INFLUX (The Indianapolis Flux Experiment)

A top-down/bottom-up greenhouse gas quantification experiment in the city of Indianapolis

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Abstract

Beginning September 2010 a collaborative research team, led by researchers at Purdue University, Penn State University, Arizona State University, the University of Colorado and NOAA/ESRL will start intensive measurements using towers and aircraft to quantify emissions of carbon dioxide and methane from the city-wide Indianapolis emissions plume. These measurements will be used in combination with bottom up inventories to evaluate the current best methodological approaches, and associated uncertainties, for quantifying urban greenhouse gas emission fluxes from atmospheric measurements. The National Institute of Standards and Technology (NIST) has enabled this effort by providing funding for 12 ground based towers at which the team will measure CO_2, CH_4 and CO continuously (CH_4 and CO at a subset of the towers), along with time-integrated flask samples at 6 of these towers which will be analyzed for $^{14}CO_2$, CO_2, CH_4, CO and a suite of halo- and hydrocarbons to enable source attribution of the measured CO_2 and CH_4 plumes. NIST has also funded 40 flights over the Indianapolis metropolitan area over the next two years. These measurements along with building-level analysis of fuel usage will enable this first high spatial and temporal resolution assessment of greenhouse gas emissions for an urban environment, and thus provide a baseline dataset for other measurement systems and analysis techniques, such as airborne or space-based remote sensing technology. Remote sensing of atmospheric greenhouse gases is likely to be an important tool in monitoring global GHG budgets, including anthropogenic emissions. This white paper proposes integration of NASA and other remote sensing assets as part of the INFLUX experiment with the goal of more fully evaluating the range of technologies available for quantifying anthropogenic GHG emissions.

Introduction

As developing nations increase their total fossil fuel use, this also increases the uncertainty in global estimates of fossil fuel use. For example, inventory data indicates that China surpassed the United States as the largest national emitter of fossil fuel CO_2 in 2006 (Gregg et al., 2008), but uncertainties on the Chinese data are ~20% for the annual national totals (vs 3-5% for the US), and substantially higher for finer scale data (e.g. Gregg et al., 2008). Further, emissions become increasingly uncertain in developed nations as the spatial and temporal resolution increases. Atmospheric budget estimates of emissions, also known as atmospheric inversions or top-down estimates, can potentially help resolve these issues. Atmospheric budget methods for evaluating GHG emissions, however, have typically been applied to global or zonal scales. A lack of high-density data has limited the applications of these methods to emissions on the scale of an urban center. The needs to resolve regional atmospheric transport and

distinguish various GHG sources (e.g. biogenic and anthropogenic CO_2) add additional complexity to this issue.

Mesoscale atmospheric models utilizing data assimilation can provide high-resolution regional atmospheric transport reanalyses. These transport models can be combined with GHG boundary conditions from global reanalyses of these gases to provide a framework for analyzing an urban GHG measurement network. Atmospheric tracers such as $^{14}CO_2$ and CO can help to deconvolute fossil fuel-derived CO_2 from other CO_2 sources. Fossil fuel-derived CO_2 is entirely devoid of the radioactive isotope ^{14}C, due to its extreme age, whereas all other sources of CO_2 (oceans and terrestrial biosphere) have ^{14}C content close to that of the atmosphere. Thus the addition of ^{14}C-free fossil fuel CO_2 lowers the ^{14}C content of atmospheric CO_2, and these additions can be precisely quantified in atmospheric samples. Fossil-derived CO_2 is also correlated with CO, though the emissions ratio varies over space and time. A combination of flask-based $^{14}CO_2$ and continuous CO measurements provides a basis for isolating fossil-derived CO_2 with high spatial and temporal resolution. Thus while the elements exist for constructing atmospheric estimates of urban GHG emissions at high spatial and temporal resolution, this type of experiment has yet to be conducted.

The primary goal of this research effort is to use highly accurate and precise tower-based and aircraft-based measurements of CO_2 (and CH_4), along with $^{14}CO_2$ and CO measurements, to test atmospheric budget estimates of fossil fuel emissions, and compare these to the high quality Hestia (http://www.purdue.edu/climate/hestia/) data product, thus quantifying the methodological uncertainties and biases present in the atmospheric methods. This effort will take place in Indianapolis, because of the relatively simple topography, and relatively isolated character of the urban source region, as well as the existing high-resolution emissions model for this city. The planned measurements will enable not only assessment of the methods used and their uncertainties, but will also reveal much about the temporal characteristics of fluxes, covering diurnal, weekly, and seasonal variability in fluxes.

Methods

Tower-based measurements

Continuous ground measurements of CO_2, CO, and CH_4 and discrete flask measurements of $^{14}CO_2$, CO_2, CH_4 and CO, stable isotopes in CO_2, and a suite of halocarbons and hydrocarbons will be conducted from medium height (75-150m) cell phone towers that are distributed around the Indianapolis metropolitan area. Twelve towers will be instrumented. Two towers will host the entire suite of trace gas measurements. Three will include CO_2, CO and flask measurements. Three will conduct CO_2 and CH_4 measurements. Four additional sites will measure CO_2 only. Each tower has been selected based on prevailing winds and the likelihood of capturing measureable signals downwind of Indianapolis and at the same time capturing background signals with corresponding towers on the upwind side of the city. All measurements will be routinely calibrated using standard gases traceable to World Meteorological Organization (WMO) standards. The flask and continuous measurements of $^{14}CO_2$, CO_2 and CO will be used in combination to obtain high resolution fossil fuel CO_2 estimates. The additional species measured will aid in identifying specific fossil fuel sources, and will also be used to examine emission ratios for these other species. Towers are being instrumented during the fall and winter of 2010-2011, and are planned to be in operation for approximately two years.

Aircraft measurements

Over the next two years, more than 40 fights of the Airborne Laboratory for Atmospheric Research (ALAR; http://www.chem.purdue.edu/shepson/alar.html) will take place, during which we will conduct high precision and accuracy measurements of CO_2 and CH_4, along with flask samples that will be analyzed for $^{14}CO_2$, CO_2, CH_4, CO, stable isotopes in CO_2, and a suite of halocarbons and hydrocarbons, to assist in source attribution. Comparison of the in-flight Picarro measurements of CO_2 and CH_4 with the NOAA/ESRL flask measurements of these gases (traceable back to WMO standards) will ensure reliable data, with known uncertainties. The ALAR wind probe enables determination of the 3D winds, which, along with temperature profiles that result in reliable boundary layer height measurement, can be used for eddy-covariance, or mass-balance-based determination of fluxes. The advantage of deploying light aircraft is that the cost is minimal and the flight plan can be quite flexible. Two recent studies done in recent collaboration between the NOAA/ESRL carbon cycle group aircraft project (http://www.esrl.noaa.gov/gmd/ccgg/aircraft/index.html) and Purdue have yielded two different successful approaches to sampling urban plumes (e.g. Mays et al., 2009 and Turnbull et al., 2010). These data also provide an effective independent test of the regional reanalyses of both meteorological conditions and atmospheric GHG concentrations that will be created with our mesoscale modeling system.

Emissions Data Product

The Hestia Project provides fossil fuel CO_2 emissions down to the building/street level every hour utilizing a bottom-up, process-driven approach that draws from Vulcan (http://www.purdue.edu/eas/carbon/vulcan/index.php, the US national emissions data product). Hestia has been demonstrated using the city of Indianapolis as a test case. The approach leverages a variety of data sources and model constructs to estimate emissions in a comprehensive, methodologically consistent manner. The approach is scalable and transferrable to other urban locations in the US and provides considerable source detail including categorization by vehicle type, building type, and fuel consumed among others. While high quality data (fuel use, transportation data, etc.) is also available for most other industrialized nations from which to generate high quality emissions inventories, the data quality is much less certain for most developing nations. Even in industrialized nations with high-quality data bases, such high-resolution inventory estimates have not been evaluated using independent methods. The ability to match such highly resolved, bottom-up inventories with atmospheric budget estimates has not yet been demonstrated. This project aims to conduct such a demonstration.

Atmospheric Inversions

The atmospheric inversion techniques developed for regional experiments in the SE of France and the US Midcontinental Intensive regional study will be used to infer anthropogenic GHG emissions from the study region. The inversion system utilizes the Weather Research and Forecast model (WRF) for creating atmospheric transport fields, the Lagrangian Particle Dispersion Model (LPDM) to estimate the areas influencing each tower observation, and a Bayesian matrix inversion to solve for spatially resolved emissions. The WRF model has the ability to employ a range of plausible descriptions of atmospheric processes (e.g. boundary layer parameterization, cloud convection parameterization) important to the transport of GHGs, the ability to simulate the transport of multiple passive tracers simultaneously, a well-developed data assimilation module suited to the production of a transport reanalysis closely fitted to regional observations, and the ability to run a nested simulation with a more coarsely resolved, large scale

flow interacting with a more highly resolved regional mesh. For INFLUX, we will run a nested grid with ~10 km horizontal resolution encompassing a significant portion of the eastern United States, with a finer mesh (~1-2 km horizontal resolution) for the ~50 km radius around Indianapolis. The model will be run in reanalysis mode, including ingestion of the available surface meteorological observations available in the Indianapolis region, and utilizing NCEP reanalysis at the continental scale. Boundary conditions for CO_2 will be taken from NOAA's Carbon Tracker system and NOAA's continental network of airborne CO_2 profiles. Estimates of fossil fuel and biogenic CO_2 fluxes and anthropogenic CH_4 emissions will be constructed from a multi-species inversion including CH_4, CO_2 and CO (calibrated to represent fossil CO_2 using $^{14}CO_2$). Fluxes will be estimates at 1-2 km spatial resolution and for weekly time intervals. Data removal experiments and multiple atmospheric transport schemes will be applied to test the robustness of the inverse flux estimates. The ALAR airborne data will be utilized for independent evaluation of the modeled GHG mixing ratio fields. Inversion results will be compared to Hestia estimates. The combination of the globally unique atmospheric data and high-resolution Hestia emissions inventory should provide an unparalleled opportunity to test the ability of atmospheric inversions to estimate urban GHG emissions.

Opportunities for Collaboration

The INFLUX study represents an unparalleled opportunity to test our ability to infer urban GHG emissions using both in situ and remote measurement methods. At present, INFLUX does not include a remote sensing component. We also anticipate that atmospheric transport will be a primary source of uncertainty in our final inversion results, and note that enhanced regional atmospheric sampling will improve our ability to evaluate WRF reanalyses of regional transport. To that end we suggest four primary areas of potential NASA (and other) collaboration in the INFLUX experiment, roughly in order of priority. We emphasize that field measurements are being deployed now, and will operate for approximately 2 years, thus the suggested observational collaborations are time-sensitive.

1. Atmospheric GHG remote sensing

The most likely area for which INFLUX can benefit NASA is to test the ability of atmospheric remote sensing assets to either infer urban GHG emissions or to evaluate the atmospheric inversion schemes by providing GHG data not utilized in the regional inversions. This is an area of considerable interest to NASA, and highly relevant to the upcoming OCO-2 and ASCENDS satellite missions. We propose, therefore, that NASA consider deploying airborne or ground-based CO_2 remote sensing technology as part of the INFLUX experiment. This could include FTIR column remote sensing, LIDAR CO_2 column remote sensing, or existing space-based (e.g. GOSAT) remote sensing assets. Deployments of any of these assets over a time period of a few to several weeks, perhaps at contrasting times of year (summer, winter) would enable substantive testing of the utility of these data. (Contacts: Davis, Shepson)

2. Remote sensing of atmospheric transport

Ground-based, long-term (many months to full experiment duration) remote sensing of boundary layer properties and lower tropospheric winds using, for example, boundary layer radar or lidar would provide an excellent means of evaluating the quality of our regional atmospheric transport fields. Airborne remote sensing would provide valuable shorter-term experiments, also with the goal of evaluating and potentially improving WRF reanalyses. (Contacts: Davis, Sweeney)

3. Remote sensing of the land surface

Enhanced remote sensing of the regional land surface (e.g. AVIRIS overflights) would benefit our effort to characterize regional emissions using inventory methods. (Contact: Gurney)

4. Alternative atmospheric inversion schemes

The data base created by this experiment will provide a unique test bed for urban atmospheric inversion methods. Additional groups interested in experimenting with regional inversion approaches are welcome to collaborate. All project data will be available to the research community as soon as basic data processing and quality analyses are complete.