Sources of variability in atmospheric CO_2 in an urban environment

Laura McGowan

8 am June 18th, 2013

Background

- On the global scale, CO_2 sources/sinks, annual budgets, and fossil fuel inventories are well known
- This is not the case at regional scales as uncertainty increases (Marland et al., 2007; Rayner et al., 2010)
  - Uncertainty increases because of
    - ↓ CO_2 measurements for a given study area
    - Large uncertainty in the modeled transport

Background

- City/urban anthropogenic CO_2 emissions
  - Most of the world's population lives in cities
    - Increased migration from rural to urban areas
  - Cities are the biggest sources of anthropogenic CO_2
  - Lack of consensus on regulation at country to global scales but cities are taking initiative
- Goal →Quantify daily variations in cross-city CO_2 mole fractions
  - Indication of detectability of city anthropogenic emissions

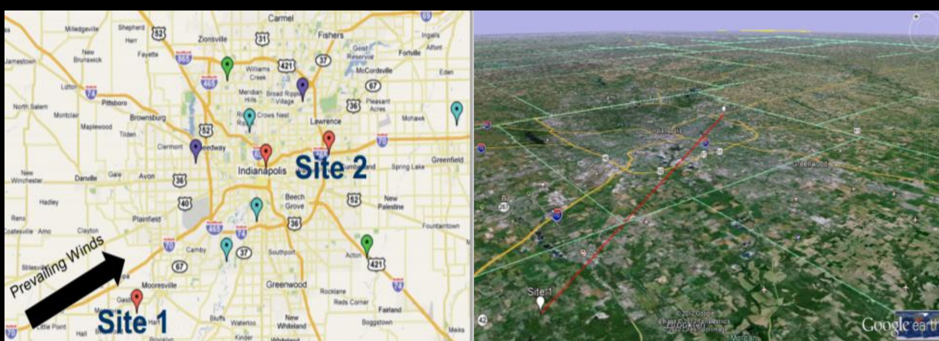
Objectives

- Quantify urban anthropogenic emissions with across-city differences
  - Determine the location and type of largest contributors to across-city CO_2 mole fraction differences
    - Are they from urban emissions?
    - Are there large contributions from outside sources? If so where?
  - Determine if build of CO_2 in urban boundary layer vary significantly from day to day
  - Determine if meteorological variables explain any variation in across-city CO_2 mole fraction differences

Objectives

- Approximate across-city CO_2 mole fraction differences due to urban emissions with simple ABL budget
  - Generalized to other urban areas
- Test importance of fossil fuel emission product resolution on modeled anthropogenic CO_2

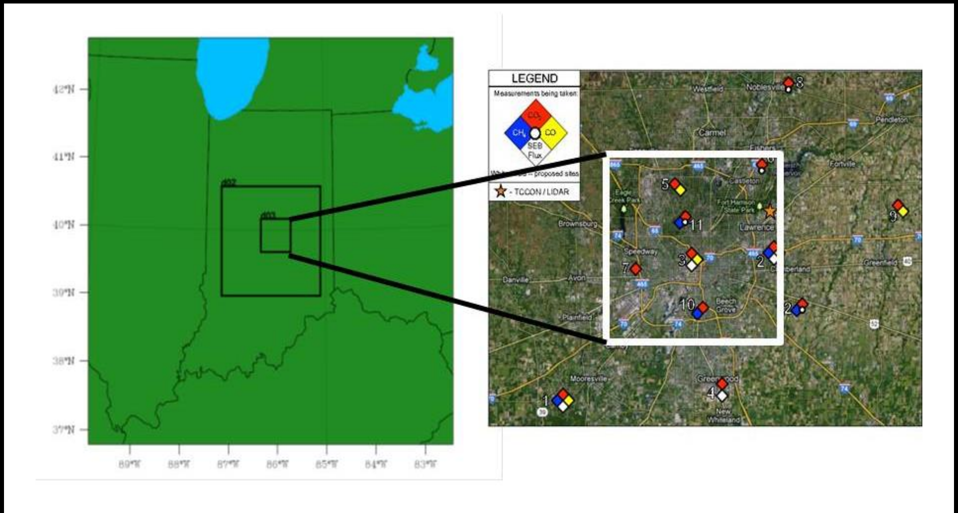
Background
INFLUX PROJECT



Left, INFLUX tower locations. Right, aerial view of Indianapolis.

- Urban scale GHG experiment
  - One of the most dense network
    - Continuous GHGs mixing ratio measurements
    - Weekly flask samples of trace gases
- Why Indianapolis, Indiana?
  - Large city isolated city, on flat terrain, simplifying transport
  - 12th largest US city by population
- Goal of the project→ quantify emissions of anthropogenic CO_2 and CH_4 at 1km^2 resolution
- Current study
  - does not use observations from the network
  - what the network could potential observe

Methods



Telescoped triple nested domains utilized in WRF-ARW simulations with Indianapolis. Grid spacing was 1, 3, and 9 km with dimensions 49, 183, and 675 km for domain one, two, and three respectively

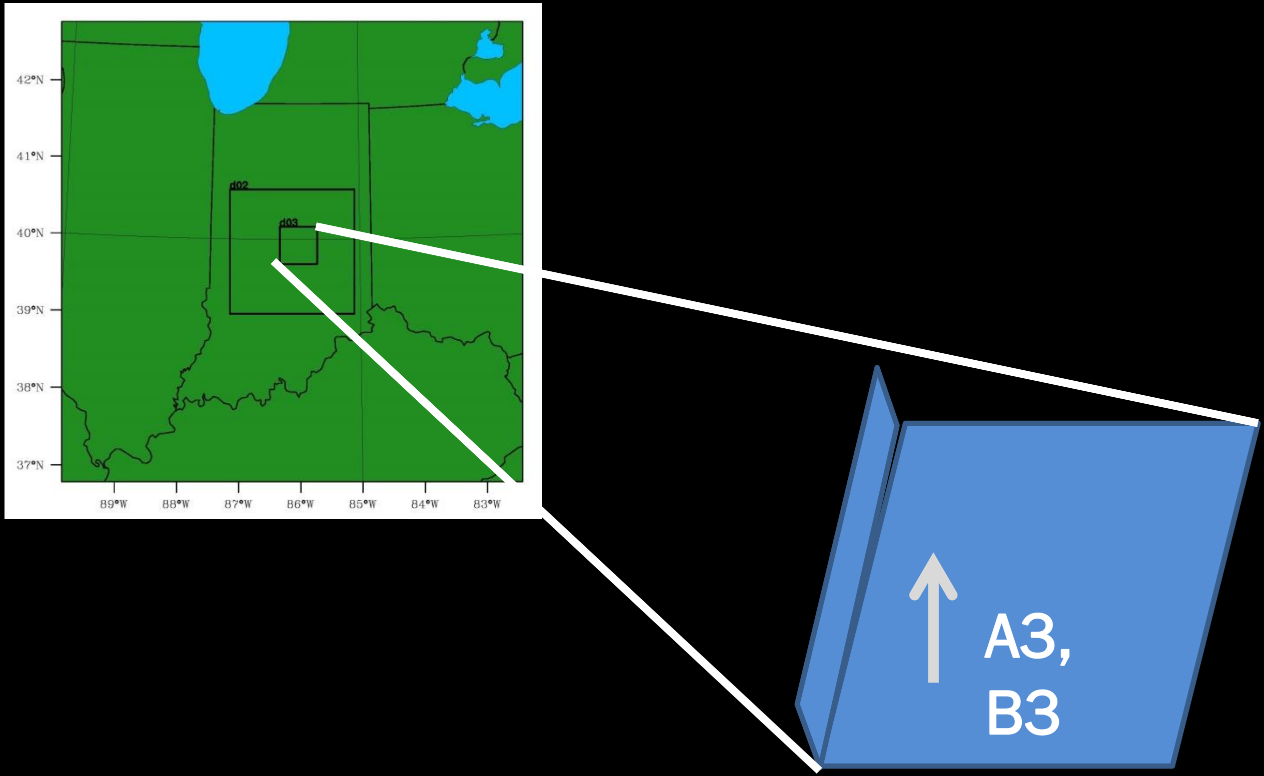
- WRF-ARW (v 3.2.1)
  - Terrestrial input data
    - U S Geological Survey (USGS)
  - Initial atmos. conditions
    - ETA/NAM reanalysis product
- GHGs simulated were anthropogenic and biogenic CO_2
- July and February 2011
  - Extremes in ABL height, ABL mixing, and biogenic flux
    - Summer a maximum
    - Winter a minimum

Methods: Emission products and tracers

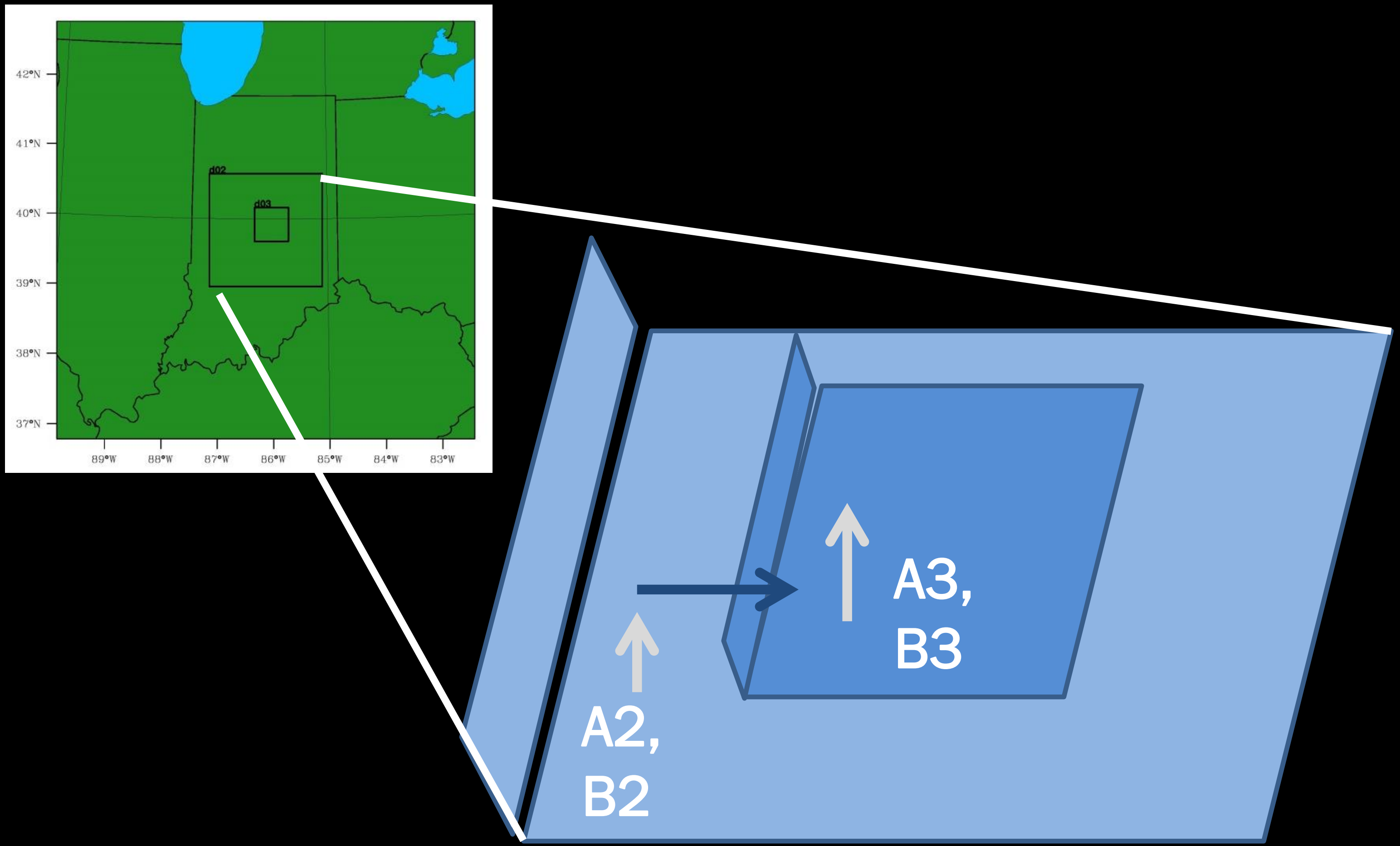
- Tracers tracked different CO_2 emission types and sources
  - Passive conserved scalars
- Emission was input into the surface of the domain and lateral boundaries
- Emission input data
  - Derived using either models and or anthropogenic emission inventory data
- Data products used were state-of-the-art inventories
- Know source of all molecules in modeled CO_2 mole fraction

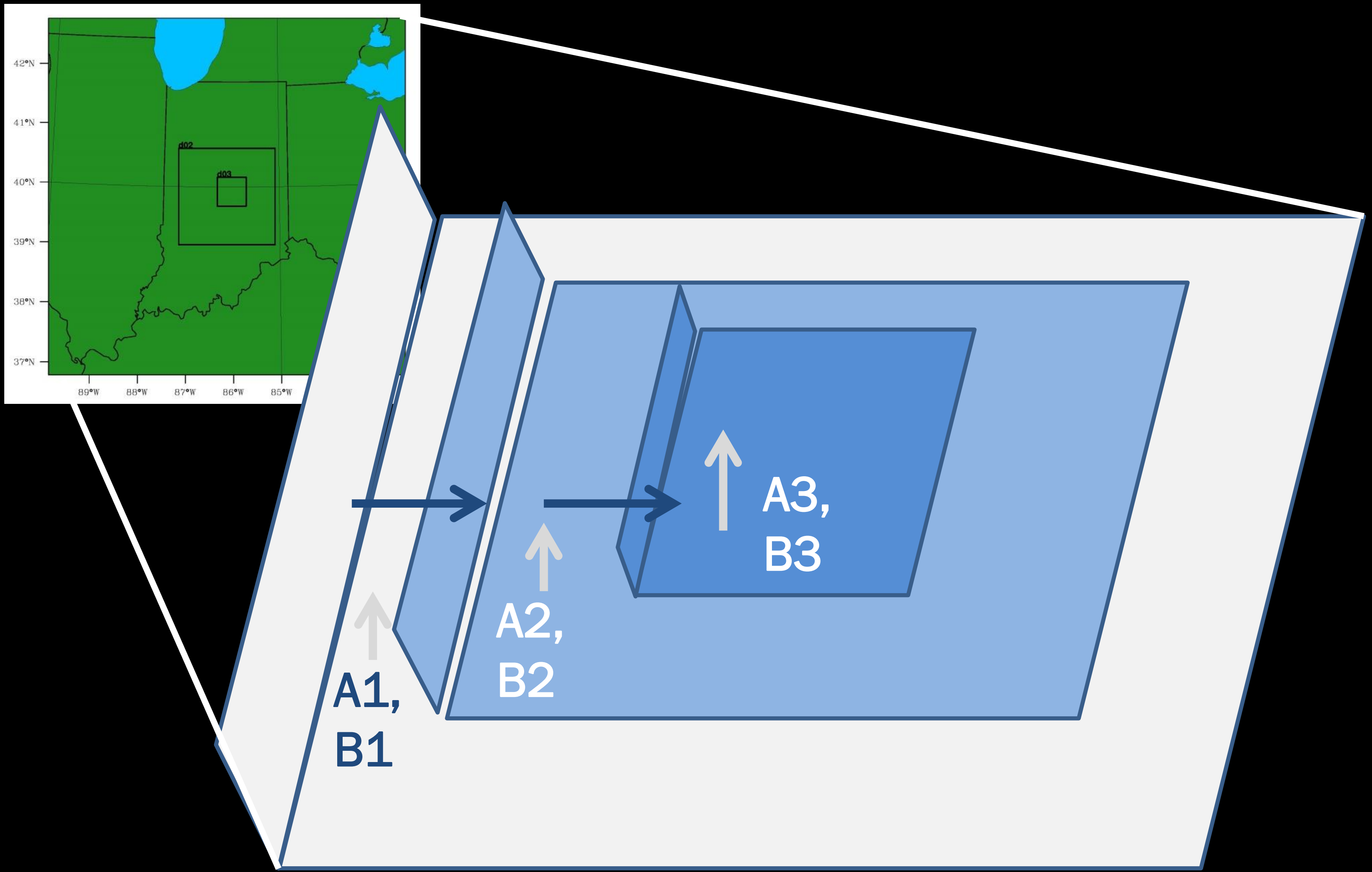
Methods: Emission products and tracers

- 2 emission data products were used for surface emissions
  - Hourly input
  - Biogenic CO_2= 2011 Carbon Tracker (CT) product, 1 degree
  - Anthropogenic $CO_{2=}$ Vulcan, 10 km^2
- The lateral boundary CO_2 input
  - 6-hourly input
  - Also a 1 degree
  - CT product
  - Anthropogenic and biogenic CO_2
- CO_2 is a passive conserved scalar in the model



Approximates the city boundaries
Therefore the focus of the study


42°N
41°N
40°N
39°N
38°N
37°N
89°W
88°W
87°W
86°W
85°W
84°W
83°W
d02
d03
A3,
B3
A2,
B2



42°N
41°N
40°N
39°N
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89°W
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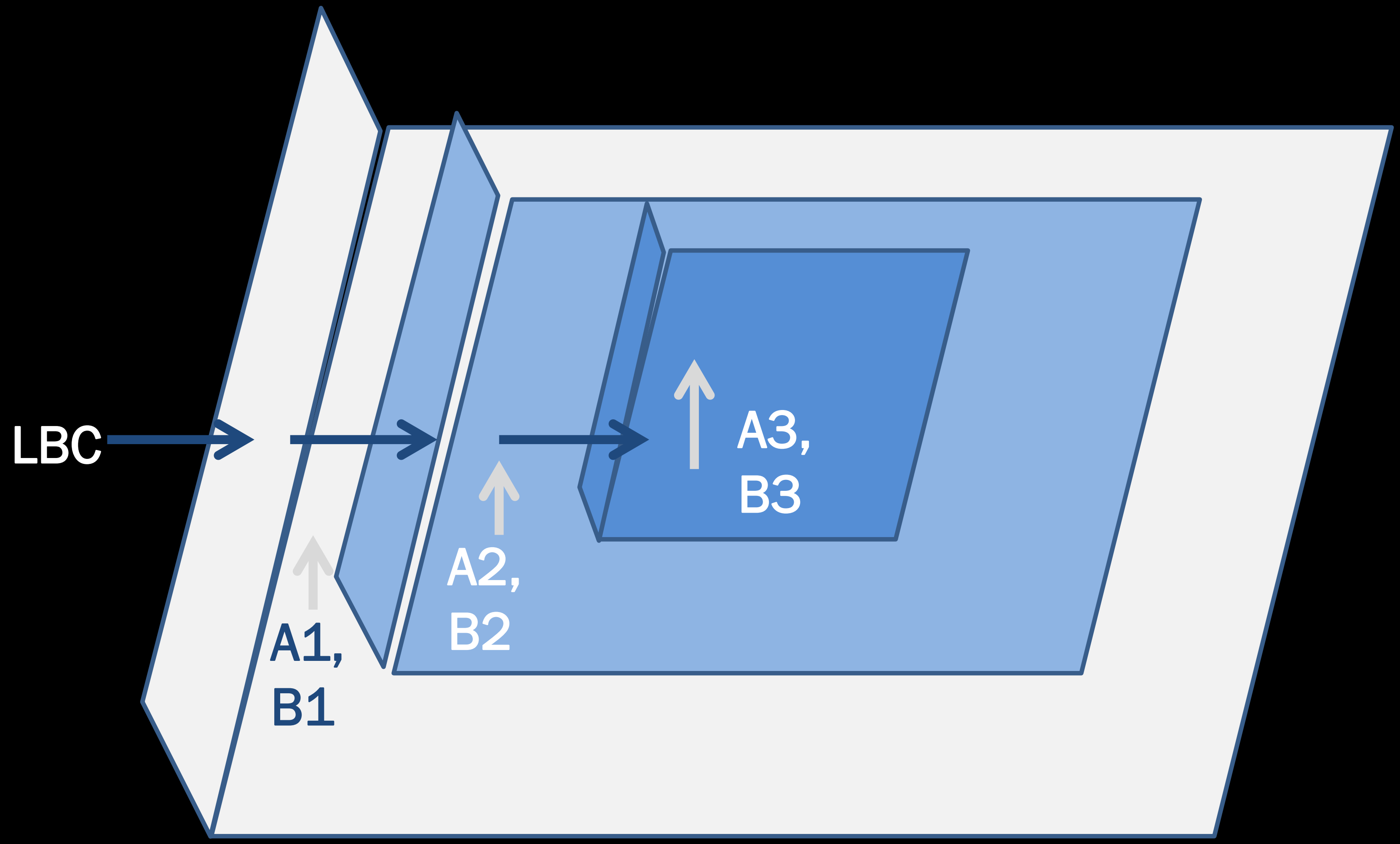
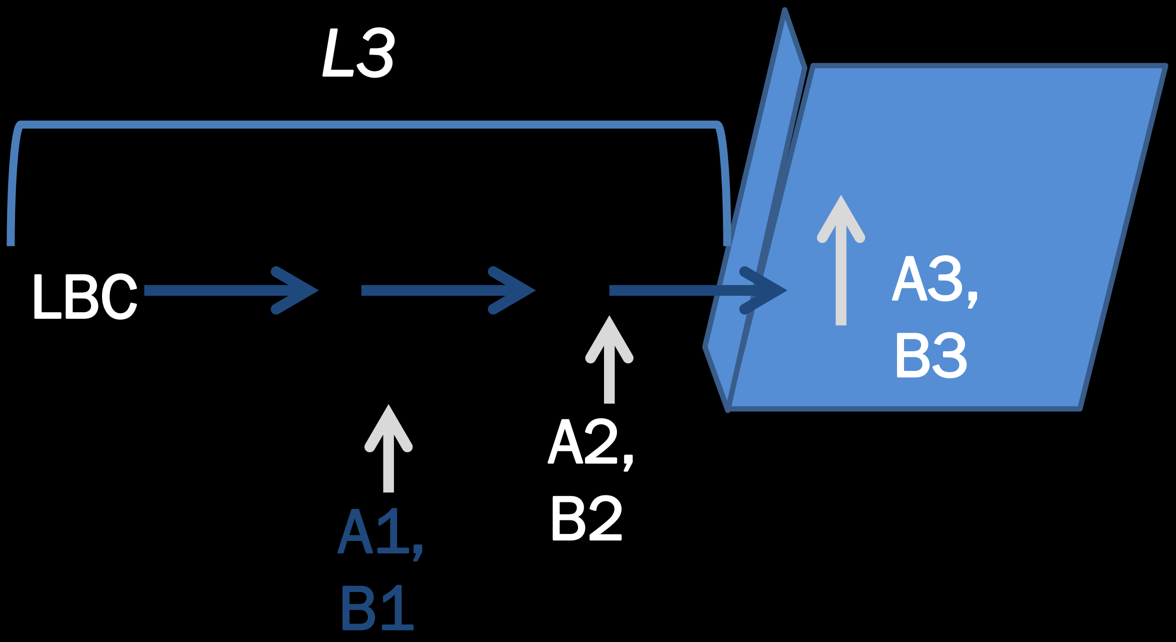
87°W
86°W
85°W
d02
d03
A1,
B1
A2,
B2
A3,
B3



LBC
A1,
B1
A2,
B2
A3,
B3

Total inflow into lateral boundaries of domain three =L3

L3 = LBC + A1 + B1 + A2 + B2



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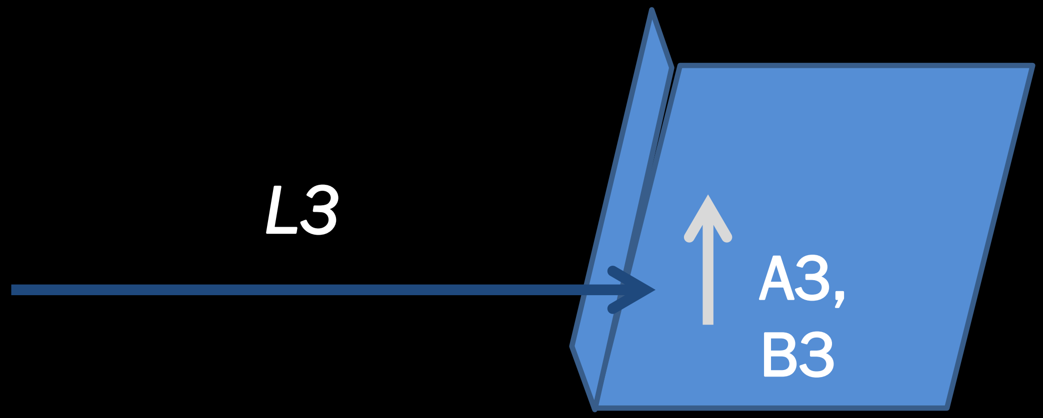
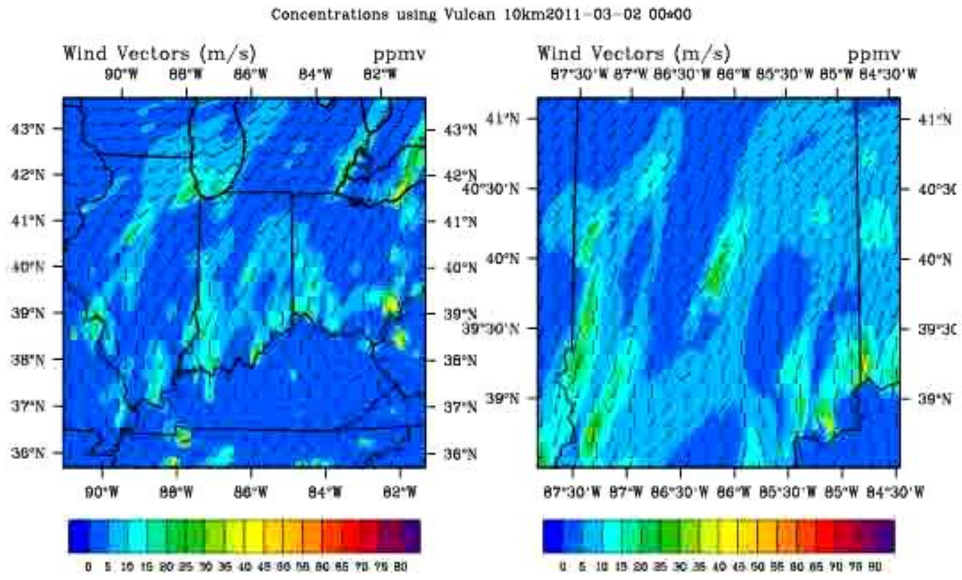
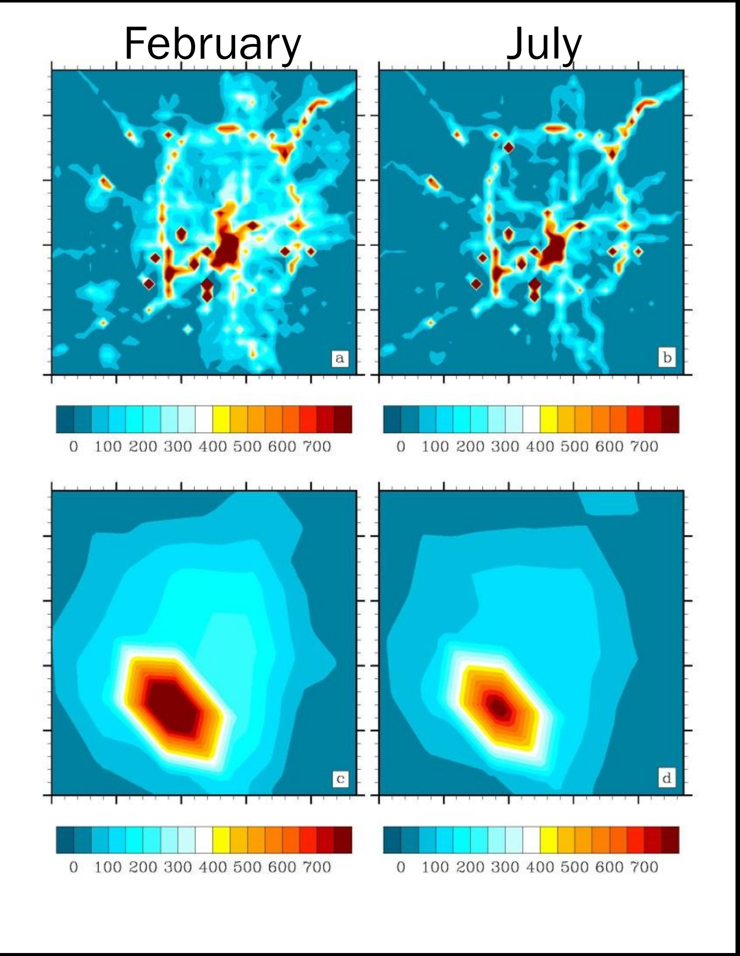



Concentrations using Vulcan 10km2011-03-02 00:00
Wind Vectors (m/s)
ppmv
Wind Vectors (m/s)
ppmv

Methods: Emission products and tracers



- Simulations were rerun with a finer resolution ($1km^2$) anthropogenic CO_2 surface flux in domain 3
  - Hestia
  - Congruent the total flux of Vulcan on the county scale
- Examine
  - Changes to spatial distribution and magnitude of anthropogenic mole fractions

Methods: Emission products and tracers

For all the analyses CO_2 mole fractions were

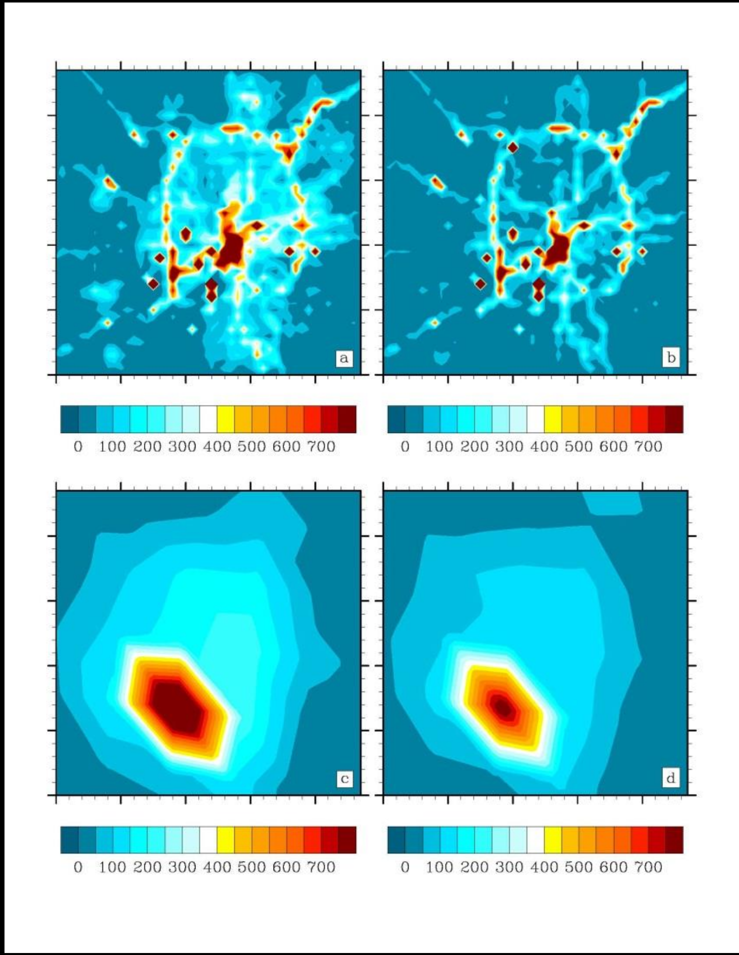
- Averaged over the well-mixed times (1000-1600 LST)
- Averaged over the lower-ABL (approximately 300 m)
  - Avoids uncertainty in modeled vertical mixing
  - Readily comparable to measurements
- Within or averaged over domain 3

$\int_{z_0}^{z_7} \int_{t_0}^{t_1} CO_2(x, y)\ dz\, dt$ or

$\int_{x_0}^{x_1} \int_{y_0}^{y_1} \int_{z_0}^{z_7} \int_{t_0}^{t_1} CO_2\ dx\, dy\, dz\, dt$

Methods: CO_2 emissions data

	Winter	Summer
	μmol m^{-2} s^{-1}	
Total Hestia	5.16	3.83
Ad3	5.32	3.88
Percent difference Ad3 to Hestia Total	-3.0%	-1.4%



Methods: Emission products and tracers

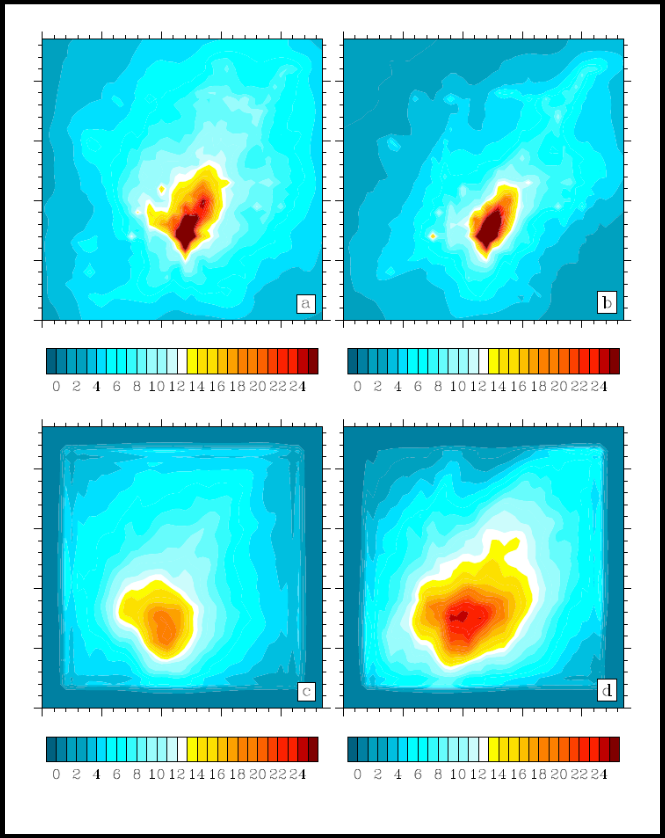
- L3 can interfere with the detectability of city CO_2 emissions
- Identify major contributors to the variability in L3
  - Future studies reduce the variability in identified regions and therefore increase the accuracy of urban CO_2 emission detection

Outline of results

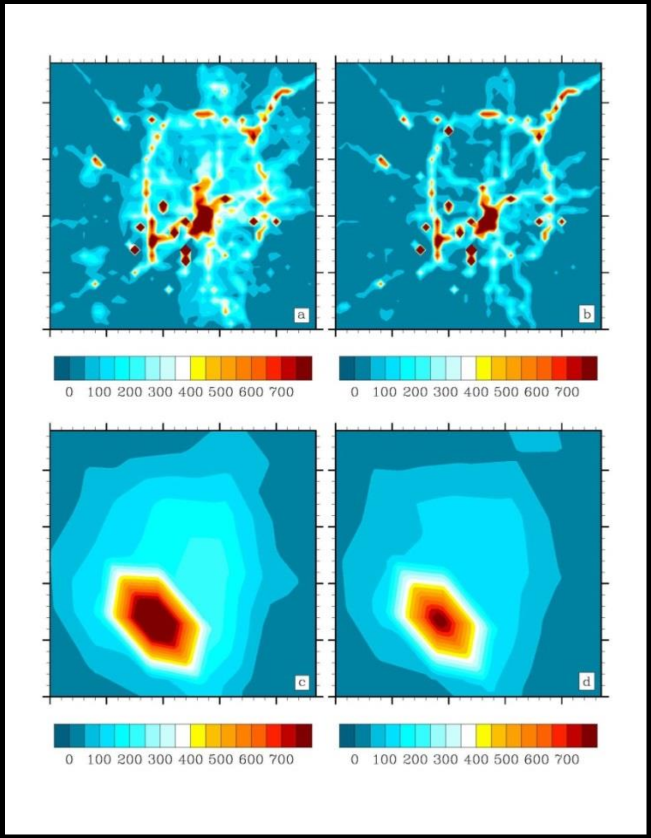
- **Evaluation of urban CO_2 mole fractions**
- Quantification of daily variations in cross-city CO_2 mole fractions
  - Cross-city differences in CO_2 with 3 methods
  - Along- and across-wind transects of CO_2
  - Meteorological correlations
  - Dimensionless CO_2 difference

Results:
Evaluation of CO_2 mole fractions

Mole fractions (ppm)



Emissions (µmol m^{-2} s^{-1})



Days 4 through 27 for February 2011 average well-mixed CO_2 mole-fraction for domain three in ppm

Results:
Evaluation of CO_2 mole fractions

Winter (ppm)	
Total	389.8
LBC	***380.6***
A1	4.2
A3	2.4
A2	1.4
B1	0.8
B2	0.3
B3	0.1

Summer (ppm)	
Total	375.2
LBC	***380.3***
B2	-6.6
B3	-3.4
A1	1.9
B1	1.4
A3	0.9
A2	0.7

- Domain lower-ABL seasonally averaged CO_2 mole fractions
- As expected, LBC two order of magnitude larger in both seasons

Results:
Evaluation of CO_2 mole fractions

Winter (ppm)	
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- Domain lower-ABL seasonally averaged CO_2 mole fractions
- As expected, LBC two order of magnitude larger in both seasons
  - A3 1 to 2 ppm
- To infer city emission have to take across city differences
  - Reduce background influence

Outline of results

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  - Cross-city differences in CO_2 with 3 methods
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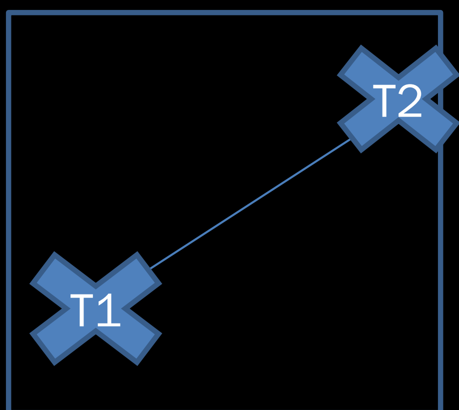
Cross-city differences in CO_2 with 3 methods

- Isolating CO_2 mole fraction from city emissions, A3, from LBC
- 3 methods calculate CO_2 differences between two cross city points that were
  - i) fixed in space along- the prevailing wind
  - ii) changed with wind direction
  - iii) changed with wind vectors
- Distance between points 30 km
  - Encompassing most urbanized areas
- Δ refers to cross-city differences

i) Fixed point

-Stationary
-along prevailing wind direction

$$\int_{t_2}^{t_1}\int_{z_0}^{z_7} CO_2(x_{f2}, y_{f2})\, dt\, dz$$

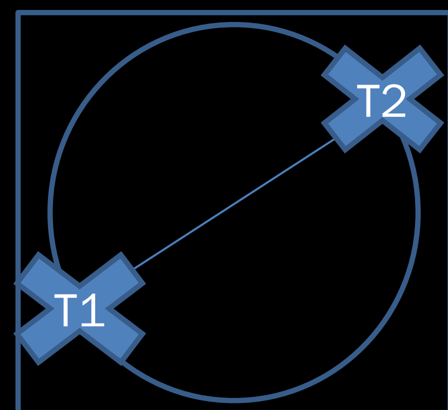


$$\int_{t_2}^{t_1}\int_{z_0}^{z_7} CO_2(x_{f1}, y_{f1})\, dt\, dz$$

ii) Wind direction

-always along wind

$$\int_{t_2}^{t_1}\int_{z_0}^{z_7} CO_2(x_{f2}, y_{f2})\, dt\, dz$$

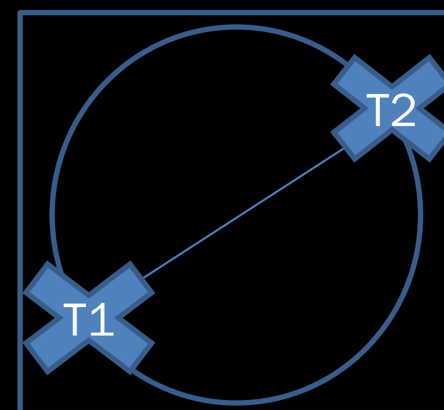


$$\int_{t_2}^{t_1}\int_{z_0}^{z_7} CO_2(x_1, y_1)\, dt\, dz$$

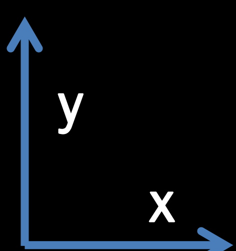
iii) Wind vector

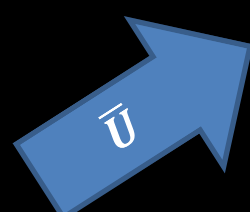
-same as direction but,
-Lagrangian sampling

$$\int_{z_0}^{z_7} CO_2(x_2, y_2, t_2)\, dz$$



$$\int_{z_0}^{z_7} CO_2(x_1, y_1, t_1)\, dz$$





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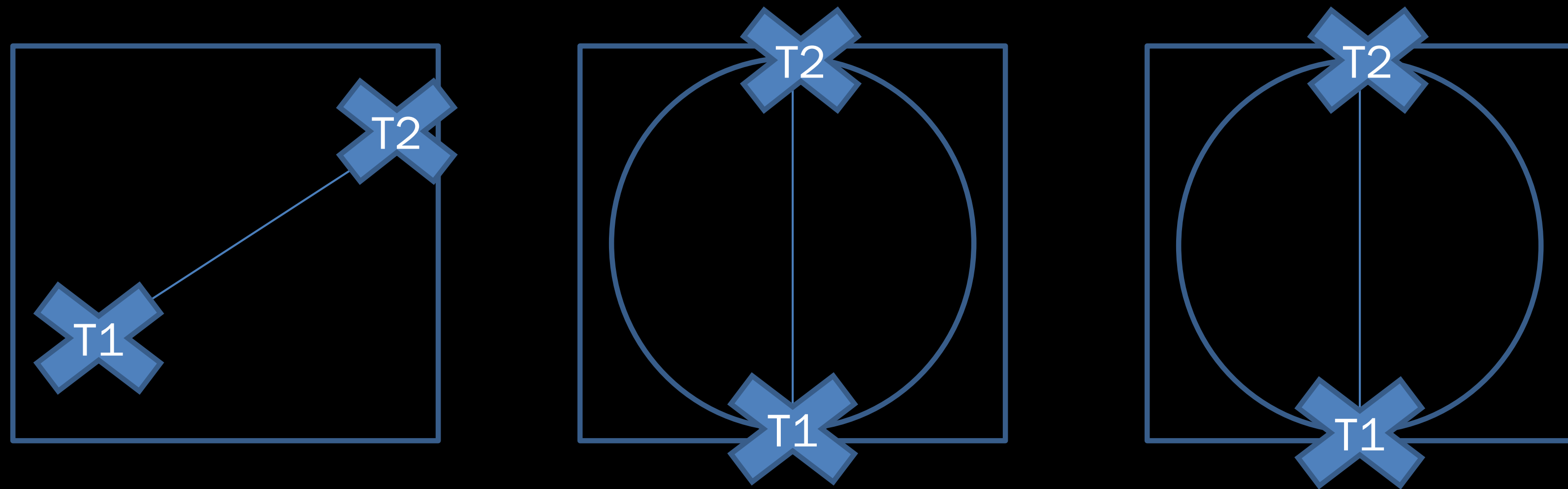

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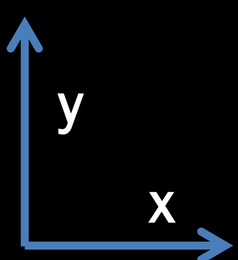

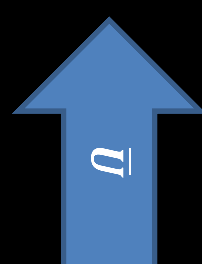

$$\int_{t_2}^{t_1}\int_{z_0}^{z_7} CO_2(x_{f2}, y_{f2})\,dt\,dz$$

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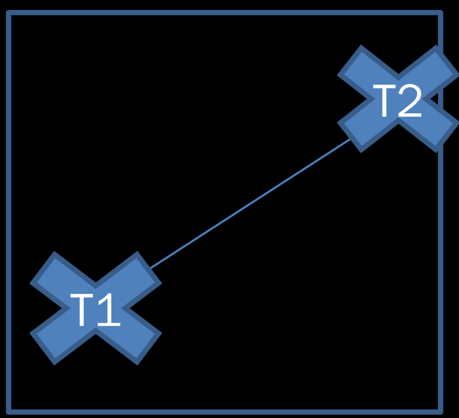

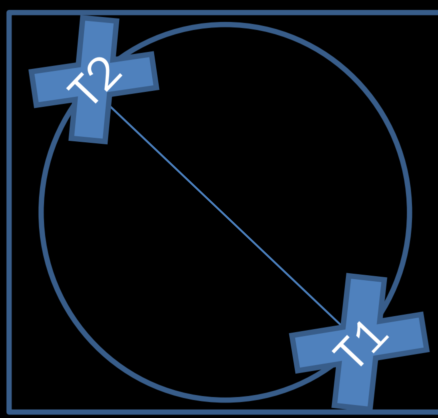

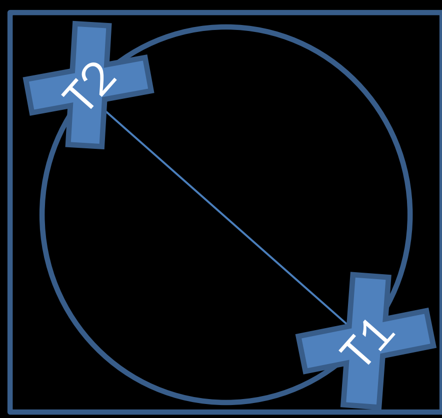

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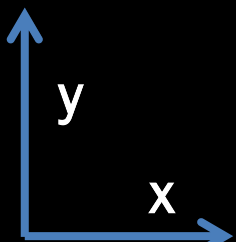

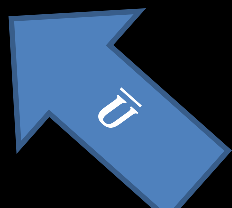

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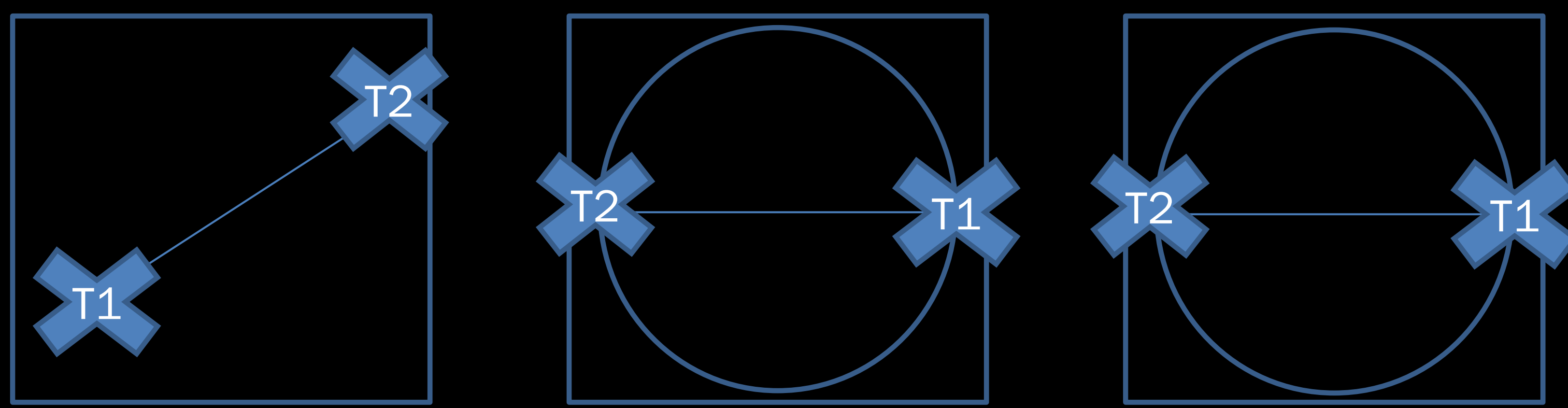

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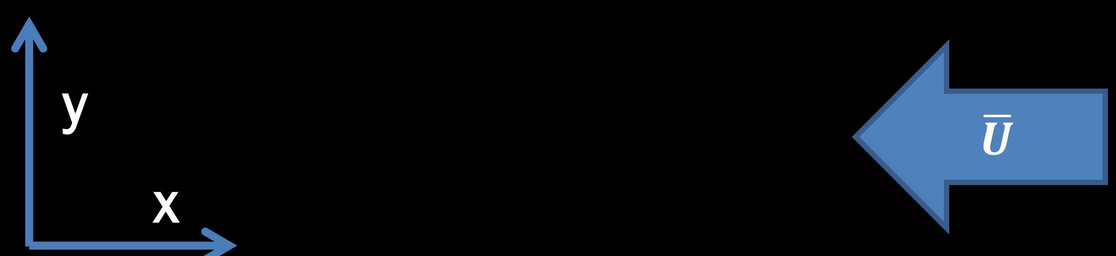

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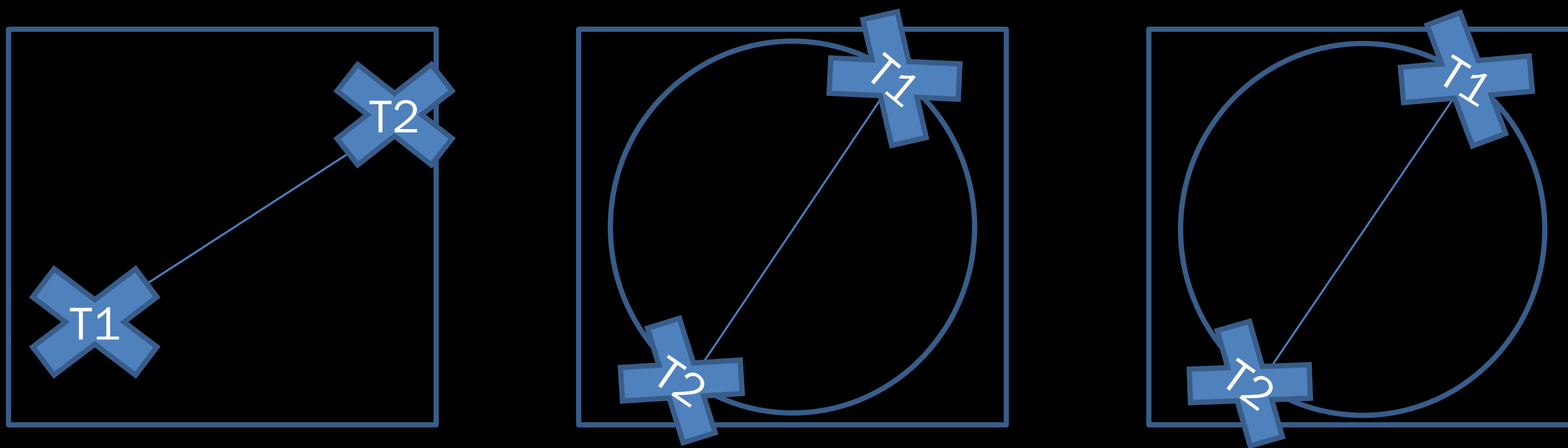

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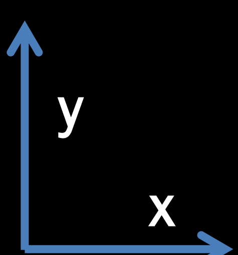
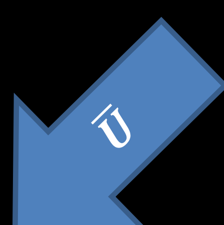
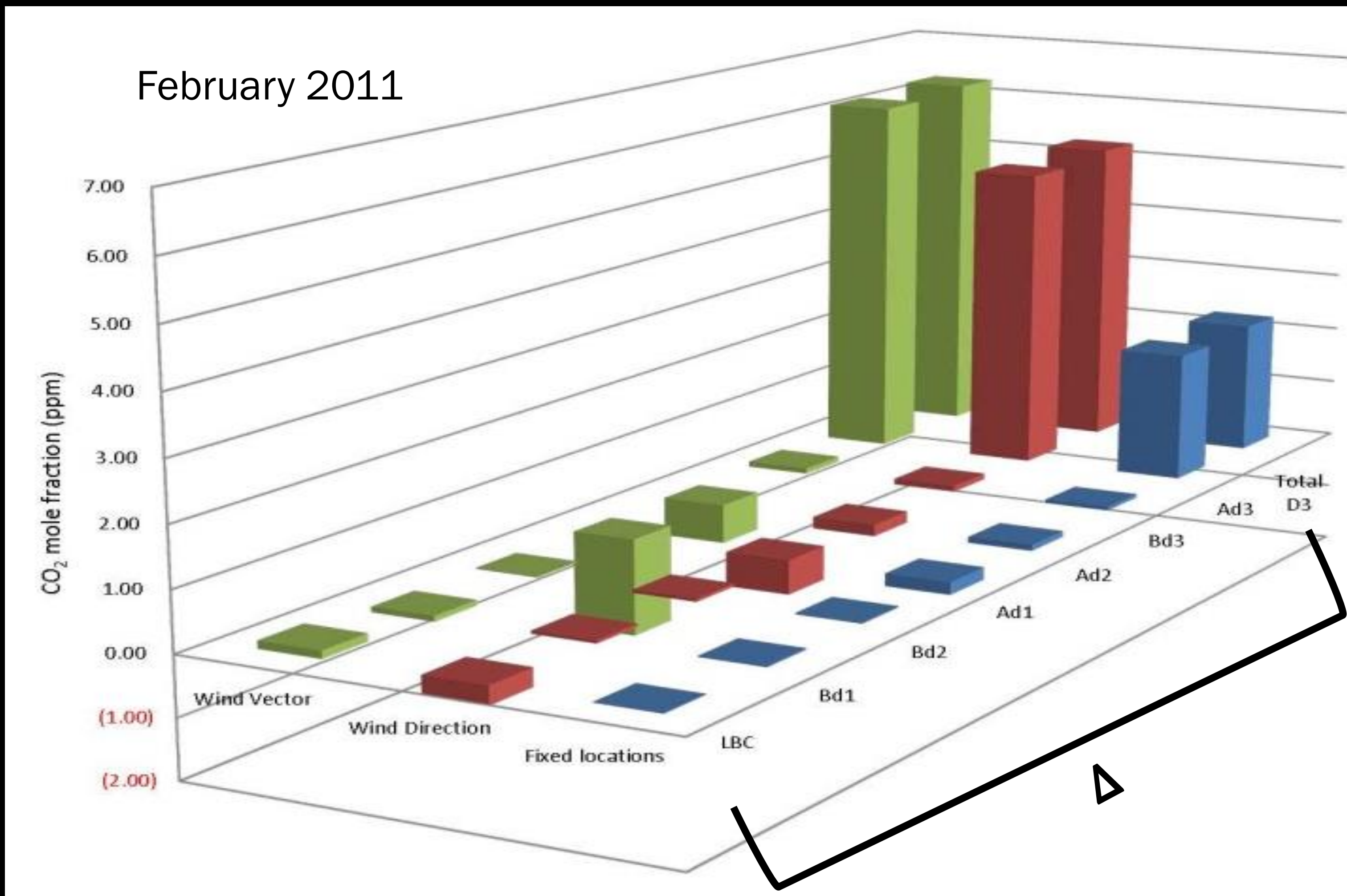




Cross-city differences in CO_2 with 3 methods



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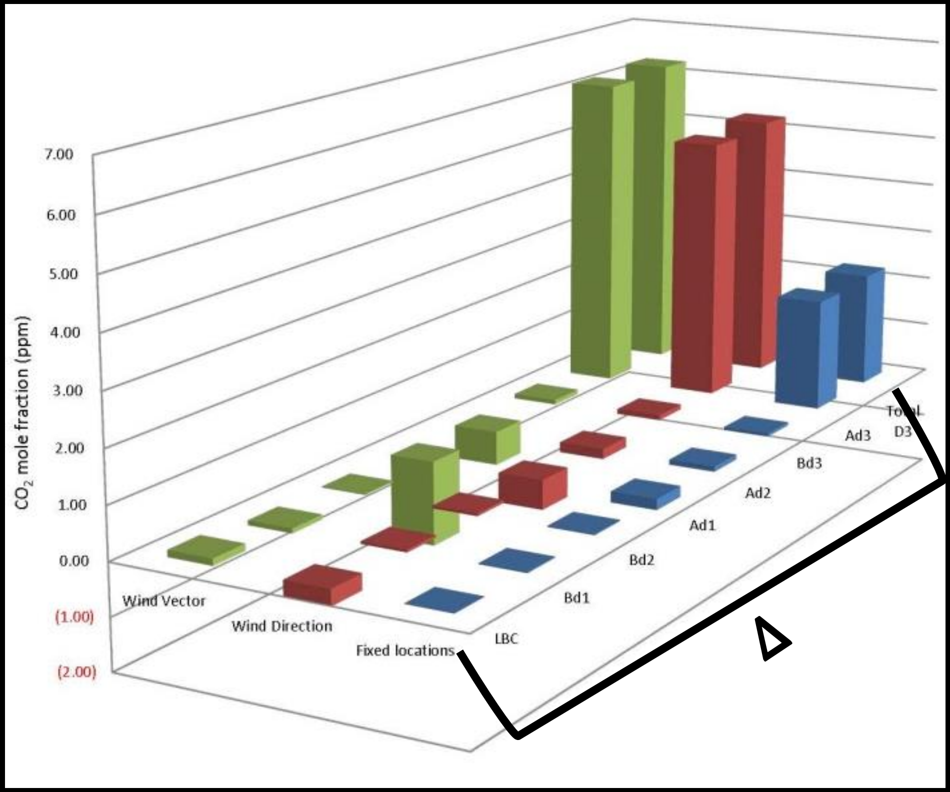
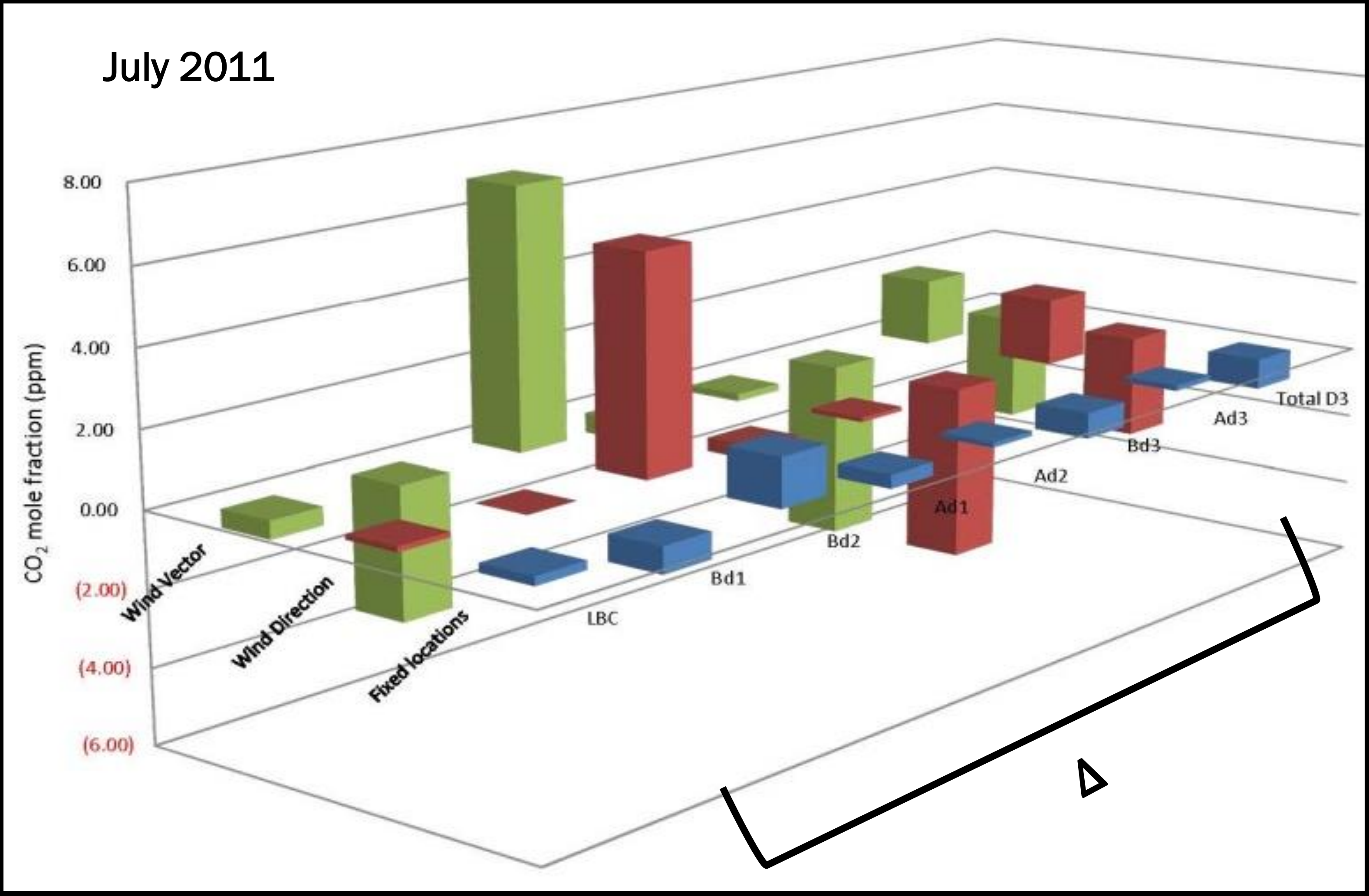
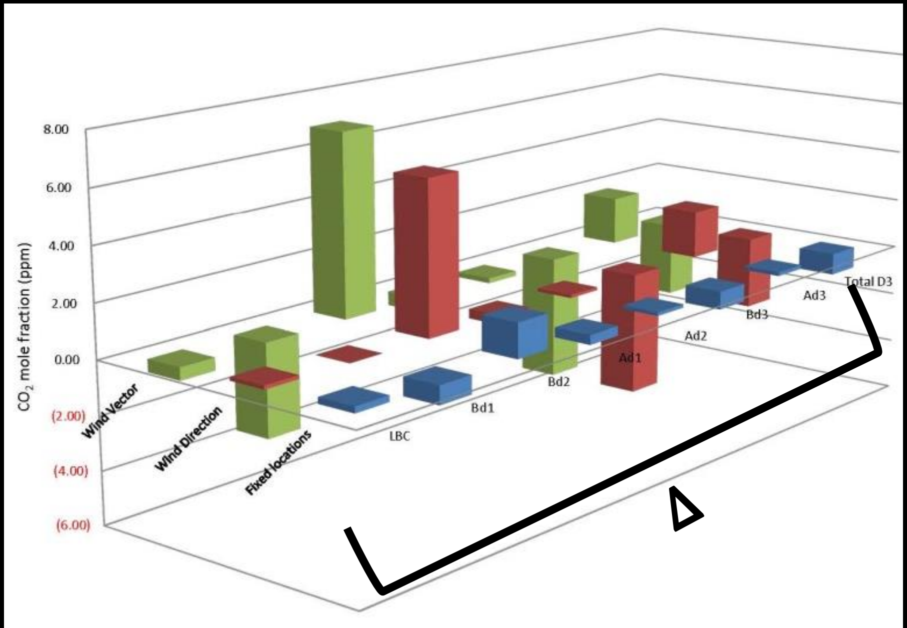


- February 2011
- A3 along-wind across city CO_2 mole fraction differences were large compared to all other CO_2 components
- **ΔA3 = 4.5 ppm**
- **ΔA1 = -0.8 ppm**

Cross-city differences in CO_2 with 3 methods



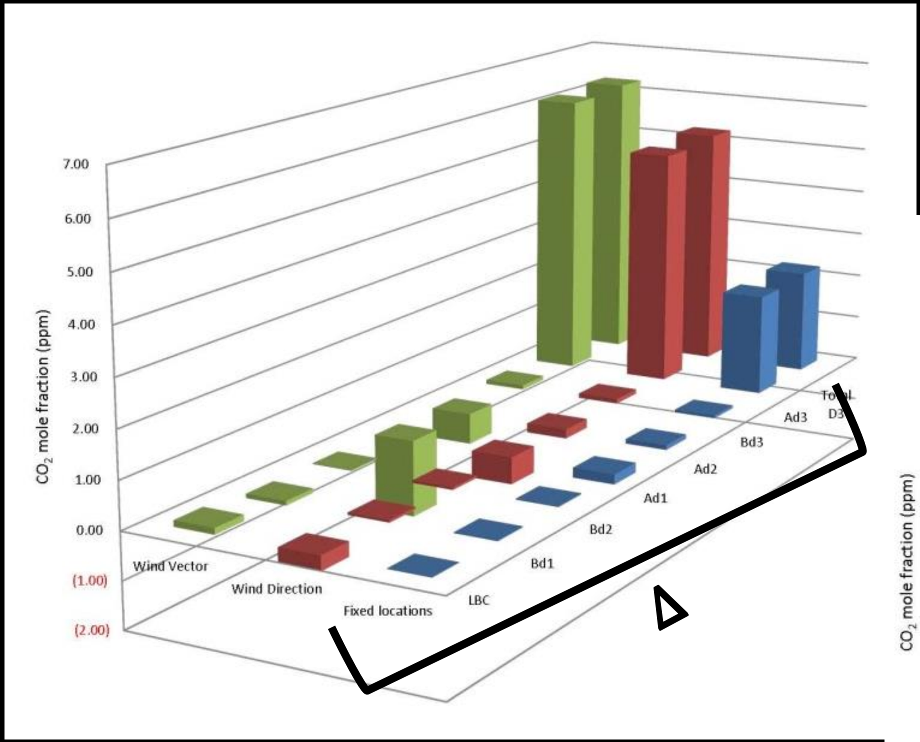
Cross-city differences in CO_2 with 3 methods



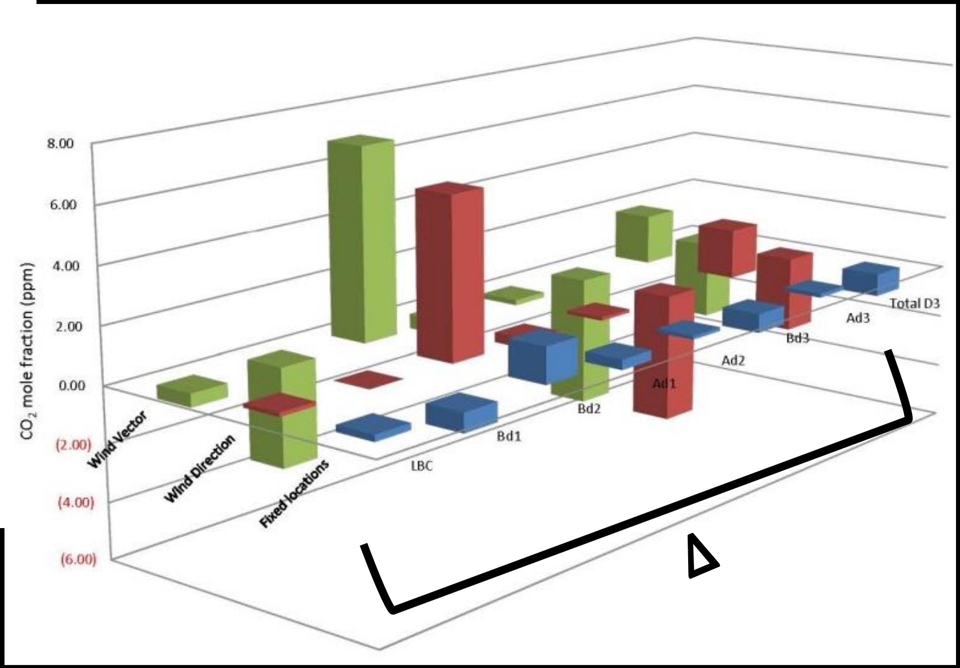
- July 2011
  - B2, B1, and LBC have largest influence
- ΔB2 =4.7 ppm
- ΔB3 = -3.4ppm
- ΔA3 = 1.2 ppm

Cross-city differences in CO_2 with 3 methods

Winter



Summer

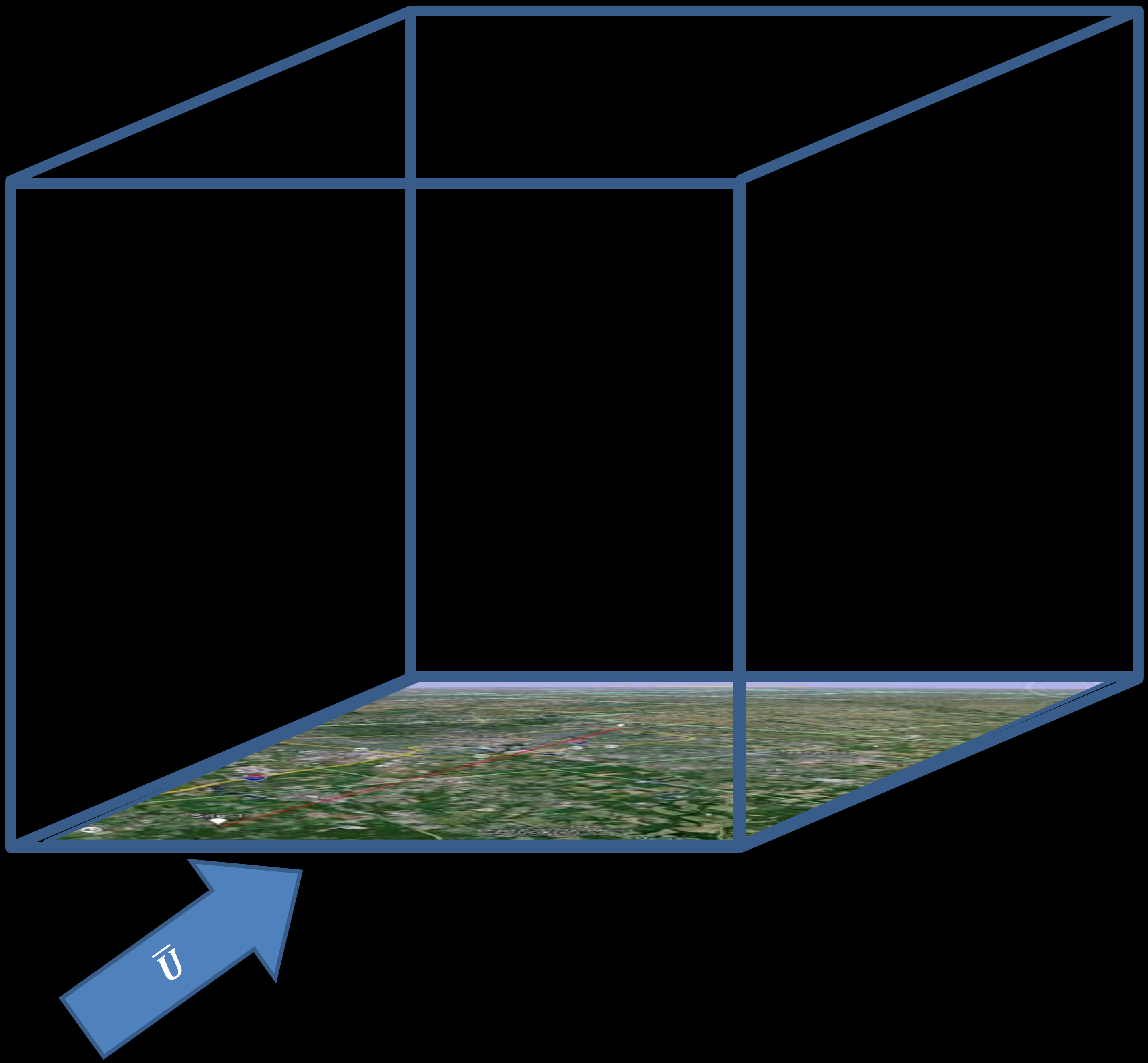


Outline of results

- Evaluation of urban CO_2 mole fractions
- Quantification of daily variations in cross-city CO_2 mole fractions
  - Cross-city differences in CO_2 with 3 methods
  - Along- and across-wind transects of CO_2
  - Dimensionless CO_2 difference
  - Meteorological correlations

Results: Cross-city transects of CO_2

- Structure and the range of the well-mixed CO_2 mole fractions
  - Same as ***wind direction method*** but
    - All values along transect (not just start and end)
    - Both along- and across-wind transects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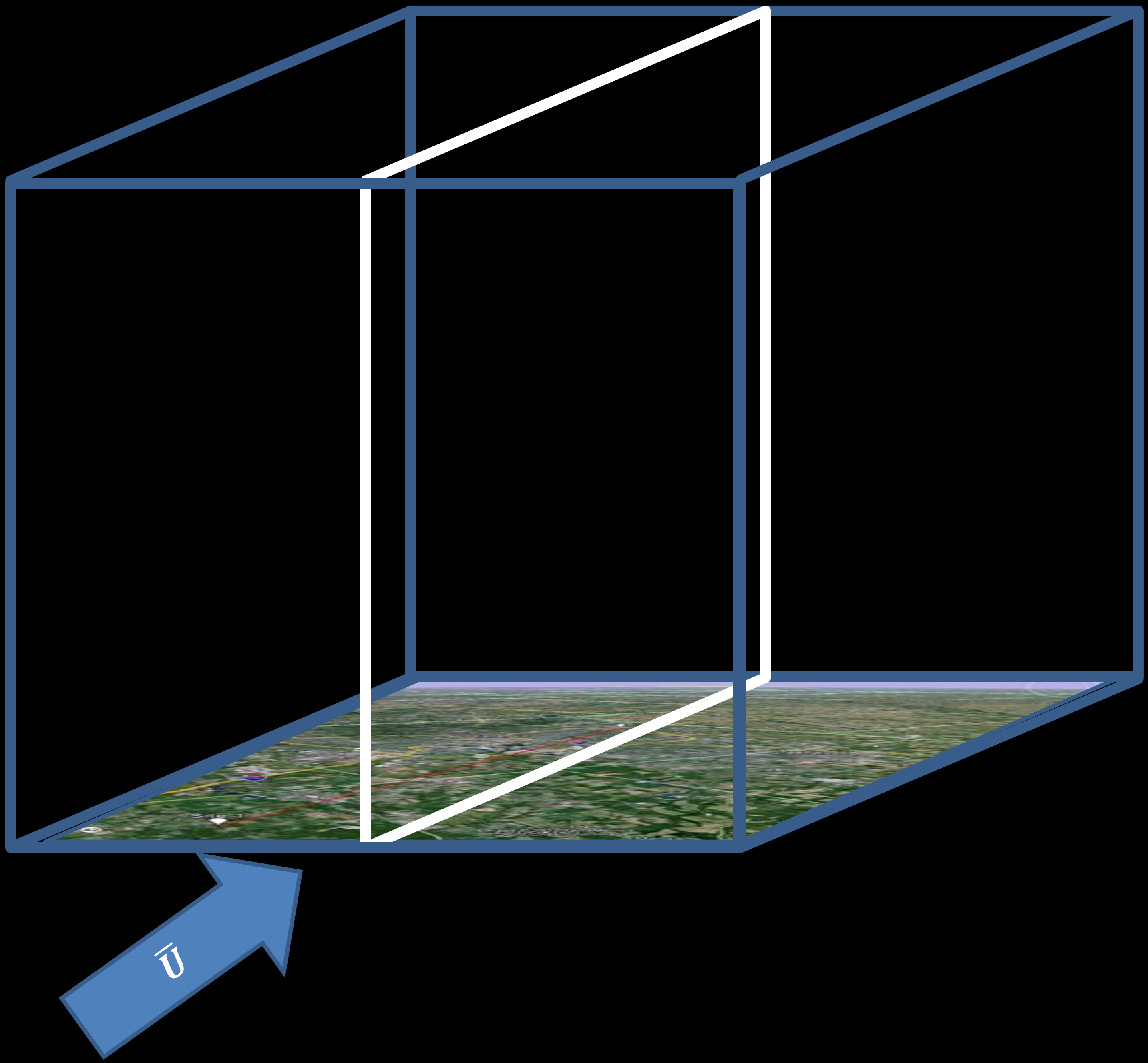
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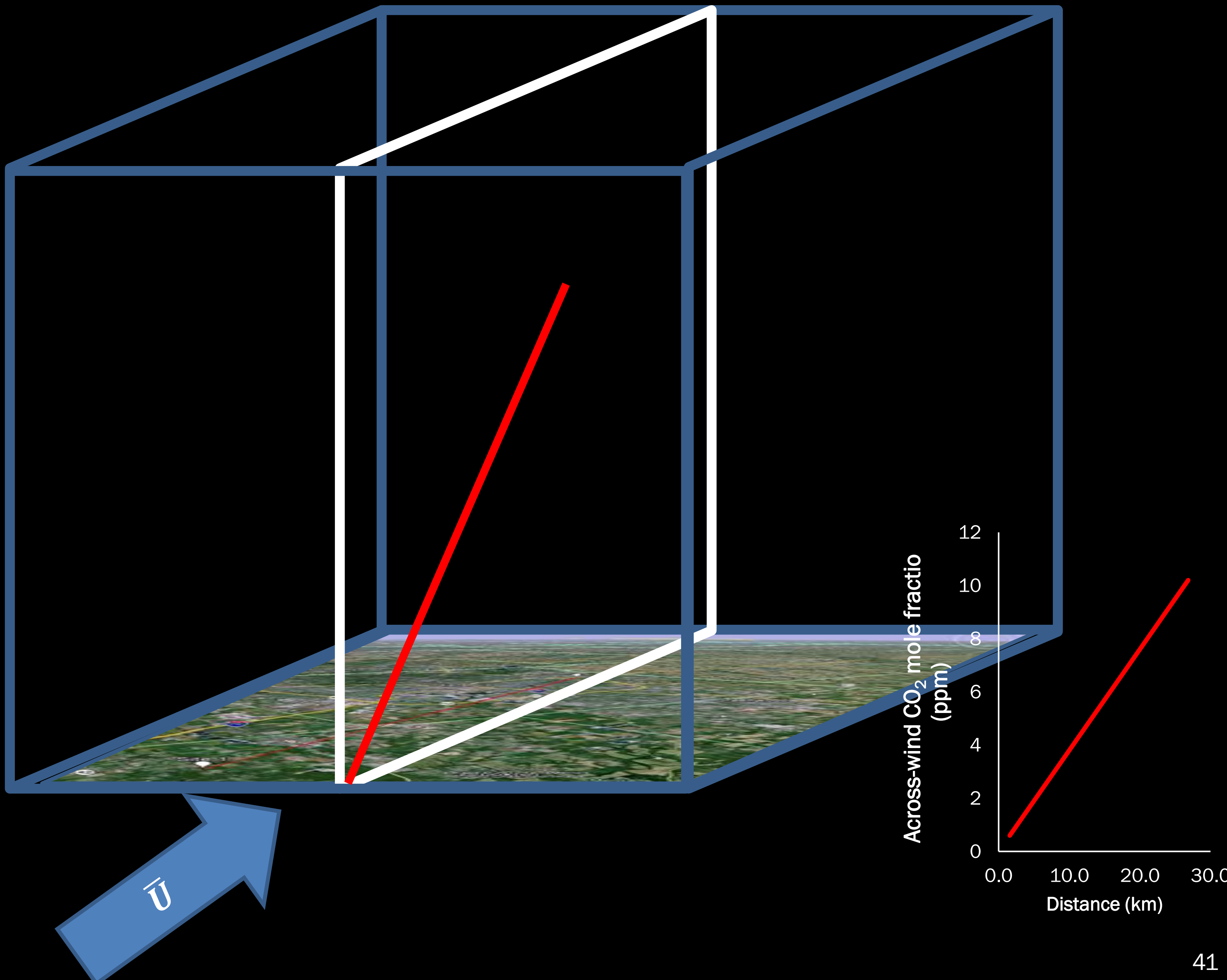
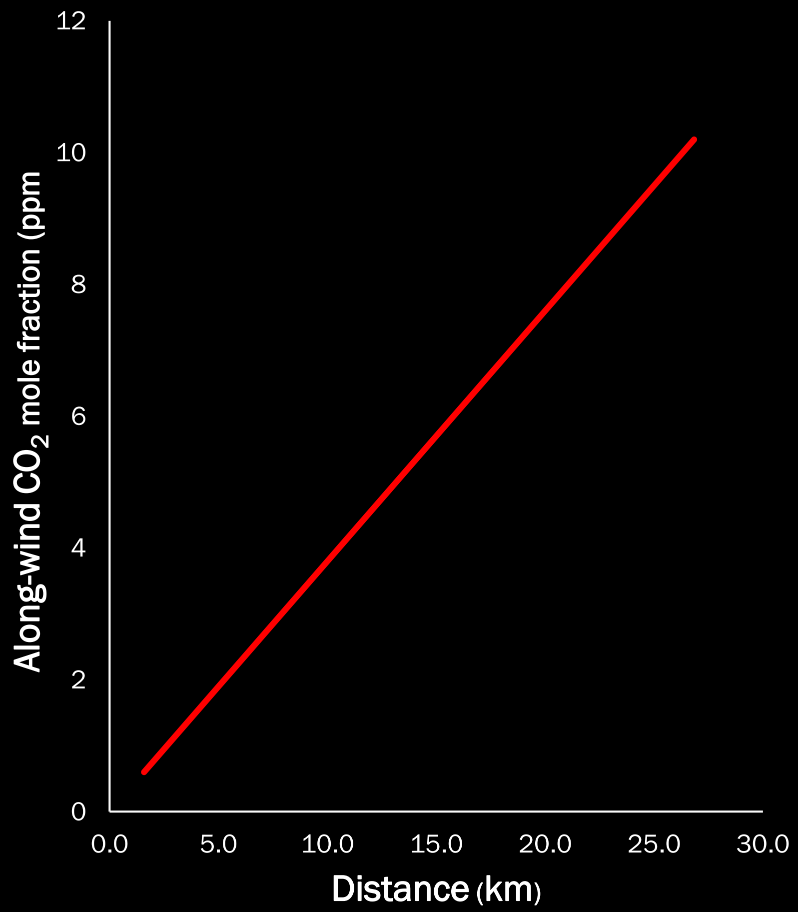
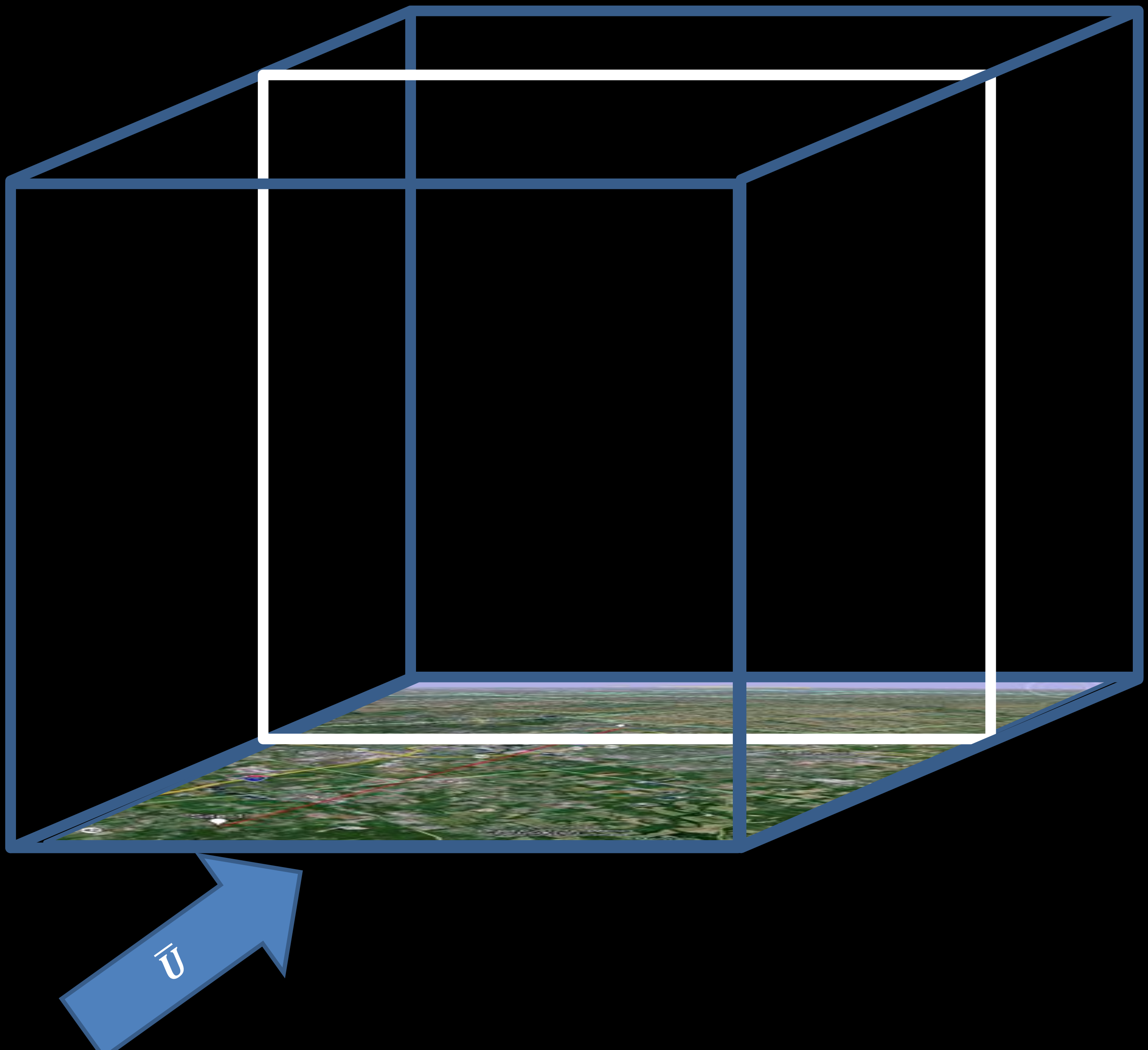
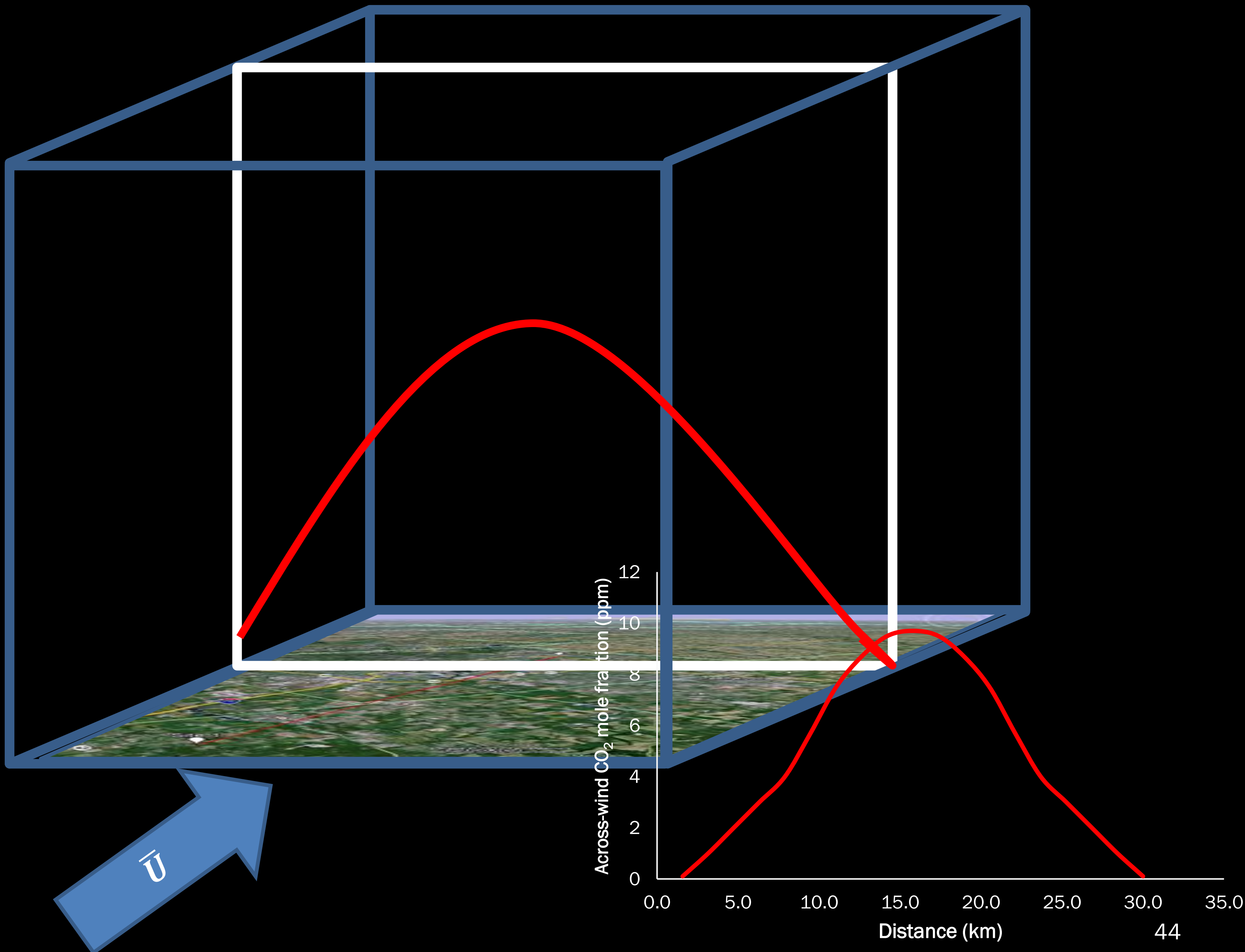


$\overline{U}$
Across-wind CO_2 mole fractio (ppm)
12
10
8
6
4
2
0
0.0
10.0
20.0
30.0
Distance (km)



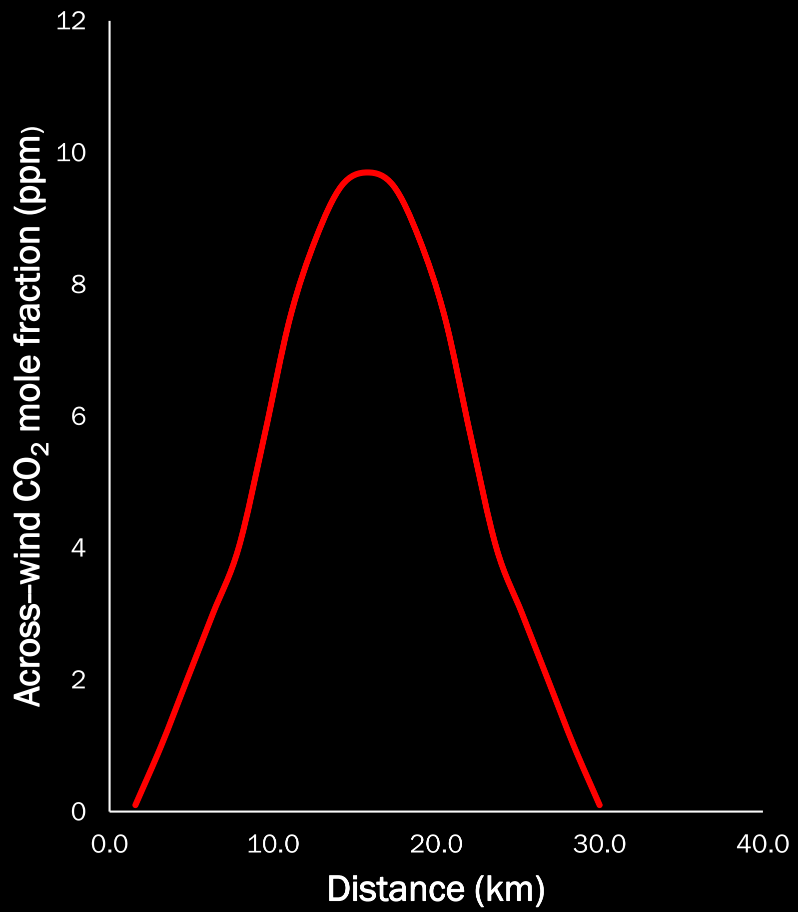
- Anticipated Along-wind A3
  - CO_2 mole fractions from city emissions should increase with distance into the city and then slowly decrease at some point beyond the city via diffusion; linear increase


$\overline{U}$

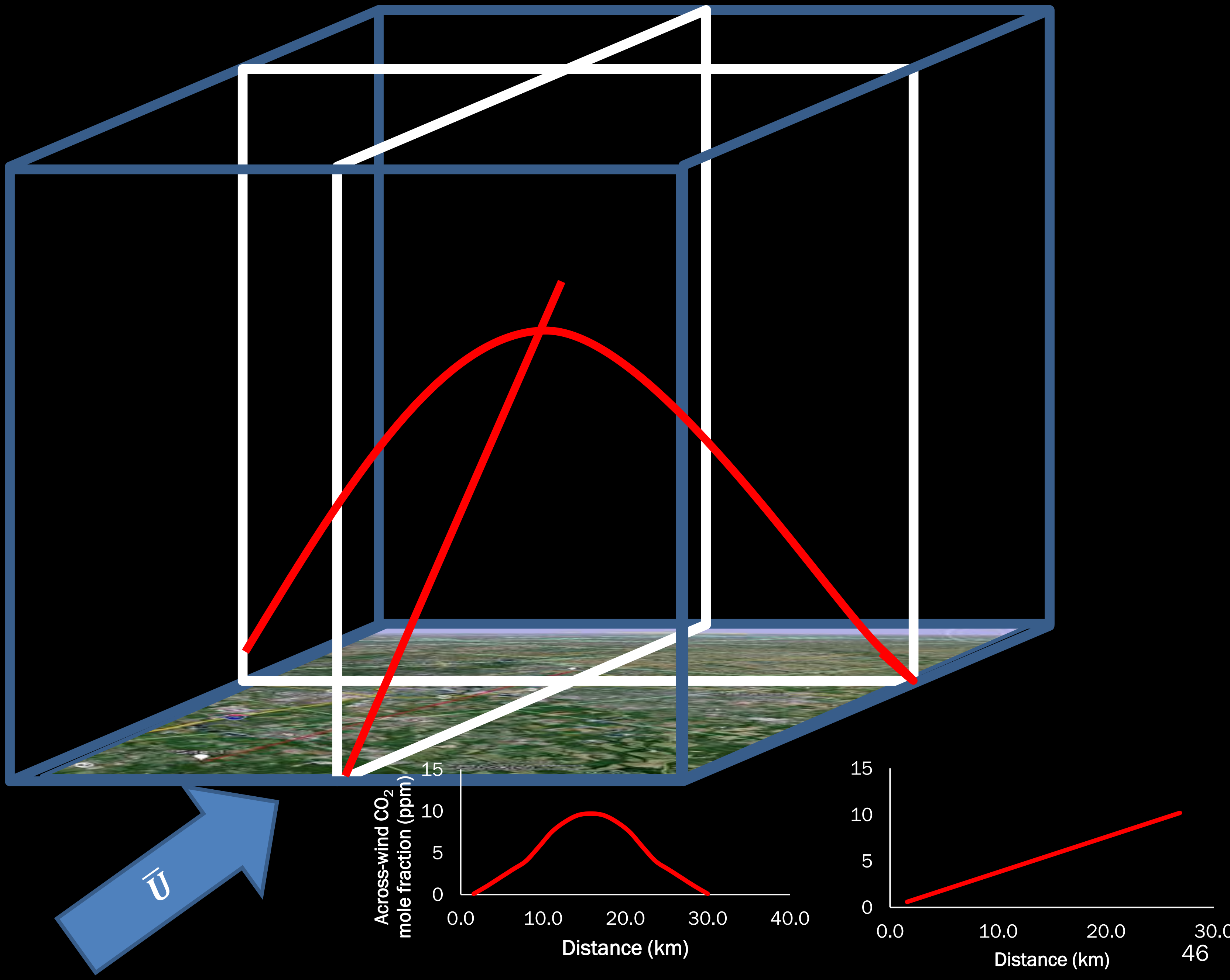


Across-wind CO_2 mole fraction (ppm)
12
10
8
6
4
2
0
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
Distance (km)
$\bar{U}$

Results: Cross-city transects of CO_2



- Anticipated cross-wind A3
  - CO_2 mole fractions from city emissions with distance until they reach center city and then decrease
- Anticipated distributions assumed constant winds

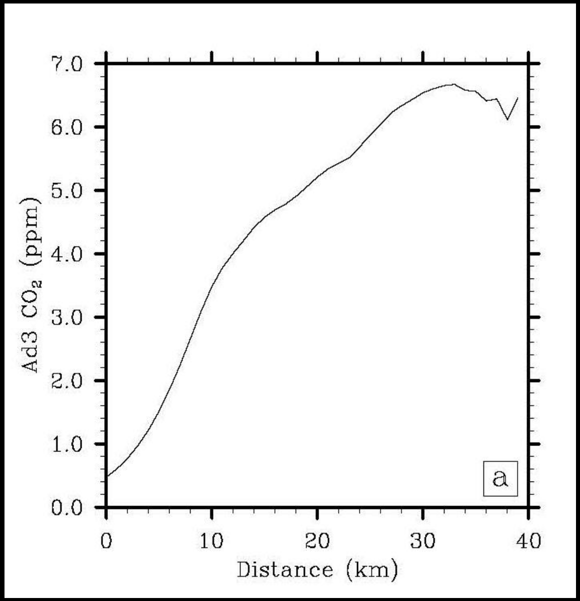


U
15
10
5
0
Across-wind CO_2 mole fraction (ppm)
0.0
10.0
20.0
30.0
40.0
Distance (km)
15
10
5
0
0.0
10.0
20.0
30.0
Distance (km)

Results:
Cross-city transects of CO_2

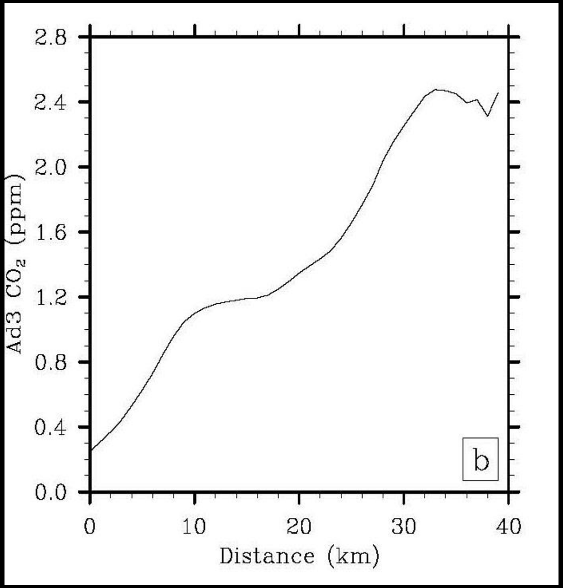
A3 Along-wind

February Average



A3 Along-wind

July Average

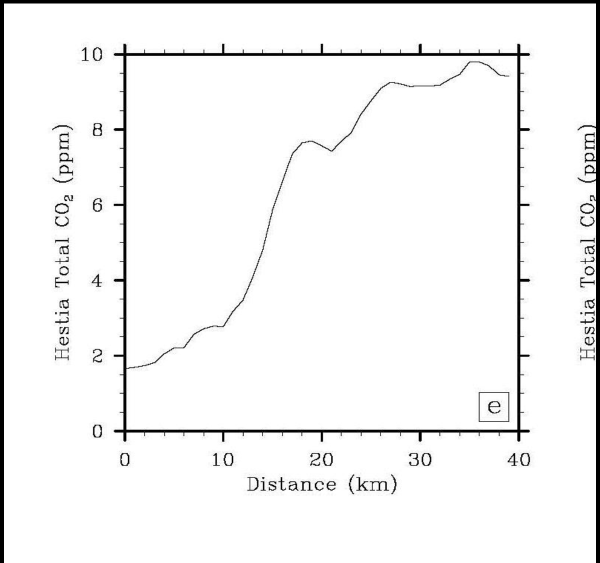


Ranges: Δ7.0 > Δ 2.8 ppm

Results:
Cross-city transects of CO_2

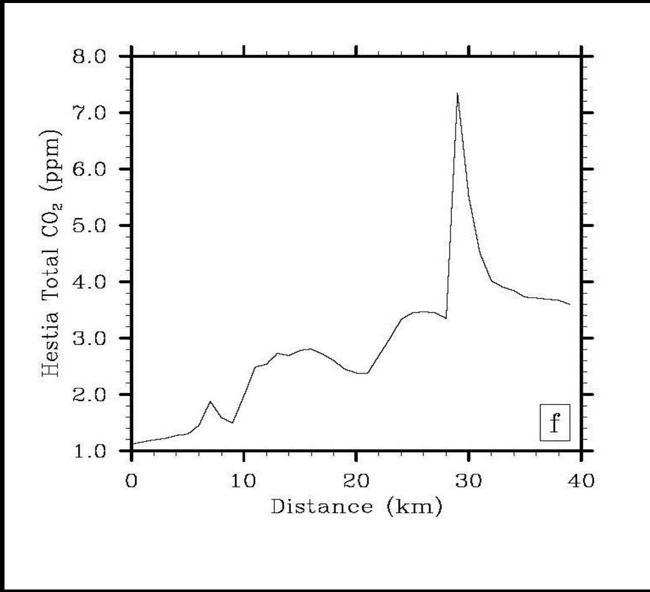
Hestia Along-wind

February Average



Hestia Along-wind

July Average

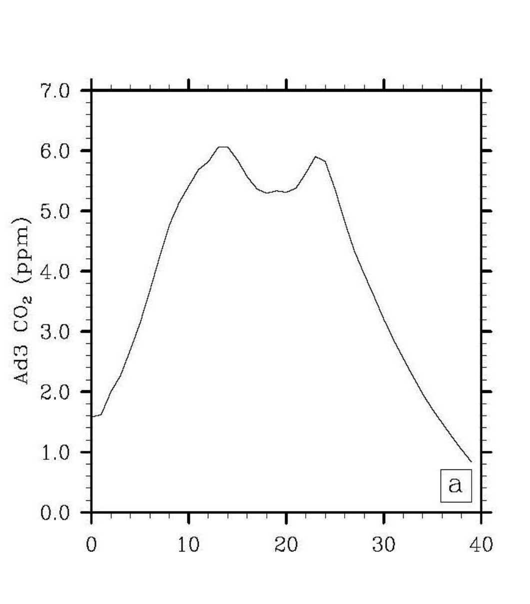


Ranges: Δ 10.0 > Δ 8.0 ppm

Results:
Cross-city transects of CO_2

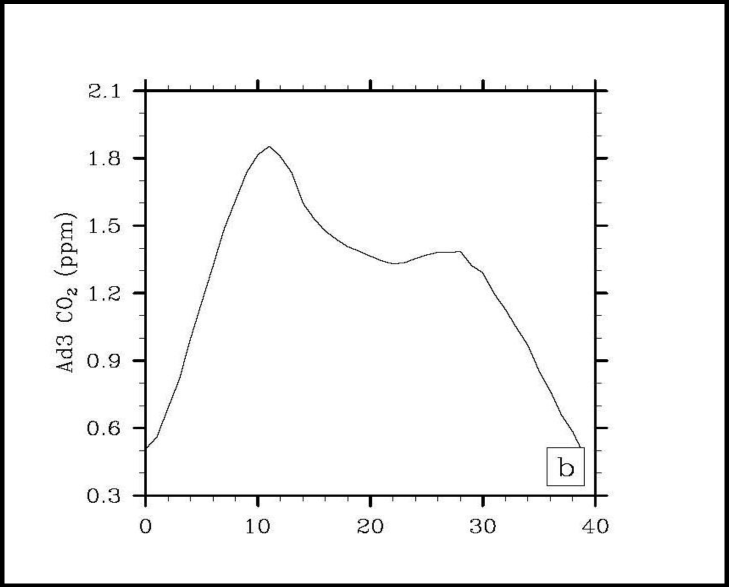
A3 Across-wind

February average



A3 Across-wind

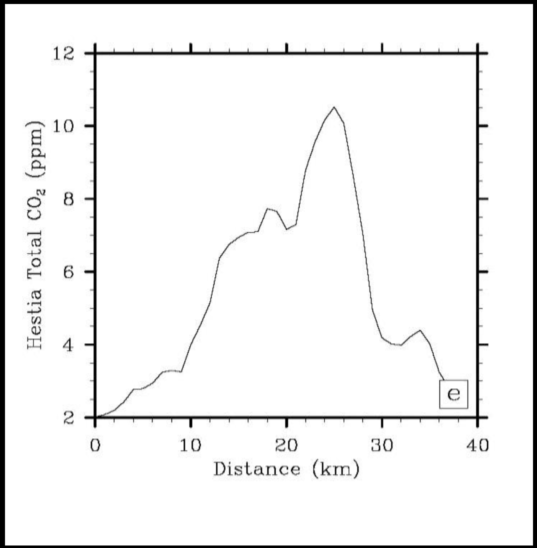
July average



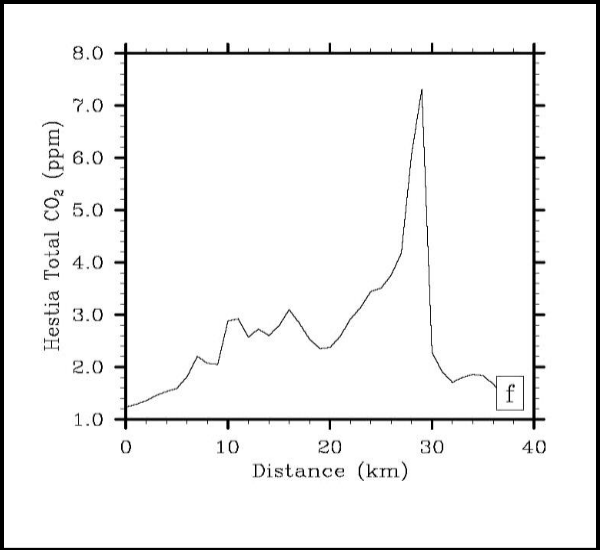
Ranges: Δ 7.0 > Δ 2.1 ppm

Results:
Cross-city transects of CO_2

Hestia total Across-wind
February average



Hestia total Across-wind
July average



Ranges: Δ 12.0 >Δ 8.0 ppm

Results: Cross-city transects of CO_2

Averages Along wind (ppm)

	Vulcan, A3	Hestia
Winter	5.18	7.93
Summer	1.87	2.80

- Average differences in A3 and Hestia larger in winter
  - Therefore increased detectability in winter
- Hestia has larger magnitude averages for along-wind cross city differences
  - (cross-wind similar values)

Results: Cross-city transects of CO_2

- Shapes consistent from day to day for
  - Vulcan and Hestia, therefore averages have significance
    - Left example of Hestia in February along-wind
  - This was not the case for L3
- Large variation in magnitude of CO_2 accumulation in urban boundary layer

Results:
Cross-city transects of CO_2

Ranges (ppm)

	Vulcan, A3	Hestia
Winter	7.28	11.51
Summer	3.05	8.82

Range =Max-Min for each day

- Hestia has larger ranges
- CO_2 depends on the resolution of the fossil fuel emissions
  - Lower resolution product underestimation spatial variability

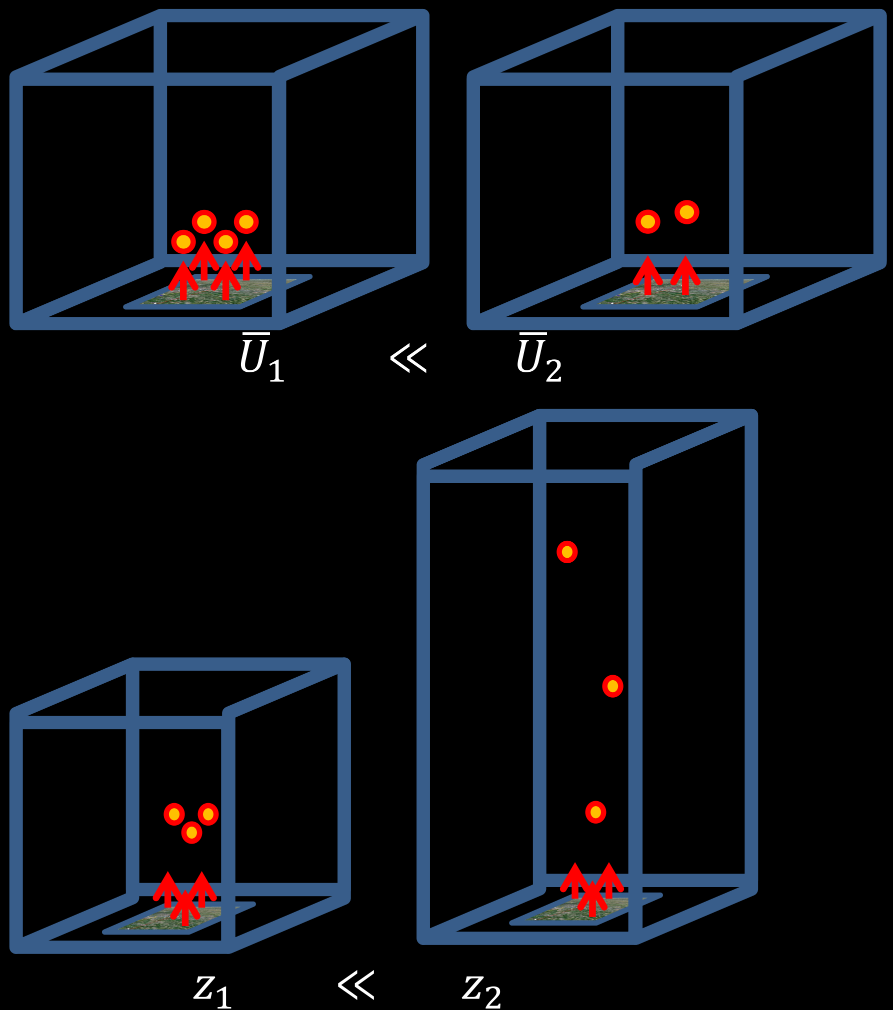
Results: Cross-city transects of CO_2

- Modeled anthropogenic CO_2 depends on the resolution of the fossil fuel emissions
  - Using a smoothed product like Vulcan to predict spatial patterns in atmospheric CO_2 over an urban ***region will likely lead to errors***
    - ***Due to unrealistically small variability***
    - ***Bias mean***

Outline of results

- Evaluation of urban CO_2 mole fractions
- Quantification of daily variations in cross-city CO_2 mole fractions
  - Cross-city differences in CO_2 with 3 methods
  - Along- and across-wind transects of CO_2
  - **Meteorological correlations**
  - Dimensionless CO_2 difference

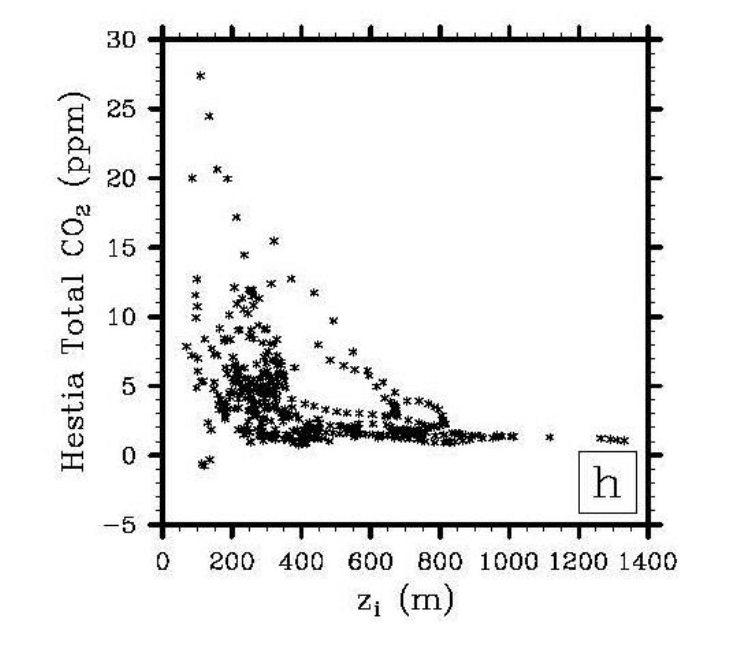
Results: Meteorological correlations



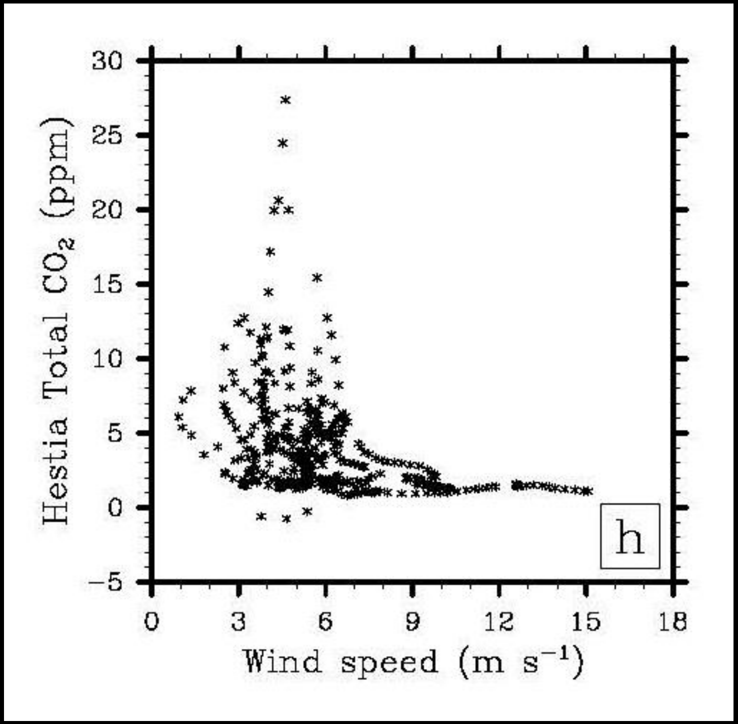
- ABL height, z_i, and wind speed, U, affect
  - Transit time of air over emission sources
  - Volume of air in which fluxes have to mix within the atmosphere
- Inverse relationships with z_i and U
- Scatterplots
  - 432 point per plot (24 days with 6 hour window with 3 outputs per hour)
  - ***wind direction method***

Meteorological correlation: Winter z_i, U

Hestia Total and z_i



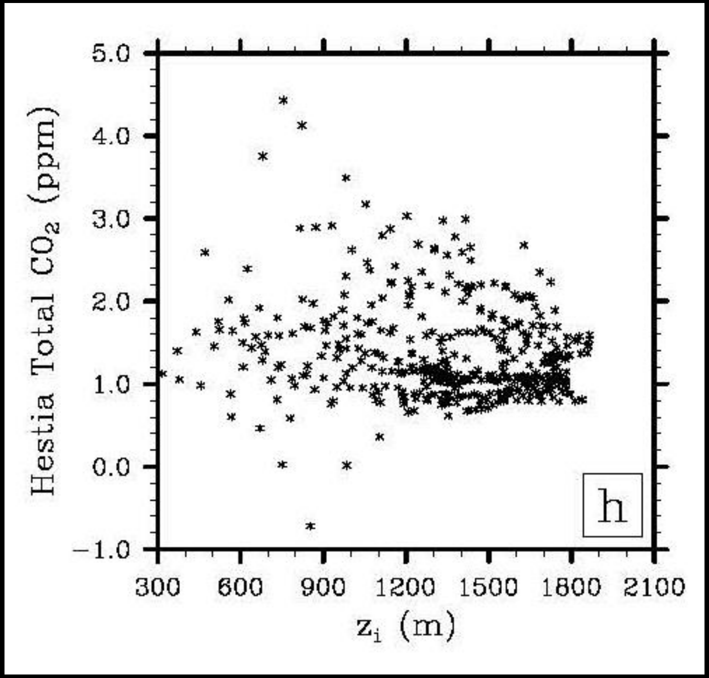
Hestia Total and U



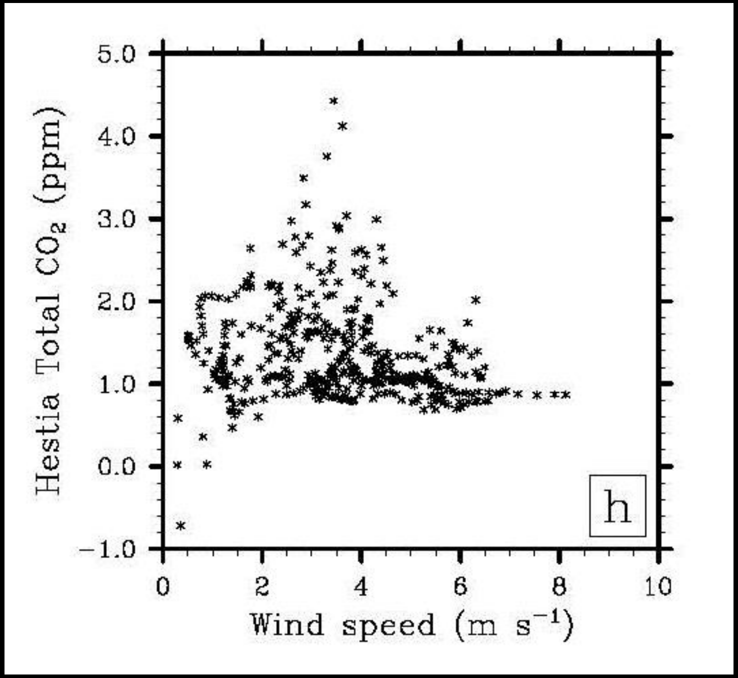
Larger CO_2differences under low z_i and wind speeds; therefore increased detection of anthropogenic city CO_2 emissions

Meteorological correlation: Summer z_i, U

Hestia Total and z_i



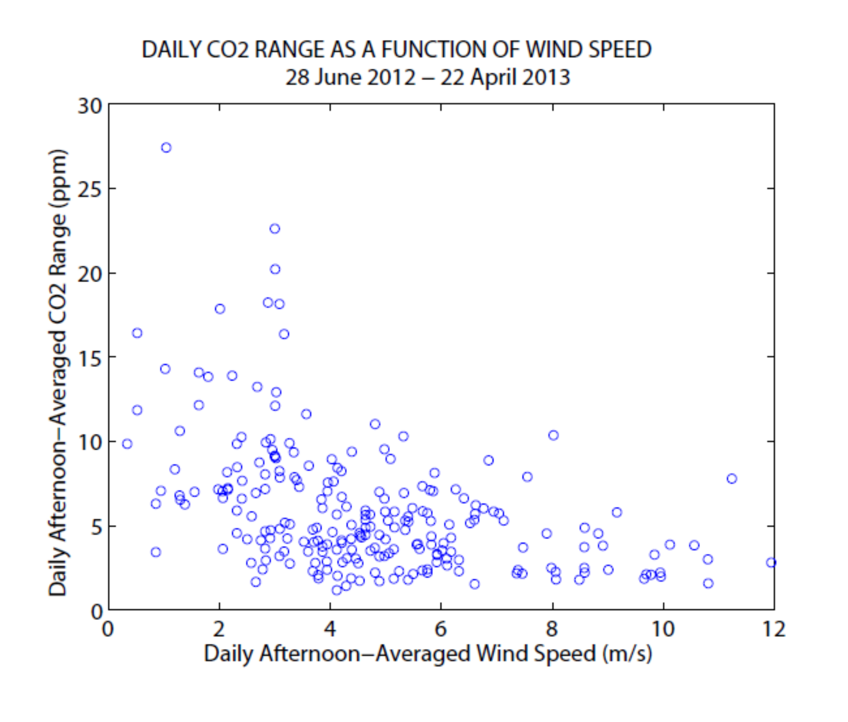
Hestia Total and U



Meteorological variables explain less of the variation in cross-city magnitude in the summer

Meteorological correlation: Comparison to Observations

INFLUX observations



Day et al. 2002

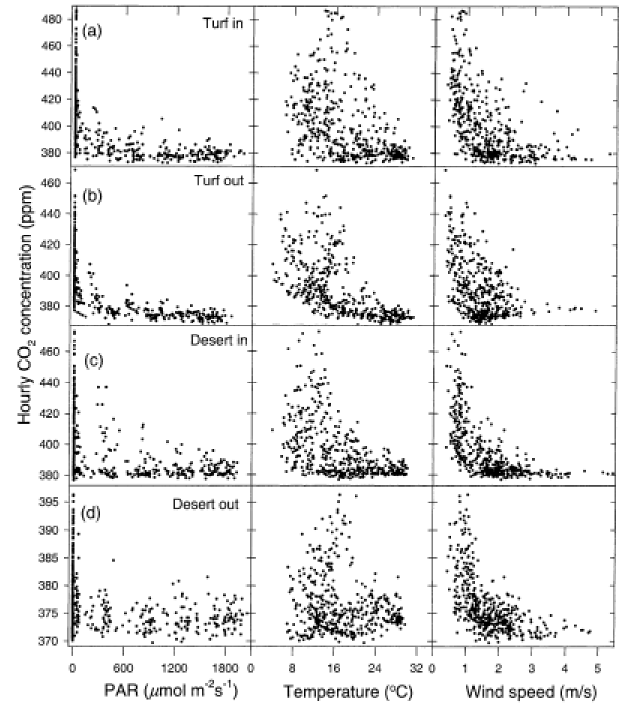


Fig. 2. Relationships between hourly mean CO_2 concentrations and PAR, air temperature and wind speed at the four sampling sites: (a) turf near the urban center, "Turf in"; (b) turf at the edge of the Metropolitan area, "Turf out"; (c) desert near the urban center, "Desert in"; (d) desert at the edge of the Metropolitan area, "Desert out". Data are hourly means from each day of the experiment.

Results: Meteorological correlations

- ABL depth and wind speed explain some variation in the across-city CO_2 mole fraction differences
  - Increased magnitude in CO_2 mole fraction differences under low wind speeds and z_i
    - therefore increased detection under these conditions
  - Winter had strongest correlations
    - Therefore quantifying urban anthropogenic emissions with across-city differences easy in the winter

Outline of results

- Evaluation of urban CO_2 mole fractions
- Quantification of daily variations in cross-city CO_2 mole fractions
  - Cross-city differences in CO_2 with 3 methods
  - Along- and across-wind transects of CO_2
  - Meteorological correlations
  - **Dimensionless CO_2 difference**

Dimensionless CO_2 difference

- Based on simple ABL budget
- Enable the along-wind, cross-city mole fraction differences to be generalized to other urban areas
- Across the city differences from A3 should be governed primarily by
  – Anthropogenic CO_2 emissions across the city
  – Horizontal wind speed
  – ABL depth

Results: Dimensionless CO_2 difference

$$K = \frac{\Delta CO_2 * z_i * U}{f_o * L}$$

$$f_o = K * \frac{\Delta CO_2 * L}{z_i * U}$$

- Derived from scalar conservation equation simplified for the ABL
- Allows for an estimation of CO_2 emissions across the city with
  - Known wind speed, U
  - ABL height, z_i
  - A3 CO_2 mole fraction difference across the city, ΔCO_2
  - Length of city, L

Results: Dimensionless CO_2 difference

- Variation in magnitude of across-city CO_2 differences can be explained with/approximated with
  - Coefficient value 0.016 used with
  - Meteorological and surface flux values

	ΔC (ppm)	z_i (km)	U (m s^{-1})	f_o (μmol m^{-2} s^{-1})	L (km)	K
Winter	6.2	0.4	6.0	609.8	32.3	0.0163
Summer	2.3	1.4	3.5	392.0	32.3	0.0167
Year	4.0	0.9	4.7	500.9	32.3	0.0165

Conclusion

- Local anthropogenic emissions lead to detectable but modest enhancements in the atmospheric CO_2 mole fraction over Indianapolis
  - As expected, most lower ABL CO_2 are from LBC
    - 380.6 ppm in winter and 380.3 ppm in summer
    - A3 was only 2.4 ppm and 0.9 ppm respectively
- Large variation in build of CO_2 in urban boundary layer
  - Explained by variability in ABL depth and wind speed
- Winter substantially easier
  - A3 largest component
  - Meteorological variables and variation

Conclusion

- Can approximate across-city CO_2 mole fraction difference
  - 0.016 used in conjunction with meteorological and surface flux values
- Resolution of the fossil fuel emissions is important
  - Low resolution products underestimate variability
- Analysis were limited to daytime
  - Results likely to change at night, especially for the biogenic components