# Aircraft-Based Measurements of the Carbon Footprint of Indianapolis

Kelly L. Mays*[†], Paul B. Shepson[†,‡], Brian H. Stirm[¢], Anna Karion[§], Colm Sweeney[§], Kevin R. Gurney[†,¥]
Department of Earth and Atmospheric Science, Purdue University, 550 Stadium Mall Drive; Department of Chemistry, 560 Oval Drive, West Lafayette, Indiana 47906

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# Supplemental Information

## SI.1 Times of Flight and Mixed Layer Height Determination

| Date | Start Transects (local time) | End Transects (local time) |
|---|---|---|
| March 28, 2008 | 11:15 am | 1:00 pm |
| April 2, 2008 | 12:15 pm | 2:00 pm |
| April 14, 2008 | 12:00 pm | 2:00 pm |
| April 15, 2008 | 12:15 pm | 2:30 pm |
| April 21, 2008 | 12:15 pm | 2:30 pm |
| November 23, 2008 | 12:30 pm | 3:00 pm |
| December 20, 2008 | 1:00 pm | 3:30 pm |
| January 7, 2009 | 12:30 pm | 2:30 pm |

Table S.1. Dates and times of experimental flights.

Vertical profiles were completed for the majority of flights, with the exceptions being March 28, 2008, December 20, 2008, and January 7, 2009 due to low level clouds. The temperature and pressure data from the vertical profiles for each profile from April 2 to April 21, 2008 were used to calculate a potential temperature, $\theta$, profile for each flight. On November 23, 2008, the profile of virtual potential temperature, $\theta_v$, was calculated, as humidity measurements were available for this flight. This does not affect the boundary layer height result. The profiles were then separated into altitude bins of twenty meters, and the mean in each bin was calculated to provide a smoother profile for analysis. A running mean and standard deviation of potential temperature (virtual potential temperature) was calculated beginning from the lowest altitude.

The height at which the θ ($\theta_v$) value exceeded the mean plus three standard deviations for at least 100 meters in the vertical was chosen to be the mixed layer height. For the three days during which vertical profiles could not be flown, the lowest extent of the cloud deck was chosen as the mixed layer height. This was determined by flying to the base of the cloud layer and noting the altitude. Table S.2 indicates the estimated mixed layer height for each flight.

| **Date** | **Mixed Layer Height Estimate ($z_i$) (meters)** |
|---|---|
| March 28 | 388* |
| April 2 | 978 |
| April 14 | 1386 |
| April 15 | 1150 |
| April 21 | 712 |
| November 23 | 626 |
| December 20 | 357* |
| January 7 | 418* |

Table S.2. Table of estimated mixed layer heights (magl). * denotes days when mixed layer was estimated as base of cloud layer.

Figure S.1 shows a representative vertical profile for the flight of April 21. Included on this plot are the vertical profiles of $CO_2$, $CH_4$, θ, and the variance of the vertical wind (from BAT probe measurements), as a measure of turbulent mixing. The concentrations of both gases decrease at the top of the mixed layer, as does $\sigma_w^2$. This figure demonstrates a typical case for the impact of the urban emissions on the boundary layer concentrations, i.e. on the order of 7-8 ppm for $CO_2$ and 40 ppb for $CH_4$.

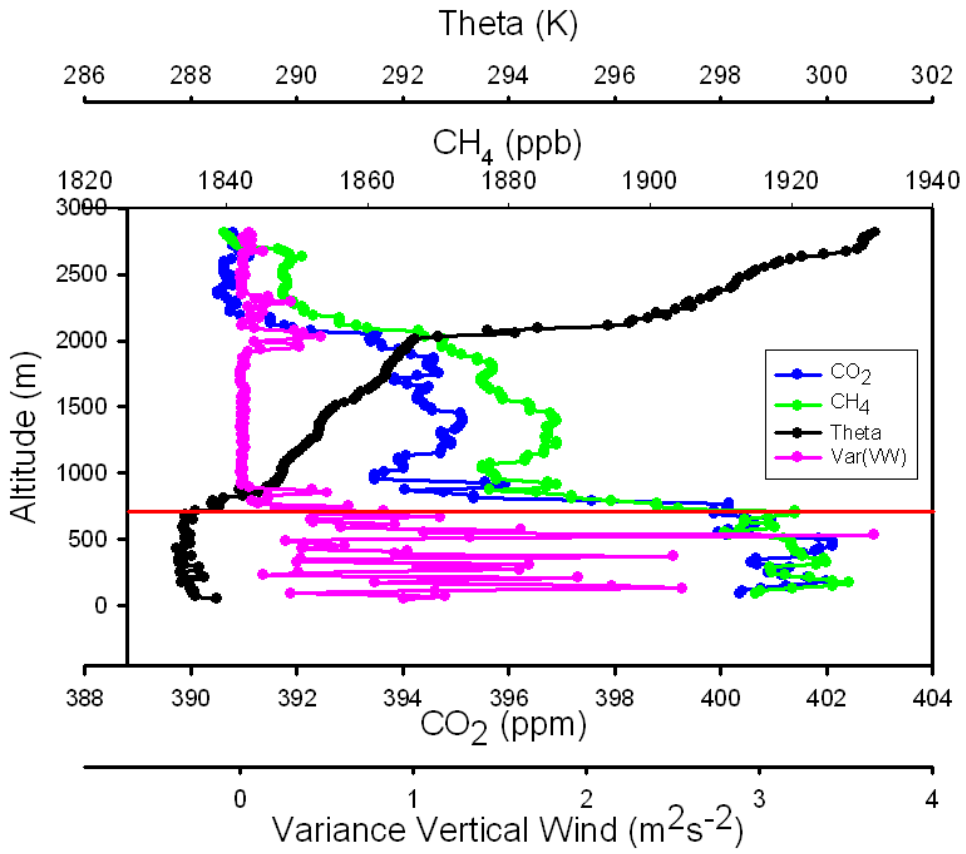



Figure S.1. Potential temperature, θ (black), vertical profile used to determine boundary layer height for April 21, 2008 along with profiles of $CO_2$ (blue), $CH_4$ (green), and the variance of the vertical wind (pink). The estimated height of the mixed layer is indicated with the red horizontal line.

**SI.2 Meteorological Conditions**

All flights originated at the Lafayette Airport (LAF), located on the southwest portion of the Purdue University campus in Lafayette, Indiana. The first day of flight took place on Friday, March 28, 2008. Surface morning winds at LAF were northwesterly at approximately 5 m/s with a surface air temperature of 2°C as reported by the automated weather station located on the airport property. Approaching Indianapolis a low ceiling was noted, limiting the maximum

flight altitude to approximately 388 meters. A cold front extending from a low pressure system centered over the northeast United States stretched to the east-southeast of Indiana over the Ohio Valley. No precipitation fell during this flight. Prior to take-off from LAF, the Hybrid Single Particle Langrangian Integrated Trajectory Model (HYSPLIT) was run with forecast data that indicated north-northeasterly winds within the PBL as well as little vertical motion *(31)*.

The second flight occurred on Wednesday, April 2, 2008. At the surface upon take-off, winds were approximately 2m/s from the north at LAF. Air temperatures at the surface were just above freezing. Broad high pressure was centered over eastern Indiana, Ohio and southwestern Michigan, which gave rise to east-northeasterly winds at Indianapolis near the surface in the PBL. HYSPLIT forward trajectories also indicated east-northeasterly winds. A strong low pressure center to the north of Maine spawned a cold front that extended along the eastern coast of the United States. No precipitation occurred on this day of flight.

The third and fourth days of flight were conducted on April 14 and 15, 2008, which fell on a Monday and a Tuesday, respectively. Surface conditions at LAF were winds between 2-4m/s and temperatures between 3°C and 5°C. On Monday high pressure rested over the central United States including Texas, Oklahoma, and Kansas. Lower tropospheric winds were from the northeast. By Tuesday the winds had turned more southerly as the higher pressure in the central United States moved east over Ohio, Southern Indiana and Kentucky southwards. Within the PBL on Monday, the winds were north-easterly, as indicated by the forward HYSPLIT trajectories *(31)* for that mid-day period. On April 15 lower tropospheric and PBL winds had turned south-southwesterly as the high pressure system traversed the area.

Monday, April 21, 2008, marked the final spring experimental flight. Surface winds were about 3m/s with a surface air temperature at LAF of 14°C, the warmest day of experimental

flights. A compact line of low pressure systems was centered over the central to west central United States with several associated fronts. PBL winds at Indianapolis during flight were southeasterly. No precipitation occurred during the flight. Low, thin clouds persisted in the early morning, but had evaporated by the time the downwind flights began.

Several flights were conducted in the late fall and early winter. Two of these flights, November 23 and December 20, took place on weekend days. November 23 fell on a Sunday and December 20 was a Saturday. Surface winds at LAF and around Indianapolis on November 23 were approximately south-southwesterly, at 4 to 6m/s with a temperature of approximately 5°C. Broad high pressure was centered over the eastern seaboard to the east of Indiana, bringing south-southwesterly winds on the backside of the system. Early morning HYSPLIT forward trajectories indicated south-southwesterly winds for the entire flight period during the day. Skies remained clear for the flight period, and no precipitation fell. December 20 brought misty conditions, with a low ceiling and more difficult flight conditions. Surface conditions at take-off included easterly flow at approximately 7m/s. Temperatures were approximately -2°C. Flow was east-southeasterly in the PBL, with a ceiling at approximately 357m. Synoptically, low pressure dominated the central United States, moving eastward during the day. HYSPLIT forward trajectories also indicated east-southeasterly flow previous to take-off.

The final flight was conducted on January 7, 2009. As was the case for the March and December flights, a low cloud deck limited the vertical extent to which ALAR could ascend. The surface wind at LAF at the beginning of the flight was westerly at 5 to 7m/s. The surface temperature was falling steadily throughout the flight from approximately -1°C at take-off to -4°C by landing. Low pressure was centered over Michigan and the western Great Lakes,

leading to the westerly flow observed at Indianapolis. The cloud deck was low during flight time, with expansive stratocumulus clouds over the area of interest.

### SI.3 Kriging Results

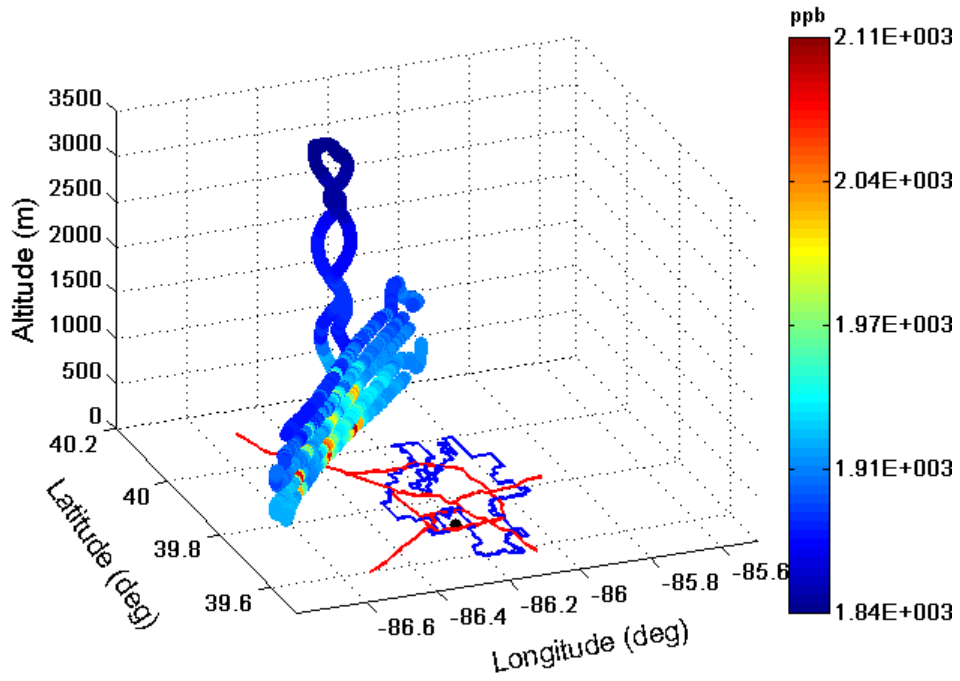



Figure S.2. 3-D view of Indianapolis (blue outline) with $CH_4$ concentrations (ppb) along flight tracks (April 21, 2008), with approximately perpendicular winds, at ~140°. Red lines are highways, and the black dot represents the Harding Street power plant.

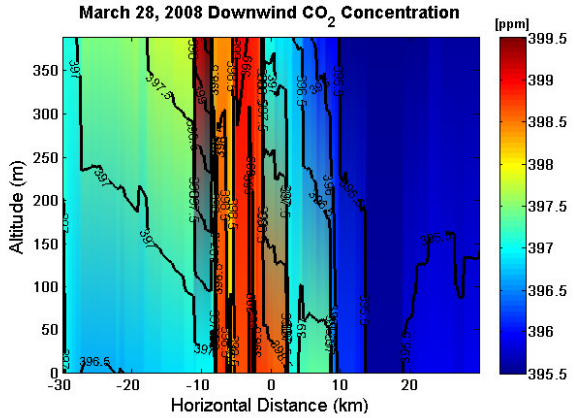
The table below illustrates the background concentrations for each flight, as calculated from the edges of the downwind planes. Edges of the vertical plane were identified by calculating a running mean and standard deviation beginning from the ends of the vertical plane, moving inward. The area over which the concentration values were less than the mean + 3σ was considered to be background air, avoiding any biases from the urban plume. For all flights, the

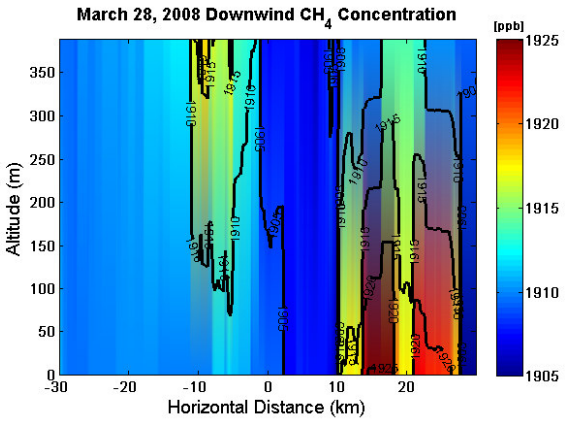
average concentration of the background air, not influenced by polluted air flowing from the city, was taken as the background concentration of each trace gas. Locations where there is an elevated area of concentration in the background air due to an upwind source outside of the city (i.e., biomass burning) and therefore are not representative of background, upwind concentrations, were discarded, and the average of only one edge was used. This is done to avoid any potential biases by smaller plumes of higher concentration upwind of the city.

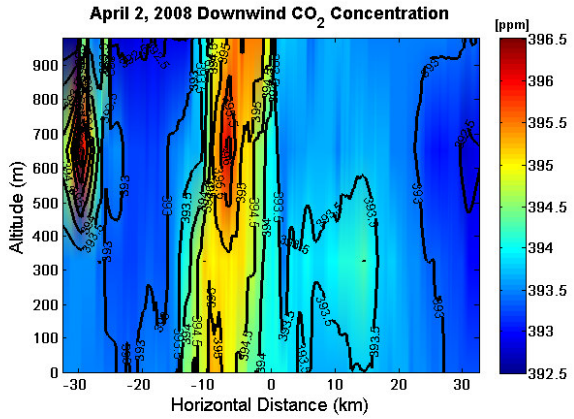
| **Date** | **Background $CO_2$ Concentration (ppm) ±1σ** | **Background $CH_4$ Concentration (ppb) ±1σ** |
|---|---|---|
| March 28, 2008 | 395.40 ± 0.21 | 1903.66 ±0.57 |
| April 2, 2008 | 393.22 ±0.31 | 1884.30 ± 3.46 |
| April 14, 2008 | 394.18 ± 0.78 | 1888.84 ± 6.32 |
| April 15, 2008 | 394.02 ± 0.80 | 1895.50 ± 4.71 |
| April 21, 2008 | 398.99 ± 1.92 | 1909.83 ± 10.36 |
| November 23, 2008 | 395.36 ± 1.89 | 1921.53 ± 12.55 |
| December 20, 2008 | 398.20 ± 1.29 | 1946.43 ± 9.40 |
| January 7, 2009 | 402.69 ± 0.04 | 1983.04 ± 2.63 |
| Mean (±1σ) | 396.5 ± 3.2 | 1917 ± 33 |

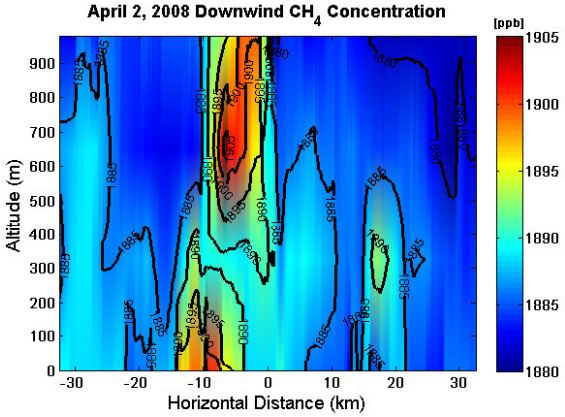
Table S.3. Background concentrations for $CO_2$ (ppm) and $CH_4$ (ppb) ± 1σ.

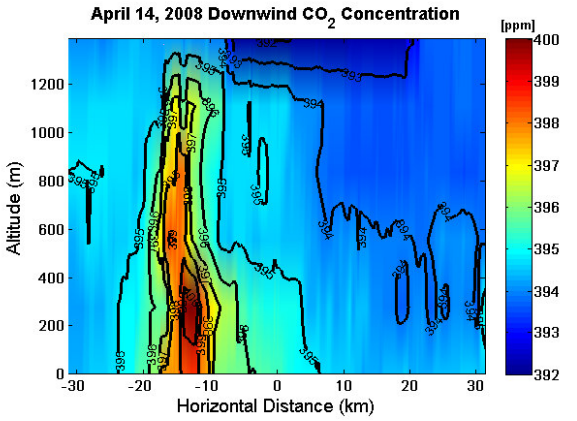
The figure below illustrates the downwind kriging results for $CO_2$ and $CH_4$ concentrations. Warmer colors illustrate higher concentrations.

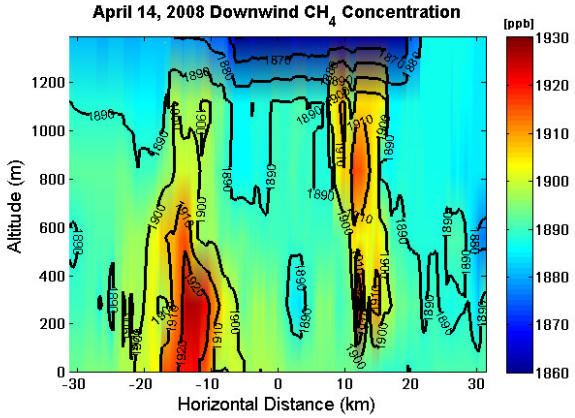

March 28, 2008 Downwind $CO_2$ Concentration
[ppm]
Altitude (m)
Horizontal Distance (km)


March 28, 2008 Downwind $CH_4$ Concentration
[ppb]
Altitude (m)
Horizontal Distance (km)

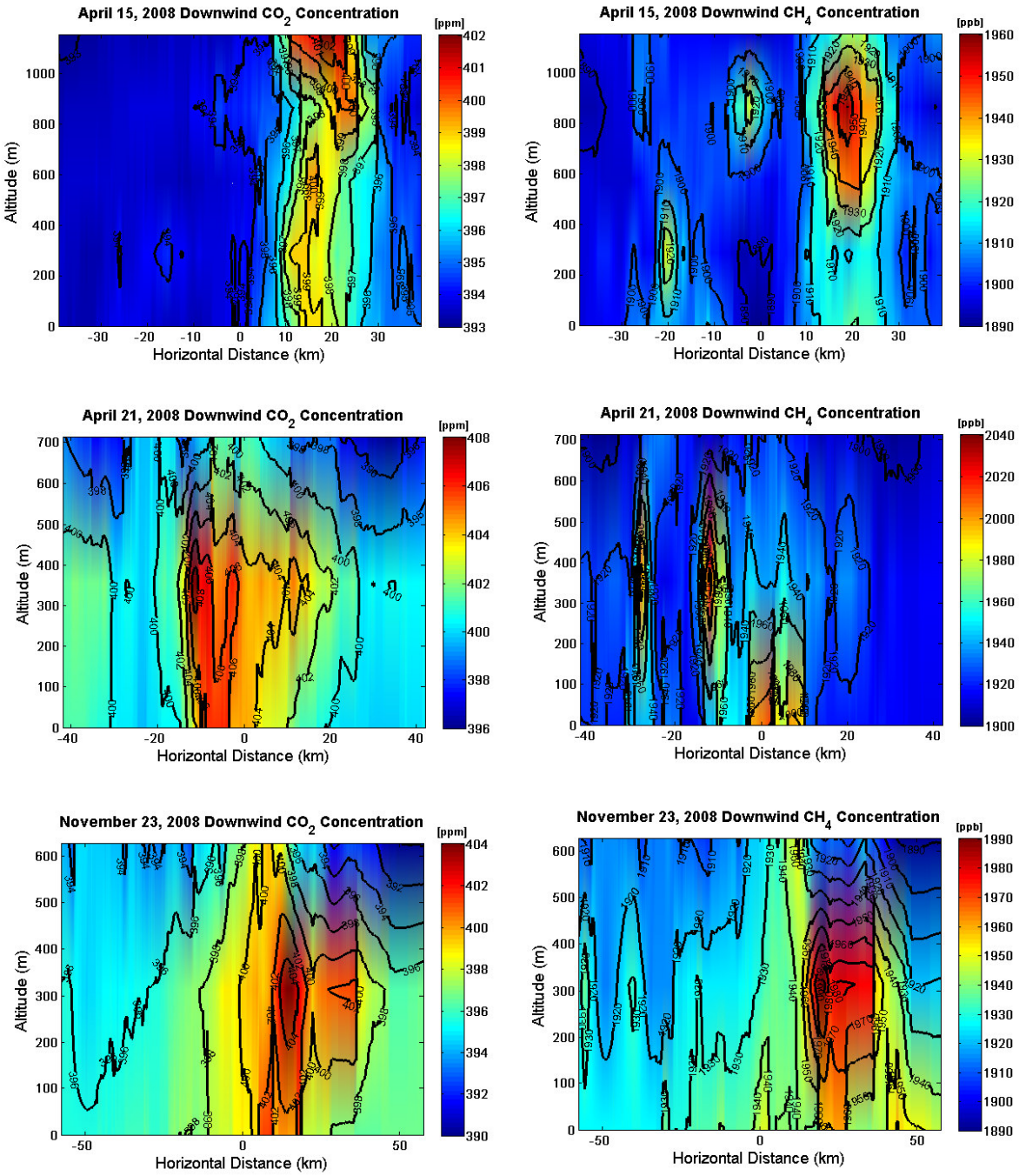

April 2, 2008 Downwind $CO_2$ Concentration
[ppm]
Altitude (m)
Horizontal Distance (km)


April 2, 2008 Downwind $CH_4$ Concentration
[ppb]
Altitude (m)
Horizontal Distance (km)


April 14, 2008 Downwind $CO_2$ Concentration
[ppm]
Altitude (m)
Horizontal Distance (km)


April 14, 2008 Downwind $CH_4$ Concentration
[ppb]
Altitude (m)
Horizontal Distance (km)

120


April 15, 2008 Downwind CO2 Concentration
[ppm]
Altitude (m)
Horizontal Distance (km)
April 15, 2008 Downwind CH4 Concentration
[ppb]
Altitude (m)
Horizontal Distance (km)
April 21, 2008 Downwind CO2 Concentration
[ppm]
Altitude (m)
Horizontal Distance (km)
April 21, 2008 Downwind CH4 Concentration
[ppb]
Altitude (m)
Horizontal Distance (km)
November 23, 2008 Downwind CO2 Concentration
[ppm]
Altitude (m)
Horizontal Distance (km)
November 23, 2008 Downwind CH4 Concentration
[ppb]
Altitude (m)
Horizontal Distance (km)

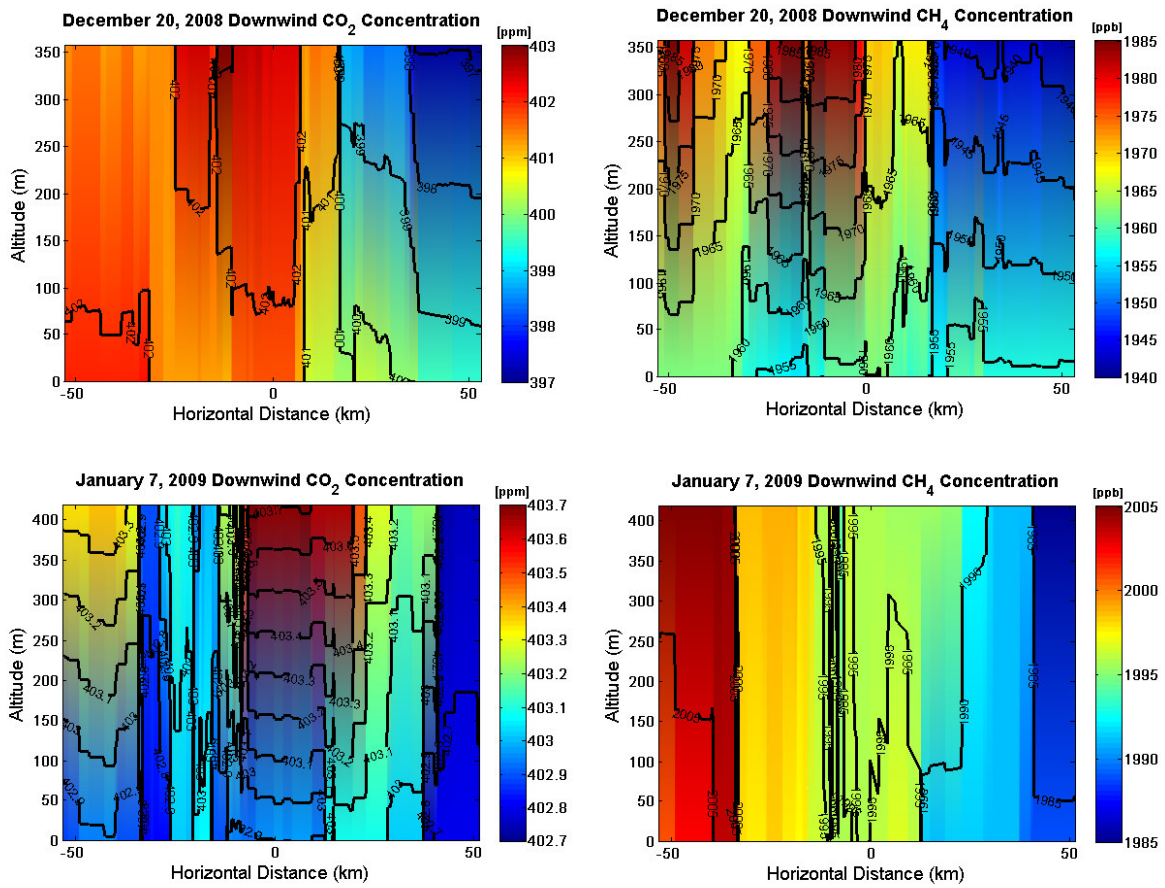



Figure S.3. Downwind $CO_2$ (left) and $CH_4$ (right) concentrations for all eight flights. Warmer colors correspond to higher concentrations. The concentration scale is in ppm for $CO_2$ and ppb for $CH_4$.

## SI.4 Vulcan

Figure S.4 illustrates an example of Vulcan output for one hour of carbon emissions for the grid cells that overlap Indianapolis. Note the grid cell with the largest concentration is near the location of the Harding Street power plant, the largest point source of carbon emissions in the city area. For that cell, the flux for this hour is ~30 $\mu$moleC/$m^2$s.

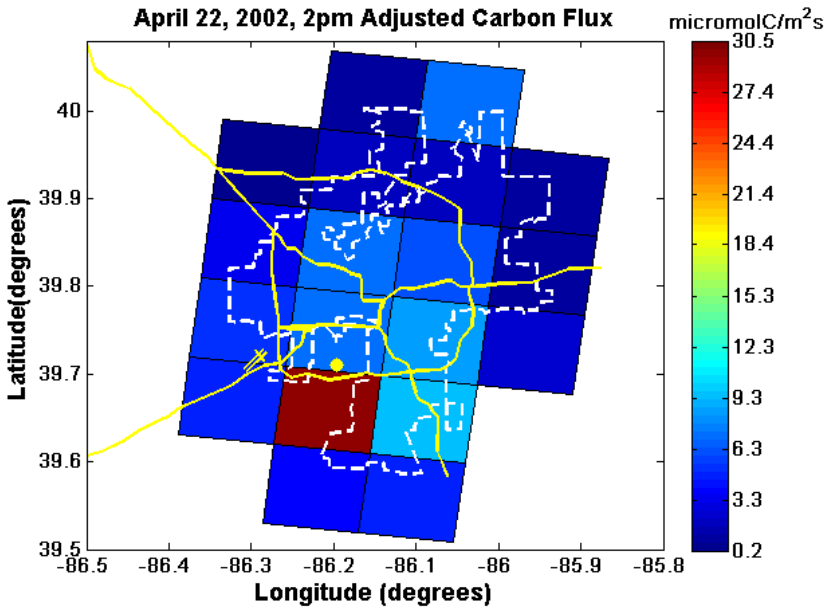
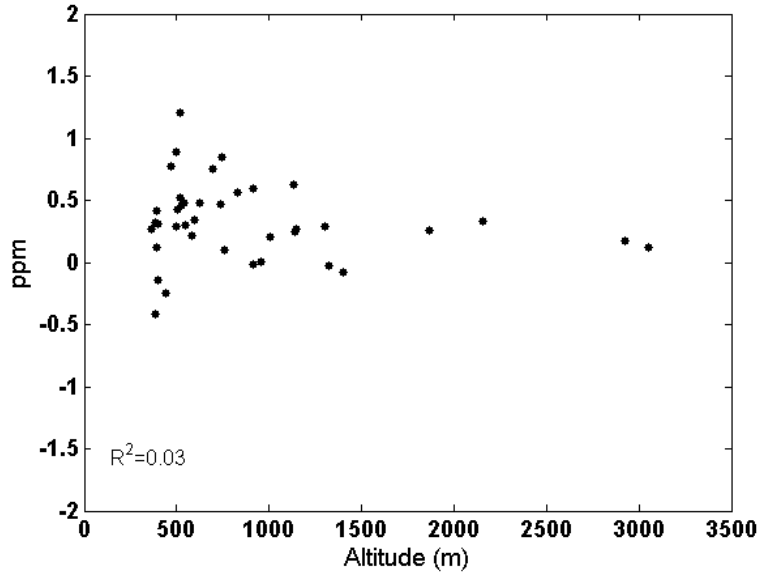



Figure S.4. Vulcan-estimated carbon emissions for April 21, 2008. for 2 pm local time. Harding Street power plant (solid circle), major highways (solid lines), and the Indianapolis International Airport (hatched lines) are marked.

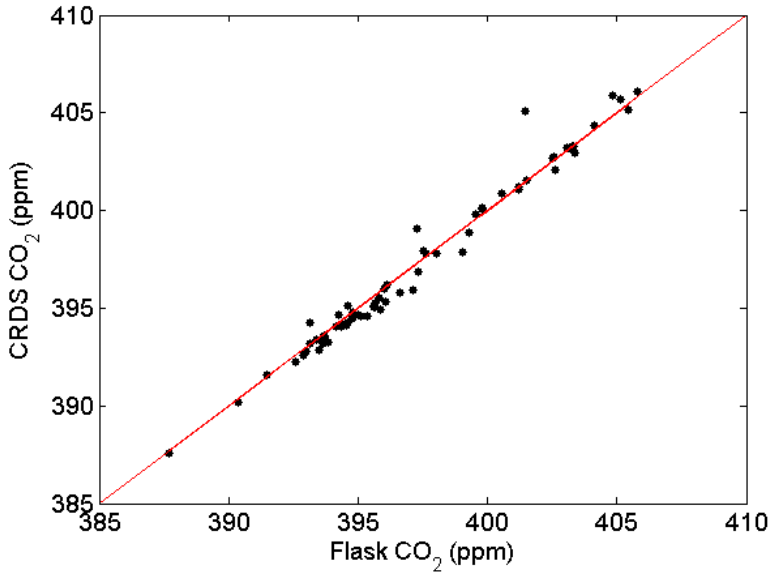
**SI.5 Flask Analyses**

Several regression analysis were done to identify any potential biases present in the comparison between flask and CRDS carbon dioxide and methane measurements. There were not biases found when the difference between the CRDS and flask-measured $CO_2$ was regressed against altitude. Additionally, there were no biases noted when the CRDS $CO_2$ and $CH_4$ were regressed against the flask $CO_2$ and $CH_4$, respectively. Figures S.5, S.6, and S.7 illustrate these regressions.



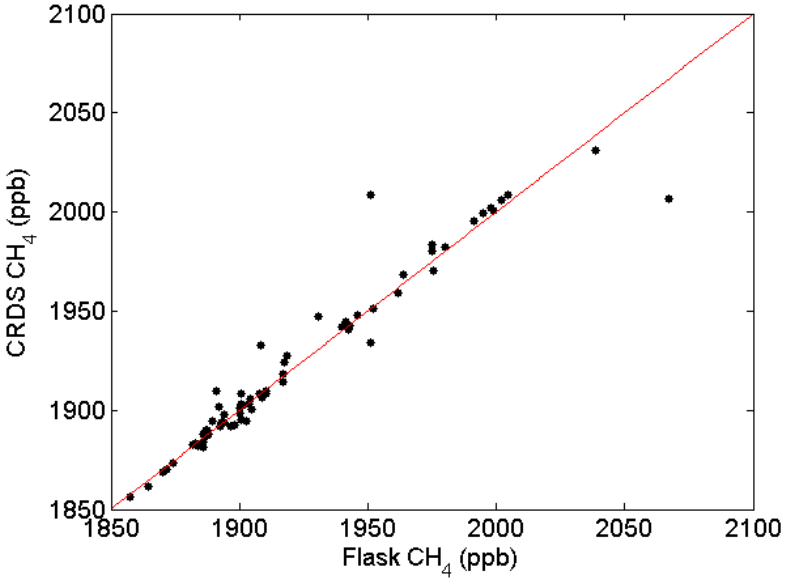

144

145 Figure S.5. Regression of the difference between CRDS $CO_2$ and flask $CO_2$ against altitude.




146

147 Figure S.6. Regression of CRDS $CO_2$ against flask $CO_2$.




148

149 Figure S.7 Regression of CRDS $CH_4$ against flask $CH_4$.

150