City Climate Finance Gap Fund

GAP FUND TECHNICAL NOTES

CARBON MONITOR CITIES 2.0: TRACKING URBAN EMISSIONS IN NEAR REAL TIME

March 2024

Carbon Monitor Cities 2.0

Tracking Urban Emissions in Near Real Time[1]

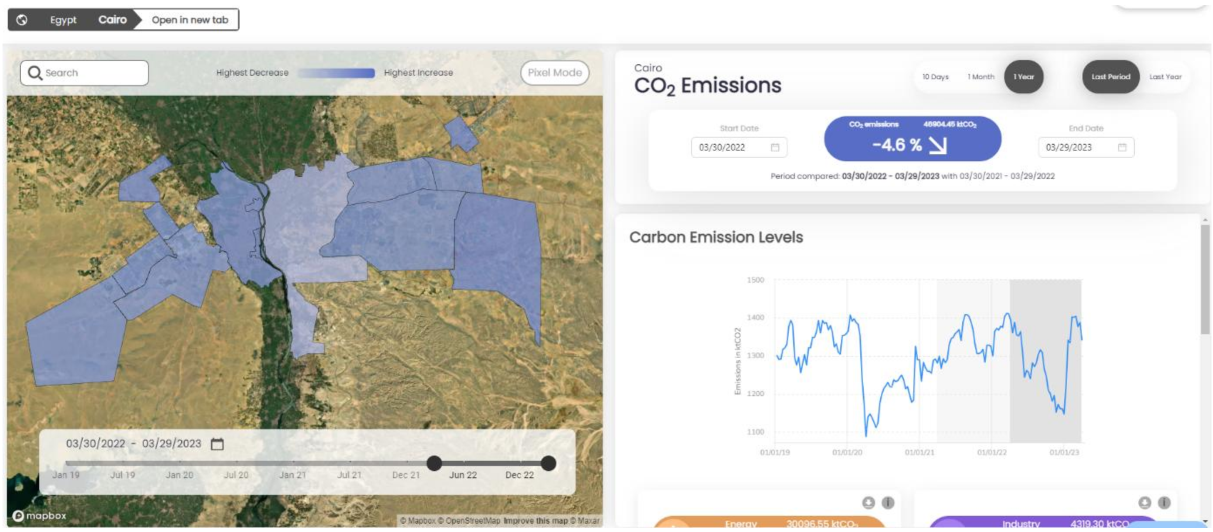

Figure 1: A screenshot showing results for the greater Cairo metropolitan area in the Carbon Monitor Cities 2.0 interface[2]

Introduction

This note describes Carbon Monitor Cities 2.0, a new approach to near-real-time monitoring of city-level greenhouse gas emissions from various sectors without the need for local data collection. With support from the City Climate Finance Gap Fund, the World Bank piloted this approach for 11 cities in three middle-income countries: Egypt, South Africa, and Türkiye.

The aim of the pilot was to demonstrate the ability to generate near-real-time data on local greenhouse gas emissions, which could allow a better understanding of the spatial and temporal patterns of urban carbon emissions in specific cities. This understanding could inform local climate change mitigation policies and investments, and also potentially be used as part of a monitoring, reporting and verification (MRV) system for carbon finance in the future. As this approach does not rely on local data collection, it can be scaled up to a large number of cities relatively easily, particularly in low-and-middle-income countries that lack data.

[1] Carbon Monitor Cities 2.0 was developed by a consortium of consultants led by Philippe Ciais at Laboratoire des Sciences du Climat et de l'Environnement (LSCE) and Antoine Benoit at Kayrros. The activity was supported by a grant from the City Climate Finance Gap Fund. It was supervised by a World Bank team which included (in alphabetical order) Chandan Deuskar, Augustin Maria, Joanna Masic, Craig Meisner, and Benjamin Stewart, with support from World Bank teams in Egypt, South Africa, and Türkiye.

[2] Any data represented in figures in this page are intended only as demonstrations of the Carbon Monitor Methodology 2.0 research methodology, and do not represent official estimates of emissions from the pilot cities endorsed by the World Bank, City Climate Finance Gap Fund, or any government entity.

Why is a better system needed to monitor urban greenhouse gas emissions?

City-level greenhouse gas emissions data is necessary as an input into identifying, planning, and monitoring urban climate change mitigation actions. Near-real-time data with a high frequency, visualized in a clear and compelling manner, can aid decision-makers to analyze the relationship between urban activities and emissions and evaluate the impacts of their actions.

However, data on local greenhouse gas (GHG) emissions is unavailable for most cities in low- and middle-income countries. While some cities have produced local GHG inventories, they are inconsistent in methodology and year, and not updated regularly. Some data sets, such as the European Commission's Emissions Database for Global Atmospheric Research (EDGAR), downscale national emissions inventories using spatial proxy data to a global grid of 10x10km cells. However, there is a lag of a few years before this data is available. Satellites measure CO_2 concentrations but face significant data gaps due to cloud cover. It is also challenging to trace CO_2 concentrations from satellite data back to original emission locations, as CO_2 can travel great distances in the atmosphere. While each of these data sources can be used for certain types of analysis, none of them meets the need for high-frequency, recent city-level emissions data.

Building on recent innovations

As an attempt to meet this need for high-frequency, low-latency city-level emissions data, a consortium of researchers at universities in France, China, and the United States developed a monitoring system called Carbon Monitor Cities, the predecessor of the system discussed in this note.[3] The Carbon Monitor Cities model disaggregated national emissions data spatially to a 0.1 degree (approximately 10x10 km) grid and temporally to a daily frequency, resulting in daily CO_2 estimates for approximately 1500 cities in 46 countries. To do this, it used EDGAR data and other point data for spatial disaggregation, and satellite data on NO_2 emissions for temporal disaggregation. Annual estimates produced using this model were close (within 15 percent) of estimates using other methods. Emissions were also disaggregated by sector into power generation, residential (buildings), industry, ground transportation, and aviation. However, there were still limitations in this original Carbon Monitor Cities model, as the spatial data needed for realistic disaggregation down to the grid-cell level was not readily available for cities outside Europe.

Aims of Carbon Monitor Cities 2.0

The World Bank, with support from the City Climate Finance Gap Fund, aimed to build on the innovations of Carbon Monitor Cities in order to identify whether it would be possible to implement the monitoring system in cities in middle-income countries, where local emissions data are often scarce. The new approach was applied to 11 cities in 3 countries—Egypt, South Africa, and Türkiye—which volunteered or were nominated by national government bodies to serve as pilot cities to

[3] Huo, D., Huang, X., Dou, X. et al. Carbon Monitor Cities near-real-time daily estimates of CO2 emissions from 1500 cities worldwide. Sci Data 9, 533 (2022). https://doi.org/10.1038/s41597-022-01657-z

demonstrate the potential for the new system.[4] Researchers from the original Carbon Monitor Cities team, at Laboratoire des Sciences du Climat et de l'Environnement (LSCE) in France and Tsinghua University in China, redeveloped their methodology to suit this context. An important aspect of the pilot was to demonstrate the ability to model emissions at scale, which meant not relying on any local data collection on a city-by-city basis, which is time consuming and difficult to scale up. In addition, an online interface was developed to visualize the data produced by the model and allow users to interact with it in order to gain insights.

Methods and Data

Scope and emissions accounting protocols used in Carbon Monitor Cities 2.0

Carbon Monitor Cities 2.0 offers a monitoring platform that quantifies CO_2 emissions of cities, including point source locations, and a temporal resolution of ten days. The platform provides a time series of historical emissions from three key emission sectors: energy, transportation (road transportation and aviation), and industry. In total, three cities in Egypt, four cities in South Africa and four cities in Türkiye were covered.

The scope of Carbon Monitor Cities 2.0 follows the BASIC+ approach of the *Global Protocol for Community-Scale Greenhouse Gas Inventories*[5] (GPC Protocol).[6] All the CO_2 emissions estimated using this approach could potentially be used by city representatives for reporting purposes within the GPC Protocol. The scope and accounting of emissions for the sectors listed above is as follows:

1. Energy

The energy sector *("Stationary Energy" in the GPC Protocol)* consists of two sub-sectors:

- The electricity generation which includes the emissions released from electricity generated using natural gas, oil, and coal. *("Energy industries" in the GPC Protocol)*
- The energy generated from direct fossil fuel combustion in residential, commercial and institutional buildings and facilities and manufacturing industries and construction. *("Residential buildings", "Commercial and institutional buildings and facilities", "Manufacturing industries and construction" in the GPC Protocol)*

2. Transportation

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[4] The cities are: Adana, Manisa, Konya, and Antalya for Türkiye; Cairo, Alexandria, Luxor for Egypt; and Johannesburg, Tshwane, Ekurhuleni, and eThekwini for South Africa.

[5] World Resources Institute. (2021, 06). *Global Protocol for Community-Scale Greenhouse Gas Inventories*. Greenhouse Gas Protocol. Retrieved October 11, 2022, from https://ghgprotocol.org/sites/default/files/standards/GPC_Full_MASTER_RW_v7.pdf

[6] According to the GPC Protocol, the BASIC level of reporting covers emissions from stationary energy and transportation (scopes 1 and 2), as well as from waste (scopes 1 and 3). BASIC+ adds industrial processes and product use, emissions and removals from agriculture, forestry and land use (AFOLU), and emissions from transboundary transportation. Thus, Carbon Monitor Cities 2.0 includes some BASIC+ sectors (stationary energy, some forms of transportation, and industrial processes related to cement manufacturing) but excludes others (such as waste, industries other than cement, and AFOLU).

a. Road transportation

The transport sector includes exclusively road transportation inside the boundaries of the city from vehicles of all types. *("On-road" in the GPC Protocol)*

b. Aviation

The aviation sector includes the emissions coming from national and international flights departing from the city or from airports in the vicinity of the city.

3. Industry

The industry sector includes exclusively emissions from the cement industry. *("Industrial processes" in the GPC Protocol)*

Methodologies by sector

Emissions linked to the aviation, energy, and industry sectors are calculated using activity indicators and emission factors following the IPCC Guidelines for emission reporting[7], following the equation:

$$Emissions = Activity \times Emission\ factor$$

The emission factors are assumed to remain constant over the period considered.

Energy

Electricity

South Africa

Coal: South Africa uses almost exclusively coal to produce its electricity. Coal power plants activities are monitored with Sentinel-2 satellite images of the clouds generated by cooling towers combined with deep-learning algorithms. This results in estimation of national electricity generated from coal grouped over a 10-day span. An emission factor is applied to obtain the emissions.[8] Power plants in each city jurisdiction are identified from the GID global database[9] and local registers provided by cities.

[7] Intergovernmental Panel on Climate Change (IPCC). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. (Intergovernmental Panel on Climate Change, 2006).
[8] http://www.erc.uct.ac.za/groups/esap/satim
[9] The Global Energy Infrastructure Emissions Database. (02, 03 2021). GIDmodel – Tracking global infrastructure emissions. Retrieved October 11, 2022, from http://gidmodel.org.cn/

Oil: It is assumed that the national production of electricity from oil is proportionate to the national production of electricity from coal. Ember's Global Electricity Review[10] and the Global Carbon Monitor[11] are used to find the electricity split.

Egypt

The Egyptian electricity generation sector is divided into two main categories. The electricity generated from natural gas, and the electricity generated from oil.

Gas: The JODI database[12] gives the monthly quantity of natural gas used for electricity generation in the country. The amount of electricity generated from natural gas in Egypt shows a predictable seasonal pattern. Based on the assumption of a regular seasonal pattern, a seasonal model is fitted to the historical data and used to predict the electricity generated from natural gas at the national level. An emission factor from IPCC is applied to obtain the emissions.[13]

Oil: It is assumed that the national production of electricity from oil is proportionate to the national production of electricity from gas. Ember's Global Electricity Review[14] and the Global Carbon Monitor[15] are used to find the electricity split.

Türkiye

Turkiye's electricity emissions come mainly from a mix of oil, coal, and natural gas. The Turkish Electricity Transmission Corporation[16] gives national hourly electricity generation data by sector of production. For each sector except coal, emission factors from IPCC (2006) are applied accordingly to obtain the emissions coming from each source. For coal, an emission factor from Ari & Koksal (2011)[17] is applied.

Low-carbon energy sources

Hydropower and renewable energy: Hydropower and renewable energies generate a small portion of Egyptian, Turkish, and South African electricity. Their weight is negligible in the CO_2 emission balance, therefore they were not considered in the carbon emissions.

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[10] Global Carbon Budget Governance. (2019, November 27). Global Carbon Project. Retrieved October 11, 2022, from https://www.globalcarbonproject.org/carbonbudget/governance.htm#gov4

[11] Source: Our World in Data based on BP Statistical Review of World Energy (2022); Our World in Data based on Ember's Global Electricity Review (2022); Our World in Data based on Ember's European Electricity Review (2022)

[12] Joint Organisations Data Initiative (JODI), www.jodidata.org

[13] IPCC (2006), 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan. Available at https://www.ipccnggip.iges.or.jp/public/2006gl/

[14] Global Carbon Budget Governance (2019)

[15] Source: Our World in Data based on BP Statistical Review of World Energy (2022); Our World in Data based on Ember's Global Electricity Review (2022); Our World in Data based on Ember's European Electricity Review (2022)

[16] Dispatcher Information System (YTBS) of Turkish Electricity Transmission Company (TEİAŞ) by TÜBİTAK MRC Energy Technologies. Available: ytbsbilgi.teias.gov.tr

[17] Ari i. Koksal M. Carbon dioxide emission from the Turkish electricity sector and its mitigation options, *Energy policy*. Vol 39, Issue 10 https://doi.org/10.1016/j.enpol.2011.07.012

Nuclear power: is used to generate around 5% of South African power. Its weight is neglectable in the CO_2 emission balance. No nuclear power is used in Türkiye and Egypt.

Therefore, those two energy sources were not considered in the CO_2 emissions.

Energy - Direct Fossil Fuel Combustion by industrial and residential use

Egypt

Egypt uses gas and oil directly for industrial and residential use.

Gas: The JODI database gives historical data on the monthly quantity of natural gas used in the country (excluding natural gas used for electricity generation) until four months ago. The amount of natural gas used as a direct fuel in Egypt does not follow a specific pattern. For this reason, the national emissions are given according to the last data available, i.e., with a four-month lagging period. An emission factor from IPCC (2006) is applied to obtain the emissions.

Oil: It is assumed that the national consumption of oil as direct fuel is proportionate to the national consumption of gas as a direct fuel. Ember's Global Electricity Review and the Global Carbon Monitor are used to find the yearly emissions linked to direct fossil fuel use.

Türkiye

Türkiye uses gas, oil, and coal directly for small industries and residential use.

Gas: The JODI database gives historical data on the monthly quantity of natural gas used in the country. The amount of natural gas used as a direct fuel in Türkiye shows a predictable seasonal pattern. Based on the assumption of a regular seasonal pattern, a seasonal model is fitted to the historical data and used to predict the amount of natural gas used as a direct fuel in the country. An emission factor from IPCC (2006) is applied to obtain the emissions.

Oil & Coal: It is assumed that the national consumption of oil and coal as direct fuels is proportionate to the national consumption of gas as a direct fuel. Ember's Global Electricity Review and the Global Carbon Monitor are used to find the yearly emissions linked to direct fossil fuel use.

South Africa

In the residential sectors, South Africa uses a mix of coal, gas, and paraffin, and other energy sources to heat, cook, and light its households. Following the GPC Protocol, only coal, gas, and paraffin were counted in the inventory. The method chosen follows the Guide to Data Collection and Collation for a Greenhouse Gas Inventory from Sustainable Energy Africa (SEA)[18]. For each energy source, the number of households using this energy is retrieved from the Statistic of South Africa department.[19]

[18] https://cityenergy.org.za/uploads/resource_422.pdf

[19] Stats SA http://superweb.statssa.gov.za/

The number of households is then converted to a monthly energy consumption.[20] An emission factor from IPCC (2006) is applied to obtain the emissions.

Disaggregation of energy use on buildings blocks

Automatic retrieval of buildings height and types from remote sensing and buildings databases

The building-level population is the key parameter for energy consumption and CO_2 emission within buildings.[21] The building height and types are estimated with semi-supervised learning at a high normalized accuracy (0.89). Three types of datasets are used: 1) building datasets, e.g., OpenStreetMap and Microsoft building footprints, 2) remote sensing images, e.g., Sentinel-2 images and VIIRS Nighttime Light, and 3) remote sensing products, e.g., global human settlement layers. The district populations are then disaggregated into building levels based on the building height and type for energy and CO_2 emission estimates.

Disaggregation of energy use and emissions to building blocks

Residential energy consumption and the associated CO_2 emissions are estimated at the building block level with a resolution of 500 m. Building block level features, such as populations, building density, personal living area, and regional poverty level, are important parameters of energy consumption and CO_2 emissions. These factors, which are estimated with the building's height and type (from the previous step) combined with open datasets, are a basic energy consumption and CO_2 emission index for the building blocks. Energy use and CO_2 emissions are also strongly correlated with various activities occurring within the buildings, such as heating and cooling operations, as well as fundamental human activity. Near real-time satellite images, including MODIS land surface temperature, VIIRS Nighttime Light, and Sentinel-5P NRTI products (NO_2, CO, SO_2, O_3), are used as activity proxies for evaluating the building block level energy use and emission intensity and disaggregating the city-level emissions.

Transportation

Road Transportation

For road transportation, the data used comes from Tom Tom's 'Traffic Stats' product. It gives, for each road segment in the city, the number of vehicles, their average speed, and the length of the road. As explained in Ntziachristos and Samaras (2021)[22] and Li et al. (2020)[23], it is possible to

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[20] https://idlbncidrc.dspacedirect.org/bitstream/handle/10625/13393/105244.pdf

[21] Liu, Z., Ciais, P., Deng, Z. et al. Near-real-time monitoring of global CO_2 emissions reveals the effects of the COVID-19 pandemic. Nat Commun 11, 5172 (2020). https://doi.org/10.1038/s41467-020-18922-7

[22] Leonidas Ntziachristos, Zissis Samaras et al. EMEP/EEA air pollutant emission inventory guidebook 2019 - Update Oct. 2021

[23] Li Y, Lv C, Yang N, Liu H, Liu Z, A study of high temporal-spatial resolution greenhouse gas emissions inventory for on-road vehicles based on traffic speed-flow model: A case of Beijing, Journal of Cleaner Production (2020), doi: https://doi.org/10.1016/j.jclepro.2020.122419.

combine these three features to obtain an activity indicator. The parabolic function describing the amount of fuel used depending on the speed is taken from Chowdhury et al. (2012)[24].

$$Activity = no. of\ vehicles\ on\ the\ road * road\ length * parabolic\ function\ (average\ speed)$$

Then, for each city, an emission factor was calibrated annually using EDGAR v7.0 (1A3b_noRES) - Global Greenhouse Gas Emissions dataset[25].

Aviation

Emissions in the aviation sector are computed from individual commercial and cargo flight data from the FlightAware database on a flight-by-flight basis. The CO_2 emissions for a given flight were estimated as the product of activity and an emission factor, both defined below. For a given flight:

- The activity is the total distance flown multiplied by the capacity of the plane and a load factor.
- The emission factor depends on the type of aircraft, its capacity, and the distance flown following the ADEME (French Environment and Energy Management Agency) methodology.[26]
- It is assumed that the load factor is constant and equal to 80% for all the flights all year round.

The CO_2 emissions are the sum of all the emissions of the *departing* flights from the city airport(s). Emissions from flights associated with a single airport in the jurisdiction of a city can be attributed to travels from: inhabitants from the city, inhabitants from other cities as well as to foreign travelers. In absence of information about these categories, we present the results using an attribution of airport emissions to the city population (taking into account the existence of neighboring cities sharing the same airport, as described in the section on disaggregation below). If a city does not have an airport, the emission patterns of the closest airport are taken.

Attribution of aviation emissions in this manner may not correspond to the accounting of emissions that a city has under its responsibility. However, the attribution of aviation emissions can be easily modified to use another approach to match cities' requirements and policies. The GPC Protocol makes no clear recommendation on this but suggests using a similar methodology ("Cities may report just the portion of scope 3 aviation emissions produced by travelers departing the city".)

Cement Industry

For the industry sector, only the cement industry is monitored. A common method relying on satellite imagery is applied to the three countries.

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[24] Chowdhury, H., Alam, F., Khan, I., Djamovski, V., Watkins, S. Impact of vehicle add-ons on energy consumption and greenhouse gas emissions, Procedia Engineering (2012) https://www.researchgate.net/publication/257726255

[25] Crippa, M., Guizzardi, D., Solazzo, E., Muntean, M., Schaaf, E., Monforti-Ferrario, F., Banja, M., Olivier, J.G.J., Grassi, G., Rossi, S., Vignati, E., GHG emissions of all world countries - 2021 Report, EUR 30831 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-41547-3, doi:10.2760/173513, JRC126363

[26] Documentation Base Carbone. (n.d.). Retrieved October 19, 2022, from https://bilans-ges.ademe.fr/documentation/UPLOAD_DOC_EN/index.htm?aerien2.htm

Cement factories in each city jurisdiction are identified from the GID global database and local registers provided by cities. The location of rotary kilns within each cement plant is labeled manually using satellite images, these rotary kilns emit heat during the clinker manufacturing process.

Sentinel-2 satellite images are then automatically analyzed for heat signals activity using machine learning to estimate a local temporal profile of activity for each cement plant. An emission factor from IPCC (2006) is applied to obtain the emissions.

Following the GPC framework, only emissions linked to industrial processes are monitored (excluding emissions coming from the combustion of fossil fuels).

Sources of uncertainty

Aviation: Uncertainties for aviation come mainly from the hypothesis of a constant passenger load factor for all the flights all year round.

Energy: For the methods using satellite imagery, uncertainties come mainly from the weather and the number of cloudy days. The cloudier the area, the less information is retrieved from imagery obtained by Sentinel-2. Uncertainties come also from the inter-annual variability of emission factors that were considered constant for this activity. According to the UN statistics, the inter-annual variability of fossil fuel is within (±1.5%). Finally, a source of uncertainties is the hypothesis that energy generated from oil and coal is proportionate to the energy generated from natural gas.

Industry: This sector is exclusively monitored via satellite imagery. Uncertainties come from the weather and the ability to give information during cloudy days. It is assumed that the cement plants are working at full capacity. As for the power sector, the inter-annual and inter-country variability of emission factors also bring some uncertainties.

Road transportation: The main source of uncertainty comes from the calibration of EDGAR data and especially the attribution of EDGAR pixels to each city. Finally, some uncertainties are linked to disaggregation. For the first version, the emissions of the aviation, energy, and industry sectors were supposed to be proportionate to the population of the cities studied.

Ongoing research will estimate the range of uncertainty for each sector as well as the overall uncertainty of the results. Validation of the previous Carbon Monitor model yielded an overall uncertainty range of 6.8%.[27]

Online interface showing emissions maps in near real time

The interactive visualization interface developed to display the data for all 11 pilot cities allows users to navigate through CO_2 emissions for the sectors described above at the city-level (Figure 2). For the energy sector only, users can also go down to the district-level (Figure 3) and at the pixel-level at 500m resolution (Figure 4). The user can compare the emissions between two different periods and

[27] Liu, Z., Ciais, P., Deng, Z. et al. Near-real-time monitoring of global CO2 emissions reveals the effects of the COVID-19 pandemic. Nat Commun 11, 5172 (2020). https://doi.org/10.1038/s41467-020-18922-7

view the evolution over the period for the sectors concerned. Users can also download the data as .csv files.

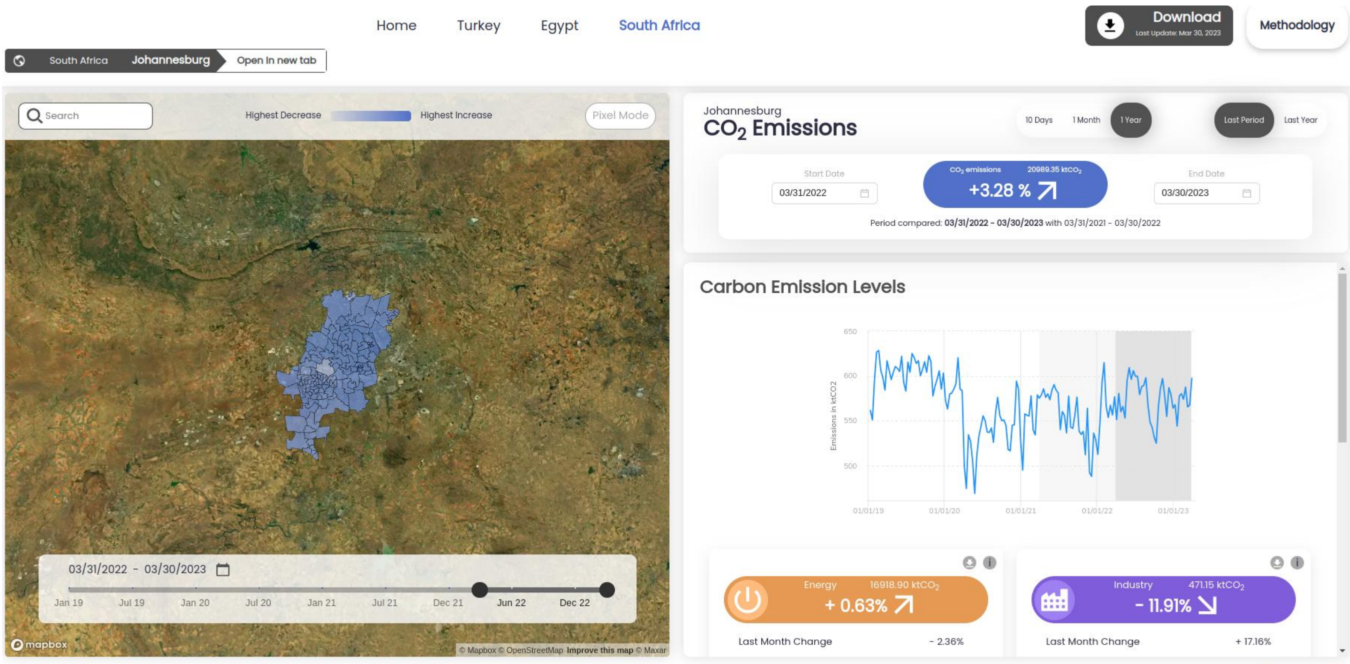

Figure 2: Johannesburg city view of Carbon Monitor Cities 2.0

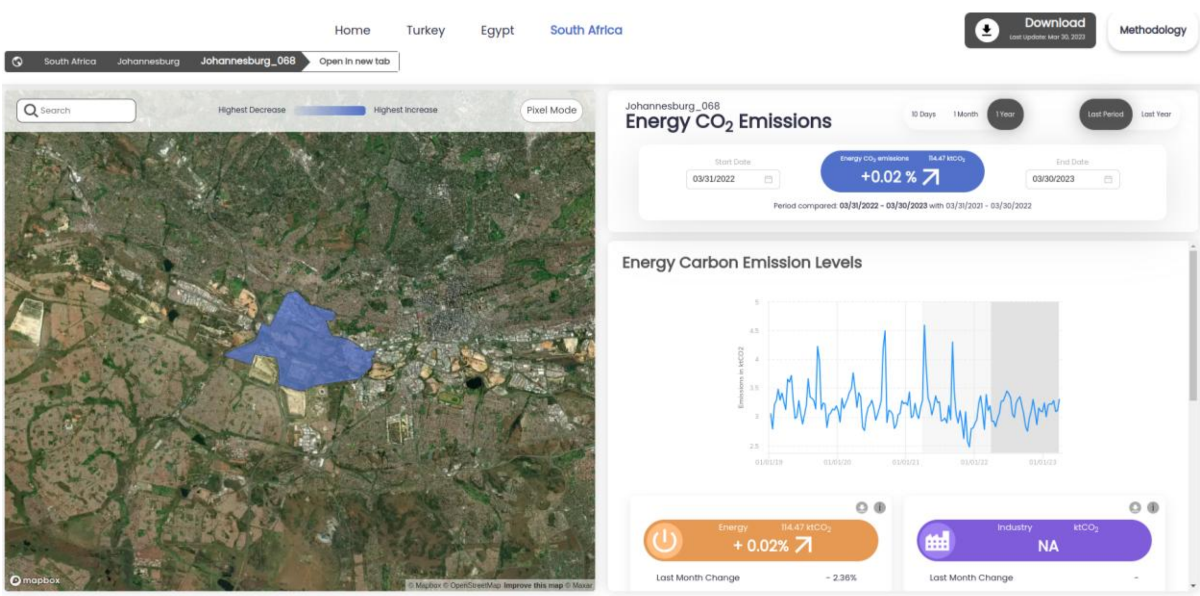

Figure 3: District view of Carbon Monitor Cities 2.0

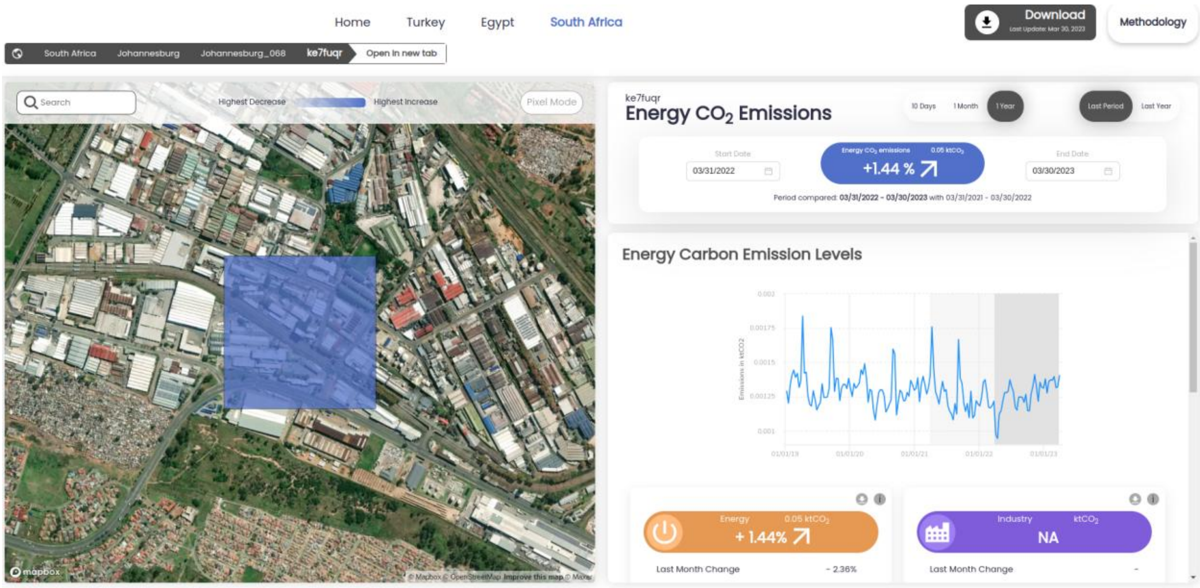

Figure 4: Pixel view of Carbon Monitor Cities 2.0

Conclusions and future directions

The Carbon Monitor Cities 2.0 pilots demonstrated that it is possible to estimate near-real-time CO_2 emissions from cities without the need for on-the-ground data collection, and to display the results in an interactive manner that is easily comprehensible to policymakers and city leaders so that they can identify the greatest contributors to emissions and measure the impact of mitigation policies.

Future activities that could build on these pilots could explore opportunities and methodologies to:

- scale up this system to a much larger number of cities in a cost-effective manner;
- explore the inclusion of additional input data sets to reduce the uncertainties involved;
- expand monitoring of the industry sector beyond cement production;
- explore ways to use machine learning to classify all building types in a city based on open data and satellite imagery for use in emissions monitoring and further refine downscaling to allow disaggregation of population and energy use down to building block level using proxies;
- explore the use of data on CO_2 concentrations directly measured by satellites as a means of improving, verifying, or complementing modeled estimates of CO_2 emissions such as those demonstrated here;
- apply this system to monitoring emissions reductions as part of monitoring, reporting, and verification (MRV) for carbon credits;
- apply this system to other pollutants, such as carbon monoxide (CO), nitrogen oxides (NOx), and methane (CH_4); and
- integrate such a monitoring system into cities' own data management systems.