



Proceeding Paper Measuring Atmospheric CO₂ for Accelerating the Low-Carbon Transition in Cities: Origins.earth, from Paris to Italy [†]

Karina Cucchi¹, Jinghui Lian¹, Andrea Rossi², Laurent Millair¹, Hervé Utard¹, Mario Adamo² and David Duccini^{1,*}

- ¹ Origins, Suez Group, 92400 Courbevoie, France
- ² Smart & Environmental Solutions, Suez Trattamento Acque, 20159 Milan, Italy
- * Correspondence: david.duccini@origins.earth
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Abstract: Despite their key role in the low-carbon transition, cities depend on methods with pressing data availability and quality issues for carbon monitoring. Origins.earth and partners have leveraged cutting-edge data and scientific knowledge to deploy an operational digital solution delivering high-quality climate data in under a month. The solution relies on networks of innovative CO₂ monitoring stations, big data, and expert knowledge, and delivers historical and current emissions and associated indicators. We demonstrate the robustness of the technology and its applicability for informing policy decisions in Paris and explore its expansion into other mature markets, with a particular focus on Italy.

Keywords: climate; measurement; low-carbon transition; digital; new business model

1. Introduction

In line with the Paris Agreement on Climate, the European Union has set an ambitious target to reduce emissions in the European Union by 55% between 1990 and 2030 and reach climate neutrality by 2050 [1]. Cities are key to the low-carbon transition, as they account for 70% of greenhouse gas (GHG) emissions and the urban population continues to increase [2–4]. In this context, city policymakers must monitor the quantity of GHG emitted on their territory, with timeliness and accuracy enabling reactivity and the adjustment of climate policies before the target years of 2030 and 2050.

Typically, cities are accountable for the task of building GHG emission inventories following guidance from international and national protocols, e.g., International Council for Local Environmental Initiatives (ICLEI) internationally, and Pôle National des Inventaires Territoriaux (PCIT) in France [5,6]. However, these self-reported inventories (SRIs) are often accessible to city stakeholders with a latency that lags in real-time by several years and is prone to large uncertainties, e.g., [7].

The quantification of GHG emissions from atmospheric measurements offers complementary accounting to the traditional bottom-up approach, and scientific capabilities are evolving rapidly [8,9]. A recent study leveraged satellite data to quantify large releases of methane in the atmosphere from oil and gas companies, they found that ultra-emitters from the oil & gas industry represent as much as 12% of global methane emissions [10]. The quantification of CO_2 emissions at the city scale from satellite observations is still at a research stage [11], but the quantification of CO_2 emissions from high-frequency atmospheric GHG measurements at well-chosen station locations has proven to be scientifically applicable on a sub-annual city-level scale, e.g., [12,13].

Origins.earth, a SUEZ company, and its partners have leveraged the proven state-ofthe-art scientific research to develop and deploy a solution delivering high-quality emission data to city stakeholders in less than one month. This solution, called MétéoCarbone[®],



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Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). offers an innovative service to cities and local governments to accelerate the implementation of the low-carbon transition.

Here, we report on the functionalities and scientific basis behind MétéoCarbone[®]. We present the robustness of the technology and evaluate its applicability for informing good decisions and driving sustainable policies, via learnings from a pilot project in the Paris area that fostered the deployment of the solution in partnership with scientific partners and city stakeholders. We then introduce its potential for expansion into other mature markets with a particular focus on Italy, to support its leaders with modern climate decision-making tools and accelerate actions to reach global low-carbon targets.

2. Presentation of the Solution

The MétéoCarbone[®] solution is built upon hardware and software science and technology, delivered to the end-user via a user-friendly digital interface, CarboneDeck[®]. Both the MétéoCarbone[®] solution and the CarboneDeck[®] digital interface are developed by Origins.earth. In this section, we first present the main views and functionalities of the CarboneDeck[®] (Section 2.1), and the science and technology powering the platform (Section 2.2).

2.1. The CarboneDeck[®] Digital Platform

CarboneDeck[®] is a digital platform that collects the results of the space/time-resolved GHG emission maps and processes the data to deliver high-quality information in a userfriendly format. The targeted audiences are technical services in the local authority's administrations, as well as decision-makers in local governments.

CarboneDeck[®] acquires monthly the outcomes of the atmospheric inversion system, calibrated upon the CO₂ concentration measures, as a space/time-resolved emission map for seven activity sectors from 2018 until the previous month. The seven activity sectors are defined following the official nomenclature in France for reporting emissions (road transportation, off-road transportation, residential, tertiary, industry, energy, and waste) [14]. CarboneDeck[®] processes this information and delivers it to the users through 3 main views with specific functionalities (Figure 1):

- 1. The data navigation view, to explore the space and time distribution of emissions, by activity sector, with filtering features over the period of observation, geographical location, and by sector of activity;
- 2. A simulation and monitoring module, to simulate future scenarios related to the implementation of specific GHG emission reduction strategies to achieve low-carbon targets and science-grounded capabilities to interpret CO₂ measurements and continually compare emissions with respect to predefined scenarios;
- 3. An analytical module with an advanced view per activity sector, which allows the calculation and continuous update of specific indicators to describe and characterize the emissions of each activity sector to effectively guide the design, implementation, and monitoring of specific policies.

The development of CarboneDeck[®] is performed within an agile framework, through iterative software-development stages (sprints), involving self-organized, cross-functional teams—including User-Interface (UI) and User-eXperience (UX) specialists—to progressively improve quality via short-term deliverables and continuous iterative interactions with end-users.





(c)

Figure 1. Screenshot of the CarboneDeck views and functionalities: (**a**) Data navigation view with map and time navigation of emissions disaggregated by sector of activity; (**b**) Simulation and monitoring module; (**c**) Dashboard of specific indicators to describe and characterize emissions from the transportation sector.

2.2. Data and Algorithms behind the Tool

This section is a brief overview of the data and algorithms leveraged in the tool. For a more comprehensive presentation, we invite the reader to read [13].

The solution is a combined hardware-software technology, based on three components (Figure 2):

- 1. An emission inventory with high spatial (1 km²) and temporal (1 h) resolution;
- 2. A network of continuous, high-precision CO₂ concentration measurement instruments;
- 3. An atmospheric inversion system based on the Bayesian approach with Gaussian error statistics to reconstruct the space/time-resolved emission map.



Figure 2. High-level presentation of the MétéoCarbone[®] science and technology chain, a combined software-hardware solution.

Origins' methodology for inventories is based on methodologies developed by Pôle National des Inventaires Territoriaux (PCIT), the body tasked by the French government to develop national guidelines for computing GHG emission inventories for local authorities [6]. The unicity of Origins' algorithms lies in building upon this methodology to further downscale emissions in space and time, with the goal to calculate emissions values for any relevant spatial resolution (e.g., road, building), for every hour, for any sector in the Standard Nomenclature for Air Pollution (SNAP) categories. Importantly, Origins' algorithms produce CO_2 emission values in near-real-time.

The emission maps are then optimized by leveraging atmospheric measurements collected by the network of continuous CO_2 concentration monitoring stations. The atmospheric inversion is implemented following a Bayesian approach, where human CO_2 emissions are optimized for the best agreement between measured CO_2 concentrations and CO_2 concentrations outputted by an atmospheric model, both measurements and priors having a prescribed error [13,15]. The city-scale Bayesian inversion system is based on the near real-time CO_2 inventory, CO_2 measurements at in-situ stations combined with the meteorological measurements, and a high-resolution atmospheric transport model (Figure 3). It provides emission values that are grounded in physical CO_2 observations in the atmosphere in near-real-time.



Figure 3. Diagram of the principle of urban CO₂ atmospheric inversion system.

3. Application on Ville de Paris: The Paris Monitoring Project

The technology and digital platform have been deployed on the Parisian territory. In this section, we introduce the context behind the project, key operational results, as well as perspectives for further development of functionalities for guiding political decisions.

3.1. Political Context and Objectives

To comply with the United Nations and European-level commitments at the national level, the French government leverages territorial (i.e., infra-national) administrative levels to implement low-carbon transition plans. The first mentions of territorial climate plans dated back in France from 2004 [16]. Today, all local authorities with more than 20,000 inhabitants are required by law to establish a Climate Plan within the framework of PCAET (Plan climat-air-énergie territorial) [14]. As far as climate commitments are concerned, the PCAET consists of: (1) the diagnosis of all emissions and energy consumption in the geographical area relative to the local authority, (2) the definition of a strategy for reducing GHG emissions, (3) the definition of an action plan, and (4) the monitoring of the implementation of the action plan and associated results in terms of emissions and energy consumption. The PCAET takes place over 6 years, with an obligatory checkpoint after 3 years.

Ville de Paris is a pioneer in the elaboration of Climate Plans, with the first diagnosis of GHG emissions and energy consumption in 2004, followed by the adoption of a climate plan in 2007 [17]. Paris's local GHG emissions were cut by 25% between 2004 and 2018. The third Climate Plan adopted in 2018 outlines a series of actions to further reduce emissions and energy consumption. In November 2021, the leadership of Ville de Paris has been recognized with the UN Global Climate Award, which acknowledges transformative local actions and innovative actions for accelerating the fight against climate change [18].

In 2020, Ville de Paris, the Laboratory of Sciences for Climate and the Environment, and Origins.earth, signed an agreement acting for the installation of urban atmospheric CO_2 measuring stations and the deployment of an observatory of CO_2 emissions in the Paris area [19]. This world première is recognized and supported by the World Meteorological Organization via the Integrated Global Greenhouse Gas Information System (IG³IS) Initiative. The agreement was signed with the ambition of enabling city officials to seamlessly monitor CO_2 emissions in the Paris urban area and continually verify the alignment of these emissions with reductions outlined in the Paris Climate Plan.

3.2. Scientific Results

A series of studies have attempted to analyze the sources and sinks of CO_2 and the spatial-temporal variability of CO_2 concentrations in the megacity of Paris with the aim of a better quantification of urban CO_2 emissions, e.g., [20,21]. Previous studies have shown that atmospheric measurements and top-down inversion models can provide low latency estimates of total CO_2 emissions over Paris, e.g., [22–24]. However, there were few events associated with a sudden change in emissions to assess the accuracy of the atmospheric

method for detecting changes. The large and sudden emissions reductions of the COVID-19 pandemic provide such a test bed.

With the MétéoCarbone[®] solution, Origins.earth estimated CO₂ emissions in Paris over two COVID-19 lockdown periods in 2020 [13]. The study used CO₂ measurements from six stations located within Paris and its vicinity, and the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) transport model at 1-km horizontal resolution driven by fossil fuel CO₂ emissions from the Origins inventory and biogenic CO₂ fluxes from the Vegetation Photosynthesis and Respiration model. The CO₂ emissions from the Paris megacity show decreases by 42~53% during the first lockdown with stringent measures, and by ~20% during the second one when restrictions were eased (Figure 4). The robustness of the inverse estimates is evaluated through a series of sensitivity tests to the changes in inversion configuration and validated against independent emission estimates made by the city environmental services. Our results demonstrate skill in MétéoCarbone[®] to identify changes in city-scale CO₂ emissions in a timely manner.



Figure 4. Estimates of the total fossil fuel CO2 emission budgets during the two lockdown periods over the Greater Paris region for the years 2018, 2019, and 2020: (a) First lockdown; (b) Second lockdown. Boxplots represent the statistical distribution of prior and posterior CO_2 estimates, both for the absolute emission budgets and the relative emission reduction ratio. The medium values of the posterior estimates among the sensitivity tests are shown in red. The prior estimates from the Origins inventory are shown in magenta [13].

Ongoing work focuses on evaluating the derived estimates of CO_2 emissions based on 6-year atmospheric inversion to better understand the seasonal and the inter-annual variations over Paris. This analysis is expected to help recognize the impact of environmental policy with the mid-term and long-term low-carbon targets.

3.3. Accelerating Use Cases for Supporting Public Policies and Fostering Citizen Buy-In in Cities

In parallel with the research work developing scientific capabilities relating to the monitoring CO_2 of emissions via urban monitoring networks, we advance the actionability of CO_2 measurements for supporting low-carbon public policies and fostering citizen buy-in, in constant dialogue with Ville de Paris and other local authorities.

The applicability of CO_2 networks in the framework of local policies lies in the agility and reliability of associated CO_2 emission information. While traditional accounting methods provide reliable emission values with a lag of 2 years, atmospheric-based emission values are accessible in under a month. Shaped and delivered via the CarboneDeck[®] digital platform, the MétéoCarbone[®] scientific and technical capabilities can therefore be leveraged to communicate emission values to city stakeholders and the general public in line with the urgency of the climate transition and the targets years of 2030 and 2050. The COVID example (Section 3.2) has shown that results of large-scale public policy decisions can be quantified in terms of a drop in CO_2 emissions within a monthly time period. The solution can enable constant public dialogue between scientists, citizens, and decision-makers in cities focusing on the impact of actions through the lens of the decarbonization of activities in cities. Reliable physically based CO_2 emissions foster the development of analytical capabilities in a multidisciplinary approach. We have started a partnership with the Master of Economics for Smart Cities and Climate Policy, which brings in an econometrical view on the analysis of public policies as they relate to CO_2 emissions, with use cases on road closures on weekends (Paris Respire) and building renovations. The political response to climate issues is complex and involves a range of environmental, social, economic, and legal expertise as well as citizen buy-in and implications. The development of multidisciplinary solutions fostered around the lens of physically based CO_2 information will support and accelerate public policy actions implemented by city-level administrations, with a dialogue focused on decarbonization.

Finally, the use of intermediary quantities in the calculation of dynamic inventories (Section 2.2) can be leveraged to discriminate social and environmental drivers of emissions. Another line of discussion with local authorities focuses on shaping dynamic inventory data and algorithms into easily accessible, timely, and actionable indicators for (1) establishing emission reduction strategies and an operational action plan, and (2) monitoring the progress of the action plan and its impact on CO_2 emission reductions.

4. Conclusions

In this paper, we introduced the MétéoCarbone solution designed for practitioners in local governments to support them with their climate policies, and the results of its deployment in collaboration with Ville de Paris, France. MétéoCarbone[®] leverages atmospheric CO₂ measurements to calculate CO₂ emissions in near-real time over the city, empowering government officials and their citizens to efficiently track the evolution of CO₂ emissions and the progress towards carbon neutrality. MétéoCarbone[®] bridges the gap between capabilities developed by the scientific community and decision-makers in local governments and can contribute to the panel of solutions to successfully hold the increase in the global average temperature to well below 2°C above pre-industrial levels as stated in the 2015 Paris Agreement.

Italy and France display analogous political, reglementary, social, and economic frameworks, with similar stakes, ambitions, and objectives. The two national frameworks are an adaptation of the European Union's target of a net domestic reduction of at least 55% in greenhouse gas emissions by 2030 compared to 1990 and achieving a climateneutral EU by 2050 [1]. Therefore, we propose that results obtained in the Paris Monitoring project be transferred to the Italian regional and municipal stakeholders (Regioni, Comuni, Agenzie Regionali e Provinciali per la Protezione dell'Ambiente—ARPA, etc.), with minor adaptations, through a two-step approach:

- 1. Implementation of a spatialized and automated dynamic inventory of GHG (spatial resolution 1 km²; temporal resolution 1 h) for regional territories;
- 2. Implementation of the continuous monitoring system of GHG (greenhouse gas) concentration at a local level, including:
 - a. Construction, deployment, and maintenance of high-precision CO2 monitoring stations;
 - b. Configuration of inverse atmospheric modeling for the monthly reconstruction of the space/time-resolved emission maps.

Both approaches will be delivered to end-users via the CarboneDeck[®] digital platform for data-driven and science-based informed decision-making, with the goal of acting on drivers of CO₂ emissions via public policies and citizen actions in constant communication around physically-based CO₂ concentrations in the atmosphere, which is what ultimately matters for the stability of the Earth's climate system.

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