atmosphere, and in the oceans?"

1.2 Science Investigation Concept

Overview: ACT-America will deploy airborne and ground-based platforms to obtain data that will be combined with data from existing in situ and remote networks and integrated with a nested ensemble of Earth system models to achieve mission goals (Figure 1-3). Aircraft instrumented with remote and in situ sensors will capture spatially extensive measurements of how weather systems interact with C sources and sinks to create the atmospheric distribution of these gases. A model ensemble consisting of a mesoscale atmospheric transport model with multiple physics and resolution options enables us to explore the impacts of model physics and resolution on atmospheric C distributions. The mesoscale model uses inputs from ensembles of global models and ecosystem and anthropogenic flux models enabling us to explore simultaneously the impact of boundary conditions and surface fluxes on atmospheric C. We will identify the models within our ensemble that are best able to simulate the measured atmospheric C distributions. We will prune outliers to create a more accurate and precise ensemble of flux and transport models. A simplified representation of such model pruning is shown in Figure 1-4. The improved model ensemble will result in more precise and accurate atmospheric inversions using the long-term measurement network. Improved quantification of OCO-2 observational uncertainties will improve its utility within the atmospheric inversion systems. *The carbon flux and atmospheric transport processes we study will be common across the mid-latitudes, and the OCO-2 evaluation will apply globally, thus the results of the study will improve atmospheric inverse flux estimates around the globe and over decades*.

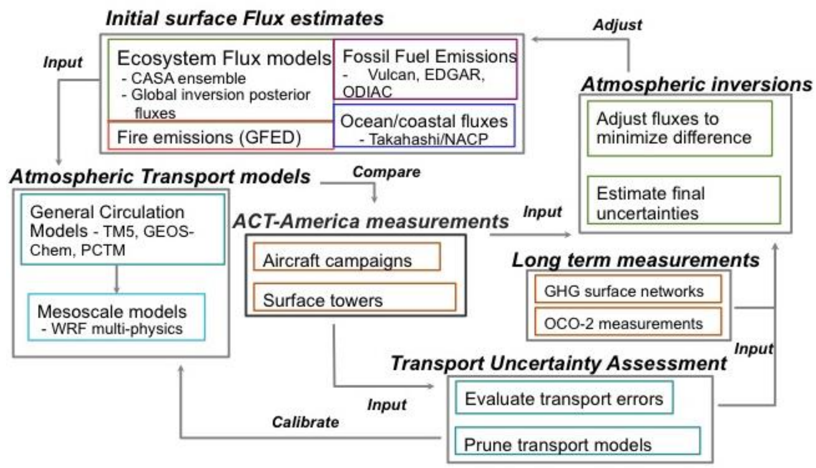


Figure 1-3. *Airborne observations will be compared to and assimilated into ensembles of regional- and global-scale models to provide rigorous quantification of CO_2 and CH_4 fluxes, and improve transport ensembles for atmospheric inversions.*

Experimental design: Our experimental design is built on a number of postulates and hypotheses. We postulate that atmospheric transport of C at mid- and high-latitudes is dominated by synoptic-scale weather – the periodic passage of low-pressure systems (mid-latitude cyclones) and intervening periods of high-pressure, fair-weather conditions. Mid-latitude cyclones create strong, organized north-south exchange of air in the cyclonic circulation, strong organized vertical motions due both to convergent lifting and large-scale flow over fronts, and strong vertical mixing via the initiation of strong updrafts and downdrafts in thunderstorms. These weather systems play a major role in creating the north-south gradients in GHGs in the northern hemisphere (Parazoo *et al.*, 2011; 2012). Erroneous simulation of these weather systems is likely a major contributor to transport-related errors in atmospheric inverse estimates of regional- to global-scale GHG fluxes (Denning *et al.*, 1995; Stephens *et al.*, 2007; Gerbig *et al.* 2008; Liu *et al.* 2011; Diaz *et al.*, submitted). Hence, we hypothesize that by improving our ability to simulate accurately and precisely the GHG transport in high- and low-pressure systems in the mid-latitudes, we will dramatically improve our ability to construct accurate and precise atmospheric inverse estimates of C sources and sinks.

In addition, the current in situ CO_2 and CH_4 observational networks are too sparse to resolve synoptic-scale atmospheric transport, and thus not suitable for deconvolving the combined influence of both flux and transport on atmospheric C mole fraction distributions. Similarly, column satellite observations from low Earth orbits are relatively sparse compared to the structure of synoptic weather systems, provide little information on the vertical distribution of GHGs, and are biased to cloud-free conditions. The high density and resolution, and large spatial domain offered by intensive airborne campaign data will provide the observational constraint required to prune both flux and transport ensembles. Sustained airborne observations will bridge the gap from case studies to general understanding.

Finally, we hypothesize that we can, *to first order* (our full analyses will not make this simplifying assumption), deconvolve the impact of fluxes and transport on atmospheric C by careful selection of meteorological conditions. This hypothesis motivates an observational design segregated into fair weather (flux dominated) and stormy weather (transport dominated) flights.

1.2.1 Fair-weather investigation concept (Goals 2 and 1)

In high-pressure, fair-weather conditions, transport of the signals from CO_2 and CH_4 sources and sinks is largely contained within the atmospheric boundary layer (ABL), the lowest 1-2 km of the atmosphere. The dominant transport processes are the interaction of clear-air convection and subsidence, governing entrainment into the ABL, and wind speed and direction within the ABL. The convection is most vigorous and transport easiest to simulate during daytime hours. These simple transport processes can be strongly constrained with aircraft observations. Assuming that the transport is strongly constrained with direct observations, it is then straightforward to constrain regional surface fluxes by flying over the region and collecting a large quantity of ABL C observations. Figure 1-4 shows *an overly simplified representation* of how we will use ACT-America's fair-weather C observations to improve our understanding of regional C fluxes.

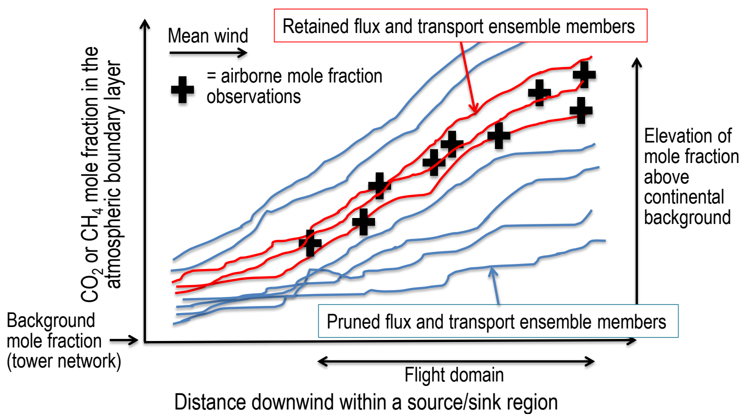


Figure 1-4. *ACT-America observations of CO_2 and CH_4 and fair-weather meteorology, combined with simulations of atmospheric C, will identify members of a model ensemble that best represent regional CO_2 and CH_4 sources and sinks. (A formal inversion will be used for Goal 2 regional flux estimates. This figure is simplified to illustrate the investigation concept.)*

Science Traceability Matrix (STM) detail: This experimental design and our quantitative objectives define the elements of our Science Traceability Matrix (STM) (Table 1-1) for Goal 2 (as well as part of the Goal 1 STM elements, which we will return to shortly). (Note that Goal 2 requirements are presented first for pedagogic reasons.) *Science requirements* for the objective of determining regional CO_2 and CH_4 fluxes to within 20% uncertainty (Goal 2) include observations of:

- Changes in CH_4 and CO_2 mole fraction in the daytime ABL downwind of major source/sink regions to a precision of 20% or better (the precision of the observed change in mole fraction is directly proportional to the precision of our regional flux estimate).
- CH_4 and CO_2 mole fractions at the upwind and free troposphere (FT) boundaries of the source/sink regions. (The FT refers to the portion of the troposphere that excludes the ABL.)
- Variability in atmospheric CO_2 and CH_4 sources and sinks across regions.

- Variability in atmospheric CO_2 and CH_4 sources and sinks across seasons.
- Atmospheric transport properties, specifically ABL depth, mean wind velocity and the thermodynamic properties (temperate and water vapor content) of the ABL and lower FT.
- Trace gases (carbon monoxide - combustion tracer, carbonyl sulfide - marks photosynthesis, and $^{14}CO_2$ - fossil fuel tracer) indicative of CO_2 source or sink to aid interpretation.

Table 1-1. Science Traceability Matrix for the baseline science objectives.

Mission Goals and Objectives	Science Requirements	Instrument Requirements	Investigation Requirements
Goal 1: Reduce transport uncertainty for temperate latitude GHG inversion studies. [MO1.1] Reduce transport uncertainty for inverse estimates of net annual biogenic N. American CO_2fluxes to 0.1 PgC yr^{-1} or less. [MO1.2] Reduce transport uncertainty in regional (10^6 km^2) net annual biogenic CO_2 flux estimates to 20 TgC yr^{-1} or less.	[SR1.1] Observe multiple high-pressure and low-pressure systems spanning summer and winter conditions. [SR1.2] Observe atmospheric CO_2 with sufficient precision to distinguish differences (3-10 ppm hourly in the midday ABL) among transport models. [SR1.3] Properties that differentiate flux vs. transport errors: ABL depth, winds, CO, H_2O, O_3, COS, $^{14}CO_2$. [SR1.4] Fair weather: Measure from the ABL to 3-4 km AGL spanning a significant fraction of system area (10^6 km^2) with sufficient resolution (20 km) to detect within-system structure. [SR1.5] Storms: Measure a significant portion of along-front (~10^3 km) and cross-frontal (100-300 km) structure from the ABL to the upper troposphere with sufficient resolution (20 km) to detect within-system structure. [SR1.6] CO_2 boundary conditions.	[IR1.1] Accuracy of CO_2 measurements: 1 ppm. <u>Airborne instruments</u>: [IR1.2] Temporal resolution: 130 sec (20 km at 150 m/s). [IR1.3] Precision for a 20km (130 sec) average: CO_2: 1 ppm; CO: 15 ppb; O_3: 8 ppb; H_2O: 0.5 g/kg; COS: 10 ppt; $^{14}CO_2$: 2 per mil; ABL depth: 100 m; Altitude above ground: (5 m); Ambient air temperature: 0.5°C; Horizontal wind speed: 1.0 m/s; Horizontal wind direction: 5°; Ambient air pressure: 0.5 mb. CO_2 column (from surface to 3km AGL) precision of 0.1%.[1] <u>Ground instruments</u>: [IR1.4] CO_2: 1-ppm hourly accuracy and precision.	[IV1.1] Collect aircraft and tower based data that meet instrument requirements. [IV1.2] Conduct campaigns spanning summer and winter. [IV1.3] Sample three or more low-pressure systems and three or more high-pressure systems within each season. [IV1.4] Conduct flight patterns whose spatial dimensions meet the fair and stormy weather science requirements. [IV1.5] Add tower instruments that fill in boundary regions. [IV1.6] Use field data to identify and quantify CO_2 errors in atmospheric transport models. [IV1.7] Identify transport model ensembles with reduced (1 ppm or less) CO_2 model-data mismatch errors and minimal bias. [IV1.8] Implement identified transport ensemble for continental inversions.
Goal 2: Provide regional-scale top-down constraint on CH_4 emissions and seasonal CO_2 fluxes across the eastern half of the U.S. [MO2.1] Determine regional (10^6 km^2) CH_4 emissions in major source regions for the period of the flight campaign to 20% uncertainty. [MO2.2] Determine regional (10^6 km^2) biogenic CO_2 fluxes in major source regions for the period of the flight campaign to 20% uncertainty.	[SR2.1] Resolve regional (10^6 km^2), fair-weather, ABL CH_4 enhancements (20-100 ppb) and CO_2 changes (10-20 ppm) with a precision of 20%. [SR2.2] Sample trace gases (CO, COS, $^{14}CO_2$) that identify CO_2 sources/sinks. [SR2.3] Measure upwind and downwind of C sources/sinks and laterally to encompass sources/sinks (~500 km), multiple seasons. [SR2.4] Measure along wind to sample enhancements of C that occur over hours to a few days (~100 km for 6 hr). [SR2.5] Measure the C content of the FT. [SR2.6] ABL depth, wind, temp, H_2O.	[IR2.1] Same instrument capabilities noted for Goal 1 with the addition of CH_4 and no requirement for O_3. [IR2.2] Accuracy and precision of airborne CH_4 measurements: 4 ppb for a 20 km (130 sec) average. <u>Ground instruments</u>: [IR2.3] The same CO_2 requirements as for Goal 1. CH_4: 4 ppb hourly accuracy and precision.	[IV2.1] Collect aircraft data meeting instrument requirements. [IV2.2] Conduct multiple fair weather aircraft flights in major CH_4 and CO_2 source/sink regions repeated for each season of the year. [IV2.3] Collect tower-based CO_2 and CH_4 measurements upwind of the source regions to fill in the existing network. [IV2.4] Estimate regional CH_4 and CO_2 sources/sinks via atmospheric inversions. [IV2.5] Use inverse flux estimates of airborne data to improve flux priors for continental-scale inversions using the long-term C observing network.
Goal 3: Evaluate the sensitivity of satellite-based passive measurements of CO_2 from OCO-2 to regional variability in tropospheric CO_2 content. [MO3.1] Quantify and	[SR3.1] Measure tropospheric column CO_2 with 0.125% (0.5 ppm) precision and 20 km spatial resolution coincident in time and space with OCO-2. [SR3.2] Quantify temporal and spatial variably in column	[IR3.1] Measure column CO_2 from surface to 8 km AGL with 0.125%[1] precision and 20 km spatial resolution. [IR3.2] Measure spatial location to within 500 m,	[IV3.1] Collect airborne CO_2 on multiple (>800 km) flights centered in time around the OCO-2 overpass and on OCO-2 track, over a variety of continental surfaces and aerosol conditions. [IV3.2] Obtain cloud, aerosol and

diagnose surface- or aerosol-related, biases in OCO-2 CO_2 measurements that are greater than 0.5 ppm with a spatial resolution of 20 km.	CO_2along track resulting from different surface types and aerosol distributions within the OCO-2 footprint.	and altitude above ground level to within 5 m, at 0.2 km spatial resolution (1.3 sec). [IR3.3] Measure ABL depth, air pressure as for goal 1. [IR3.4] Measure atmospheric CO_2 column at 0.2 km resolution with 1.0% precision. [IR3.5] Measure aerosol distribution and surface reflectance variability at 0.2 km. resolution	land surface properties with A-train satellite instruments (Calipso, MODIS). [IV3.3] Compute column CO_2 above 8 km with inversion systems. [IV3.4] Compare OCO-2 and ACT-America column CO_2 amounts at 2.25 km and 20 km resolution. [IV3.5] Diagnose causes of OCO-2 and ACT-America column CO_2 differences. [IV3.6] Utilize OCO-2 high res data in continental inversions.

[1]0.125% in column CO_2 is roughly equivalent to 0.5 ppm in column mean mole fraction. Column CO_2 precisions are presented in % since comparisons to models and to OCO-2 will be conducted in these native measurement units.

Instrument precision and accuracy requirements for CO2 and CH4 in Table 1-1 are derived using our current knowledge of how regional sources and sinks affect atmospheric mole fractions based on previous measurement campaigns (e.g., Karion et al., 2013a; Miller et al., 2013; Miles et al., 2012) and model simulations (Normile et al., 2013).Regional, daytime ABL CO_2 enhancements and depletions due to regional to continental biogenic fluxes range from +10 ppm in winter to –20 ppm in summer. Daytime ABL CH_4 enhancements from regional emissions range from 20 to 100 ppb. These enhancements must be resolved with precision and accuracy of 20% or better to reach the flux uncertainty objective.

Meteorological instrument precision and accuracy are chosen to keep uncertainty in regional atmospheric transport to a very low level. Regional meteorological data, both airborne and from the operational weather network, will be assimilated into our atmospheric transport models (Rogers *et al.*, 2013) to minimize transport errors and optimize flux accuracy. Trace gas precision and accuracy requirements are based on observations of variability in these species in the atmosphere (Montzka *et al.*, 2007; Turnbull *et al.*, 2006; Lehman *et al.*, 2013).

The investigation requirements include sustained measurements to capture repeated realizations of fluxes and weather conditions over multiple seasons. Regional C sources and sinks will be estimated with regional, short-term atmospheric inversions that synthesize the airborne data, prior flux models, and high-resolution atmospheric transport models. *The improved regional CO_2 and CH_4 flux estimates satisfy goal 2 and its associated objectives*.

1.2.2 Stormy-weather investigation concept. (Goal 1)

We hypothesize that atmospheric distributions of CO_2 and CH_4 in the presence of mid-latitude cyclones are dominated by atmospheric transport. Thus, aircraft data collected in and around synoptic storms will provide a strong test of our ability to simulate atmospheric transport of these gases (Goal 1). As with the fair-weather case, we will assemble *an ensemble* of both flux and atmospheric transport models (Figure 1-3), compare these modeled C mole fractions to observations, and prune the ensemble (Figure 1-4). We anticipate that this pruning will focus primarily on variations in atmospheric transport, rather than fluxes. In truth, both fair and stormy weather flights will be used to evaluate and improve atmospheric transport.

STM detail: This experimental design and our quantitative objectives define our STM (Table 1-1) for Goal 1. *Science requirements* to achieve objectives 1.1 and 1.2 include observations of:

- Multiple high- and low-pressure weather systems across multiple seasons with sufficient spatial resolution to detect CO_2 distributions within these systems, and sufficient spatial domain to encompass a large fraction of the structures within these systems.

- Atmospheric CO_2 with sufficient precision to distinguish among different atmospheric transport model simulations of CO_2.
- Atmospheric CO_2 lateral boundary conditions.
- Atmospheric properties that can distinguish between flux and transport errors, including atmospheric transport variables (e.g., ABL depth, wind velocities, temperature) and trace gases (e.g., carbon monoxide - combustion tracer, water vapor - ABL tracer, ozone - stratospheric and polluted air tracer, carbonyl sulfide - marker for photosynthesis and $^{14}CO_2$ - fossil fuel tracer) indicative of airmass and CO_2 origins.

Instrument requirements for CO_2 measurements are evaluated in two ways. First, the observations must have the precision needed to distinguish among different simulations of atmospheric transport. Second, we consider the measurement precision required to reduce the model data “mismatch error” used in current atmospheric inversion systems by a factor of 3, an error that is dominated by errors in atmospheric transport.

We ran continental simulations of different physical parameterizations of the Weather Research and Forecast model (WRF) (Normile *et al.*, 2013), and regional simulations (Diaz *et al.*, submitted) with WRF and Transport Model 5 (TM5), the global scheme used in CarbonTracker (Peters *et al.*, 2007) to quantify CO_2 differences between transport models. All transport simulations had identical CO_2 surface fluxes and lateral boundary conditions. The WRF-TM5 comparisons show hourly, midday ABL mole fraction differences in the U.S. midcontinent that range from 5 to 20 ppm. The more conservative WRF-WRF comparison shows midday differences in ABL CO_2 mole fraction in the U.S. east of the Rockies that are typically 3-6 ppm. Measurements that could distinguish 1-ppm differences in CO_2 mole fractions in the midday ABL (typically 1 to 2 km deep) would easily distinguish model-model transport differences sufficient to enable reduction of transport uncertainty by a factor of 3 or more (objective 1.1).

Transport uncertainty (or model-data mismatch error) is currently estimated to be about 4 ppm for hourly CO_2 in the continental, midday ABL (Peters *et al.*, 2007). To reduce uncertainty in the flux estimates from regional inversions by a factor of 3 this transport uncertainty must also be reduced by a factor of 3. Thus, our measurements must be able to identify hourly differences in CO_2 caused by transport of 1 ppm or less (objective 1.1). Similarly, the hourly transport uncertainty applied to a regional ($\sim 10^6$ km^2) inversion that achieved ~30 TgC yr^{-1} posterior uncertainty (objective 1.2) was 3 ppm for daytime ABL observations (Lauvaux *et al.*, 2012a). Observations that could reduce this error to 1 ppm would reduce the uncertainty to less than 20 TgC yr^{-1} regional inversion (objective 1.2). Both lines of investigation, therefore suggests that CO_2 observations with 1-ppm accuracy and precision in the midday ABL with 20-km spatial resolution will satisfy objectives 1.1 and 1.2.

Instrument requirements for meteorological observations are defined, as for Goal 2, to provide tight constraints to atmospheric fields in the study domain. When studying atmospheric transport we will not assimilate the airborne meteorological data, but reserve it to test transport simulations. Instrument requirements for trace gases are drawn from the documented spatial variability of these gases in the atmosphere. Both types of observations will be used to differentiate flux vs. transport related errors.

Investigation requirements include sampling many different synoptic systems across many seasons ensuring that the findings will be broad and general. We will use the observations to identify *atmospheric transport ensemble members* that best reproduce mid-latitude cyclone transport and mixing of CO_2 and CH_4, and quantify the transport uncertainty in that subset of the model ensemble (Goal 1). Ensemble members will incorporate varied model physics, resolution, lateral boundary conditions (for both meteorology and CO_2) and surface fluxes. *Identification of* *the transport model ensemble that minimizes transport errors in atmospheric inversions satisfies Goal 1 and its associated objectives*.

We hypothesize that transport model resolution will be a critical variable in achieving the transport fidelity required to meet objectives 1.1 and 1.2. We also hypothesize that only a subset of the physical parameterizations options in our ensemble is capable of the required transport fidelity. Finally, we hypothesize that the model-data comparisons will define a transport model ensemble that is well-centered on the mean atmospheric C distributions across many weather systems and provide a rigorous quantification of (considerably reduced) atmospheric transport errors. If we find that our model ensemble is unable to encompass the observations this will be valuable quantification of the need for the model development; the data gathered by the ACT-America mission would provide a critical foundation for this model development.

1.2.3 OCO-2 spatial data evaluation. (Goal 3)

Our comparisons with OCO-2 observations will quantify the observational uncertainty that is appropriate when using OCO-2 CO_2 measurements at high spatial resolution over the continents. Appropriate quantification of those uncertainties makes the OCO-2 observations a stronger contributor to the long-term, global observational network and atmospheric inversions. This proposed high-resolution evaluation is not duplicated in the current OCO-2 evaluation plan which is based on comparison to Total Carbon Column Observing Network (TCCON) sites and comparison to global inversion reanalyses that ingest the existing long-term observational network (Crisp, personal communication).

STM detail: The *science* and associated *instrument requirements* in the traceability matrix were determined by 1) targeting a level of uncertainty and spatial resolution that would provide highly beneficial tropospheric column CO_2 measurements for atmospheric inversions, (0.5 ppm, 20 km) and 2) the desire to equal or improve upon the level of bias that can currently be identified and removed by comparison to the TCCON (0.5 ppm). Requirements for examining OCO-2 column data at pixel-level resolution (2.25km) were derived from the need to understand the OCO-2 retrievals as a function of surface reflectance and atmospheric aerosol distribution, so that our findings can be generalized beyond our specific flight tracks and atmospheric conditions. To assess the impacts of the surface and atmospheric variability on the OCO-2 pixel-level retrievals, a statistically significant data set is needed within each OCO-2 footprint, and hence higher spatial sampling resolution (0.2 km) is required of the column CO_2 measurements with a measurement uncertainty in each sample that matches or exceeds the expected retrieval precision for OCO-2 (0.3% at 2.25 km resolution, Crisp, 2010)

Our STM requirements were written assuming that most of the CO_2 column and its variability are captured between an 8-km aircraft altitude and the surface. That part of the CO_2 column above 8 km, which is generally more spatially homogeneous than the lower troposphere, will be provided by data-driven model reanalyses. Since most of the variability in atmospheric CO_2 is in the ABL, measurements of ABL depth and ABL CO_2 are also required. Note also that our CO_2 remote column instrument requirements are in terms of number density units, which is the native unit of the proposed instrument. We plan to conduct comparisons in those units, but we will also be able to convert to column average mole fraction equivalents using precise measurements of platform altitude, air pressure, range to surface and meteorological reanalyses.

1.2.4 Improvements in continental-scale atmospheric inversions (Overarching goal)

We will re-evaluate the North American carbon balance from 2009 to 2018 using the ongoing, long-term C observational network, the next-generation inversion systems developed via Goals 1 and 2, and the improved characterization of OCO-2 data quality obtained through Goal 3. Our anticipated results are illustrated schematically in Figure 1-5. The results from this project will be propagated into the long-term, global inversion systems participating in this study (NASA

CMS, NOAA CarbonTracker). This level of improvement will enable atmospheric inversions to provide the precision, accuracy, and spatial resolution in flux diagnoses that, for the first time, will serve as useful constraints for regional model evaluation and regional emissions monitoring.

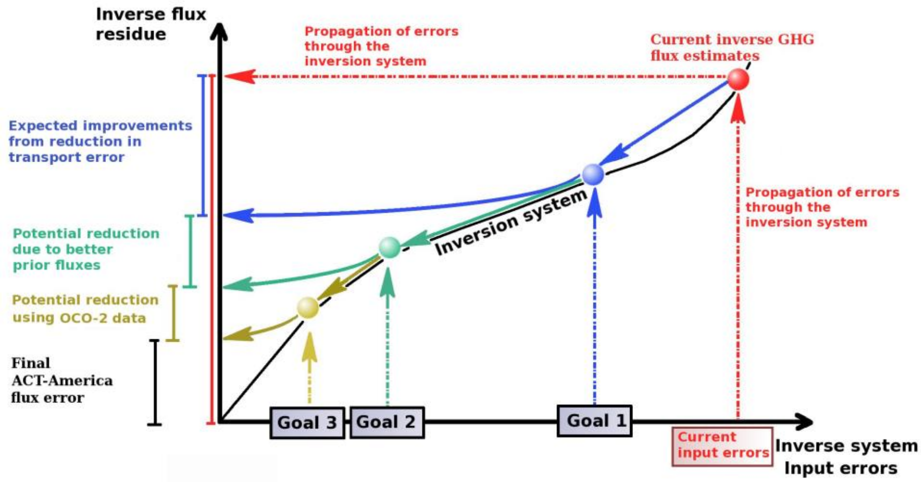


Figure 1-5. *ACT-America will reduce uncertainty in atmospheric inversions and enable their use as practical tools for emissions monitoring and carbon-climate model evaluation and improvement, serving, for example, NASA's Applied Sciences program.*

1.3 Science Requirements for the Threshold Mission

The science requirements for the baseline mission are defined in Section 1.2. The threshold mission compromises on the degree of improvement in Goals 1 and 2 and their associated objectives. Reducing transport uncertainty in atmospheric inversions by a factor of 2 rather than a factor of 3 (objective 1.1) and determining regional, seasonal CO_2 and CH_4 sources and sinks to an uncertainty of 30% rather than 20% (objectives 2.1 and 2.2) would still be highly beneficial. The threshold objectives can be met with a reduced amount of airborne data, enabling descope options described in sections 2, 4 and 5. The evaluation of OCO-2 (Goal 3), while highly valuable, is not essential and is thus not included in the threshold mission.

2 Science Implementation

The ACT-America science implementation plan delivers a high quality, spatially and temporally extensive atmospheric carbon dioxide (CO_2) and methane (CH_4) (hereafter C) data set across key C source and sink regions of the eastern half of the U.S. It includes 2-3 times more continental lower tropospheric C observations than any previous greenhouse gas (GHG) measurement campaign. ACT-America is explicitly focused on developing the next generation of atmospheric inversion models. It would be the first mission to evaluate atmospheric transport of GHGs by mid-latitude weather systems and the high-resolution performance of OCO-2 column CO_2 measurements. ACT-America will be a 5-year mission including five 6-week campaigns using the NASA P-3B and UC-12 aircraft covering all 4 seasons and 3 regions of the central and eastern United States (Figure 2-1). The aircraft will measure the 3-dimensional distribution of C at synoptic spatial scales, focused on the atmospheric boundary layer (ABL) and lower free troposphere (FT) and including both fair and stormy weather. Ensembles of flux, atmospheric transport, and C data assimilation models provide comprehensive modeling and analysis systems. The science team includes leading experts from all relevant disciplines.

2.1 Investigation Location

The eastern half of the United States, a region that includes a highly productive biosphere, vigorous agricultural activity, extensive gas and oil extraction, dynamic, seasonally varying weather patterns and the most extensive GHG and meteorological observing networks on Earth, serves as an ideal setting for the ACT-America mission. Sustained airborne C measurements over three source/sink regions (Figure 2-1) satisfy the spatial domain investigation requirements of the ACT-America STM (Table 1-1). The existing long-term C measurement network, supplemented with a small number of additional tower-based measurements, satisfies the requirements for knowledge of C background conditions. The fluxes and atmospheric transport processes found in this region are common across the mid-latitudes, thus our results will have global applications.

The three study regions indicated in Figure 2-1 are chosen because:

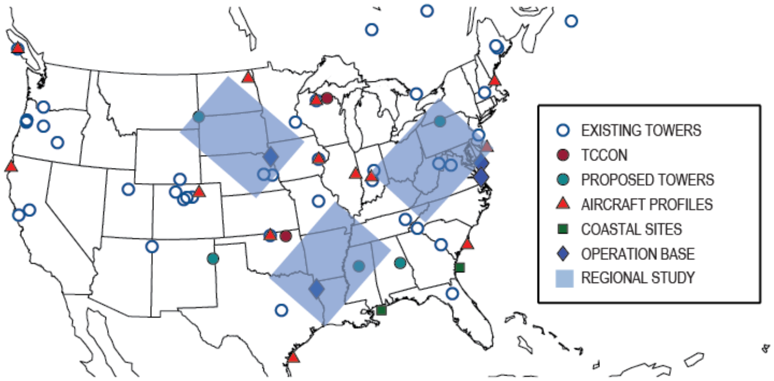


Figure 2-1. *Sustained airborne and tower-based measurements will be focused over three regional CO_2 and CH_4 source/sink regions in the U.S. The campaign will build upon and improve the utility of our nation's existing investment in long-term C observations, noted on the figure. The study areas are identified with a box that has the dimensions of the proposed fair weather flight pattern.*

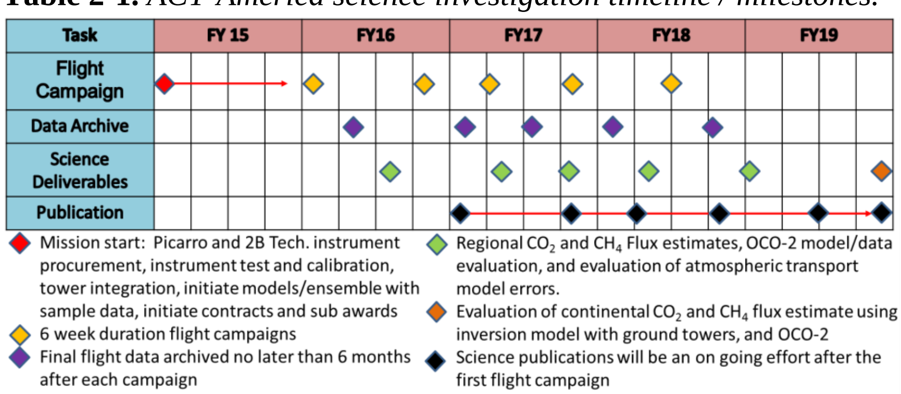
- The U.S. east of the Rockies is the dominant North American biogenic source/sink region for CO_2 (Huntzinger *et al.*, 2012) and is a major source region for biogenic and anthropogenic CH_4 emissions (Miller *et al.* 2013; Allen *et al.*, 2013);
- The regions encompass a variety of biomes (Midwest agriculture, Northeast forests, Southeast coastal forests and agriculture) and oil and gas extraction zones (Bakken – midwest; Marcellus – northeast; Fayetteville/Haynesville – southeast);
- Each region is large enough to encompass the weather systems that are the target of the study, and the regions encompass a broad range of mid-latitude weather environments.

Colocation of the mission with the world's most extensive, long-term C observational network maximizes the data density available for the difficult task of deconvolving flux and transport errors in our model ensemble. Our campaign's observations will be complemented by (Figure 2-1): 1) the NOAA aircraft GHG profiling network, 2) NOAA and collaborators' tower- and mooring-based, continuous in situ GHG network, 3) two TCCON sites, and 4) satellite GHG observations from both Greenhouse Gases Observing Satellite (GOSAT) (if still operating) and OCO-2 (July 2014 launch).

2.2 Investigation Timeline

The ACT-America mission, which includes five, 6-week flight campaigns spread across 4 seasons and 3 years will provide robust and general understanding of regional C fluxes, atmospheric transport and OCO-2 measurement characteristics. An overview of the major science milestones is shown in Table 2-1. Progress towards our three goals and their associated objectives will be made with each flight campaign. The overall goal of improved continental atmospheric inversions with the long-term C measurement network

Table 2-1. *ACT-America science investigation timeline / milestones.*



will be achieved at the end of the mission as the findings regarding the three mission goals are integrated into a next-generation atmospheric inversion system. Progress towards goals throughout the mission will be documented via peer-reviewed publications.

First Year Preparations include the procurement, calibration, and installation of tower-based and airborne commercial off-the-shelf in situ instruments, drafting aircraft flight plans and securing necessary permission within the 3 flight regions, and preparing and optimizing the airborne remote sensors for multi-year deployment. The ensemble modeling system will be assembled, exchange of data among modeling systems will be tested, and platforms for model-model and model-data comparison and assimilation will be constructed.

Airborne Campaigns - Years 2-4: We propose to conduct five airborne field campaigns, scheduled for the fall of 2015 (FY 16), summer of 2016 (FY 16), winter of 2016 (FY 17), summer of 2017 (FY 17), and spring of 2018 (FY 18), covering all four seasons and with redundant sampling of the most active biological season, summer. Each campaign will consist of deployments for 2 weeks to each of the three study regions. Four science flights are scheduled for each regional deployment, allowing for approximately two fair and two stormy-weather flights per region. Two OCO-2 underflights will be conducted during each campaign. The mission will thus include a total of approximately 30 fair-weather flights, 30 stormy-weather flights, and 10 OCO-2 underpass flights. This measurement density achieves the repeated realizations of flux and weather conditions required by the investigation requirements.

Final Year will focus on integration of the findings from goals 1-3 to improve continental-scale atmospheric inversions of C fluxes over North America for the past decade. <u>Hardware disposition and close-out plan</u>: All capital gain equipment purchased (Picarro and 2B Technologies instruments) will be returned to NASA Langley. Data archives will be finalized (section 2.7) and a final report will be issued.

2.3 Aircraft and Ground-Based Instruments

ACT-America will deploy a comprehensive suite of high-quality, field-tested trace gas and meteorological instruments that exceed mission requirements. A mix of remote and in situ instruments enables extensive spatial coverage of key atmospheric variables (Table 2-2).

The primary measurement requirements (Table 1-1) are for spatially comprehensive, high accuracy and precision measurement of CO_2 and CH_4. Three measurement technologies, the Multifunctional Fiber Laser Lidar (MFLL) active column CO_2 and range sensor (Dobler *et al.*, 2013), Picarro G2401-m cavity ring-down spectrometer (CRDS) for CO_2, CH_4, CO, and H_2O dry air mole fraction (Karion *et al.*, 2013b), and NOAA Carbon Cycle Greenhouse Gases group (CCGG) programmable flask packages (which provide analyses of 55 different trace gases including CO_2 and CH_4; Karion *et al.*, 2013b) are chosen.

The MFLL provides high-fidelity retrievals of column CO_2 number density and range between the airborne platform and the ground in cloud-free regions (Dobler *et al.* 2013; Lin *et al.* 2013). Flown in the lower FT, this instrument provides a unique capacity to map variability incolumn CO_2 number density through the ABL and lower FT. The column remote sensing capability of the MFLL is required to achieve the spatial sampling called for in Table 1-1. MFLL column integrated CO_2 number densities will be compared to the numerical models of tropospheric CO_2 and to OCO-2 column integrated CO_2 number density observations. As a result, column integrated oxygen measurements, which are typically used to infer the surface pressure needed to calculate the column-integrated CO_2 mole fraction (XCO_2) are not required for this mission. The portion of the CO_2 column above 8km not measured by the MFLL will be estimated using our inversion models. The surface elevation will be found using precise ranging from the MFLL altimeter accounting for the aircraft's position combined with a high resolution digital elevation map. The MFLL total column XCO_2 can also be constructed using the MFLL partial column number density measurement from 8 km, an aircraft pressure measurement, model reanalyses of surface pressure, precise ranging from the MFLL altimeter and a digital elevation map.

In situ meteorological instruments provided by the P-3B aircraft will be similar to what is currently flown on the P-3B for the EVS-1 mission Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality (Discover-AQ). We will also fly the High Spectral Resolution Lidar (HSRL, Hair *et al.*, 2008) on the same platform as the MFLL to obtain continuous measurements of ABL depths and aerosol distributions. Measurements of trace gases associated with either CO2 and CH4 sources or sinks or with atmospheric airmass origins and transport histories are beneficial to our first two goals. We include measurements of carbon monoxide (CO - combustion tracer), water vapor (H_2O - ABL tracer), ozone (O_3 - stratospheric and polluted air tracer), carbonyl sulfide (COS - marker for photosynthesis) and $^{14}CO_2$ (fossil fuel tracer) using Picarro, 2B Technologies (Bertschi *et al.*, 2004), and NOAA flask instruments. Our tower platforms will utilize the Picarro G2301 CRDS for CO_2 and CH_4 measurements. The Master Equipment List (section 6.1) provides more details concerning instrumentation. Calibration methods and procedures are described in section 3.5.1.

Table 2-2. *Instrumentation proposed for ACT-America. Instrument requirements are described in Table 1-1. Instrument accuracy, precision and calibration details are given in sections 3.3 and 3.5.1, and Table 3-2.*

Instrument (Platform)	Variables Measured	Sampling Frequency	Data Latency (Archiving)[1]	Purpose of measurement
MFLL (P-3B)	Column CO_2 number density, altimetry, surface reflectance	10 Hz	1 day (≤6 months)	Core GHG CO_2 measurement & ranging capability
HSRL (P-3B)	ABL height, aerosol distribution	2 Hz, 30m vertical resolution	1 day (≤4 months)	Transport model constraint, OCO-2 validation
Picarro Air (P-3B & UC-12)	CO_2, CH_4, CO, H_2O mole fraction	1 Hz	1 day (≤4 months)	Core GHG measurements, combustion & airmass tracer
2-B Tech. (P-3B & UC-12)	O_3 mole fraction	1 Hz	1 day (≤4months)	Airmass tracer
Atm. state and nav. (P-3B)	GPS Lat.-Lon, Wind speed, direction, Press., Temp.	1 Hz or higher	1 day (≤6 months)	Evaluate atmospheric transport models
Atm. State and nav. (UC-12)	GPS Lat. and Lon., Pressure, Temperature	1 Hz or higher	1 day (≤6 months)	Evaluate atmospheric transport models
Flasks (P-3B & UC-12)	Multiple trace gases. See table 3-2	12 flasks / aircraft / flight	1 month (≤6 months)	Core GHG measurements, GHG source tracers.
Picarro Ground	CO_2, CH_4, H_2O mole fraction	1 Hz	1 day (≤6 months)	Core GHG measurements.

[1]Data latency is considered to be the time between when the observations were made and when the initial level 1 data is reported to the archive to check for instrument health and measurement integrity. Archiving is considered to be the time required for final archiving of level 2 data after the end of each field deployment.

2.4 Investigation Platforms

ACT-America will deploy two highly reliable airborne platforms that together provide spatial and temporal sampling capabilities that meet the rigorous mission investigation requirements. The science requirements for our first two goals include spatially comprehensive measurements spanning a significant fraction of the area of high- and low-pressure systems and encompassing C source/sink regions, with measurements within and above the well-mixed (daytime) ABL. Two aircraft are needed to cover domains of hundreds of kilometers at multiple altitudes within the hours (roughly 10-18 Local Standard Time) when the ABL is well mixed. Two aircraft also benefit goal 3 by providing both partial column CO_2 data and in situ ABL measurements that will enhance our ability to identify sources of column CO_2 variability.

The airborne platforms selected for the ACT-America mission are the NASA Wallops P-3B and NASA Langley UC-12**.** The P-3B is selected as the remote sensing and in situ measurement platform because of its endurance (> 8 hours), thus ability to fly within and above the ABL, and payload capacity, thus ability to host remote and in situ instruments. The UC-12 is selected for in situ measurements. The NASA P-3B and UC-12 aircraft will field nearly identical in situ instrument suites, as noted in Table 2-2. Tower-based instruments will be deployed on communications towers (Richardson *et al.*, 2012b).

2.5 Flight Plans

Data from the **fair-weather flights** are intended to quantify regional CO_2 and CH_4 fluxes (goal 2), and to evaluate fair weather atmospheric C transport processes (goal 1). The flight pattern (Figure 2-2) is designed to provide extensive sampling of the ABL and lower FT in source/sink regions, meeting the requirements for the fair weather investigation (Table 1-1, Section 1.2.1).The P-3B aircraft will fly a U-shape pattern with flight legs perpendicular to the wind, sampling FT and ABL properties downwind of the sources and sinks of C. The P-3B will fly at roughly two times the midday ABL depth, (~3-4 km above ground level (AGL)) with periodic descents and ascents (5 to 10 times in a 6-8-hr flight) to sample the ABL. Although clear sky conditions will be targeted, the P-3B will conduct more profiling if low-altitude clouds interfere with the remote sensors. The UC-12 aircraft will partake in two flights per day and will sample a subset of the P-3B flight path focusing on long transects in the ABL with periodic ascents to the FT. A nominal flight plan is shown in Figure 2-2. The time stamps denote the transit time between waypoints. The level of complexity of the fair-weather flights is low as the flight patterns are simple geometric shapes whose waypoints and exact dimensions can be moved to adapt to weather and air traffic. The two aircraft will operate over the same time period, but precise coordination is not required.

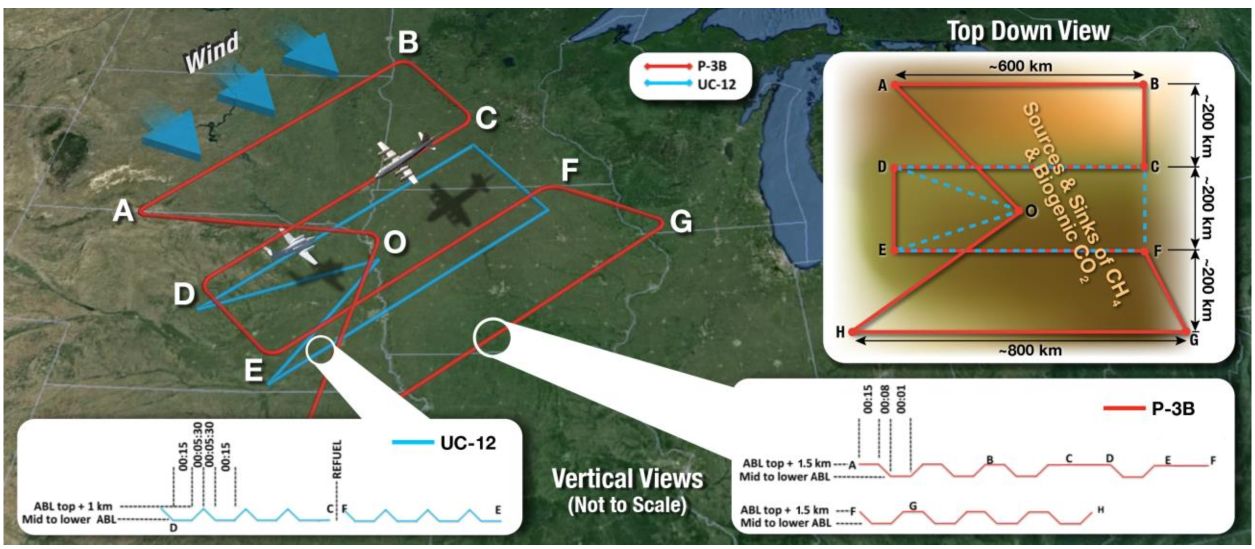


Figure 2-2. *Fair-weather flights will provide data needed to determine regional CO_2 and CH_4 sources and sinks (goal 2) and evaluate fair weather atmospheric transport (goal 1). Each flight will provide extensive sampling of ABL and FT C mole fractions and meteorological conditions in the vicinity of regional C sources and sinks. Precise flight dimensions will be adapted to weather conditions and C source and sink distributions in each region.*

Data from **stormy-weather flights** will be used in combination with the data from fair-weather flights to evaluate the transport of C in the mid-latitudes (goal 1). The flight plans (Figure 2-3)include flight legs parallel to and crossing frontal boundaries at two or more altitudes, and crossing the frontal zone at two or more locations, meeting the requirements for the stormy-weather investigation (Table 1-1, Section 1.2.2).

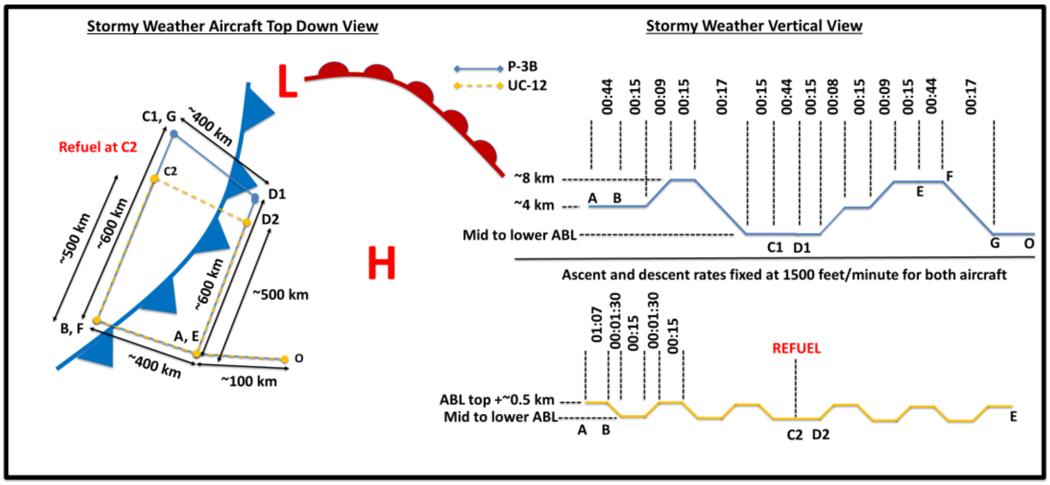


Figure 2-3. *Stormy-weather flights will be used to evaluate and improve modeled atmospheric transport of CO_2 and CH_4 by mid-latitude cyclones. Flight plans will sample CO_2, CH_4, meteorological variables and trace gases across frontal structures responsible for transport of GHGs. Flights may cover both cold and warm fronts if allowed by storm location and structure.*

The two aircraft will navigate in a structured, but not highly restrictive flight pattern around frontal structures using onboard navigation tools and, guidance on weather and aircraft hazard from air traffic control as well as from meteorologists and the project scientist/staff at the aircraft base location. The science goals do not require precise waypoints and altitudes; these can be adjusted during flight. The P-3B will focus on the upper altitudes using in situ instruments and, when cloud cover allows, remote sensing. The UC-12 will sample a subset of the P-3B flight track and focus on level legs within the ABL with periodic profiling to the FT. The two aircraft will operate in the same time window, but precise coordination is not required. These flights will avoid convective cores, eliminating substantial flight risks.

The pattern for the **OCO-2 inter-comparison flights** (Figure 2-4) is designed to obtain data to evaluate the degree to which OCO-2 column CO_2 measurements capture true spatial variability in column CO_2 content over the continents. Two OCO-2 underflights will be conducted during each campaign and will be selected to cover varying surface reflectance, topography, and aerosol and cloud cover, all possible sources of bias in the OCO-2 measurements. The P-3B flights will be 1000 km in length and flown at 8 km (28 kft) altitude to maximize the fraction of the atmospheric column sampled by the MFLL. The UC-12 aircraft will sample a shorter (~360 km) leg in the ABL, often the largest source of variability in column CO_2.The UC-12 flight will be centered with the P-3B and both aircraft will be vertically stacked during the OCO-2 overpass. Suitable OCO-2 ground tracks are abundant, since the satellite tracks are approximately N-S lines spaced every 120 km (though not sampled sequentially). The resulting airborne measurement of column integrated CO_2 number density up to 8 km will be combined with ACT-America reanalyses of atmospheric CO_2 above 8 km and compared to OCO-2 column CO_2 estimates at 2.25 km resolution, satisfying the requirements for goal 3 (Table 1-1, Section 1.2.3).

Science data summary. The mission proposed yields 70 science flights per aircraft, 528 hours for the P-3B and 396 hours for the UC-12, dedicated in a roughly 3:3:1 ratio across the 3 flight patterns. The amount of high-quality lower FT C data would exceed any past campaign by a factor of 2-3. A total of approximately 23 Terabytes of airborne- and ground-based data will be collected. These instruments, flight hours and plans satisfy the investigation requirements for the baseline science objectives. The threshold science objectives can be met while eliminating the one redundant summer campaign and the OCO-2 flights. HSRL, the ozone sensor, and some flask sampling can also be de-scoped without sacrificing the threshold science objectives.

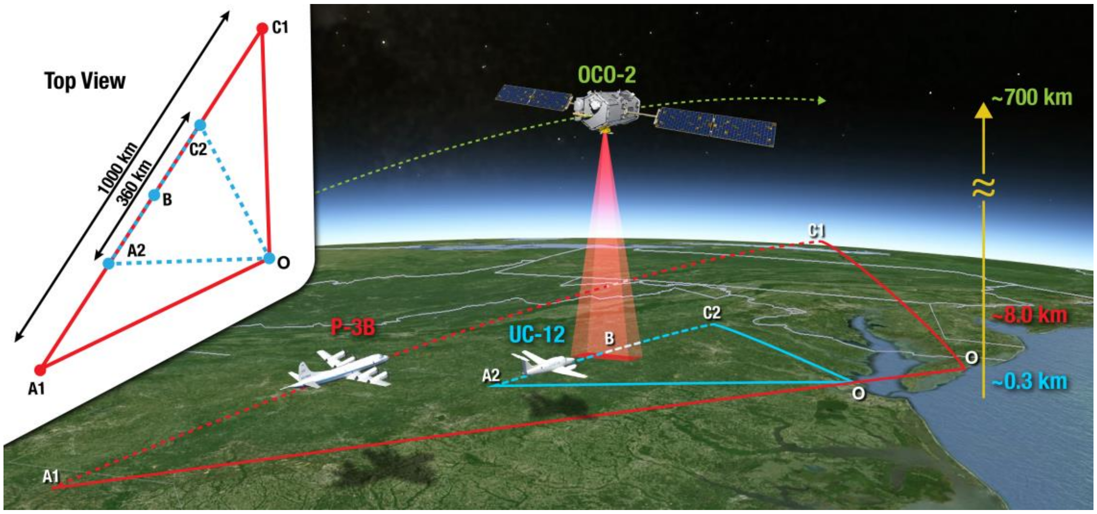


Figure 2-4. *Underflights of OCO-2 will provide high-precision, high-spatial-resolution measurements of the majority of the atmospheric CO_2 column. These data will be used to evaluate OCO-2 measurements of high-resolution spatial structure in column CO_2 over continental surfaces.*

2.6 Numerical Modeling and Model-Data Syntheses

ACT-America brings together 1) flux and transport models to make ensemble predictions of CO_2 and CH_4 mole fractions to compare to mission observations, and 2) inverse modeling systems needed to infer regional C fluxes using atmospheric C observations.

The Penn State regional inversion and ensemble modeling system (Lauvaux *et al.*, 2012a; Diaz *et al.*, 2013; Normile *et al.*, 2013) is the centerpiece of our analysis system. It will be used for regional inversions using aircraft data (goal 2), to create atmospheric C ensemble predictions required for model evaluation (goal 1), to provide CO_2 reanalyses in the upper troposphere (goal 3) and to integrate mission progress on all three goals into a next-generation North American inversion (overarching goal). This system utilizes the Weather Research and Forecast model (WRF**,** Skamarock and Klemp, 2008) for atmospheric transport, the Lagrangian Particle Dispersion Model (LPDM; Uliasz, 1994) for computing influence functions, and a Bayesian inversion framework for optimizing fluxes (Lauvaux *et al.* 2012a). This system will be run in forward (ensemble atmospheric C predictions) and inverse (solve for C sources and sinks) modes. The WRF model will be 1) implemented with a wide variety of land-surface, cloud physics, cloud convection, and planetary boundary layer schemes to create model physics ensembles (Diaz *et al.*, 2013); 2) run at multiple spatial resolutions from cloud-resolving up to the scale of global inversion systems, and 3) run with different meteorological initial and boundary conditions to create transport ensembles. Data assimilation algorithms (Rogers *et al.*, 2013) will use operational (goals 1, 2 and 3) and ACT-America airborne meteorological data (goals 2, 3) to improve transport fidelity.

The Penn State regional system requires surface C fluxes and atmospheric C boundary and initial conditions, both of which will also be varied in ensemble fashion. The Penn State system has already been coupled to output from two of the three global inversion systems participating in this project and all of the surface flux algorithms. The flux model ensembles, C boundary condition ensembles (from global inversions) and transport ensemble will be combined (Figure 1-3) to create atmospheric C mole fraction ensembles, which include the ability to track C sources (e.g., fossil vs. biogenic CO_2).

Biogeochemical and emissions inventory models. The Carnegie-Ames-Stanford Approach-Global Fire Emissions Database (CASA-GFED) is our source for biogenic CO_2 flux ensembles. CASA-GFED includes physiological processes involved with uptake of CO_2 by photosynthesis and the release of CO_2 through respiration and fires (Randerson *et al.*, 1996; van der Werf *et al.*, 2006; 2010). An ensemble will be constructed by varying model parameters. Vulcan (Gurney *et al.*, 2009), the satellite-derived Open-source Data Inventory for Anthropogenic CO_2 (ODIAC) product (Oda *et al.*, 2011) and the Carbon Dioxide Information Analysis Center (CDIAC) inventory will provide CO_2 fossil fuel emissions estimates. Emission Database for Global Atmospheric Research (EDGAR) will provide CO_2 and CH_4 emissions estimates.

Global carbon inversion systems. This project utilizes four global inversion systems, each of which includes its own flux and atmospheric transport models and performs an inversion using atmospheric C mole fraction observations to optimize fluxes. These systems provide a comparison to our regional transport modeling (goal 1), provide boundary conditions for our regional analyses (goals 1 and 2), and provide upper atmospheric column CO_2 estimates needed to complete our OCO-2 evaluation (goal 3). These four systems are 1) Carbon Tracker CO_2 (Peters, *et al.*, 2007), 2) Carbon Tracker CH_4 (Bruhwiler *et al.*, submitted), 3) the NASA Carbon Monitoring System (CMS) flux pilot product (Liu *et al.* 2013), and 4) the Colorado State/ Parameterized Chemistry Transport Model (PCTM) 4DVar system (Baker *et al.*, 2006b 2010). These systems span the state of the science, use both remote and in situ C observations, and include the primary quasi-operational systems in the U.S.

The project will also test an alternative inversion approach, the regional Geostatistical Inverse Model (GIM) system (e.g., Miller *et al.*, 2013) and alternative meteorological simulations via the U. Oklahoma "Spring Project" and the Colorado State University "super-parameterization" Community Earth System Model.

2.7 Data Management

The ACT-America Data Management Plan (DMP) will be modeled after the Langley led and managed EVS-1 DISCOVER-AQ DMP. The ACT-America DMP will ensure easy data exchange between science team members and provide timely data access to the public. Observational data will be released within 6 months of each field campaign; model-data syntheses will be released within 1 year.

Data generation: Instrument scientists will generate raw (level 0) data, analyzed/calibrated (level 1) data, and derived (level 2) data. Modeling Co-Investigators (Co-Is) will generate model input and output (level 3) data addressing all of the mission goals.

Data format and metadata requirements: ACT-America in-situ measurements shall be delivered in the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT) format and remote sensing observations can be provided in either HDF-5 or ICARTT format. Model results will be provided in netCDF 4 format. ACT-America metadata will meet the NASA Distributed Active Archive Center (DAAC) collection level and granule level metadata format requirements. Instrument scientists will provide sufficient metadata to describe the measurement quantities, uncertainties, and technique for each instrument. Modeling Co-Is will provide a description of their modeling tools and output.

Data repository and distribution: During the project life cycle, (1) ACT-America measurement data will reside on the data repository maintained by the Airborne Science Data for Atmospheric Composition group (ASD-AC) at NASA Langley Research Center. This group has over 20 years of experience in managing airborne science data including the DISCOVER-AQ, Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys. (SEAC4RS), and Deep Convection Clouds & Chemistry (DC3) tropospheric chemistry and air quality studies. Preliminary level 1 data are due 24 hours after each flight and the final derived data are due no later than 6 months after each deployment. The ASD-AC staff will generate merged data products to facilitate data processing and analysis. (2) ACT-America tower data, modeling inputs (prior fluxes and boundary conditions), and modeling results will be stored at Oak Ridge National Labs (ORNL). The ORNL team will facilitate the sharing of model data among science team members.

Post-mission stewardship and access: ACT-America final data will be transferred to an assigned DAAC for post-mission stewardship and public access. The ASD-AC staff will be responsible for the transfer process of the instrument data, whereas the ORNL team will be responsible for the model data products. Specific activities will include preparation of the collection level and granule level metadata files and coordination with DAAC staff for the physical transfer of the data and release to the public.

2.8 Science Team

The science team (Table 2-3) includes carbon cycle and instrument scientists, and data and mission management experts, many of whom share long-term, collaborative work relationships, guaranteeing a closely-knit team able to produce groundbreaking research results.

Table 2-3. *Scientific roles and responsibilities for ACT-America science team members. Many of the team members' contributions fit multiple categories. Their full contributions and expertise are listed in their respective statements of work and biographical sketches. Science team activities are supported in Work Breakdown Structure (WBS) element 4 unless noted otherwise.*

Science Team Member	Roles/Responsibilities	Expertise
	Leadership	
[1]Kenneth Davis, Penn State	Principal Investigator	Carbon cycle science, flux measurement methods, boundary layer meteorology
Syed Ismail, NASA LaRC	Project Scientist	Development and deployment of lidar remote sensing systems
	Instrument scientists	
[4]Amin Nehrir, NASA LaRC	P-3B instrument lead	Development and deployment of trace gas laser remote sensing technologies for tropospheric chemistry and carbon cycle science.
[4]Michael Obland, NASA LaRC;	UC-12 instrument lead	Instrument operator, project scientist, or principal investigator in 15 airborne measurement campaigns
[5]Chris Hostetler, NASA LaRC	HSRL lead	Lidar remote sensing of atmospheric aerosols
[5]Jeremy Dobler, Exelis Inc.	MFLL lead	Active and passive remote sensing development, field and airborne deployment. MFLL Chief Scientist.
[5]Melissa Yang, NASA LaRC	Picarro/O_3 measurements lead, flask operation	Extensive experience in CO_2 measurements with DISCOVER-AQ, SEAC4RS and ASCENDS.
[5]John Barrick, NASA LaRC	UC-12 navigation and meteorological measurements lead	Over 20 years of development and deployment of aircraft navigational and in situ meteorological measurements.
[5]Natasha Miles, Penn State	Tower measurement lead	Deployment, operation and analysis of highly-calibrated, automated, CO_2/CH_4 measurements
	Global Atmospheric and Inversion Modeling Co-Is	
[1]David Baker, Colorado State	CO_2 global inversions with in situ and satellite C data,	Variational C data assimilation, transport error analyses, application of satellite C observations
Lori Bruhwiler, NOAA ESRL	CH_4 global inversions	Lead scientist for Carbon Tracker – CH_4
[1]Andrew Jacobson, U. Colorado	CO_2 global inversions with in situ C data	Lead scientist for Carbon Tracker – CO_2
Pieter Tans, NOAA ESRL	Model-data syntheses	Lead of NOAA's global carbon cycle group, climate change forcing
Kevin Bowman, NASA JPL	CO_2 global inversions with satellite C data	Lead scientist for JPL's NASA Carbon Monitoring System Flux Pilot study
	Regional Atmospheric and Inversion Modeling Co-Is	
Thomas Lauvaux, Penn State	Regional C inversions, ensembles and analyses	Developer of the Penn State regional inversion and ensemble modeling system, regional inversions
Berrien Moore, U. Oklahoma	Alternative mesoscale transport model ensemble	C cycle remote sensing systems, investigator for the "spring project" model ensemble, climate policy and outreach
A. Scott Denning, Colorado State	Storm-scale transport analyses	Global and regional atmospheric modeling, transport error analyses, carbon cycle science
[1]Anna Michalak, Carnegie	Geostatistical inversions of aircraft	Geostatistical atmospheric inversions, statistical methods, in situ and

Institute of Science	observations	satellite data analyses
	Ecosystem Carbon Modeling Co-I	
Jim Collatz, NASA Goddard	CASA-GFED ensembles	Terrestrial carbon cycle modeling, CASA developer
	Aircraft Observational Studies Co-Is	
Anna Karion, U. Colorado	Flask analyses	Airborne CH_4 and CO_2 mass balance analyses, airborne instruments
Gabrielle Petron, U. Colorado	CH_4 and trace gas analyses	CH_4 regional inversions and trace gas studies
Joseph Berry, Carnegie Institute of Science	Atmospheric transport analyses with COS	Terrestrial ecology, carbon cycle science, COS as a tracer of photosynthesis
[1]John Miller, U. of Colorado	$^{14}CO_2$ data analyses	Fossil C emissions, ^{14}C analysis methods, isotopic studies
	OCO-2 evaluation Co-Is	
[1,2]Chris O'Dell, Colorado State	OCO-2 data lead	Retrieval of CO_2 with near-IR spectroscopic observations, OCO-2 data
Bing Lin, NASA LaRC	Aerosol, cloud and surface reflectance measurements	Atmospheric radiative transfer, global energy budget, satellite and airborne remote sensing, climate change and variability
Edward Browell, NASA LaRC	MFLL — OCO-2 comparisons	Lidar remote sensing, airborne field campaigns, atmospheric sciences, model-measurement comparisons
	Data Management Co-Is	
[3]Gao Chen, NASA LaRC	Airborne data manager	Atmospheric composition, airborne data systems.
Robert Cook, Oak Ridge National Laboratory	Model documentation and data manager	Model-data synthesis, carbon cycle science, data management methods

[1]OCO-2 science team member, [2]OCO-2 CO_2 retrieval development lead, [3]Discover-AQ data manger, [4]WBS 7, [5]WBS 5.

3 Investigation Implementation

ACT-America implements technologically mature, high-performance science instruments on proven aircraft platforms and gathers coordinated data from aircraft, ground, and satellite sensors to enable mission goals to be achieved. The appropriate expertise is in place within the ACT-America team to implement the operations and logistics, calibration and validation, investigation assurance, and carbon cycle science activities necessary to meet all ACT-America mission objectives.

3.1 Measurement Platform System Capabilities

The NASA P-3B and UC-12 aircraft, used to gather suborbital data for the ACT-America mission, exceed all performance characteristics required to execute the ACT-America science campaigns. The ACT-America mission requires both airborne and ground measurements, including 1) remote measurements of column CO_2 number densities from various altitudes and meteorological conditions, 2) in situ measurements of CO_2, CH_4, trace gases and meteorological variables in the Atmospheric Boundary Layer (ABL) and free troposphere (FT), and 3) in situ measurements of CO_2, CH_4, and H_2O collected 100 m above ground level (AGL) or higher from towers. The airborne platform functional requirements, which are determined from the Science Traceability Matrix (STM), are met by using the NASA P-3B and UC-12 aircraft, whose operating and performance characteristics are shown in Table 3-1. The ground requirements are met by using instrumented towers described in Section 3.3.3. Both the UC-12 and the P-3B have the capacity to carry their respective payloads (Figure 3-1 and Table 3-2) with weight margins >20%. Both NASA aircraft are extremely reliable, having been utilized in many other flight campaigns with similar flight profile requirements, most recently the Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) mission, and also require no modification to accommodate the science measurement instrument suite. ACT-America can use either the NASA Langley UC-12 or B-200 aircraft for the flight campaigns since these aircraft are identical with regards to instrument integration, operations, and their ability to complete the ACT science objectives. The capability to utilize either aircraft significantly reduces the risk of not having an aircraft available due to maintenance or other unforeseen conflicts. The backup aircraft for the P-3B is the NASA C-130 aircraft, which likewise has the capabilities to fulfill the role of the P-3B if needed.

Table 3-1. *The NASA P-3B and UC-12 aircraft have the appropriate characteristics and margins required to execute successfully the ACT-America mission.*

Aircraft	NASA Center[1]	Effective Duration (Hours)	Max Altitude (Feet)	Airspeed (Knots)	Allowable Payload Weight (Lbs)	ACT Payload Weight[2] (Lbs)	Weight Margin[3]	Allowable Payload Power (Watts)	ACT Payload Power (Watts)	Power Margin[3]
P-3B	WFF	9	28000	330	14478	4888	63%	89800	4142.9	95%
UC-12	LaRC	3	28000	260	1100	770	23%	4200	671	82%

[1]WFF = Wallops Flight Facility, Wallops Island, Virginia; LaRC = Langley Research Center, Hampton, Virginia

[2]Payload weights include the weight of all ACT instruments, instrument racks, peripheral equipment, and all crew including researchers, pilots, and flight crew. See the Master Equipment List in the appendices, for individual instrument mass and power. Aircraft characteristics can be found at http://airbornescience.nasa.gov.

[3]Margin = [AC Capability - (Payload Current Best Estimate) (1 + Uncertainty)]/AC Capability. Uncertainty = 10% due to the extensive flight history and high TRL of all ACT-American instruments.

3.2 Logistics

The ACT-America team leverages extensive experience from decades of aircraft measurement campaigns, including the recent Langley-managed DISCOVER-AQ Earth Venture mission that similarly uses the P-3B and UC-12 aircraft. Each of the five ACT-America flight campaigns consists of measurements in three regions: the Northeast with bases at NASA Wallops Flight Facility (the home of the P-3B) and NASA Langley Research Center (the home of the UC-12 and B-200), the Midwest basing out of Sioux City, Iowa, and the South basing out of Shreveport, Louisiana. Utilizing the home airfields for one of the regions reduces ACT travel costs, risks, and logistical efforts. Sioux City and Shreveport have all the necessary maintenance facilities required to operate successfully the P-3B and UC-12 while deployed, including fuel, hangar space, and runway length, and both locations were vetted and selected by the P-3B and UC-12 Aircraft Managers at NASA Wallops and NASA Langley. While basing out of the NASA centers, both aircraft will have access to their full complements of maintenance personnel, consumables, and spares. While deployed to the other two regions, the streamlined deployment team nominally consists of the Logistics Officer, Principal Investigator (PI), Project Scientist (PS), Instrument Scientists, and a minimum number of scientists and technicians traveling with the aircraft. Critical consumables and spares are deployed with each aircraft and other spares and equipment are shipped to each location via ground transportation. The ACT-America team spends about 2 weeks in each region, performing four to five science flights in that time, allowing for flexibility in coordinating flight schedules with the weather systems moving through each region. Daily teleconferences are held with the ACT-America science team and with mission meteorologists to plan, execute, and discuss the results of each science flight. Internet connections and office space are procured at each deployment location so that preliminary field data can be processed, uploaded to servers at the Langley Atmospheric Sciences Data Center (ASDC), and provided the next day to the field flight planning team.

3.3 Instrumentation

The instruments selected for the ACT-America mission have proven measurement accuracy, precision, and heritage exceeding the requirements needed to achieve the ACT science goals. The P-3B payload includes two remote sensing instruments: the Multi-Functional Fiber Laser Lidar (MFLL, Dobler *et al.* 2013), a Laser Absorption Spectrometer (LAS) for measuring CO_2 column number density weighted to the near surface atmosphere as well as range to the surface and surface reflectance, and the High Spectral Resolution Lidar (HSRL, Hair *et al.* 2008)), an aerosol backscatter lidar for measuring ABL depth and aerosol distributions (Table 3-2). The P-3B also carries a comprehensive suite of in situ sensors measuring CO_2, CH_4, carbon monoxide (CO), ozone (O_3), and H_2O (water), and flasks that measure CO_2 and CH_4 as well as GHG tracers, particularly CO, COS, and $^{14}CO_2$. The UC-12 has an identical suite of in situ sensors and flask sampling capability (Table 3-2). In situ sensor redundancy for CO_2, CH_4 and

CO on each aircraft provides the opportunity to evaluate in flight performance of the measurements. Both aircraft are also equipped to provide high accuracy and precision meteorological measurements. All instruments meet or exceed the precision and accuracy levels required by the STM over the requisite averaging scale. Most instruments exceed the STM requirements at their native resolutions, which are higher than those required by the STM.

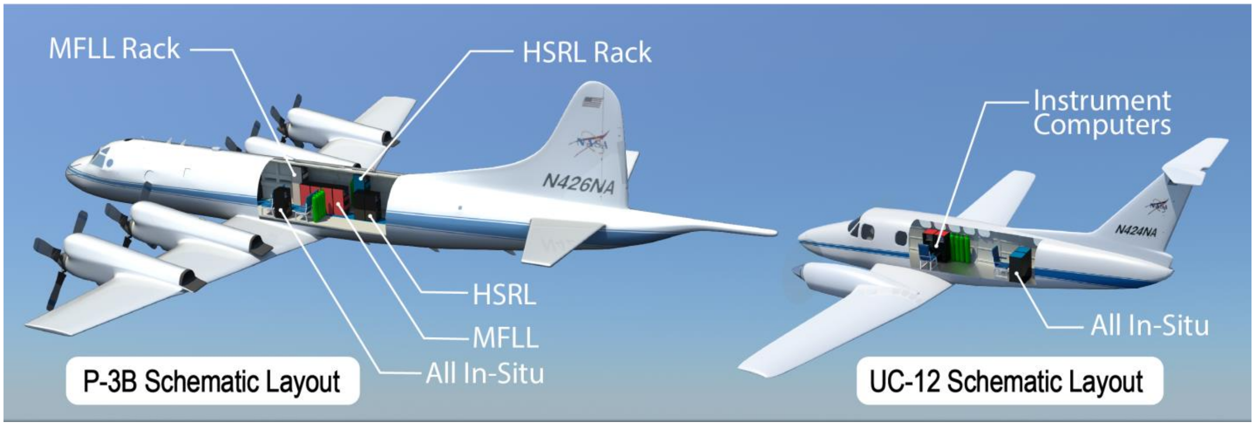


Figure 3-1. *The WFF P-3B aircraft and the LaRC UC-12 aircraft are the platforms for remote (P-3B) and* in situ *(P-3B and UC-12) science measurements. The two aircraft carry a suite of GHG and GHG tracer measurements that enable the ACT science objectives to be addressed. All instruments used in ACT are TRL 8 or higher and have flown on previous science campaigns.*

Table 3-2. *The ACT-America instruments provide the necessary measurements and measurement precisions required to achieve the mission objectives.*

Instrument	Platform	Technique	TRL	Species/ Parameter	Instrument Precision (Averaging Time)	STM Precision Requirement [over 20 km (~130 sec) unless otherwise noted]
MFLL	P-3B	LAS[1]	8	CO_2 Column Density[4]	≤0.08% (10 sec) ≤0.25% (1 sec)	0.1% 1% (0.2 km)
		Pseudorandom Number Altimetry		Range to ground	< 1m (0.1 sec)	5 m (0.2 km)
HSRL	P-3B	Pulsed Lidar	9	ABL Height[5]	≤ 100 m (10 sec)	100 m
Picarro G2401-m	P-3B, UC-12	CRDS[2]	9	CO_2	≤ 0.15 ppm (5 sec)	1 ppm
				CH_4	≤ 1 ppb (5 sec)	4 ppb
				CO	≤ 30 ppb (5 sec)	15 ppb
				H_2O	≤ 0.12 g/kg (5 sec)	0.5 g/kg
2B Technologies Model 205	P-3B, UC-12	Laser Spectrometer	9	O_3	1 ppb (10 sec)	8 ppb
Picarro G2301	Tower	CRDS[2]	9	CO_2	≤ 0.07 ppm (5 sec)	1 ppm hourly
				CH_4	≤ 0.5 ppb (5 sec)	4 ppb hourly
Flasks	P-3B, UC-12	GC/ MS[3]	9	CO_2, CH_4, CO, $^{14}CO_2$, COS	0.2 ppm CO_2;1 ppb CH_4; 2 per mil $^{14}CO_2$;2 ppt COS; (all 10 sec)	1 ppm CO_2; 4 ppb hourly CH_4; 2 per mil $^{14}CO_2$; 10 ppt COS
Environmental Parameters Suite	P-3B	INS[3]	9	Wind Speed and Direction	1 m/s; +/- 5 degrees (0.1 sec)	1 m/s; 5 degrees
	P-3B, UC-12	Various		Pressure	0.25 mbar (0.015 sec)	0.5 mbar
				Temperature	0.2 degrees Celsius (0.15 sec)	0.5 degrees Celsius

[1]LAS = Laser Absorption Spectroscopy; [2]CRDS = Cavity Ring-Down Spectroscopy; [3]GC/MC = Gas Chromatography/Mass Spectroscopy; [3]INS = Inertial Navigation System; Note that location, altitude, air speed, and aircraft pitch, roll, and yaw, are also provided and recorded by onboard aircraft systems. [4]MFLL also provides surface reflectance variability. [5]HSRL also

provides aerosol distribution variability. See the Master Equipment List in the appendices (6.1) for individual instrument mass and power.

3.3.1 Remote Sensing Instruments

MFLL: The MFLL, shown in the left hand side of Figure 3-2 during science flights on the NASA DC-8 aircraft, is a suite of Continuous-Wave (CW) lidar instruments consisting of: 1) an intensity modulated multi-frequency single-beam synchronous-detection Laser Absorption Spectrometer (LAS) operating at 1571 nm for measuring the column amount of CO_2 number density between the aircraft and the surface or to cloud tops, and surface reflectance, and 2) a Pseudo-random Noise (PN) altimeter at 1596 nm for measuring the path length from the aircraft to the scattering surface and/or cloud tops..

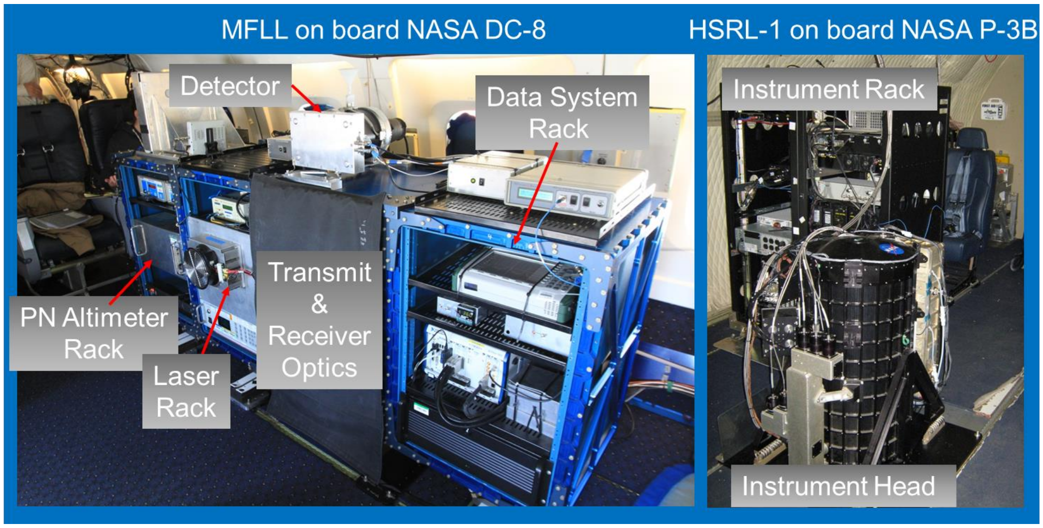


Figure 3-2. *Left: The ITT Exelis MFLL instrument, shown here as a full system integrated on the NASA DC-8 aircraft, remotely measures column densities of CO_2 and path length between the P-3B aircraft and the ground or cloud surface. Right: The HSRL, shown here integrated on the NASA P-3B aircraft, will provide measurements of the height of the atmospheric boundary layer. Both remote sensors have been flight-proven through multiple aircraft missions and are integrated on the NASA P-3B aircraft for ACT-America.*

The LAS instrument, developed by Exelis, Inc. (previously ITT Space Systems, LLC) in 2004 (Dobler, *et al.*, 2013, Lin, *et al.*, 2013, Dobbs *et al.*, 2007, 2008a), has been extensively evaluated in 1000+ hours of ground testing and in 13 multi-day flight campaigns conducted over a variety of meteorological conditions and surface types during both days and nights (Browell *et al.*, 2008, 2009, 2012). The LAS CO_2 column measurements have a precision of 0.08% for a 10-s horizontal average (~1.5 km on P-3B) over land and 0.18% over water. These precision values are equivalent to relative CO_2 mole fraction precisions of about 0.30 ppm and 0.72 ppm, respectively. Absolute comparisons of CO_2 remote and in situ measurements showed an absolute accuracy of 0.65 ppm of CO_2 (Dobler, *et al.*, 2013, Browell *et al.*, 2012), meeting the 1 ppm CO_2 accuracy requirement. Based on this extensive flight testing, the LAS instrument meets the CO_2 column measurement requirements of the mission and is considered to be at TRL-8.

HSRL: The NASA Langley Research Center airborne HSRL, shown on the right hand side of Figure 3-2, has been deployed in nearly 20 atmospheric measurement campaigns primarily to make accurate, calibrated measurements of cloud and aerosol properties in support of atmospheric composition, climate, and air quality studies (Hair *et al.*, 2008). The primary products of the LaRC HSRL are profile measurements of aerosol extinction (at 532 nm), backscatter (at 532 and 1064 nm), and depolarization (at 532 and 1064 nm) along its aircraft flight track. The primary product of HSRL for ACT-America is accurate measurements of the height of the ABL. Decades of research show that airborne lidar is a reliable approach for measuring ABL height (e.g., Melfi *et al.*, 1985; Davis *et al.*, 2000; Grabon *et al.*, 2010) and evaluating atmospheric models (Desai *et al.*, 2005; Reen *et al.*, 2006, 2013). Comparison of HSRL-derived ABL heights with ABL heights derived from a ceilometer and radiosondes indicate that the HSRL-derived ABL height meets the precision requirements of the STM (Scarino *et al.*, 2013). The NASA Langley HSRL is a mature airborne instrument that has previously flown on the P-3B and will provide proven measurements of ABL depth. In addition, changes in aerosol distribution will be used to interpret OCO-2 / MFLL comparisons.

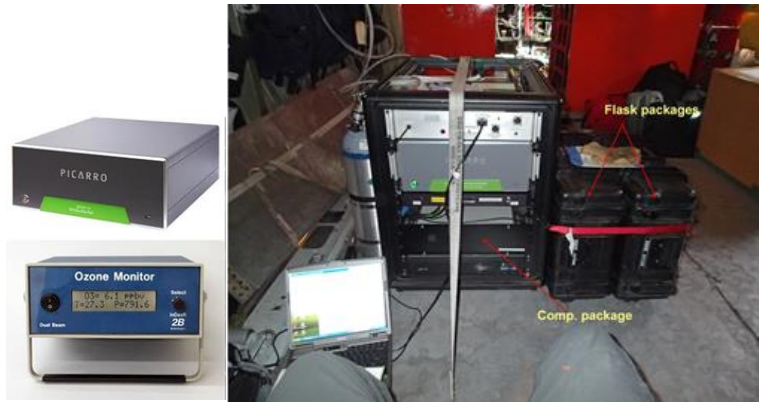


Figure 3-3. *Top Left: The Picarro analyzer, shown here integrated on the NASA DC-8 aircraft, will provide continuous measurements of CO, CO_2, CH_4, and H_2O mole fractions. Bottom Left: The 2B Technologies Model 205 continuously measures O_3. Right: The NOAA programmable flask packages, shown here integrated on the NOAA C-130 aircraft, will provide measurements of CO_2, CH_4, CO, isotopes of CO_2, and COS. All instruments meet the requirements of the ACT-America STM.*

3.3.2 Airborne In Situ *Instruments*

Picarro continuous CO_2/CH_4/H_2O/CO: The P-3B and UC-12 both have Picarro instruments, shown in Figure 3-3. The Picarro instruments have been extensively tested on aircraft flights (Karion *et al.*, 2013a, b; Mays *et al.*, 2009; Turnbull *et al.*, 2011).Picarro analyzers are based on Wavelength-Scanned Cavity Ring Down Spectroscopy (WS-CRDS), a time-based measurement utilizing a near-infrared laser to measure a spectral signature of molecular absorption. Gas flows through a 35 35-cc optical cavity with an effective path length of up to 20 km and pressure of 140 Torr. Extremely stable and high-precision measurements are achieved through cavity temperature, pressure, and wavelength laser frequency control to better than 0.002°C, 0.00003 atm and 1 MHz, respectively. Aircraft instruments are similar to surface-based sensors, but use faster flow rates, solid-state data storage, and additional vibration isolation. These instruments exceed the precision requirements of the STM for all four gases (Table 3-2, Karion et al., 2013a). Accuracies of 0.2 ppm for CO_2 and 2 ppb for CH_4 (Karion et al., 2013a) also exceed mission accuracy requirements of 1 ppm for CO_2 and 4 ppb for CH_4.

2B Technologies Continuous O_3: The Model 205 O_3 monitor, shown in Figure 3-3, uses two ultraviolet beams in two cells to simultaneously measure O_3-scrubbed air and unscrubbed air. This model has been approved by the Environmental Protection Agency as a Federal Equivalent Method (FEM) and is the fastest UV-based O_3 monitor available. The O_3 monitor has been previously flown on tropospheric chemistry field missions and meets the accuracy and precision requirements laid out in the STM (Bertschi et al. 2004).

Flask Measurement System: The NOAA Earth System Research Laboratory (ESRL) carbon cycle group has developed programmable flask packages (PFP) used in their aircraft network since 2003 and the tall tower measurement network since 2006 (Figure 3-3). The PFPs hold twelve 0.7-L silicate glass flasks that can be triggered manually or automatically at specific altitudes, times or locations. Measurements of CO_2, CH_4, CO and other trace gases are made on one of two nearly identical automated analytical systems; the same systems are used in the ESRL ground, tall tower, and aircraft networks (Conway *et al.*, 1994; Dlugokencky *et al.*, 1994; Novelli *et al.*, 1998). COS (and hydrocarbons and halocarbons) will be measured via Gas Chromatography/Mass Spectrometry measurements. PFP flask sample responses are calibrated against whole air working reference gases, which, in turn, are calibrated with respect to gravimetric primary standards. At selected times, duplicate flasks will be collected and analyzed for $^{14}CO_2$. Accuracy and precision for these measurements are 0.2 ppm for CO_2,2 ppb for CH_4 (Karion *et al.*, 2013a), 2 ppb for CO (Novelli et al., 1998) 2 ppt for COS (Montzka et al., 2007) and 2 per mil for $^{14}CO_2$, matching or exceeding the STM accuracy and precision requirements.

Environmental Parameters Suite: Water vapor, pressure, and ambient temperature are measured on both aircraft. Wind direction and speed will be measured on the P-3B only. Water vapor will be measured using a 3-stage chilled mirror hygrometer to make dew/frost point measurements with an accuracy of 0.2°C. Ambient temperature will be derived using a Rosemount non-deiced model 102 total air temperature probe with a precision of 0.2°C. Horizontal and vertical winds on board the P-3B are calculated from high precision pressure transducers and aircraft position and attitude data generated by Honeywell inertial navigation positioning systems. Wind speed direction will be measured to within 5 degrees while horizontal winds will have an accuracy of ±1 m/s. Both measurements are made at 10-Hz intervals.

3.3.3 Surface Measurements

ACT-America will install five Picarro CO_2/CH_4/H_2O instruments on existing communications towers, filling gaps that exist in or near our three study regions in the existing tower network (Figure2-1). Specific sites will be selected in science-critical locations based on tall tower and local Ethernet or cell phone data connection availability. Data will be collected at 100 m AGL or higher. Daily, automated data transfer to the Langley Atmospheric Science Data Center will allow remote monitoring of instrument status and investigation planning. The tower-based investigators continuously operated five similar tower installations in the Midwest from 2007-2009 (Richardson *et al.*, 2012b; Miles *et al.*, 2012) and are currently operating 12 such installations around the city of Indianapolis (Miles *et al.*, 2013). Additional measurements that will be used in this study include NOAA moorings along the East and Gulf coasts, the Total Carbon Column Observing Network (TCCON) sites at Park Falls, Wisconsin (WLEF) and the Department of Energy-Atmospheric Radiation Measurement (DOE-ARM) Central Facility, OK sites, and the NOAA Aircraft (biweekly vertical profiles) and Tall Tower networks. These data are all accessible to the public. ACT-America investigators have extensive background working with these networks and the responsible investigators and programs.

3.4 Instrument Development Approach

No instrument development is required for the ACT-America mission. All instruments necessary to accomplish the ACT-America baseline and threshold science requirements are currently at or above TRL-8 (Table 3-2) and have extensive flight heritage. Costs for appropriate spare parts are included for each instrument in the ACT-America budget.

3.5 Calibration/Validation, Safety and Investigation Assurance

Before each ACT-America flight campaign, we establish that each element of the mission is performing at or above the level of performance required to achieve the mission goals through a comprehensive Integration, Test, and Validation (IT&V) program. The ACT-America instruments, aircraft, mission operations, and ground systems are validated in pre-operational demonstrations that include coordinated flights of the P-3B and UC-12 manned by mission operations staff and using mission ground data systems and operational procedures. The ACT-America IT&V flow (Figure 3-4) starts with performance validation of each instrument and ground system, with performance validation of combined elements performed during successive stages of tests. Commitment letters for all facilities required for IT&V are included in Section 6.3.1.

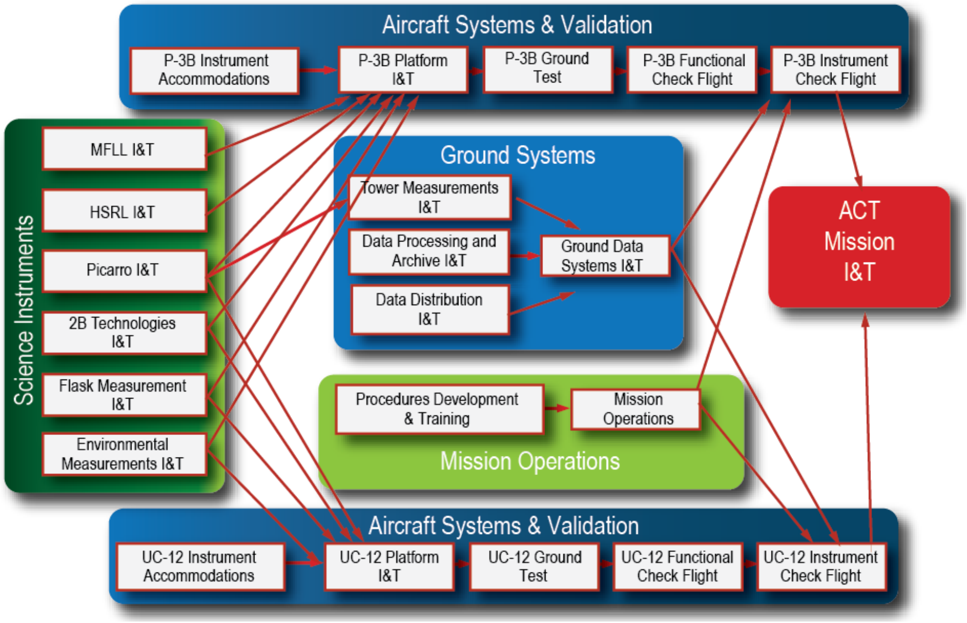


Figure 3-4. *Every ACT-America mission element undergoes comprehensive performance validation prior to each operation deployment. The ACT-America team is familiar with these Integration and Test (I&T) requirements and procedures through our extensive experience with other airborne flight campaigns, such as DISCOVER-AQ.*

3.5.1 Instrument Calibration and Validation Activities

<u>Flight testing procedures</u>: The ACT-America team has extensive experience in flying airborne instruments for atmospheric measurements, and this experience will be used in planning and executing the calibration and validation (Cal/Val) activities, shown schematically in Figure 3-4.

Initial science instrumentation Cal/Val will be performed in laboratory and ground tests by the responsible research scientists prior to aircraft and tower IT&V (Figure 3-4, "Science Instruments"). The ACT-America schedule includes ample systems preparation time to allow for instrument maintenance prior to each campaign. All required maintenance is performed on the aircraft prior to instrument integration. Once integrated, a comprehensive science instrument Cal/Val program begins (Figure 3-4, "Aircraft Systems & Validation") including ground tests for both ground and flight instruments, and extensive airborne testing for the aircraft instruments.

The instruments and aircraft systems undergo joint ground tests to verify nominal operability prior to the execution of functional check flights (FCFs) for each aircraft. The FCFs verify correct operation of all aircraft systems during flight without science instruments operating and typically last <2 hours per aircraft. Upon successful completion of the FCFs, the aircraft performs typically 1-2 instrument check flights (ICFs) to validate in-flight operations of the science instruments.

These ICFs will include 100-km legs over land at 5-km altitudes with spirals at the start and end of a flight to provide in situ profiles from near the surface to flight altitudes to compare with the remote column measurements. In situ trace gas and meteorological profiles will sample atmospheric layering throughout the lower troposphere that can be compared with the HSRL to confirm its functionality for detecting ABL depth. ICFs are conducted under a range of atmospheric and surface conditions to validate the measurement performance of the sensors and typically last 2-4 hours each. The ICFs also present the opportunity to test and verify ACT-America procedures, mission operations, and flight data processing and management.

The flight tests are scheduled to occur during the 2-week integration period prior to each ACT-America campaign, and as all of the ACT-America instruments have flight heritage, experience has shown that all required Cal/Val activities can be performed in this period. At the end of the Cal/Val activity, we expect to have validated the performance of the remote and in situ instruments to the required measurement performance standards stated in the STM for the ACT-America mission as well as the procedures and mission operations that will ensure that ACT-America goals are achieved.

In addition, during the ACT-America deployments, we will continually verify the performance of the instruments by comparing the UC-12 underflight data with the frequent P-3B descent and ascent in situ profiles, continually assessing the in situ trace gas measurements via aircraft inter-comparisons and comparisons between flask and continuous measurements. This approach to continuous quality assurance for all sensors has been successfully used in conjunction with airborne lidar measurements of O_3 and H_2O in over 33 major NASA airborne field experiments conducted all over the world(Browell et al., 2005).

Instrument calibration procedures: Picarro continuous in-situ analyzers will be routinely calibrated in-flight to show that their measurements are accurate to better than the required 1 ppm for CO_2 and 4 ppb for CH_4 using reference tanks from NOAA/ESRL that are calibrated with respect to the NOAA gravimetrically-prepared standards for CO_2, CH_4, and CO, and are on the WMOX2007 (CO_2) and WMOX2004 (CH_4 and CO) mole fraction scales (Zhao and Tans, 2006; Dlugokencky *et al.*, 2005; Novelli *et al.*, 1991). Data calibrations and water corrections will be performed as described in Karion, *et al.*, (2013a). Trace gas measurements of air collected in NOAA flasks are all also reported on these same World Meteorological Organization (WMO) standard scales. Flask sample collection and measurement methods are described in detail in the previous four references.

The MFLL has internal calibration and normalization subsystems and does not require calibration for retrievals of column CO_2 number density and range to the surface and cloud tops. Comparisons with in situ measurements will be made on each science flight. CO_2 column number density and laser altimetry from the MFLL data will be processed after each flight following Dobler et al., (2013). The HSRL relies on internal self-contained calibration during each flight for accurate retrievals of aerosol intensive and extensive properties (Hair et al., 2008) which are used for the ABL height retrieval (Scarino et al., 2013). The 2B Technologies Trace Gas Analyzer reports O_3 mole fractions and is calibrated prior to each flight with an instrument accompanied NIST traceable O_3 calibration source set at ambient background levels. No post-analysis aside for quality assurance is required prior to archiving.

3.5.2 Aircraft Performance Validation

Program Preliminary Design Reviews (PDRs), Critical Design Reviews (CDRs), and Systems Requirements Reviews (SRRs) are held for each aircraft to ensure that instrument-to-aircraft interfaces are well defined. Safety of flight operations is reviewed annually by Airworthiness and Safety Review Boards (ASRBs). Qualified aircraft personnel fabricate the aircraft instrument accommodations and install science instrumentation. After instrument integration, an Experimental Systems Readiness Review (ESRR) is convened to verify readiness for each aircraft and a series of FCFs and ICFs are performed to ensure that the aircraft and the instruments are operating correctly. Aircraft FCFs are performed at Wallops and Langley for the P-3B and UC-12, respectively, and the instrument ground tests and ICFs are performed as described in Section 3.5.1.

3.5.3 Mission Operations

The ACT-America mission operations and procedures are based on Langley's extensive flight campaign experience and will be evaluated through a mission PDR and Flight Readiness Review (FRR) prior to the first campaign. Data processing and archiving equipment and procedures are set up well in advance of the first campaign to allow for significant system testing and interaction with the instrument scientists who are contributing to the archive.

The Wallops Flight Facility (WFF) and LaRC aircraft personnel have extensive experience in obtaining flight clearances in all types of airspace utilized during ACT-America. The ACT-America flight patterns are flexible and can be adapted to avoid flying directly over urban areas or other controlled air space. Significant advance planning and coordination with Federal Aviation Administration air-traffic-control authorities starts immediately and occurs during the year leading up to the first ACT-America campaign and continuously throughout the ACT-America mission. Stormy weather flights will avoid convective cores, eliminating substantial flight risks. Aircraft coordination is only required at takeoff with selected flight times and patterns.

The PS makes day-to-day flight decisions during the ACT-America campaigns working in close consultation with the PI, taking into account local weather conditions and meteorological forecasts, instrument and aircraft requirements, and ACT-America objectives. The PI guides flight selection and location focusing on the scientific needs and objectives. The PS deploys with the aircraft during every ACT-America campaign to assist in decision-making. OCO-2 underflights are directly coordinated with the OCO-2 operations team to ensure that the satellite is collecting science data along the ground track of each ACT-America underflight.

3.5.4 Systems Engineering, Safety and Investigation Assurance (SIA)

The ACT-America study uses proven LaRC personnel, facilities, and tools to implement a robust, integrated management structure for project implementation. We have on our team senior engineers with extensive backgrounds in project management, systems engineering, and mission assurance. The ACT-America system engineering activities are guided by NPR 7123.1A - NASA Systems Engineering Processes and Requirements and a project-specific Systems Engineering Management Plan. The ACT-America SIA activities for the mission are conducted according to Center Interim Directive 5300.1 Program/Product Assurance and LPR-1710.16, Aviation Operations & Safety Manual.

References and citations

Allen, D., V. M. Torres, J. Thomas, D. W. Sullivan, *et al.*, (2013), Measurements of methane emissions at natural gas production sites in the United States, Proc. Nat. Acad. Sci., 110, 17601-17602, doi:10.1073/iti4413110.

Alvarez, R. A., S. W. Pacala, J. J. Winebrake, W. L. Chameides, and S. P. Hamburg, (2012), Greater focus needed on methane leakage from natural gas infrastructure, Proc. Nat. Acad. Sci., 109, 6435-6440, doi: 10.1073/pnas.1202407109.

Baker, D. F., R. M. Law, K. R. Gurney, P. Rayner, P. Peylin, A. S. Denning, P. Bousquet, L. Bruhwiler, Y. H. Chen, P. Ciais, I. Y. Fung, M. Heimann, J. John, T. Maki, S. Maksyutov, K. Masarie, M. Prather, B. Pak, S. Taguchi, and Z. Zhu, (2006a). TransCom 3 inversion intercomparison: Impact of transport model errors on the interannual variability of regional CO_2 fluxes, 1988-2003, *Global Biogeochemical Cycles*, **20**, GB1002, doi:10.1029/2004GB002439.

Baker, D.F., S.C. Doney, and D.S. Schimel (2006b): Variational data assimilation for atmospheric CO_2, *Tellus-B,* 58 (5), 359-365, doi:10.1111/j.1600-0889.2006.00218.x.

Baker, D. F., H. Bösch, S. C. Doney, and D. S. Schimel (2010): Carbon source/sink information provided by column CO_2 measurements from the Orbiting Carbon Observatory, *Atmos. Chem. Phys.*, 10, 4145-4165.

Bergamaschi, P., C. Frankenberg, J.F. Meirink, M. Krol, F. Dentener, T. Wagner, U. Platt, J. O. Kaplan, S. Korner, M. Heimann, E.J. Dlugokencky, and A. Goede (2007) Satellite chartography of atmospheric methane from SCIAMACHY on board ENVISAT: 2. Evaluation based on inverse model simulations, J. Geophys. Res., vol. 112, doi:10.1029/2006JD007268.

Bertschi, I. T., D. A . Jaffe, L. Jaegle, H. U. Price, J. B. and Dennison (2004). PHOBEA/ITCT 2002 airborne observations of transpacific transport of ozone, CO, volatile organic compounds, and aerosols to the northeast Pacific: Impacts of Asian anthropogenic and Siberian boreal fire emissions, J. Geophys. Res. **109**, D23S12, doi:10.1029/2003JD004328.

Bousquet, P., P. Ciais, J. B. Miller, E. J. Dlugokencky, D. A. Hauglustaine, C. Prigent, G. R. Van der Werf, P. Peylin, E.-G. Brunke, C. Carouge, R. L. Langenfelds, J. Lathie`re, F. Papa, M. Ramonet, M. Schmidt, L. P. Steele, S. C. Tyler and J. White, (2006). Contribution of anthropogenic and natural sources to atmospheric methane variability. Nature, 443, 439-443.

Bréon, François-Marie, Ciais, Philippe (2010), Spaceborne remote sensing of greenhouse gas concentrations. Comptes rendus. Geoscience, 342, p. 412. DOI: 10.1016/j.crte.2009.09.012

Browell, E.V., W.B. Grant, S. Ismail. (2005). Airborne Lidar Systems, in *Laser Remote Sensing*, edited by Takashi Fujii and Tetsuo Fukuchi, Taylor & Francis, NY, pp. 723-779.

Browell, E.V., M.E. Dobbs, J. Dobler, S. Kooi, Y. Choi, F. W. Harrison, B. Moore III, and T.S. Zaccheo. (2008). Airborne demonstration of 1.57-μm laser absorption spectrometer for atmospheric CO2 measurements, Proceedings 24th International Laser Radar Conference, Boulder, CO, 23-27 June. 2008.

Browell, E. V., M.E. Dobbs, J. Dobler, S. Kooi, Y. Choi, F. W. Harrison, B. Moore III, and T.S. Zaccheo. (2009). First airborne Laser Remote Measurements of Atmospheric Carbon Dioxide, Presented at Fourth Symposium on Lidar Atmospheric Applications, 2009 AMS Annual Meeting, Phoenix, Arizona, (Abstract and Video Presentation available via: http://ams.confex.com/ams/89annual/techprogram/paper_146526.htm), 10-15 January, 2009.

Browell, E.V., J. Dobler, S. Kooi, M. Fenn, Y. Choi, S. Vay, W. Harrison, and B. Moore III. (2012). Airborne Validation of Laser CO2 and O2 Column Measurements, *Proc. 92nd AMS Annual Meeting*, New Orleans, LA, (Abstract and Video available from AMS) January 22-26, 2012.

Bruhwiler, L., E. Dlugokencky, K. Masarie, M. Ishizawa, A. Andrews, J. Miller, C. Sweeney, P. Tans, D. Worthy, (submitted), CarbonTracker-CH4: An assimilation system for estimating emissions of atmospheric methane, Atmospheric Chemistry and Physics.

Chevallier, F., and C. W. O'Dell, (2013). Error statistics of Bayesian CO2 flux inversion schemes as seen from GOSAT. Geophys. Res. Lett., 40, 1252-1256, doi:10.1002/grl.50228. JD007375.

Chevallier, F., L. Feng, H. B¨osch, P. I. Palmer, and P. J. Rayner (2010a), On the impact of transport model errors for the estimation of CO2 surface fluxes from GOSAT observations, Geophys. Res. Lett., 37(21).

Chevallier, F., Ciais, P., Conway, T.J., Aalto, T., Anderson, B. E.,Bousquet, P., Brunke, E. G., Ciattaglia, L., Esaki, Y., Fröhlich, M., Gomez, A. J., Gomez-Pelaez, A. J., Haszpra, L., Krummel, P., Langenfelds, R., Leuenberger, M., Machida, T., Maignan, F.,Matsueda, H., Morguí, J. A., Mukai, H., Nakazawa, T., Peylin, P., Ramonet, M., Rivier, L., Sawa, Y., Schmidt, M., Steele, P., Vay, S. A., Vermeulen, A. T., Wofsy, S., and Worthy, D. (2010b).

CO2 surface fluxes at grid point scale estimated from a global 21 year reanalysis of atmospheric measurements, J. Geophys. Res., 115, D21307, doi:10.1029/2010JD013887.

Ciais, P.P. Tans, M. Trolier, J.W.C. White, and R.J. Francey. (1995). A Large Northern Hemisphere Terrestrial CO2 Sink Indicated by the 13C/12C Ratio of Atmospheric CO2. Science, 269, 1098-1102. doi: 10.1126/science.269.5227.1098

Conway, T. J., P. P. Tans, *et al.* (1994). Evidence for interannual variability of the carbon-cycle from the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Laboratory Global Air Sampling Network. Journal of Geophysical Research-Atmospheres 99(D11): 22831-22855.

Crisp, D (2004), The Orbiting Carbon Observatory (OCO) mission. Advances in Space Research, *34 (4),* 700-709, doi:10.1016/j.asr.2003.08.062.

Crisp, D., Miller, C. E., and DeCola, P. L. (2008). NASA Orbiting Carbon Observatory: measuring the column averaged carbon dioxide mole fraction from space, J. Appl. Remote Sens., *2*, 023508, doi:10.1117/1.2898457

Crisp, D., (2010). Measuring CO_2 from space: The NASA Orbiting Carbon Observatory-2, 61st International Astronautical Congress, Prague, CZ. International Astronautical Federation. IAC-10-D9.2.8

Davis, K.J., N. Gamage, C. Hagelberg, D.H. Lenschow, C. Kiemle and P.P. Sullivan, (2000). An objective method for determining atmospheric structure from airborne lidar observations. *J. Atmos. Oceanic Tech.*, **17**, 1455-1468.

Denning, A. S., I. Y. Fung, and D. Randall, (1995), Latitudinal gradient of atmospheric CO2 due to seasonal exchange with land biota, Nature, 376, 240-243.

Denning *et al.*, (2005) The Science Implementation Strategy for the North American Carbon Program. Prepared for the U.S. Carbon Cycle Scientific Steering Group and Interagency Working Group by the NACP Implementation Strategy Group. www.nacarbon.org.

Desai, A.R., Davis, K.J., Senff, C., Ismail, S., Browell, E.V., Stauffer, D.R. and Reen, B.P., 2005. A case study on the effects of heterogeneous soil moisture on mesoscale boundary layer structure in the southern Great Plains, USA. Part I: Simple prognostic model. Boundary Layer Meteorology, doi:10.1007/s10546-005-9024-6.

Diaz Isaac, L. I., K. Davis, T. Lauvaux, N. Miles, and S. Richardson, (2013). Quantification of transport errors in regional CO2 inversions using a physics-based ensemble of WRF-Chem simulations. Presented at the Fall 2013 AGU Meeting, San Francisco, CA, 9-13 December 2013.

Diaz Isaac, L. I., K. Davis, T. Lauvaux, N. Miles, S. Richardson, A. Jacobson, and A. Andrews, submitted: Model-data comparison of Mid-Continental intensive (MCI) field campaign atmospheric CO2 mole fractions. Atmos. Chem. Phys.

Dlugokencky, E. J., Steele, L. P., Lang, P. M., and Masarie, K. A. (1994). The growth rate and distribution of atmospheric methane., J. Geophys. Res.-Atmos., 99, 17021-17043.

Dlugokencky, E. J., E. G. Nisbet, *et al.* (2011), Global atmospheric methane: budget, changes and dangers. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences 369(1943): 2058-2072Dlugokencky, E. J., Myers, R. C., Lang, P. M., Masarie, K. A., Crotwell, A. M., Thoning, K. W., Hall, B. D., Elkins, J. W., and Steele, L. P. (2005). Conversion of NOAA atmospheric dry air CH4 mole fractions to a gravimetrically prepared standard scale, Journal of Geophysical Research: Atmospheres, 110, D18306, 10.1029/2005JD006035.

Dobbs, M. E., W. Sharp, E. V. Browell, S. Zaccheo, and B. Moore III (2007). A sinusoidal modulated CW integrated path differential absorption lidar for mapping sources and sinks of carbon dioxide from space, Proceedings 14th Coherent Laser Radar Conference, Snowmass, CO, 8-13 July, 2007.

Dobbs, M., J. Dobler, M. Braun, D. McGregor, J. Overbeck, B. Moore III, E. Browell, and T. Zaccheo (2008a). A modulated CW fiber laser-lidar suite for the ASCENDS mission, Proceedings 24th International Laser Radar Conference, Boulder, CO, 23-27 June, 2008.

Dobler, J. T., F. W. Harrison, E. V. Browell, B. Lin, D. McGregor, S. Kooi, Y. Choi, and S. Ismail (2013). Atmospheric CO2 column measurements with an airborne intensity-modulated continuous wave 1.57 µm fiber laser lidar, Applied Optics, 52 (12), 2874-2892.

Eldering, A. *et al.* (2013). The Proposed OCO-3 Mission, the 9thInternational Workshop on Greenhouse Gas Measurements from Space (IWGGMS-9), Yokohama, Japan, May 29-31, 2013.

European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL). (2009). Emission Database for Global Atmospheric Research (EDGAR), release version 4.0. http://edgar.jrc.ec.europa.eu.

Friedlingstein, P., and Coauthors, (2006), Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. Journal of Climate, 19, 3337-3353.

Gerbig, C., S. K¨orner, and J. C. Lin (2008), Vertical mixing in atmospheric tracer transport models: error characterization and propagation, Atmos. Chem. Phys., 8(3), 591–602, doi:10.5194/acp-8-591-2008.

Grabon, Jeffrey S., Kenneth J. Davis, Christoph Kiemle and Gerhard Ehret, (2010). Airborne Lidar Observations of the Transition Zone Between the Convective Boundary Layer and Free Atmosphere During the International H2O Project (IHOP) in 2002. Boundary-Layer Meteorol,134, 61–83, DOI 10.1007/s10546-009-9431-1

Gregory, J. M., C. D. Jones, P. Cadule, P. Friedlingstein, (2009). Quantifying carbon cycle feedbacks, Journal of Climate, 22, 5232-5250. DOI: 10.1175/2009JCLI2949.1

Gurney, K. R., R. M. Law, A. S. Denning, P. J. Rayner, D. Baker, P. Bousquet, L. Bruhwiler, Y. H. Chen, P. Ciais, S. Fan, I. Y. Fung, M. Gloor, M. Heimann, K. Higuchi, J. John, T. Maki, S. Maksyutov, K. Masarie, P. Peylin, M. Prather, B. C. Pak, J. Randerson, J. Sarmiento, S. Taguchi, T. Takahashi, and C. W. Yuen, (2002). Towards robust regional estimates of CO2 sources and sinks using atmospheric transport models. *Nature*, **415**, 626-630.

Hair, J. W., C. A. Hostetler, A. L. Cook, D. B. Harper, R. A. Ferrare, T. L. Mack, W. Welch, L. R. Izquierdo, and F. E. Hovis (2008), Airborne high spectral resolution lidar for profiling aerosol optical properties, Applied Optics, 47 (36), 6734-6753.

Hayes, D. J., Turner, D. P., Stinson, G., McGuire, A. D., Wei, Y., West, T. O., Heath, L. S., de Jong, B., McConkey, B. G., Birdsey, R. A., Kurz, W. A., Jacobson, A. R., Huntzinger, D. N., Pan, Y., Post, W. M. and Cook, R. B. (2012), Reconciling estimates of the contemporary North American carbon balance among terrestrial biosphere models, atmospheric inversions, and a new approach for estimating net ecosystem exchange from inventory-based data. Global Change Biology, 18: 1282¨C1299. doi: 10.1111/j.1365-2486.2011.02627.x

Howarth, Robert W. (2011), Methane and the greenhouse-gas footprint of natural gas from shale formations A letter. Climatic change (0165-0009), 106 (4), p. 679. doi: 10.1007/s10584-011-0061-5

Huntzinger, D.N., Post, W.M., Wei, Y., Michalak, A.M., West, T.O., Jacobson, A.R., Baker, I.T., Chen, J.M., Davis, K.J., Hayes, D.J., Hoffman, F.M., Jain, A.K., Liu, S., McGuire, A.D., Neilson, R.P., Potter, C., Poulter, B., Price, D., Raczka, B.M., Tian, H.Q., Thornton, P., Tomelleri, E., Viovy, N., Xiao, J., Yuan, W., Zeng, N., Zhao, M., Cook, R. (2012) North American Carbon Program (NACP) regional interim synthesis: Terrestrial biosphere model intercomparison. Ecological Modelling, 232, 144-157, doi:10.1016/j.ecolmodel.2012.02.004.

Karion, C. Sweeney, G. Pétron, G. Frost, J. Kofler, B. R. Miller, T. Newberger, S. Wolter, R. Banta, W. A. Brewer, E. Dlugokencky, M. Hardesty, P. Lang, S. A. Montzka, R. Schnell, P. Tans, M. Trainer, R. Zamora, (2013a) Methane emissions estimate from airborne measurements over a western US natural gas field, Geophys. Res. Lett., 40, doi:10.1002/grl.50811.

Karion, C. Sweeney, S. Wolter, T. Newberger, H. Chen, A. Andrews, J. Kofler, D. Neff and P. Tans (2013b). Long-term greenhouse gas measurements from aircraft. Atmospheric Measurement Techniques 6(3): 511-526.

King A. W., D. J. Hayes, D. N. Huntzinger, T. O. West, and W. M. Post. (2012), North America carbon dioxide sources and sinks: magnitude, attribution, and uncertainty. Frontiers in Ecology and the Environment 10(10): 512-519. doi:10.1890/120066

Kort, E. A., J. Eluszkiewicz, *et al.* (2008), Emissions of CH4 and N2O over the United States and Canada based on a receptor-oriented modeling framework and COBRA-NA atmospheric observations. Geophysical Research Letters 35(18): 5.

Lauvaux, T. and K.J. Davis, in press. Planetary boundary layer errors in mesocale inversions of column-integrated CO_2 measurements. J. Geophysical Research – Atmospheres.

Lauvaux, T., A. E. Schuh, M. Uliasz, S. Richardson, N. Miles, A. E. Andrews, C. Sweeney, L. I. Diaz, D. Martins, P. B. Shepson, and K. J. Davis, (2012a), Constraining the CO2 budget of the corn belt: exploring uncertainties from the assumptions in a mesoscale inverse system, *Atmos. Chem. Phys*., **12**, 337-354.

Lauvaux, T., A. E. Schuh, M. Bouquet, L. Wu, S. Richardson, N. Miles, and K. J. Davis, (2012b), Network design for mesoscale inversions of CO_2 sources and sinks, *Tellus B*, 64, 17980, http://dx.doi.org/10.3402/tellusb.v64i0.17980

Le Quere, C., and Coauthors, (2009), Trends in the sources and sinks of carbon dioxide. Nature Geoscience, 2, 831-836, doi:10.1038/NGEO1689.

Lehman, S. J., Miller, J. B., Wolak, C., Southon, J., Tans, P. P., Monzka, S. A., Sweeney, C., Andrews, A., LaFranchi, B., Guilderson, T. P., and Turnbull, J. C. (2013). Allocation of Terrestrial Carbon Sources Using 14CO2: Methods, Measurement, and Modeling, Radiocarbon.

Lin, B, S. Ismail, F. W. Harrison, E. V. Browell, A. R. Nehrir, J. Dobler, B. Moore, T. Refaat, and S. A. Kooi (2013), Modeling of intensity-modulated continuous-wave laser absorption spectrometer systems for atmospheric CO2 column measurements, Applied Optics, 52 (29), 7062-7077.

Liu, J., I. Fung, E. Kalnay, and J.-S. Kang (2011), CO_2 transport uncertainties from the uncertainties in meteorological fields, Geophys. Res. Lett., 38(12), doi:10.1029/2011GL047213.

Liu *et al.*, (2013), Carbon Monitoring System (CMS) 4D-variational assimilation system: Observing System Simulation Experiment with simulated ACOS-GOSAT XCO2. Submitted to *Atmospheric Chemistry and Physics Discussions*.

Marquis, M. and P. Tans (2008), Climate change - Carbon crucible. Science 320(5875): 460-461.

Matthews, E., (1989), Global Data Bases on Distribution, Characteristics and Methane Emission of Natural Wetlands: Documentation of Archived Data Tape. NASA TM-4153. National Aeronautics and Space Administration.

Mays, K. L. , P. B. Shepson, B. H. Stirm, A. Karion, C. Sweeney and K. R. Gurney (2009). “Aircraft-Based Measurements of the Carbon Footprint of Indianapolis”. *Environmental Science & Technolog*y 43(20): 7816-7823 DOI: 10.1021/es901326b.

Melfi, S. H., J. D. Spinhirne, S.-H. Chou, and S. P. Palm, (1985). Lidar observations of vertically organized convection in the planetary boundary layer over the ocean. *J. Climate Appl. Meteor.*, **24,** 806–821.

Michalak, Anna M., Robert B. Jackson, Gregg Marland, Christopher L. Sabine, and the Carbon Cycle Science Working Group, (2011), A U.S. Carbon Cycle Science Plan, available at http://carboncycle.joss.ucar.edu/sites/default/files/documents/USCarbonCycleSciencePlan-2011.pdf

Miles, N. L., S. J. Richardson, K. J. Davis, T. Lauvaux, A. E. Andrews, T. O. West, V. Bandaru, and E. R. Crosson, (2012), Large amplitude spatial and temporal gradients in atmospheric boundary layer CO2 mole fractions detected with a tower-based network in the U.S. upper Midwest, *J. Geophys. Res*., **117**, G01019, doi:10.1029/2011JG001781.

Miles, Cambaliza, Davis, Hardesty, Iraci, Gurney, Karion, Lauvaux, McGowan, Richardson, Sarmiento, Shepson, Sweeney, Turnbull, Whetstone (2013). On network design for the detection of urban greenhouse gas emissions: Results from the Indianapolis Flux Experiment (INFLUX). Presented at the 9th International Carbon Dioxide Conference, Beijing, China; 3-7 June 2013.

Miller, C. E., D. Crisp, *et al.* (2007), Precision requirements for space-based X-CO2 data. Journal of Geophysical Research-Atmospheres 112(D10).

Miller, S. M., Wofsy, S. C., Michalak, A. M., Kort, E. A., Andrews, A. E., Biraud, S. C., Dlugokencky, E. J., Eluszkiewicz, J., Fischer, M. L., Janssens-Maenhout, G., Miller, B. R., Miller, J. B., Montzka, S. A., Nehrkorn, T., and Sweeney, C. (2013), Anthropogenic emissions of methane in the United States, Proceedings of the National Academy of Sciences, 10.1073/pnas.1314392110.

Montzka, S. A., *et al.* (2007), On the global distribution, seasonality, and budget of atmospheric carbonyl sulfide (COS) and some similarities to CO2. Journal of Geophysical Research: Atmospheres 112(D9): D09302.

Montzka, S. A., E. J. Dlugokencky, *et al.* (2011), Non-CO2 greenhouse gases and climate change. Nature 476(7358): 43-50.

National Research Council, (2007). “Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond”, the National Academies Press, Washington, D.C.

Normile, Caroline P., Kenneth J. Davis, Liza I. Diaz Isaac, Thomas Lauvaux, Joseph A. Berry, Edward V. Browell, and Scott Denning (2013). Can we distinguish fluxes from transport in regional-scale atmospheric inversions? Proceedings of the Fall Meeting of the American Geophysical Union, December, 2013, San Francisco, CA.

Novelli, P. C., Elkins, J. W., and Steele, L. P. (1991). The development and evaluation of a gravimetric reference scale for measurements of atmospheric carbon monoxide. , J. Geophys. Res.-Atmos., 96, 13109-13121, 10.1029/91jd01108.

Novelli, P.C., K.A. Masarie, and P.M. Lang, (1998). Distributions and recent trends of carbon monoxide in the lower troposphere." Journal of Geophysical Research, Vol.103, No.D15, p. 19,015-19,033.

Pacala, S.W., and Coauthors, (2010), Verifying Greenhouse Gas Emissions: Methods to Support International Climate Agreements, National Research Council Draft Report, The National Academies Press, Washington, DC, USA.

Parazoo, N. C., A. S. Denning, R. Kawa, K. Corbin, R. Lokupitia, I. Baker, and D. Worthy (2008), Mechanisms for synoptic transport of CO2 in the mid-latitudes and tropics, Atmos. Chem. Phys., 8, 7239-7254.

Parazoo, N. C., A. S. Denning, J. A. Berry, A. Wolf, D. A. Randall, S. R. Kawa, O. Pauluis, and S. C. Doney (2011), Moist synoptic transport of co2 along the mid-latitude storm track, Geophys. Res. Lett., 38(9), doi: 10.1029/2011GL047238.

Parazoo, N. C., A. S. Denning, S. R. Kawa, S. Pawson, and R. Lokupitiya (2012), Co2 flux estimation errors associated with moist atmospheric processes, Atmospheric Chemistry and Physics, 12(14), 6405–6416, doi:10.5194/acp-12- 6405-2012.

Peters, W., and Coauthors, 2007: An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker. Proceedings of the National Academy of Sciences, **104,** 18925-18930, doi:10.11073/pnas.0708986104.

Peylin, P., Law, R. M., Gurney, K. R., Chevallier, F., Jacobson, A. R., Maki, T., Niwa, Y., Patra, P. K., Peters, W., Rayner, P. J., Rodenbeck, C., van der Laan-Luijkx, I. T., and Zhang, X. (2013), Global atmospheric carbon budget: results from an ensemble of atmospheric CO2 inversions, Biogeosciences, 10, 6699-6720, doi:10.5194/bg-10-6699-2013.

Raczka, B. M., Kenneth J. Davis, Deborah Huntzinger, Ronald P. Nielson, Benjamin Poulter, Andrew D. Richardson, Jingfeng Xiao, Ian Baker, Philippe Ciais, Trevor Keenan, Beverly Law, Wilfred M. Post, Daniel Ricciuto, Kevin Schaefer, Hanqin Tian, Enrico Tomellieri, Hans Verbeeck, (2013). Evaluation of Continental Carbon Cycle Simulations with North American Flux Tower Observations, Ecological Monographs, **83**, 531-556, doi: 10.1890/12-0893.1

Randerson, J.T., M.V. Thompson, C.M. Malmstrom, C.B. Field and I.Y Fung, (1996). Substrate limitations for heterotrophs: Implications for models that estimate the seasonal cucle of atmospheric CO_2. *Global Biogeochemical Cycles*, 10, 585-602. 96GB01981

Rayner, P.J. and D. M. O'Brien, (2001). The utility of remotely sensed CO_2 concentration data in surface source inversions, *Geophys. Res. Lett.*, **28**, 175-178.

Reen B.P., D.R. Stauffer, K. J. Davis, and A.R. Desai, 2006: A case study on the effects of heterogeneous soil moisture on mesoscale boundary-layer structure in the Southern Great Plains, USA, Part II: Mesoscale modeling. Boundary-Layer Meteorology, 120, 275-314.

Reen, Brian P., David R. Stauffer and Kenneth J. Davis, (2013) Land-surface heterogeneity effects in the planetary boundary layer. In press, *Boundary-Layer Meteorology*.

Ricciuto, D. M., M. P. Butler, K. J. Davis, B. D. Cook, P. S. Bakwin, A. E. Andrews, and R. M. Teclaw, (2008), Causes of interannual variability in ecosystem-atmosphere CO_2 exchange in a northern Wisconsin forest using a Bayesian synthesis inversion. Agricultural and Forest Meteorology, 148, 309-327, doi:10.1016/j.agrformet.2007.08.007

Richardson, A.D., R.S. Anderson, M.A. Arain, A.G. Barr, G. Bohrer, G. Chen, J.M. Chen, P. Ciais, K.J. Davis, A.R. Desai, M.C. Dietze, D. Dragoni, S.R. Garrity, C.M. Gough, R. Grant, D.Y. Hollinger, H.A. Margolis, H. McCaughey, M. Migliavacca, R.K. Monson, J.W. Munger, B. Poulter, B.M. Raczka, D.M. Ricciuto, A.K. Sahoo, K. Schaefer, H. Tian, R. Vargas, H. Verbeeck, J. Xiao, Y. Xue. (2012a). Terrestrial biosphere models need better representation of vegetation phenology: Results from the North American Carbon Program

Site Synthesis. Global Change Biology, 18: 566-584. doi: 10.1111/j.1365-2486.2011.02562.x.

Richardson, Scott J., Natasha L. Miles, Kenneth J. Davis, Eric R. Crosson, Chris W. Rella, Arlyn E. Andrews (2012b), Field Testing of Cavity Ring-Down Spectroscopy Analyzers Measuring Carbon Dioxide and Water Vapor. *J. Atmos. Oceanic Technol.*, 29, 397–406. doi: http://dx.doi.org/10.1175/JTECH-D-11-00063.1

Rogers, R. E., A. Deng, D. R. Stauffer, B. J. Gaudet, Y. Jia, S. Soong, S. Tanrikulu, 2013: Application of the Weather Research and Forecasting Model for Air Quality Modeling in the San Francisco Bay Area. *J. Appl. Meteor*., **52**, 1953-1973.

Scarino, A. J., M. D. Obland, J. D. Fast, S. P. Burton, R. A. Ferrare, C. A. Hostetler, L. K. Berg, b. Lefer, C. Haman, J. W. Hair, R. R. Rogers, C. Butler, A. L. Cook, and D. B. Harper (2013), Comparison of mixed layer heights from airborne high spectral resolution lidar, ground-based measurements, and the WRD-Chem model using CalNex and CARES, Atmos. Chem. Phys. Discuss., 13, 13721-13772

Schaefer K., C. Schwalm, C. Williams, M.A. Arain, A. Barr, J. Chen, K.J. Davis, D. Dimitrov, T.W. Hilton, D.Y. Hollinger, E. Humphreys, B. Poulter, B. M. Raczka, A. D. Richardson, A. Sahoo, P. Thornton, R. Vargas, H. Verbeeck, R. Anderson, I. Baker, T. A. Black, P. Bolstad, J. Chen, P. Curtis, A. R. Desai, M. Dietze, D. Dragoni, C. Gough, R. F. Grant, L. Gu, A. Jain, C. Kucharik, B. Law, S. Liu, E. Lokipitiya, H. A. Margolis, R. Matamala, J. H. McCaughey, R. Monson, J. W. Munger, W. Oechel, C. Peng, D. T. Price, D. Ricciuto, W. J. Riley, N. Roulet, H. Tian, C. Tonitto, M. Torn, E. Weng, X. Zhou, (2012). A Model-Data Comparison of Gross Primary Productivity: Results from the North American Carbon Program Site Synthesis. *Journal of Geophysical Research*, **117**, doi:10.1029/2012JG001960.

Skamarock, W.C. and Coauthors, 2008. A description of the advanced research WRF Version 3. NCAR Technical Note NCAR/TN-475+STR, University Corporation for Atmospheric Research, Boulder, CO, USA, 113 pages.

SOCCR (The First State of the Carbon Cycle Report), (2007), The North American Carbon Budget and Implications for the Global Carbon Cycle. A report by the Climate Change Science Program and the Subcommittee on Global Change Research, National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA.

Stephens, B. B., and Coauthors, 2007: Weak northern and strong tropical land carbon uptake from vertical profiles of atmospheric CO2. Science, 316, 1732-1735, doi:10.1126/science.1137004.

Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (2013). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA.

Tans, P P, I.Y. Fung, T. Takahashi, (1990). Observational contraints on the global atmospheric CO2 budget. Science, 247, 1431-1438, doi:10.1126/science.247.4949.1431

Turnbull, J. C., J. B. Miller, S. J. Lehman, P. P. Tans, R. J. Sparks, and J. R. Southon (2006), Comparison of 14CO2, CO and SF6 as tracers for determination of recently added fossil fuel CO2 in the atmosphere and implications for biological CO2 exchange, Geophys. Res. Lett., 33, L01817, doi:10.1029/2005GL024213.

Turnbull, J. C., A. Karion, M. L. Fischer, I. Faloona, T. Guilderson, S. J. Lehman, B. R. Miller, J. B. Miller, S. Montzka, T. Sherwood, S. Saripalli, C. Sweeney and P. P. Tans (2011).

Assessment of fossil fuel carbon dioxide and other anthropogenic trace gas emissions from airborne measurements over Sacramento, California in spring 2009. Atmospheric Chemistry and Physics **11**(2): 705-721.

Uliasz, M., 1994: Lagrangian particle dispersion modeling in mesoscale applications. In: Environmental Modeling II, P. Zanetti, ed., Computational Mechanics Publications, 71-102.

US Environmental Protection Agency (2013a). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011, EPA, Washington, D.C.

US Environmental Protection Agency (2013b). EPA Needs to Improve Air Emissions Data for the Oil and Natural Gas Production Sector, Report No. 13-P-0161 February 20, 2013. EPA, Washington, D.C.

van der Werf GR, Randerson JT, Giglio L, Collatz GJ *et al.*, Interannual variability of global biomass burning emissions from 1997 to 2004. Atmospheric Chemistry and Physics 6, 3423-3441, 2006

van der Werf GR, Randerson JT, Giglio L, Collatz GJ, *et al.*, Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997-2009), Atmospheric Chemistry and Physics 10, 11707-11735, 2010

Wunch, D., *et al.* (2010). Calibration of the total carbon column, observing network using aircraft profile data, *Atmos. Meas. Tech.*, 3, 1351-1362, doi: 10.5194/amt-3-1351-2010

Wunch, D. *et al.*, (2011). A method for evaluating bias in global measurements of CO2 total columns from space, Atmos. Chem. Phys., 11, 12317-12337, doi:10.5194/acp-11-12317-2011.

Yokota, T., Yoshida, Y., Eguchi, N., Ota, Y., Tanaka, T., Watanabe, H., and Maksyutov, S.: Global Concentrations of CO_2 and CH_4 Retrieved from GOSAT: First Preliminary Results, SOLA, 5, 160–163, 2009.

Zhao, C. L., and Tans, P. P. (2006). Estimating uncertainty of the WMO mole fraction scale for carbon dioxide in air, Journal of Geophysical Research, 111, D08S09, 10.1029/2005jd006003.