B.i. Eddy covariance flux observations

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B.i.1 General introduction to the method

The Eddy Covariance (EC) technique measures the net exchange of one or more scalars between a surface (the footprint) and the atmosphere at high temporal resolution (typically half-hourly). The method is unique in terms of urban greenhouse gas (GHG) monitoring in that it is the only method whereby local net surface-atmosphere fluxes are inferred directly from measurements at single locations. The working assumption is that, under certain conditions the measured turbulent fluxes, properly corrected for other flux components not directly detected (storage, advection, see below) are in equilibrium with net surface-atmosphere exchange integrated over a footprint extending upwind. The footprint of the measurements is variable in time and a function of the measurement height, turbulence and wind direction. It typically extends hundreds of meters around the measurement point. Eddy Covariance can be applied to measure greenhouse gas (GHG) fluxes that can be analysed in relation to emission control strategies applied in the cities (e.g. vehicular traffic limitations, house heating strategies etc.), to infer integral emission factors and integral emission signatures for an entire urban area, to assess the role of urban vegetation in the GHG balance of cities or to assess the accuracy of gridded emissions inventories (e.g. Velasco et al., 2014). Eddy covariance is also used to measure latent and sensible heat fluxes, and the momentum flux, all of which are important drivers of turbulent mixing in the atmospheric boundary layer.

The method provides unique information in terms of temporal resolution and integration of emission sources (e.g. traffic, building emissions, human metabolism etc.) and sinks (e.g. vegetation uptake). It is the only method that measures directly net GHG fluxes over a relatively large area, typically at neighbourhood scale in cities, integrating all the sources and sinks in the footprint. The method is also quasi-instantaneous, as the time from the sources/sinks to the measurement point is in the order of minutes, hence fluxes, particularly under well mixed conditions and when properly processed, represent an instantaneous flux at the surface below. However, it is challenging (but not impossible) to retrieve long-term GHG budget estimates from Eddy Covariance data in urban areas due to changing footprints and the more heterogeneous surface and source/sink patchiness in comparison to more uniform natural ecosystems. The measurements integrate over a relatively small area (up to few square kilometres) and cannot be used to measure the GHG budget of an entire city. Nonetheless, the area of the city sampled flux towers can be expanded by increasing measurement heights and/or by operating multiple stations within the city. Surface exchanges measured using the Eddy Covariance technique have shown good correspondence with high resolution inventory techniques in urban areas (Christen et al. 2011, Gioli et al. 2015, Goret et al. 2019, Ward et al. 2015, Järvi et al., 2019). They have also been used to evaluate the land surface models used in urban meteorological simulations (e.g. Sarmiento et al, 2017). The direct flux measurements at the high temporal resolution offered by the technique are a unique resource also in studying rapid changes in behaviour such as the case of the COVID lockdown analysis done in ICOS very rapidly (Papale et al. 2020) and then in other following studies (Nicolini et al. 2022, Sugawara et al. 2021, Lamprecht et al. 2021) where looking to relative changes in time allowed for a quantification of local emission reductions. Relative changes in time are robust in their estimation and the use of wind sectors can also highlight local differences in the composition of emission sources and sinks. Integrated with other data such vehicular traffic counts can be used to disentangle the different contributions. There are several studies where the Eddy Covariance technique has been applied to measure GHG fluxes and to understand the source / sink dynamics of GHGs in urban areas (e.g. Ao et al. 2014, Christen 2014, Crawford et al. 2011, Crawford et al. 2015, Gioli et al. 2012, Grimmond et al. 2002, Helfter et al 2016, Karl et al. 2017, Järvi et al. 2018, Lietzke et al. 2015, Stagakis et al. 2019, Velasco et al. 2014, Vogt et al. 2005).

B.i.2 Principles of the observational technique

The method is based on high frequency measurements of vertical wind speed and mole fraction of a GHG and through the analysis of the covariance between the two over a pre-fixed integration period. From the covariance, it is possible to calculate the turbulent exchange between the surface and the atmosphere. The measurement system requires an ultrasonic 3D anemometer and a fast gas analyser that must be synchronized. Data are in general collected at a frequency of 10 to 20 Hz in order to capture the smaller eddies that contribute to the turbulent mixing of the GHG. The Eddy Covariance system should ideally be placed high enough above the surface to measure in the well mixed surface layer and avoid the influence of the local elements. The optimal measurement height is above the roughness sublayer which is typically 2–5 times the mean surrounding building height in an urban area (for details see Oke et al. 2017). A second recommendation is that, although GHG emission sources and sinks in the measurement region can be dispersed spatially in a heterogeneous manner, sources and sinks of GHGs in the measurement region should ideally be homogenously distributed; however, this criterion is less critical that the requirement that the urban roughness creating the turbulence should be uniform. This means that an urban Eddy Covariance system should ideally be placed in areas with roughly uniform building heights and densities with regard to approaching flow directions. More details about setting up an EC system in urban environments can be found in Feigenwinter et al. (2012) or Velasco et al. (2010).

Data collected are then processed to apply quality controls and final calculation of the fluxes over an integration period of 30 to 60 minutes typically (i.e. each flux estimates represent the average flux in the integration period).

The flux measured at the measurement point represents the average flux from the variable footprint and is expressed in µmol m^{-2} s^{-1} or nmol m^{-2} s^{-1} depending on the gas species. Improvements in instrumentation have made it relatively easy to measure methane (CH_4) fluxes (Gioli et al. 2012, Helfter et al. 2016, Pawlak and Fortuniak 2016). Other GHG fluxes can also be measured (such as N_2O; Famulari et al. 2010, Järvi et al. 2014 or O_3, Karl et al. 2020) given analysers fast enough (about 10Hz) to detect the high frequency turbulent variations.

The methods and tools for the fluxes quality control and calculation are already well established thanks to the experience in the natural ecosystem applications and for this reason mostly ready to be applied also in the context of urban environments (e.g. Aubinet et al. 2012). Nevertheless the is a strong need to evaluate their direct applicability in the urban environment and the possible adaptation to the urban context or the development of new tests.

B.i.2.1 Flux partitioning

Eddy Covariance measurements of GHGs track the net sources and sinks of the footprint, irrespective of whether they are of fossil fuel or biogenic origin. For CO_2, the net flux is the sum of all fossil fuel emissions, biomass and, in some contexts, garbage burning, and human, plant and soil respiration minus photosynthesis by urban vegetation. Several studies have shown that human respiration can make up a significant fraction (>10%) of total net emissions in densely populated areas (Björkegren & Grimmond, 2018, Järvi et al. 2019, Velasco et al., 2013, Moriwaki & Kanda, 2004). Eddy covariance measurements of CH_4 and N_2O also integrate fossil fuel emissions (leakage, incomplete combustion) and biogenic processes in cities (Christen, 2014, Annex A.b.). Hence a challenge with EC measurements in cities is separating the net emissions into different contributors. This is not straightforward, and for urban applications, no standard method currently exists. Different approaches have shown the potential using modelling for selected processes to remove them (e.g. Järvi et al. 2019), statistical modelling (e.g. Crawford et al. 2014), artificial neural networks (e.g. Menzer et al. 2015) or stable isotope fluxes.

B.i.2.2 Storage and advection fluxes

The Eddy Covariance setup described above measures the exchanges between the urban surface and the atmosphere happening through the turbulent transport. There are however conditions where the turbulence is not sufficient and in these cases the city emissions are either accumulated below the EC system (referred to in the EC literature as the storage flux) and/or transported out through lateral non-turbulent transport (horizontal advection). Situations with low turbulence, however, are less common in cities than over rural or natural surfaces, as the surface layer over a city is much more commonly neutral and unstable due to the significant roughness and the substantial releases of sensible heat, especially at night (Christen and Vogt 2004).

Storage can be calculated using measurements of the mole fraction of the scalar below the EC system (typically along a vertical profile, see for example Bjorkeren et al. 2015; Yi et al, 2000) while for the advection, although there have been tests to measure it (e.g. Yi et al, 2000), the most common approach is to detect periods where advection is likely and remove them from the data set (see for example Aubinet et al. 2012). The complexity of the urban environment may necessitate a different level of complexity in the measurements and methods. The storage component (CO_2 or other gas accumulated below the EC system) can be quite spatially heterogeneous due to the distribution of emission sources and the structure of the city including the near-surface air flow (size of the roads, height of the buildings, presence of trees, etc.) as demonstrated in Crawford et al. (2014). For this reason, the number of mole fraction measurement points needed to estimate the rate of change of storage under the system with high accuracy is larger than the number required for a more homogeneous environment. For the horizontal advection the complexity is in the selection of the threshold level of turbulence (quantified by a threshold in the square root of the momentum flux, also knowns as the friction velocity, u_*) that is site dependent. The methods to estimate this site specific threshold value are based on assumptions that cannot be made in an urban environment and for this reason the only solution available is to use a predefined threshold value that however adds uncertainty in particular to calculate budgets.

B.i.2.3 Footprint estimation

There are different modelling approaches to estimate the footprint of the flux measurements that are in general function of the measurement height, buildings mean height, variability in the surface (e.g. if all the buildings have the same height or if there is large heterogeneity) and wind characteristics (wind speed, wind direction and their variability).

Most of the methods have been developed for aerodynamically homogeneous surfaces and for this reason are not easily applicable to most urban environments. Some of these models are also relatively fast and straightforward to apply (e.g. Kljun et al., 2015) and are typically used as first guess and rough estimate on the extent of the footprint.

There are also more complex models and approaches available that can be used in strongly complex situations like in cities, but they are often difficult to use and resources demanding. The most common approach is based on large eddy simulation modelling that has been also applied for urban footprint estimation (e.g. Glazunov et al. 2016, Auvinen et al. 2017).

Depending on the position of the EC system and the characteristic of the footprint, important and useful information can be also retrieved without a proper estimation of the footprint area but analysing the fluxes for specific wind sectors, for example characterized by a specific source (traffic, heating, vegetation, etc.). This is particularly useful when measurements from the same sector are compared to detect anomalies, peaks and trends (see for example Crawford et al. 2014).

B.i.3 Instrument maintenance

An EC system can be operated unsupervised, yet all sensors require regular standard maintenance, cleaning and factory calibrations. The gas analyser also needs a periodic field calibration to check and correct the readings at zero (an air mixture without the target gas) reading and a known mole fraction (e.g. around 400 ppm for CO_2), with the first more important than the second because it directly affects the mole fraction variation measurements used as basis to calculate the fluxes (see Fratini et al. 2014). Unlike the mole fraction measurements used for urban inversions, which must be calibrated with very high absolute accuracy, EC measurements rely on the fast-response, relative precisions of the sensors, so lower quality gas calibration standards are acceptable (e.g. for CO_2 1 ppm is sufficient).

B.i.4 Companion measurements

Eddy Covariance measurements, while unable to encompass an entire city's GHG emissions, are excellent for studying local processes and testing the process-based models used to estimate fluxes. In the urban environment these models include ecosystem flux models, models or inventories of anthropogenic GHG emissions, and land surface energy balance and momentum flux models. The EC flux measurements are most easily interpreted if local measurements that would be used as inputs to these models are collected simultaneously.

Ecosystem and surface energy balance analyses benefit from on-site measurements of common meteorological variables such as air temperature, relative humidity (in some cases also vertical profiles), air pressure, precipitation and radiation (shortwave up/down and longwave up/down). Additional measurements could also include soil temperature, soil water content, water table depth, soil physical properties and soil heat fluxes in case of vegetated areas present in the footprint. In these cases, other ecosystem properties commonly measured at rural EC sites (including but not limited to leaf area index, above and below ground carbon stocks, species distributions, and leaf chemistry) are also valuable. Urban flux measurements benefit from the long history of ecosystem studies using this technique. Recommended measurements from well known long-term EC measurement programs (NEON, AmeriFlux, ICOS) serve as excellent references.

Information about anthropogenic activities is needed if the objective is to evaluate the mechanisms driving anthropogenic emissions. The variables needed to develop urban emissions inventories provide a sound guide for potential process-level measurements in these settings. The most obvious and useful example is accurate and time-resolved information on vehicular traffic within the footprint, ideally with sensors distributed along the most important and representative roads (e.g. see Buckley et al. 2016). Cameras can be used to count the number of cars or monitor their amount in parking lots in commercial areas. In case of footprints characterized by residential or commercial areas, information about the heating systems is also important and could be collected using consumption and inventory approaches. Finally, although generally not easily accessible, mobility data generally collected by smartphones have been demonstrated to be of extreme interest in identifying emissions coming from humans and vehicles (e.g. Nicolini et al. 2022, Velasco 2021).

B.i.5 Data quality considerations

The assumptions underlying the EC technique are based on a number of conditions that can be difficult to satisfy in an urban environment. One condition is that observations should be made above the roughness sublayer where turbulence is uniform and GHG fluxes from individual sources/sinks are blended. In urban areas, the height of the buildings can be quite heterogeneous, making this condition very difficult to satisfy, and complicating the interpretation of measurements. In addition, in areas where emissions are heterogeneous, the storage component is difficult to estimate accurately (see above) and so only data when turbulence is sufficient can be considered in case storage correction is not feasible. The spatial heterogeneity of emissions and a possible uneven distribution of the wind direction distribution should be also considered if the aim is to calculate a flux value representative of the measurement area. In these cases, Schmutz et al. (2016) propose to use methods based on a directional horizontal averaging, where all the wind sectors and emissions areas are weighted in order to reduce the risk of biases. This approach however can work only when long-term time series are available because a sufficient number of observations are needed also from the less represented sectors.

Data quality check and filtering procedures including stationary test and despiking can be adapted from natural ecosystem studies where significant development has been accomplished (e.g. Vitale et al., 2020). Gap filling can be made using statistical tools already largely applied in natural ecosystems ranging from moving look-up tables to multiple imputation methods and machine learning tools (e.g. see Järvi et al. 2012, Menzer et al. 2015, Schmutz et al. 2016) or simple models of emissions. In all cases however a careful evaluation of the direct applicability of the already existing methods and their adaptation to the specific urban environment conditions is needed.

B.i.6 Sampling location considerations

The choice of sampling location depends on the research objective. For the study of GHG emissions from urban systems we envision three possible objectives: 1) direct measurement of anthropogenic GHG emissions; 2) direct measurement of the GHG fluxes from vegetation within the urban environment and 3) measurements of the surface energy and momentum fluxes that drive atmospheric turbulence. In all cases the limitations noted about the height of the roughness sublayer, heterogeneous turbulence conditions and heterogeneous GHG fluxes should be considered. Sites with relatively homogeneous flux footprints, and with towers that extend above the roughness sublayer are ideal. Siting of an EC flux tower-based on these considerations is a simple matter for low-stature, urban vegetation such as turfgrass, but is more challenging if the objective is to measure anthropogenic GHG emissions which are often mixed with urban vegetation and are often heterogeneous relative to the dimensions of an EC flux footprint, also considering that EC towers cannot be used to measure large point sources (such as chimneys of power plants). In terms of platforms, it is necessary to find a compromise among the technical EC requirements, the legal aspects and the feasibility in terms of maintenance of the instruments. In general, thin and tall telecommunication towers are a good option because they are ready to host sensors and in general accessible. Locating the EC system on a building top is not advisable, as the turbulence near the rooftop could be severely altered by the building, unless a tower can be extended from the top of the building to install the EC system (Feigenwinter et al., 2012). In general, isolated and bulky high-rise buildings should be avoided not only as measurement platforms but also in the footprint as they can cause severe anomalies in the turbulence field making the data difficult to interpret.

B.i.7 Sampling strategy

Short-term (weeks to months) and long-term (years) measurements are both valuable. The high temporal resolution of the EC method enables a site's fluxes to be characterized relatively quickly and the time needed to sample all wind directions sufficiently in the case of a heterogeneous flux footprint. Short-term measurement can be deployed and redeployed across an urban area to capture variability in urban emissions across space. The ability to maintain these systems for years in the same location also enables the establishment of long-term monitoring important to detect trends and patterns. Currently there are between 10 and 20 long-term urban EC stations active in Europe and an estimation of about 40 globally. A coordination of the existing stations is under construction in the context of the ICOS European Research Infrastructure where, also thanks to the Pilot Application in Urban Landscapes (PAUL) Horizon2020 European project, new methods for data processing will be developed and the use of tall towers with large footprint for multiple GHGs monitoring will be tested (https://cordis.europa.eu/project/id/101037319). Shorter-term deployments intended to quantify urban turbulence conditions or for specific local studies have been deployed in different examples in Europe and USA, like the study still ongoing around the city of Indianapolis in the US (Sarmiento et al, 2017).

Today it is also possible to have near-real-time products with the fluxes processed and made available in a few hours, providing useful information for real time ingestion in models or to provide indications in the context of the emissions management by public administrations. Co-location with other instruments to monitor different emission compartments in the footprint would clearly help the attribution and could contribute to an integrated monitoring system. For example, the co-location with isotopes mixing ratios can help the partitioning and attribution of the fluxes to different sources (e.g. Venturi et al., 2020).

B.i.8 References

Ao X., Grimmond C.S.B., Chang Y. et al. (2016), Heat, water and carbon exchanges in the tall megacity of Shanghai: challenges and results, *International Journal of Climatology*, 36(14), 4608–4624, doi:10.1002/joc.4657.

Aubinet M., Vesala T. and Papale D. (Eds.) (2012), *Eddy Covariance*, doi:10.1007/9784–007–2351–1.

Auvinen M., Järvi L., Hellsten A. et al. (2017), Numerical framework for the computation of urban flux footprints employing large eddy simulation and Lagrangian stochastic modelling, *Geoscientific Model Development*, 10(11), 4187–4205, doi:10.5194/gmd-10–4187–2017.

Björkegren A.B., Grimmond C.S.B., Kotthaus S. et al. (2015), CO_2 emission estimation in the urban environment: Measurement of the CO_2 storage term, *Atmospheric Environment*, 122, 775–790, doi:10.1016/j.atmosenv.2015.10.012.

Buckley S.M., Mitchell M.J., McHale P.J. et al. (2016), Variations in carbon dioxide fluxes within a city landscape: Identifying a vehicular influence, Urban *Ecosystems*, 19(4), 1479–1498, doi:10.1007/s11252–013–0341–0.

Christen A. and Vogt R. (2004), Energy and radiation balance of a central European city, *International Journal of Climatology*, 24(11), 1395–1421, doi:10.1002/joc.1074.

Christen A., Coops N.C., Crawford B.R. et al. (2011), Validation of modelled carbon dioxide emissions from an urban neighbourhood with direct eddy covariance measurements, *Atmospheric Environment*, 45(33), 6057–6069, doi:10.1016/j.atmosenv.2011.07.040.

Christen A. (2014), Atmospheric Measurement Techniques to quantify greenhouse gas emissions from cities, *Urban Climate*, 10, 241–260, doi:10.1016/j.uclim.2014.04.006.

Crawford B., Grimmond C.S.B. and Christen A. (2011), Five years of carbon dioxide fluxes measurements in a highly vegetated suburban area, *Atmospheric Environment*, 45(4), 896–905, doi:10.1016/j.atmosenv.2010.11.017.

Crawford B. and Christen A. (2014), Spatial source attribution of measured urban eddy covariance CO_2 fluxes, *Theoretical and Applied Climatology*, 119(3–4), 733–755, doi:10.1007/s00704–014–1124–0.

Famulari D., Nemitz E., Di Marco C. et al. (2010), Eddy covariance measurements of nitrous oxide fluxes above a city, *Agricultural and Forest Meteorology*, 150(6), 786–793, doi:10.1016/j.agrformet.2009.08.003.

Feigenwinter C., Vogt R. and Christen A. (2011), Eddy Covariance Measurements Over Urban Areas, *Eddy Covariance*, 377–397, doi:10.1007/9784–007–2351–1_16.

Fratini G., McDermitt D.K. and Papale D. (2014), Eddy covariance flux errors due to biases in gas concentration measurements: origins, quantification and correction, *Biogeosciences*, 11(4), 1037–1051, doi:10.5194/bg-11–1037–2014.

Gioli B., Toscano P., Lugato E. et al. (2012), Methane and carbon dioxide fluxes and source partitioning in urban areas: The case study of Florence, Italy, *Environmental Pollution*, 164, 125–131, doi:10.1016/j.envpol.2012.01.019.

Gioli B., Gualtieri G., Busillo C. et al. (2015), Improving high resolution emission inventories with local proxies and urban eddy covariance flux measurements, *Atmospheric Environment*, 115, 246–256, doi:10.1016/j.atmosenv.2015.05.068.

Glazunov A., Rannik Ü., Stepanenko V. et al. (2016), large eddy simulation and stochastic modelling of Lagrangian particles for footprint determination in the stable boundary layer, *Geoscientific Model Development*, 9(9), 2925–2949, doi:10.5194/gmd-9–2925–2016.

Goret M., Masson V., Schoetter R. et al. (2019), Inclusion of CO_2 flux modelling in an urban canopy layer model and an evaluation over an old European city centre, *Atmospheric Environment* 3, 100042, doi:10.1016/j.aeaoa.2019.100042.

Grimmond C.S., King T., Cropley F. et al. (2002), Local scale fluxes of carbon dioxide in urban environments: methodological challenges and results from Chicago, *Environmental Pollution* 116, 243–254, doi:10.1016/s0269–7491(01)00256–1.

Helfter C., Tremper A.H., Halios C.H. et al. (2016), Spatial and temporal variability of urban fluxes of methane, carbon monoxide and carbon dioxide above London, UK, *Atmospheric Chemistry and Physics*, 16(16), 10543–10557, doi:10.5194/acp-16–10543–2016.

Järvi L., Nordbo A., Junninen H. et al. (2012), Seasonal and annual variation of carbon dioxide surface fluxes in Helsinki, Finland, in 2006–2010, *Atmospheric Chemistry and Physics*, 12(18), 8475–8489, doi:10.5194/acp-12–8475–2012.

Järvi Leena; Nordbo A., Rannik Ü. et al. (2014), Urban nitrous oxide fluxes measured using the eddy covariance technique in Helsinki, Finland, *Boreal Environment Research* 19(supplement B, 2014): 108–121.

Järvi L., Rannik Ü., Kokkonen T.V. et al. (2018), Uncertainty of eddy covariance flux measurements over an urban area based on two towers, *Atmospheric Measurement Techniques*, 11(10), 5421–5438, doi:10.5194/amt-11–5421–2018.

Järvi L., Havu M., Ward H.C. et al. (2019), Spatial Modelling of Local-Scale Biogenic and Anthropogenic Carbon Dioxide Emissions in Helsinki, *Journal of Geophysical Research: Atmospheres*, 124(15), 8363–8384, doi:10.1029/2018jd029576.

Karl T. et al. (2017), Urban eddy covariance measurements reveal significant missing NOx emissions in Central Europe, *Scientific Reports*, 7(1), doi:10.1038/s41598–017–02699–9.

Karl T. et al. (2020), Studying Urban Climate and Air Quality in the Alps: The Innsbruck Atmospheric Observatory, *Bulletin of the American Meteorological Society*, 101(4), E488–E507, doi:10.1175/bams-d-19–0270.1.

Kljun N., Calanca P., Rotach M.W. et al. (2015), A simple two-dimensional parameterization for Flux Footprint Prediction (FFP), *Geoscientific Model Development*, 8(11), 3695–3713, doi:10.5194/gmd-8–3695–2015.

Lamprecht C., Graus M., Striednig M. et al. (2021), Decoupling of urban CO_2 and air pollutant emission reductions during the European SARS-CoV-2 lockdown. *Atmospheric Chemistry and Physics*, 21(4), 3091–3102, https://doi.org/10.5194/acp-21–3091–2021.

Lietzke B., Vogt R., Feigenwinter C. et al. (2015), On the controlling factors for the variability of carbon dioxide flux in a heterogeneous urban environment, *International Journal of Climatology*, 35(13), 3921–3941, doi:10.1002/joc.4255.

Menzer O., Meiring W., Kyriakidis P.C. et al. (2015), Annual sums of carbon dioxide exchange over a heterogeneous urban landscape through machine learning based gap filling *Atmospheric Environment* 101, 312–327, 10.1016/j.atmosenv.2014.11.006.

Moriwaki R. and M. Kanda (2004), Seasonal and Diurnal Fluxes of Radiation, Heat, Water Vapour, and Carbon Dioxide over a Suburban Area, *Journal of Applied Meteorology*, 43(11), 1700–1710, doi:10.1175/jam2153.1.

Nicolini G., Antoniella G., Carotenuto F. et al. (2022), Direct observations of CO_2 emission reductions due to COVID-19 lockdown across European urban districts. *Science of the Total Environment*, 154662, https://doi.org/10.1016/j.scitotenv.2022.154662.

Oke T.R., Mills G., Christen A. et al. (2017), *Urban Climates*, doi:10.1017/9781139016476.

Papale D., Antoniella G., Nicolini G. et al. (2020) Clear evidence of reduction in urban CO_2 emissions as a result of COVID-19 lockdown across Europe. Integrated Carbon Observation System (ICOS). https://data.icos-cp.eu/objects/w6pTmRGYKqAm3c-siQrg5kgd, accessed 27 October 2021.

Pawlak W. and Fortuniak K. (2016), Eddy covariance measurements of the net turbulent methane flux in the city centre – results of 2-year campaign in Łódź, Poland, *Atmospheric Chemistry and Physics*, 16(13), 8281–8294, doi:10.5194/acp-16–8281–2016.

Sarmiento D.P., Davis K.J., Deng A. et al. (2017), A comprehensive assessment of land surface-atmosphere interactions in a WRF/Urban modelling system for Indianapolis, IN, edited by D. Helmig and P. Palmer, *Elementa: Science of the Anthropocene*, 5, doi:10.1525/elementa.132.

Schmutz M., Vogt R., Feigenwinter C. et al. (2016), Ten years of eddy covariance measurements in Basel, Switzerland: Seasonal and interannual variabilities of urban CO_2 mole fraction and flux, *Journal of Geophysical Research: Atmospheres*, 121(14), 8649–8667, doi:10.1002/2016jd025063.

Stagakis S., Chrysoulakis N., Spyridakis N. et al. (2019), Eddy Covariance measurements and source partitioning of CO_2 emissions in an urban environment: Application for Heraklion, Greece, *Atmospheric Environment*, 201, 278–292, doi:10.1016/j.atmosenv.2019.01.009.

Sugawara H., Ishidoya S., Terao Y. et al. (2021), Anthropogenic CO_2 emissions changes in an urban area of Tokyo, Japan, due to the COVID-19 pandemic: A case study during the state of emergency in April–May 2020, *Geophysical Research Letters*, 48, doi.org/10.1029/2021GL092600.

Velasco E. and Roth M. (2010), cities as net sources of CO_2: Review of atmospheric CO_2 exchange in urban environments measured by eddy covariance technique, *Geography Compass*, 4(9), 1238–1259, https://doi.org/10.1111/j.1749–8198.2010.00384.x.

Velasco E., Perrusquia R., Jiménez E. et al. (2014), Sources and sinks of carbon dioxide in a neighbourhood of Mexico City, *Atmospheric Environment*, 97, 226–238, 10.1016/j.atmosenv.2014.08.018.

Velasco E. (2021) Impact of Singapore's COVID-19 confinement on atmospheric CO_2 fluxes at neighbourhood scale. *Urban Climate* 37, 100822, 10.1016/j.uclim.2021.100822

Venturi S. et al. (2020), Seasonal and diurnal variations of greenhouse gases in Florence (Italy): Inferring sources and sinks from carbon isotopic ratios, *Science of the Total Environment*, 698, 134245, doi:10.1016/j.scitotenv.2019.134245.

Vitale D., Fratini G., Bilancia M. et al. (2020), A robust data cleaning procedure for eddy covariance flux measurements, *Biogeosciences*, 17(6), 1367–1391, doi:10.5194/bg-17–1367–2020.

Vogt R., Christen A., Rotach M.W. et al. (2005), Temporal dynamics of CO_2 fluxes and profiles over a central European city, *Theoretical and Applied Climatology*, 84(1–3), 117–126, doi:10.1007/s00704–005–0149–9.

Yi C., Davis K.J., Bakwin P.S. et al. (2000), Influence of advection on measurements of the net ecosystem-atmosphere exchange of CO_2 from a very tall tower, *Journal of Geophysical Research: Atmospheres*, 105(D8), 9991–9999, doi:10.1029/2000jd900080.