Eddy Covariance Measurements in Urban Environments

White paper prepared by the AmeriFlux Urban Fluxes ad hoc committee

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Preface. This white paper was prepared by an AmeriFlux ad hoc committee on Urban Fluxes, in response to a request by the DOE Program Manager for the AmeriFlux Management Project. It provides a brief summary of the committee's assessment of the challenges and opportunities for eddy covariance (EC) flux measurements in urban environments, including built and terrestrial areas, and gives technical recommendations.

1. Background

Globally, urban landscapes account for a small (377,000-533,000 km^2) but growing fraction of terrestrial land area (Ouyang et al., 2019) and contribute a disproportionally high amount of energy and mass flows due to the increasing world population, high energy and food consumption. Direct measurement of the net exchanges of momentum and scalars such as CO_2 and CH_4 between the land surface and the atmosphere at high temporal resolution (e.g., 30 minutes) and spatial resolution can be made using tower-based observations, such as the eddy covariance (EC) technique. More spatially coarse measurements can be made by aircraft-based observations using the mass-balance approach. An EC system can be installed on tall structures (e.g., tall towers or on top of buildings) to continuously record net surface flux within the inertial sublayer where airflow is not distorted by obstructions (Roth, 2000). The application of the EC technique in urban environments is challenging, due mostly to the highly heterogeneous landscape and it requires hands-on interpretation of the collected observations. Nevertheless, EC measurements deployed in urban environments can provide important insights on fluxes of trace gases (e.g., CO_2, CO, NO_x, CH_4, aerosol particles) and energy (sensible and latent heat, solar radiation). This white paper provides a synoptic update of the challenges and solutions for EC flux measurements in urban environments, whether in "green" or "gray" parts of urban areas, distills the dimensions of applications, and issues recommendations.

2. Applications of EC in urban environments and open questions

EC measurements in urban areas have been used to understand how urban systems function and the impact of urban systems on greenhouse gas emission, local-regional air pollution, and weather. Thus, despite the difficulty in making and interpreting urban flux measurements, they have proven useful for a wide suite of scientific inquiries (see Appendix B for projects or publications highlighting the role of urban fluxes in carbon cycling). Here we list a few of the types of studies and findings in the literature. Studies of land-atmosphere interactions have been useful for determining heat and pollutant dispersion as well as for accurate weather forecasting (Karsisto et al., 2015). The urban fabric alters airflows and turbulence and, together with particulate matter pollution, has been found to affect timing, location and intensity of rainfall (Grimmond et al., 2010; Demuzere et al., 2017). Likewise, the impact of heat waves can be exacerbated in urban areas not only by the amount of impervious area and building density and material, but also by the types and distribution of vegetation (e.g. Livesley et al., 2016, Ramamurthy and Bou-Zeid, 2017; Wetherley et al., 2018, 2021). Urban-flux studies have addressed: (i) urban turbulence and the emissions of greenhouse gases (GHGs) (e.g. Christen et al., 2011; Nordbo et al., 2012); (ii) other air pollutants (e.g. Park et al., 2010; Lee et al., 2015; Deventer et al., 2015; Valach et al., 2015); and (iii) parameterizations in biospheric models for urban biogenic carbon fluxes (Wu et al., 2021). Other EC flux studies have also related (i) urban turbulence measurements to urban morphology (Nordbo et al., 2012), (ii) flux of carbon to the fractions of gray (built environment) versus green (vegetated) areas and their seasonality (Peters et al., 2012; Jarvi et al., 2019; Reed et al., in review), as well as (iii) to the traffic within the footprint of the measurement platform (e.g. Hiller et al., 2011; Jarvi et al., 2012; Park and Schade 2016, Menzer and McFadden 2017). Stable isotopic analysis has been coupled with flux measurements to identify the sources of trace gases (Pataki et al., 2011; Lee et al., 2015, Park et al., 2018).

There are many outstanding scientific questions that are ripe for addressing with EC measurements in urban environments, and many questions about the best way to apply EC systems to address them. These scientific and methodological questions include:

- How can we use urban EC measurements to further improve land-surface model fidelity in numerical weather forecasting? Do we need a more multi-scale, urban-surface parameterization?
- How can we gain more granular insights (diurnal cycle scale) into urban GHG emissions using high temporal resolution EC measurements? Do we need a network of EC towers or more strategically placed surface-specific representative measurements to interpret fluxes in relation to spatially changing land cover?
- Can urban EC flux measurements help constrain sector-specific emissions, particularly partitioning fossil fuel versus biogenic CO_2 fluxes? What additional species (e.g. isotopes, ancillary trace gases) can and should be measured to provide sector-specific information?
- Can we create urban “mega” sites that will allow and encourage citizen involvement to broaden the database and potentially accompany urban surface manipulations to test hypotheses and/or GHG mitigation strategies?
- How can we best make use of urban EC flux sites to bridge the gap between bottom-up (Gurney et al., 2021) and top-down GHG emission estimates (Mays et al., 2009; McKain et al., 2012; Heimburger et al., 2017; Broquet et al., 2018; Hedelius et al., 2018; Sargent et al., 2018; Turnbull, et al., 2018; Plant et al., 2019; Lauvaux et al., 2020; Yadav et al, 2021)? In this case, bottom up means using economic data and top down means using concentration measurements.
- How can we best leverage remote sensing data and products, as well as other ecosystem, infrastructure, and socio-economic data from urban landscapes to enhance current bottom-up, process-oriented models of urban fluxes?
- Can Artificial Intelligence technology (e.g., Graph Neural Networks and Recurrent Neural Networks in deep learning) help predict urban fluxes, including understanding both of bottom-up flux estimates and of flux footprint models?

3. Flux networks and Urban Fluxes

The number of urban eddy flux sites is growing, in part because of recognition of these scientific questions and because networks are welcoming them despite the measurement challenges. There are eight AmeriFlux sites that list Urban as their dominant cover type, and several more towers that will be joining soon. Most of these were started in the past seven years; right now only two tower teams have published BASE (flux/met) data available for downloading. The EU ICOS network has more than 15 sites, most of which are also fairly new. See Appendix C for a list of some urban flux sites. In addition to the AmeriFlux working group that wrote this white paper, an important cross-network and cross-continent activity is the WMO’s effort “Towards an International standard for Urban GHG Monitoring and assessmenton urban fluxes," via the committee IG3IS Urban Greenhouse Gas Emission Observation and Monitoring Best Research Practices with representation from ICOS, AmeriFlux, and other networks.

4. Challenges with EC deployment in Urban Environments

Compare to EC flux measurements made in more homogeneous environments, EC flux measurements made in urban environments require additional care in filtering the observations, gap-filling (Menzer et al., 2015), flux partitioning (Menzer and McFadden 2017), and it requires constructing flux budgets on multiple time scales in order to provide meaningful results and insights (Schmutz et al., 2016).

There are several restrictions on EC measurements over complex, rough surfaces (e.g., required installation heights) that become even more challenging in some urban environments. The primary limitation originates from the deep roughness sublayers, where airflows are influenced by individual obstructions, and Monin–Obukhov similarity theory is no longer valid. Across the globe, the physical settings of any two urban areas are different (Chen et al., 2021). Worse yet, the physical landscape structure within any city can over the scale of a few blocks or 100's of meters, smaller than the few kilometers that are the nominal footprint length for EC measurements.

Unlike with homogeneous natural vegetation, cities have numerous and varied small-scale activities (e.g. traffic, commercial activities, manufacturing) that can directly affect the source-sink strength of GHGs and energy. These urban features can be highly variable over a matter of hours. Nevertheless, the assemblage of buildings, road networks, trees, and other objects in a city can be regarded as the urban canopy, analogous to the vegetation canopy (Oke 1976).

Overall, each urban environment has its specific hard and soft physical structures, emissions pathways, and diverse emission mechanisms including spatial and temporal changes that are associated with human activities (e.g., holidays, rush hours) (Chen et al., 2016; Cao et al., 2018). Thus, a single tower with a nominal footprint extent of hundreds of meters to a few kilometers is not representative of the target city as a whole which typically extend many 10's of kilometers. Thus intensive studies have used multiple towers (e.g., INFlux) and mobile towers (Chen et al., 2002; Peters and McFadden 2012; Hiller et al., 2011), complemented with models such as vegetation light-use efficiency models (Miller et al., 2018), or land models (e.g., Christen et al., 2011; Jarvi et al., 2019) to quantify ecosystem fluxes within larger urban areas.

The challenges for applying the EC method in urban environments include:

- Installing flux towers in urban landscapes can be extremely challenging due to FAA regulations, public perceptions, planning regulations, zoning policies, etc. In particular, obtaining permission to install new towers or mount sensors on existing structures can be difficult, time consuming, and socially challenging.
- Obtaining access to the measurement sites on third-party property to conduct regular preventive maintenance can be difficult. Moreover, the higher abundance of aerosols in urban areas requires more frequent cleaning of instrument optics.
- There are health and safety concerns specific to the urban environment, such as working at heights, interacting with people who are unfamiliar with the activity, and physical security of the site and equipment.
- High building heights can require instruments that are so tall that measurements are made at a substantial fraction of the mixing height. While this relaxes requirements for sensor response time, it can result in poorly quantified storage and advection errors as well as low frequency losses.
- The failure of standard EC technique stationarity assumptions to hold at all times can create errors in the estimation of the magnitude of the measured fluxes and their uncertainties.

- Footprint complexity and representativeness vary spatially, making attribution of EC observations to surface sources and characteristics challenging.
- Accounting for point sources (including mobile point sources such as vehicles) is another challenge that varies temporally.

5. Technical Recommendations

Measurement location: a good characterization of the source area is of highest importance for the useful interpretation of the EC observations. An urban EC system should avoid large discontinuities within its footprint and does not need to be placed in a strictly homogeneous landscape, as long as the scale of the heterogeneity within its footprint is such that it can be interpreted by selecting samples and analyzing them according to footprint composition. Flux footprint models that use reliable estimates of the turbulent transfer processes in the inertial surface layer, informed by the urban morphology, provide useful surface source area insights. We therefore strongly recommend checking the estimates given by parameterized footprint models (e.g. Kljun et al., 2015) before deciding on using an existing platform for EC measurements, or placement of a new platform and EC system. An alternative is to develop a cluster towers (3-5) so that EC measurements represent different sets of urban landscapes, which can be also used in large eddy simulations to best reflect the fluxes of an urban system.

Measurement height: For measuring in a high density of built structures, the EC system should ideally be placed high enough above the surface to measure in the well-mixed surface layer (at least during stationary conditions) and avoid any direct influence of local sources as well as building wakes. The optimal measurement height is above the roughness sublayer which is typically 2-5 times the mean surrounding average building or tree height in an urban area, whichever is taller (Raupach et al., 1991). At the same time, very high measurement heights lead to storage and advection errors that are difficult to quantify. Additional measurement systems must be deployed and/or this makes measurements above neighborhoods with tall buildings impractical. For measuring in parks and green areas of cities, the EC system may be placed as low as possible (i.e., subject to the need to be 1 meter above vegetation height) to create relatively homogeneous footprints.

Instrument setup: Similar to the practice above natural ecosystems, sonic anemometers should be installed facing towards the predominant wind direction relative to the mounting structure in order to minimize flow distortion, and sensor shadowing. Key sensors (e.g. gas analyzers and sonic anemometers) installed at 2-3 levels should be considered.

Data QA/QC: As for any EC observations, attention should be paid to standard data quality control procedures used above vegetated surfaces and based on: (1) instrument errors; (2) precipitation occurring during or just before the measurement period; (3) physically reasonable thresholds applied to raw data, including restricting for standard deviation; (4) criteria combining diagnostics and daily statistics of measured quantities; and (5) detection of outliers. However, these QA/QC steps might not be sufficient in the case of urban environments, in particular if one wants to separate contribution from micro-scale anthropogenic sources (Kotthaus and Grimmond, 2012) from other sources of interest within the footprint of the EC system.

The EC method is based on the Monin–Obukhov similarity theory and requires the presence of turbulent flow, which means that in the case of low turbulence (e.g., during calm periods, which are typical at night in natural environments) the measurements are not valid and must be filtered out. In urban environments, this is less of an issue because night time turbulence is expected to be higher than over natural ecosystems (except for tall measurement heights where a decoupling between the measurement point and the ground can occur). It should be noted that the tests for well-developed turbulence (e.g., Foken et al., 2004) are based on the comparison with reference functions of the normalized standard deviation of the vertical wind component (σ_w/u_*) as a function of stability. These reference functions are not universally applicable in the urban environment (e.g. Järvi et al., 2012).

5. References

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9. Gunnar Schade, Texas A&M University (gws@geos.tamu.edu)
10. Stavros Stagakis, University of Basel, Switzerland (stavros.stagakis@unibas.ch)
11. Jocelyn Turnbull, GNS Science and University of Colorado (jocelyn.turnbull@noaa.gov)
12. Roland Vogt, University of Basel, Switzerland (roland.vogt@unibas.ch)

APPENDIX B: Examples for application of urban flux data: projects or publications highlighting the role of urban fluxes in carbon cycling (not a comprehensive list)

1/ In North America:

- Baltimore, MD: The Baltimore Ecosystem Study (BES) aims to understand metropolitan Baltimore as an ecological system. The program brings together researchers from the biological, physical, and social sciences to collect new data and synthesize existing information on how both the ecological and engineered systems of Baltimore (https://baltimoreecosystemstudy.org/).
    - Crawford, B., C. S. B. Grimmond, and A. Christen. 2011. Five years of carbon dioxide fluxes measurements in a highly vegetated suburban area. Atmospheric Environment 45: 896–905.

- Houston, TX: deployment to YellowCab's communication tower (website no longer active). Multi-year (2007-2013) intensive study to quantify the VOC, CO_2, and energy fluxes between a typical older neighborhood north of downtown Houston, and the atmosphere (TAMU, EPA and NOAA funding). Focus was initially on surface and turbulence characterization, then VOC fluxes, including isoprene, later on flux partitioning of carbon between biogenic and anthropogenic CO_2 sources.
    - Park, C., et al. Flux measurements of volatile organic compounds by the relaxed eddy accumulation method combined with a GC-FID system in urban Houston, Texas, Atmos. Environ., 44(21–22), 2605– 2614, doi:10.1016/j.atmosenv.2010.04.016, 2010.
    - Park, C., G. W. Schade, and I. Boedeker, Characteristics of the flux of isoprene and its oxidation products in an urban area, J. Geophys. Res., 116, D21303, doi:10.1029/2011JD015856, 2011.

- Kota, S.H., C. Park, M.C. Hale, N.D. Werner, G.W. Schade, Q. Ying, Estimation of VOC emission factors from flux measurements using a receptor model and footprint analysis, Atmos. Environ., 82, pp. 24-35, 10.1016/j.atmosenv.2013.09.052, 2014.
- Park, C.; Schade, G.W.; Werner, N.D.; Sailor, D.J.; Kim, C.H. Comparative estimates of anthropogenic heat emission in relation to surface energy balance of a subtropical urban neighborhood. Atmos Environ, 126, 182-191, doi:10.1016/j.atmosenv.2015.11.038, 2016.
- Park, C.; Schade, G.W. Anthropogenic and Biogenic Features of Long-Term Measured CO_2 Flux in North Downtown Houston, Texas. J Environ Qual, 45, 253-265, doi:10.2134/jeq2015.02.0115, 2016.
- Some relevant work is not published yet: partitioning net CO_2 fluxes into biogenic- and anthropogenic-components using energy balance fluxes Hs and L (was NOAA funded).

- Indianapolis, IN: Flux measurements deployment both to quantify the regional surface energy balance to improve numerical weather models used to interpret atmospheric GHG observations, and to quantify the contributions of various portions of the urban system to the urban carbon cycle.
  - Indianapolis Flux Experiment (INFLUX, https://sites.psu.edu/influx/)
  - Davis, K.J., A. Deng, T. Lauvaux, N.L. Miles, S.J. Richardson, D.P. Sarmiento, K.R. Gurney, R.M. Hardesty, T.A. Bonin, W.A. Brewer, B.K. Lamb, P.B. Shepson, R.M. Harvey, M.O. Cambaliza, C. Sweeney, J.C. Turnbull, J. Whetstone and A. Karion, The Indianapolis Flux Experiment (INFLUX): A test-bed for developing urban greenhouse gas emission measurements. *Elem Sci Anth*: 2017;5:21. https://doi.org/10.1525/elementa.188, 2017.
  - Wu, K., T. Lauvaux, K. J. Davis, A. Deng, I. Lopez-Coto, K. R. Gurney and R. Patarasuk, 2018. Joint inverse estimation of fossil fuel and biogenic CO2 fluxes in an urban environment: An observing system simulation experiment to assess the impact of multiple uncertainties. Elem Sci Anth. 2018;6(1):17. DOI: http://doi.org/10.1525/elementa.138
  - Wu, K., 2020, Joint estimation of fossil fuel and biogenic CO_2 fluxes in an urban environment, Ph.D. dissertation, The Pennsylvania State University.
  - Wu, K. K. J. Davis, N. L. Miles, S. J. Richardson, T. Lauvaux, K. Keller, J. C. Turnbull, D. P. Sarmiento, N. V. Balashov, K. R. Gurney, J. Liang, and G. Roest, Evaluating an emissions inventory using atmospheric CO_2 flux measurements and source partitioning in a suburban environment, in preparation.

- Los Angeles, CA:
  - The Los Angeles Megacity Carbon Project is an urban greenhouse gas measurement testbeds established by NIST to demonstrate scientifically-robust greenhouse gas measurement capabilities at urban and regional scales (https://megacities.jpl.nasa.gov/portal)

- Minneapolis-Saint Paul, MN
  - Multi-year (2004-2009) intensive study to quantify the CO_2, water vapor, and energy exchanges from the vegetated fraction of the urban environment, to partition biogenic vs anthropogenic CO_2 fluxes, to separate flux contributions from the major plant functional types, to measure their dynamics over the annual cycle, to develop machine-learning methods for gap-filling, to analyze their spatial variations within the urban environment, and to extrapolate fluxes by plant functional type to the scale of a large metropolitan region (web site no longer active).

- Menzer, O., W. Meiring, P. C. Kyriakidis, and J. P. McFadden. 2015. Annual sums of carbon dioxide exchange over a heterogeneous urban landscape through machine learning based gap-filling. Atmospheric Environment 101: 312–327.
- Menzer, O. and J. P. McFadden. 2017. Statistical partitioning of a three-year time series of direct urban net CO_2 flux measurements into biogenic and anthropogenic components. Atmospheric Environment 170: 319–333.
- Miller, D. L., D. A. Roberts, K. C. Clarke, Y. Lin, O. Menzer, E. B. Peters, and J. P. McFadden. 2018. Gross primary productivity of a large metropolitan region in midsummer using high spatial resolution satellite imagery. Urban Ecosystems 21(5), 831–850.

- Montreal, Canada:
  - Energy Flux Project (no longer active)
  - Bergeron, O. and Strachan, I. B. 2010. Wintertime radiation and energy budget along an urbanization gradient in Montreal, Canada. Int. J. Climatol.

- Phoenix, AZ:
  - Flux tower to facilitate neighborhood-scale investigations of atmospheric processes in a Phoenix, AZ suburb, capitalizing on comprehensive measurements of energy (heat and radiation) and matter (water and carbon dioxide) exchanges between the atmosphere and the urban surface. This project contributed to research investigating how urbanization affects local weather, climate, and air quality (https://sustainability-innovation.asu.edu/caplter/research/long-term-monitoring/urban-flux-tower/)
  - Chow, W. T., F. Salamanca, M. Georgescu, A. Mahalov, J. M. Milne and B. L. Ruddell. 2014. A multi-method and multi-scale approach for estimating city-wide anthropogenic heat fluxes. Atmospheric Environment 99(December):64-76. DOI: 10.1016/j.atmosenv.2014.09.053
  - Chow, W. T., T. J. Volo, E. R. Vivoni, G. D. Jenerette and B. L. Ruddell. 2014. Seasonal dynamics of a suburban energy balance in Phoenix, Arizona. International Journal of Climatology 34(15):3863-3880. DOI: 10.1002/joc.3947

- Salt Lake City, UT
  - Analyze measurements from a range of data streams such as in-situ ground-based networks (e.g., the Salt Lake City CO2 Network), the Total Carbon Column Observing Network (TCCON), mobile laboratories (see below), and NASA's Orbiting Carbon Observatory-2 (OCO-2) to understand greenhouse gas emissions at the process-level. CO_2 Network (https://lair.utah.edu/)
  - Lin, J. C., and Coauthors, 2018: CO_2 and carbon emissions from cities: linkages to air quality, socioeconomic activity and stakeholders in the Salt Lake City urban area. *Bull. Am. Meteorol. Soc.*, doi:10.1175/BAMS-D-17-0037.1.
  - Mitchell, L., and Coauthors, 2018: Long-term urban carbon dioxide observations reveal spatial and temporal dynamics related to urban form and growth. *Proc. Natl. Acad. Sci.*,. www.pnas.org/cgi/doi/10.1073/pnas.1702393115.
  - Ramamurthy, P., and E. R. Pardyjak, 2011: Toward understanding the behavior of carbon dioxide and surface energy fluxes in the urbanized semi-arid Salt Lake Valley, Utah, USA. *Atmos. Environ.*, **45**, 73–84, doi:http://dx.doi.org/10.1016/j.atmosenv.2010.09.049. http://www.sciencedirect.com/science/article/pii/S1352231010008356..

- Vancouver, Canada:
  - Research based on measurements at this (no longer active) site contributed to the development of new models to support weather forecasting and climate projections in cities, dispersion modelling, air pollution meteorology, greenhouse gas emission modelling, and conservation of water resources in the context of sustainable urban design and planning (https://ibis.geog.ubc.ca/~achristn/infrastructure/sunset.html).
  - Christen, A., Coops N.C., Crawford B.R., Kellett R., Liss K.N., Olchovski I., Tooke T.R., van der Laan M., Voogt J. A., 2011: 'Validation of modeled carbon-dioxide emissions from an urban neighborhood with direct eddy-covariance measurements, Atmos. Environ., 45, 6057-6069.
  - Crawford B., Christen A., 2015: 'Spatial source attribution of measured urban eddy covariance carbon dioxide fluxes'. Theor. Appl. Climatol., 119, 3-4, 733 - 755.

- Washington, D.C. and Baltimore, MD:
  - GHG concentrations are measured with a suite of instrumentation on aircraft and a high-accuracy tower network. Urban biosphere influences on GHG fluxes is also studied through the NIST-FOREST (https://www.nist.gov/northeast-corridor-urban-test-bed)

2/ In Europe:

- Basel
  - Station database https://mcr.unibas.ch/dolueg2/index.php?project=overview
  - BUBBLE Project: Multiple measurements, including urban EC, to investigate the urban boundary layer.
    https://www.mcr.unibas.ch/dolueg2/projects/campaigns/BUBBLE/index.htm
    Rotach, M. W. et al. BUBBLE - An urban boundary layer meteorology project. Theor. Appl. Climatol. 81, 231–261 (2005).
  - diFUME Project: Using urban Eddy Covariance measurements along with indirect bottom-up modelling to monitor the urban CO2 exchange in high temporal and spatial resolution. https://mcr.unibas.ch/difume/
  - Feigenwinter, C., Vogt, R. & Christen, A. Eddy Covariance Measurements Over Urban Areas - Eddy Covariance: A Practical Guide to Measurement and Data Analysis. in (eds. Aubinet, M., Vesala, T. & Papale, D.) 377–397 (Springer Netherlands, 2012). doi:10.1007/978-94-007-2351-1_16
  - Vogt, R., Christen, A., Rotach, M. W., Roth, M. & Satyanarayana, A. N. V. Temporal dynamics of CO2 fluxes and profiles over a Central European city. Theor. Appl. Climatol. 84, 117–126 (2006).
  - Lietzke, B. & Vogt, R. Variability of CO2 concentrations and fluxes in and above an urban street canyon. Atmos. Environ. 74, 60–72 (2013).
  - Lietzke, B., Vogt, R., Feigenwinter, C. & Parlow, E. On the controlling factors for the variability of carbon dioxide flux in a heterogeneous urban environment. Int. J. Climatol. 35, 3921–3941 (2015).
  - Schmutz, M., Vogt, R., Feigenwinter, C. & Parlow, E. Ten years of eddy covariance measurements in Basel, Switzerland: Seasonal and interannual variabilities of urban CO_2 mole fraction and flux. J. Geophys. Res. 121, 8649–8667 (2016).

- CoCO2: Towards an EU Monitoring and Verification Support system for anthropogenic CO_2 emissions based on Earth Observation and in-situ observations. Urban Eddy Covariance is used to evaluate and calibrate urban bottom-up models https://www.coco2-project.eu/

- Heraklion
    - Station database http://rslab.gr/heraklion_eddy.html
    - Urban fluxes project: Energy fluxes observed form space. Urban Eddy Covariance is used as evaluation methodology http://urbanfluxes.eu/
    - BRIDGE project: SustainaBle uRban plannIng Decision support accountinG for urban mEtabolism. Introducing urban metabolism concept and measurement methodologies. http://www.bridge-fp7.eu/
    - Stagakis, S., Chrysoulakis, N., Spyridakis, N., Feigenwinter, C. & Vogt, R. Eddy Covariance measurements and source partitioning of CO2 emissions in an urban environment: Application for Heraklion, Greece. Atmos. Environ. 201, 278–292 (2019).

- ICOS:
    - PAUL: Pilot Application in Urban Landscapes towards integrated city observatories for greenhouse gases. Urban Eddy Covariance and tall-tower eddy covariance as one of the methods for monitoring urban CO2 fluxes and evaluation atmospheric inversion models. https://www.icos-cp.eu/event/1064
    - http://www.icos-etc.eu/icos/working-groups/work-group?wgroup=19
    - https://data.icos-cp.eu/objects/w6pTmRGYKqAm3c-siQrg5kgd

- London:
    - Helfter, C., Famulari, D., Phillips, G. J., Barlow, J. F., Wood, C. R., Grimmond, C. S. B., and Nemitz, E.: Controls of carbon dioxide concentrations and fluxes above central London, Atmos. Chem. Phys., 11, 1913-1928, 2010.
    - Helfter, C., Tremper, A. H., Halios, C. H., Kotthaus, S., Bjorkegren, A., Grimmond, C. S. B., Barlow, J. F., and Nemitz, E.: Spatial and temporal variability of urban fluxes of methane, carbon monoxide and carbon dioxide above London, UK, Atmos. Chem. Phys. , 2016, 10543–10557, 10.5194/acp-16-10543-2016, 2016.

3/ In Asia:

- Beijing:
    - IAP: https://acp.copernicus.org/articles/12/7881/2012/ , ongoing.
    - APHH-Beijing: https://acp.copernicus.org/articles/special_issue932.html

- Delhi:
    - DelhiFlux: https://www.urbanair-india.org/delhiflux

- Singapore :
    - Roth, M., C. Jansson, E. Velasco. 2016. Multi-year energy balance and carbon dioxide fluxes over a residential neighborhood in a tropical city. International Journal of Climatology 37(5) : 2679–2698.

4/ In Australasia:

- Auckland :
    - Weissert, L. F., Salmond, J. A., Turnbull, J. C., and Schwendenmann, L.: Temporal variability in the sources and fluxes of CO_2 in a residential area in an evergreen

subtropical city, Atmospheric Environment, 143, 164-176, 10.1016/j.atmosenv.2016.08.044, 2016.

- Melbourne
  - Coutts, A. M., J. Beringer, N. J. Tapper. 2007. Characteristics influencing the variability of urban CO2 fluxes in Melbourne, Australia. Atmospheric Environment 41 : 51–62.

APPENDIX C: List of flux towers in urban areas (not a comprehensive list)

AmeriFlux Network (8 sites):

1. MX-Iit (https://ameriflux.lbl.gov/sites/siteinfo/MX-Iit): Instituto de Ingeniería y Tecnologia - UACJ, POC: Felipe Adrian Vazquez-Galvez
2. US-KUO (https://ameriflux.lbl.gov/sites/siteinfo/US-KUO): KUOM tower, POC: Joe McFadden (2006-2009, discontinued in 2009)
3. US-MWS (https://ameriflux.lbl.gov/sites/siteinfo/US-MWS): Michigan State University Campus Site - Spartans, POC: Jiquan Chen
4. US-MWU (https://ameriflux.lbl.gov/sites/siteinfo/US-MWU): Battle Creek Area Mathematics and Science Center, POC: Jiquan Chen
5. US-SDU (https://ameriflux.lbl.gov/sites/siteinfo/US-SDU): South Denver Urban Tower, POC: Dean Anderson (discontinued)
6. US-WEP (https://ameriflux.lbl.gov/sites/siteinfo/US-WEP): West Edge Parking Lot, POC: Scott Ollinger
7. US-Ylw (https://ameriflux.lbl.gov/sites/siteinfo/US-Ylw): Yellow Cab urban, POC: Gunnar Schade (discontinued in 2014; data from summer 2007 to end 2013, with a near 1-yr gap in between)
8. CA-VSu (has been registered in 2016 but lost, https://ibis.geog.ubc.ca/~achristn/infrastructure/sunset.html): Vancouver-Sunset (discontinued, 2008-2017), PI: Andreas Christen

ICOS Network (>15 sites):

1. Helsinki, Finland (2 sites) Kumpala (FI-KMP) and Hotel Torni, University of Helsinki
2. Pesaro, Italy: Italian Research Council
3. Florence, Italy: Italian Research Council
4. Heraklion, Greece (2 sites): Foundation for research and Technology Hellas FORTH
5. London: UK Centre for Ecology and Hydrology and University of Reading
6. Berlin: Technische Universität Berlin
7. Basel, Switzerland (2 sites): University of Basel
8. Vienna: Austria, Vienna Urban Carbon Laboratory (VUCL) (4-year project beginning 2021)
9. Paris, Munich, Zürich (>1 tower per city) as part of ICOS-PAUL (Pilot Application in Urban Landscapes) (4-year project beginning 2021) https://www.icos-cp.eu/event/1064

Other networks:

- US-China Carbon Consortium (USCCC) has several sites in Beijing, Taiyuan, Nanjing, and other cites.

Example of a rooftop EC installation at the Michigan State University campus (PI: Jiquan Chen).