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Towards a better understanding of urban air quality management capabilities in Latin America

Juan Felipe Franco[a,*], Lars Gidhagen[b], Ricardo Morales[c], Eduardo Behrentz[d]

[a] School of Engineering, Universidad de los Andes. Carrera 1 No. 18A -70 Edificio Pedro Navas - Piso 3, Bogotá, Colombia
[b] Swedish Hydrological and Meteorological Institute (SMHI). Norrkoping, Sweden
[c] School of Engineering, Universidad de los Andes, Bogotá, Colombia
[d] Universidad de los Andes, Bogotá, Colombia

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ABSTRACT

Urban air quality management (AQM) refers to the activities aimed at reducing air pollution in order to protect human health and the environment in a city. This work presents the formulation of the Urban Air Quality Management Capabilities Index (CECA) and the results of its pilot application in ten Latin American cities. CECA offers a comprehensive and systematic analysis of a city's capacity to formulate and implement air quality management strategies. It is comprised of 31 indicators classed across nine dimensions and three main components (*technical capabilities, data capabilities, exploiting capabilities).* We defined a specific scoring scale for each indicator. Scores in the scale were determined from surveys administered to local authorities and experts. The pilot application of CECA in Latin America demonstrated that the index provides relevant information on the needs and possibilities for cities to implement primary and rapid actions to reduce air pollution. Within the ten pilot cities, Mexico City and Santiago stand out for leading AQM capabilities. They have integrated technical knowledge into long-term AQM plans and implementation strategies. Consequently, both cities have managed to strengthen their institutions and policies to set effective command and control mechanisms, while proposing incentives for technological improvements. The group of cities with CECA intermediate and low scores evidenced that AQM is starting to emerge in the region. An essential aspect to improve across such cities is the transition to a comprehensive AQM, that goes much further than monitoring. Continuous assessment is needed to improve urban capabilities to address air pollution and to promote interactions among cities in finding solutions. Furthermore, CECA approach encourages cities to prioritize urban AQM, while fosters a comprehensive view and multisector action at local, regional and national scales.

1. Introduction

Air pollution is a growing global problem (Gulia et al., 2018; Baklanov et al., 2016; Krzyzanowski et al., 2014) and its health consequences constitute a major concern in urban areas around the world (Rao et al., 2017; Landrigan et al., 2017; Hsu et al., 2016). The negative impacts of air pollution on health lead to economic and social costs (WHO and OECD, 2015), mainly attributed to premature deaths (Martinez et al., 2018), higher expenditures on healthcare and losses in productivity (Lanzi et al., 2018; Sullivan et al., 2018). Recent estimations indicate that annual global welfare losses are in the order of trillions of US dollars. This number represents between 2.2% (in North Africa) and 7.5% (in East and South Asia) of the gross domestic product across these regions (WB & IHME, 2016).

With this environmental concern, decision-makers face a wealth of data regarding air quality. Different indicators and indexes have been established to quantify and communicate air pollution emissions, concentrations and human health impacts (Sheng and Tang, 2016; Hsu et al., 2013; Bell et al., 2011; Plaia and Ruggieri, 2011). These indicators, however, say little about cities' capabilities to implement control strategies and to accomplish air quality goals. Such aspects are essential for the Air Quality Management (AQM) cycle (EPA, 2018) and go beyond the technical evaluation of the problem.

Determining the capabilities of a city to plan and manage urban air pollution is a way to understand and quantitatively describe how well local authorities are coping with the challenge of air pollution, and to which extent they are able to convert the available technical data into policy-relevant information for decision-makers and the public in

* Corresponding author.
E-mail addresses: jffranco@uniandes.edu.co (J.F. Franco), lars.gidhagen@smhi.se (L. Gidhagen), r.moralesb@uniandes.edu.co (R. Morales), ebehrent@uniandes.edu.co (E. Behrentz).

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general. Few research studies have been conducted on methods to assess urban AQM capabilities. Studies for Asia (Schwela et al., 2006) and Europe (Beattie et al., 2002a; 2002b; Peterson and Williams, 1999; EEA, 1998) have evaluated the status and challenges of air pollution in a large group of cities, setting baselines in terms of urban AQM capabilities in those regions. The results of such analyses allowed the identification of urban AQM management gaps and aspects that cities should strengthen to cope with the problem.

These assessments in European and Asian cities have been based on a composite index earlier proposed by the Global Environmental Monitoring System for Air Pollution Study - GEMS/AIR (EEA, 1998). As one of the first systematic approaches for measuring management performance, such AQM index gave valuable information regarding the city's capabilities to improve urban air quality. Nonetheless, the dichotomous (yes or no options) rating scales used in that effort may fall short to evaluate AQM. Given today´s air pollution challenges, we need more comprehensive and sophisticated tools. Particularly, in terms of indexes, there is a need to represent different areas and levels of detail in air quality planning and management, and to consider broader analytical rating scales in the evaluation.

The objective of the present study was to formulate an improved urban AQM capabilities composite index—named CECA (for its acronym in Spanish: Índice de Capacidades de Gestión de la Calidad del Aire Urbano); and to carry out a pilot test demonstrating the index's potential usefulness in Latin American cities. Moreover, CECA's formulation process and the comparative analysis conducted for several cities in the subcontinent, allowed us to identify determinants and good practices in urban AQM that may apply to cities worldwide.

2. CECA index formulation

Air quality management refers to the activities aimed at reducing air pollution in order to protect human health and the environment in a specific geographical area (EPA, 2018). It is based on a good understanding of local air pollution problems and solutions in a broad public health context (Brunt et al., 2016). Effective AQM involves air quality objectives, monitoring, emission inventories, model tools, control strategies, regulatory frameworks, and private sector and community participation (Gulia et al., 2015). Considering all these interdependent aspects, together with the theorical functions of indicators (quantification, simplification and communication) (Huovila et al., 2019), we developed the Urban Air Quality Management Capabilities Composite Index (CECA). CECA formulation and pilot application followed the multi-step process summarized in Fig. 1.

2.1. Preliminary research

The initial phase of this project consisted of a review of earlier approaches to urban AQM capabilities assessment (Miranda et al., 2015; Naiker et al., 2011; Schwela et al., 2006; Beattie et al., 2002a; 2002b; Peterson and Williams, 1999; EEA, 1998). Table 1 shows a comparison of the aspects related to the present study. We also reviewed composite indexes applied to broader environmental (Hsu et al., 2016; OECD, 2002) and sustainability assessments (Klopp and Petretta, 2017; EIU, 2017; Pupphachai and Zuidema, 2017; Sabiha et al., 2016; Wiréhn et al., 2015). Such analysis provided a general context and helped generate the guidelines for CECA definition.

Besides the fact that preceding assessments focused on Europe and Asia, not including America Latina, the main differences between the CECA Index and the existing approaches described in Table 1 are related to: i) CECA indicators' score is given by a numerical scale representing city's performance in a specific feature. The scale ranges from the lowest level of development (or a fundamental condition) to the technical state-of-the-art (or ideal reference condition). As presented later, an expert panel reviewed and discussed the analytical scale for each indicator. ii) CECA application method bases on structured interviews with a guide questionnaire. It allows obtaining the necessary data to rate each indicator, but also additional information helping to understand good practices and determinants for AQM at each city.

2.2. CECA analytical formulation

2.2.1. Expert panel

CECA first draft was discussed, and feedback was obtained from a volunteer advisory panel composed of experts from government agencies, academia and multilateral nongovernmental organizations. We invited to the panel specialists with state-of-the-art technical knowledge in the field of AQM and with an understanding of the challenges that authorities in Latin American cities face while working for improving air quality. The panel members participated through face-to-face or individual virtual interviews, and electronic mail exchanges.

Experts from the following institutions were part of the consulting panel: Environment and Health Administration of Stockholm, Clean Air Institute, Climate and Clean Air Coalition, Environmental Engineering

Fig. 1. Summary of CECA formulation and pilot application process.

Table 1
Summary of AQM approaches.

Study	EEA, 1998	Peterson and Williams, 1999	Beattie et al., 2002a; 2002b	Schwela et al., 2006	Naiker et al., 2011	This study
Region of analysis	Europe	Global	Great Britain	Asia	South Africa	Latin America
General approach	Composite index previously defined by WHO/UNEP	Composite index previously defined by WHO/UNEP	Qualitative comparative analysis case study	Composite index previously defined by WHO/UNEP	Qualitative analysis review	Composite index formulated for this study + Structured interviews
Indicators scoring methodology	Scores from questionnaire answers (yes/no questions)	Scores from questionnaire answers (yes/no questions)	n/a	Scores from questionnaire answers (yes/no questions)	n/a	Scores from questionnaire answers (open-ended and multiple-choice questions)
Application method[1]	on-line	on-line	on-line	on-line	n/a	on-site
Scoring scale	Overall index 0-100 Sub-indices 0-25	Overall index 0-100 Sub-indices 0-25	n/a	Overall index 0-100 Sub-indices 0-25	n/a	Overall index 0-1 Sub-indices 0-1
Aggregation	No weighting Additive aggregation	No weighting Additive aggregation	n/a	No weighting Additive aggregation	n/a	No weighting Geometric aggregation
Further analysis	Recommendations and way forward	n/a	Comparison for urban and rural areas	Questionnaire internal logic review	Emphasis on AQM challenges	Identification of good practices and determinants

[1] On-line method refers to questionnaires remotely filled in by local staff in each city; on-site refers to expert visiting a city and filling in the questionnaire during structured interviews.

Research Center at Universidad de los Andes (Colombia), Industrial Engineering Department at Universidad de los Andes, Institute of Hydrology, Meteorology and Environmental Studies of Colombia, Institute for Energy and the Environment of Brazil, Latina and Latino American Studies Program at University of Missouri-Kansas City, Lasallian Center for Environmental Research and Modeling at Universidad de la Salle (Colombia) and Swedish Meteorological and Hydrological Institute.

The comments from the expert panel included recommendations on CECA's structure, indicators definition, the application methodology, and the interpretation of its results. Such insights were incorporated into a refined CECA analytical framework with redefined indicators' scoring scales, dimensions, and components, together with weighting and aggregation criteria.

2.2.2. CECA Analytical Framework: Index's structure, indicator definitions and scoring methodology

CECA is comprised of 31 indicators allocated across nine dimensions and three components (see Fig. 2). The first component addresses *technical capabilities* in three dimensions including air quality measurements, understanding of emission sources, and use and sophistication level of modeling tools. The second component refers to *data capabilities* in the dimensions of data validation and analysis, data usage, and data dissemination. The third component is related to *exploiting capabilities.* It refers to the city´s capabilities to facilitate air quality improvements through the necessary institutional interaction, developing policy and regulation frameworks, and by using its take-action potential.

We defined a scoring scale for each indicator to quantify the performance of the city concerning a specific AQM feature. The scoring scale goes from the lowest level of development (or the very basic condition for that aspect) to the technical state-of-the-art (or ideal reference level). The higher the score, the better the performance. Tables 2 and 3 show examples of the analytical scoring scale for indicators 7 and 25, respectively. We present the full outline of the CECA analytical framework in the supplementary research data.

Indicator scores are determined from the responses that local authorities and experts give to a questionnaire designed explicitly for CECA (see Section 2.3). Each indicator score is normalized using minimum-maximum transformation to a 0 to 1 scale; with 0 denoting lowest performance and 1 representing the best outcome. This normalization allows expressing the scores of different AQM features in a comparable way, as suggested by Sabiha et al. (2016) and Wiréhn et al. (2015). Equation 1 shows the normalization formula, adapted from a procedure frequently used by the United Nations Development Programme when computing the Human Development Index (UNDP, 2015) and previously described by the Institute of Development Studies (Sharp, 2003).

Equation 1.

$$Y_{i_{normalized}} = \frac{Y_i - Y_{min}}{Y_{max} - Y_{min}}$$

Where: Y_i = indicator score; Y_{min} = minimum value on the indicator's scoring scale; Y_{max} = maximum value on the indicator's scoring scale.

We consider CECA's components and dimensions as equally essential aspects when assessing local urban AQM capabilities. Recognizing the plurality of weighting and aggregation methods for composite indexes (Greco et al., 2018; Gan et al., 2017; Munda, 2012; Munda and Nardo, 2005), we defined CECA to be simple to understand, while transparent and objective. We applied a hierarchically no-weighting scheme for components and dimensions. This does not necessarily mean that individual indicators have equal weights since each CECA dimension includes a different number of them (see Fig. 2). The characteristics of this type of scheme are further explained in Greco et al. (2018) and Munda and Nardo (2005).

Equation 2 shows the mathematical representation of CECA. To

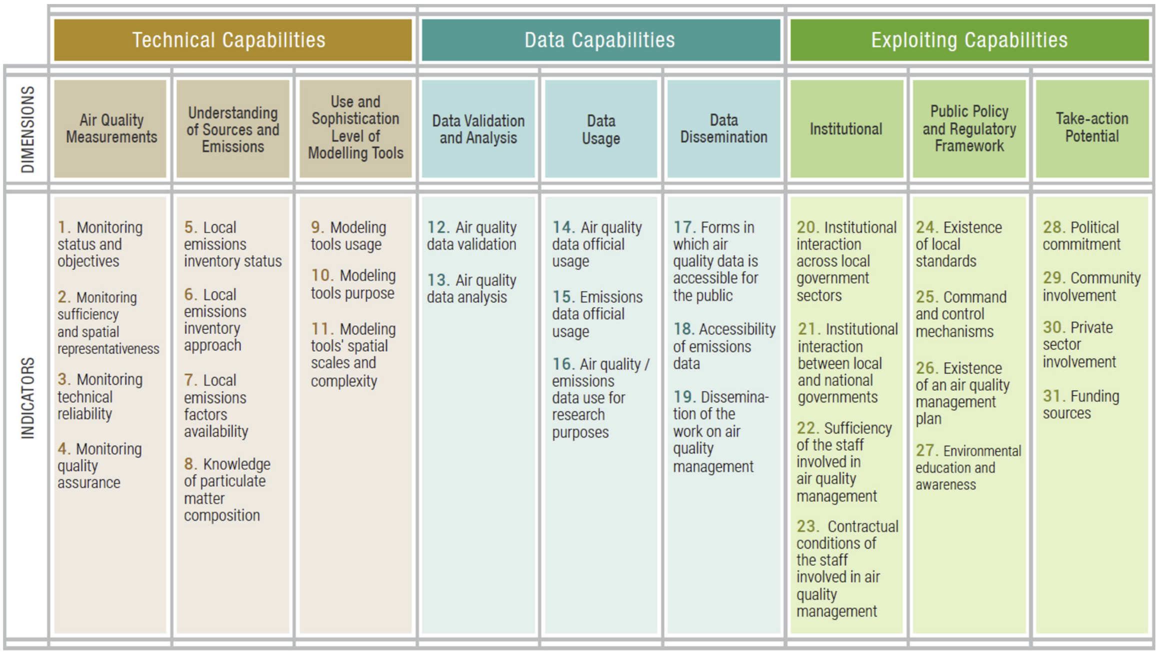

Fig. 2. CECA analytical framework: components, dimensions and indicators.

aggregate CECA's indicators, we used a geometric mean method in order to keep the calculation simple and to reduce the issue of compensability within indicators, i.e., the possibility of offsetting a disadvantage on some particular feature (low score on a specific indicator or dimension) by a sufficiently large advantage on another (Greco et al., 2018). In other words, cities with lower scores in a given dimension will not be able to fully compensate in other dimensions to get a high final CECA score.

One of the implications of the geometric mean approach is the treatment of the zero values, i.e., when a city obtained the minimum performance for one indicator. To deal with this case, we used an additive method previously proposed in different composite index aggregations (De la Cruz and Kreft, 2018; Martín-Fernández et al., 2003).

Equation 2.

$$\text{CECA} = \left(\prod_{k=1}^{3} \text{CECA Component}_k\right)^{\frac{1}{3}}$$

$$\text{CECA Component}_k = \left(\prod_{j=1}^{3} \text{CECA Dimension}_j\right)^{\frac{1}{3}}$$

$$\text{CECA Dimension}_j = \left(\prod_{i=1}^{n} \text{CECA Indicator}_i\right)^{\frac{1}{n}}$$

Where: CECA Indicator is the normalized score for each indicator (i) within the dimension (j) and component (k); n represents the number of indicators within each dimension.

We grouped CECA final values into a five score-range scale, assigning a word code and a descriptor to each range (see Table 4). This scale was defined to help understand and communicate CECA results, also providing a general description of its implications in the state of AQM capabilities. Besides, this word coding will be useful as a reference point for classification when applying CECA to a larger group of cities.

2.3. CECA questionnaire's structure

CECA indicators are calculated from the responses by local authorities and experts to a custom-made questionnaire. CECA questionnaire has four sections. The introductory general-context section is designed to identify the city and the person/institution(s) who answer the questionnaire. This section also offers a set of open-ended questions to obtain an overview of the city's air quality condition, as well as its AQM strengths and weaknesses. The other three sections of the questionnaire correspond to each of the three CECA components (technical capabilities, data management capabilities and exploiting capabilities). The CECA questionnaire is presented in the supplementary research data.

As frequently used in social research methods (Trochim, 2006), questions related to CECA components are of different types: a) Multiple-choice questions, used to qualify each indicator and to give a score according to an analytical ordinal scale; b) Dichotomous questions and open-ended questions, used to gain more insight into the feature assessed for a specific indicator.

We pretested the questionnaire in two Colombian cities (Bogotá and Medellin). We visited each of these cities to interview and to administer the questionnaire to experts from government and academia. With

Table 2
Indicator 7 definition and scoring scale.

Indicator	Description	Units	Scoring Scale
Local Emissions Factor Availability	It aims at assessing the availability and representativeness of the emission factors used in the current emissions inventory	1-5	1- No emissions inventory available 2- Default emission factors for all sources 3- Default emission factors for mobile sources; emission factors for industry sources adapted to local fuel-conditions 4- Default emission factors for industry sources; locally estimated/validated emission factors for mobile sources 5- Both mobile and industry sources emission factors estimated/adapted/validated for local conditions

Table 3
Indicator 25 definition and scoring scale.

Indicator	Description	Units	Scoring Scale
Command and Control Mechanisms	Identifies the existence and relevance of command and control mechanisms, sanctions and incentives	1-4	1- No formal mechanism to penalize those who do not comply with the norm 2- Formal mechanisms to penalize those who do not comply with the norm, but these are not appropriate (e.g., not enforced, it is better or cheaper to pay a fine) 3- Formal mechanisms to penalize those who do not comply with the norm and these are considered appropriate 4- Formal mechanisms to penalize those who do not comply with the norm and these are appropriate. There are also incentives for those who implement additional improvements

Table 4
CECA Index word code.

CECA score range	Word code	Description
0.00 - 0.20	Low capabilities	Cities with little or no evidence of their AQM work, with essential needs to develop technical, data and exploiting capabilities to address the challenge of urban air pollution.
0.21 - 0.40	Limited capabilities	Cities with some evidence of their AQM work, with essential needs identified but with no further actions to improve technical, data and exploiting capabilities to address urban air pollution.
0.41 - 0.60	Emerging capabilities	Cities with some evidence of the work on AQM, with specific needs identified and which are starting to act to improve technical, data and exploiting capabilities to address urban air pollution.
0.61 - 0.80	Developing capabilities	Cities with evidence, available for the public, of the work on AQM, which are developing actions to improve technical, data and exploiting capabilities to address urban air pollution.
0.81 - 1.00	Leading capabilities	Cities with full evidence of a comprehensive approach on AQM, that stand out in each of the three CECA components, and which are a reference in terms of urban AQM capabilities in the region.

these results, we adjusted the technical and methodological details of questions and response options. When possible, we also included in the visit protocol a field visit to labs, data centers and monitoring stations. These pretests were also useful to adjust the range of the scoring scales of some indicators, opening score options that reflect intermediate performance.

3. CECA pilot study methodology

The pilot study aimed to illustrate CECA applications and potential, and to validate the methodological approach. We selected Latin America as a case study because it is a region for which the urban and economic contexts involve challenging air pollution issues. Also, the different priority levels manifested for addressing the problem, makes Latin American urban centers a natural laboratory for air pollution management assessment.

3.1. Latin american urban context

Latin American has recently experienced an accelerated urbanization process and dynamic economic growth (UN, 2018; Toumi et al., 2017). Such conditions had led to an increase in industrial activities, motorization rates and fuel consumption (Hidalgo and Huizenga, 2013). Due to the lack of appropriate and effectively implemented environmental regulation, the economic growth has resulted in higher emissions of air pollutants (Baklanov et al., 2016; Franco, 2012; Gurjar et al., 2008). As a consequence, several cities in Latin America have poor air quality, experimenting unhealthy concentrations of particles and ozone (O_3) (Romieu et al., 2012; Green and Sánchez, 2012; WMO, 2012).

Over 100 million people in the region are exposed to pollution levels exceeding the World Health Organization (WHO) guidelines and at least 58,000 premature deaths annually (WHO, 2014; Romero-Lankao et al., 2013). This causes significant costs to the region's economy, associated with unhealthy conditions and premature mortality. Recent estimations indicate that annual welfare losses in Latin America and the Caribbean are in the order of 150 billion of US dollars (WB and IHME, 2016). For countries such as Colombia, Ecuador, El Salvador, Guatemala y Peru there are evidences that the costs of outdoor air pollution may be equivalent to about 1% of the national gross domestic product (Sander et al., 2015; Della-Maggiora and López-silva, 2006).

3.2. Pilot cities selection

Table 5 shows characteristics of the selected pilot cities. We considered various criteria to guide the selection process, including population, geographical location, economic dynamics, air quality conditions and willingness to participate. The final sample comprised a group of 10 cities including large and midsize cities with low and high pollution levels, located within different Latin American sub-regions (i.e., Central America, Northern South America, and Southern South America).

3.3. CECA application

We visited each pilot city to have meetings with local actors, including authorities, academics and consultants. We administered CECA's questionnaire in one-on-one interviews. The conversation was flexible, which allowed us to identify new issues, to confirm findings from other sources and to get insights from the interviewees regarding AQM good practices. In addition to the interviews, we visited - when possible – monitoring network stations, air quality and emissions laboratories, and integrated information centers.

4. CECA pilot application results

4.1. CECA index general interpretation

CECA application revealed that cities understand air quality as an urban environmental challenge in Latin America and they showed a wide range of AQM capabilities to cope with it. CECA results are an indicative profile of where cities stand today in terms of AQM, and what are the main aspects to improve. These results are a starting point for a more comprehensive AQM and an invitation for cities to continuously evaluate and improve their capabilities in the area.

Table 6 presents CECA scores for the ten pilot cities, disaggregated

Table 5
CECA pilot cities.

City	Criteria						
	Country	Geographical location	Urban area (km^2)	Population (millions)	Size[1]	Air quality condition[2]	Willingness to participate[3]
Santiago	Chile	Southern South America	462	6.5	Mega	Fair	3
Montevideo	Uruguay	Southern South America	212	1.7	Large	Good	2
Belo Horizonte	Brazil	Southern South America	331	2.6	Large	Fair	2
Sao Paulo	Brazil	Southern South America	1,523 (Sao Paulo) 2,139 (Gran Sao Paulo)	12.0 (Sao Paulo) 21.0 (Gran Sao Paulo)	Mega	Fair	2
Quito	Ecuador	Northern South America	352	2.6	Large	Good	2
Manizales	Colombia	Northern South America	38	0.4	Midsize	Fair	3
Bucaramanga	Colombia	Northern South America	33 (Bucaramanga) 93 (metro area)	0.6 (Bucaramanga) 1.4 (metro area)	Midsize	Fair	2
Cali	Colombia	Northern South America	121	2.4	Large	Fair	2
San Salvador (metro area)	El Salvador	North and Central America	652	2.2	Large	Bad	3
Mexico City	Mexico	North and Central America	702	9.0 (Mexico City) 21.0 (metro area)	Mega	Fair	3

[1] According to population: midsize (between 100,000 and 1 million inhabitants); large (between 1 million and 3 million inhabitants); mega (more than 3 million inhabitants).
[2] Classed according to the latest annual particulate material concentration data reported by the city to the WHO urban air quality database, and its comparison with WHO guidelines. It is common for each city to report to this initiative a concentration of particulate matter resulting from averaging the annual value for all their monitoring stations.
[3] This logistics criterion evaluates authorities and local experts' availability and willingness to participate in the study. It goes from 1 to 3, being three the optimal condition.

Table 6
CECA scores (by dimensions) for the ten pilot cities.

Components	Technical Capabilities			Data Capabilities			Exploiting Capabilities				
Dimensions	Air Quality Measurements	Understanding of Sources and Emissions	Use and Sophistication Level of Modelling Tools	Data Validation and Analysis	Data Usage	Data Dissemination	Institutional	Public Policy and Regulatory Framework	Take-action Potential	CECA score	CECA's word code
Mexico City	1.00	1.00	1.00	0.82	1.00	1.00	0.93	1.00	0.76	0.94	Leading capabilities
Santiago	1.00	0.88	0.79	1.00	0.91	0.75	1.00	1.00	0.90	0.91	Leading capabilities
Sao Paulo	0.90	0.80	0.67	0.82	0.91	0.79	0.71	0.74	0.78	0.77	Developing capabilities
Quito	0.89	0.46	0.26	0.82	0.44	0.85	0.66	0.60	0.58	0.58	Emerging capabilities
Belo Horizonte	1.00	0.31	0.26	0.72	0.50	0.48	0.45	0.26	0.54	0.49	Emerging capabilities
Cali	0.90	0.16	0.26	0.82	0.35	0.69	0.45	0.52	0.64	0.47	Emerging capabilities
Manizales	0.60	0.69	0.26	0.45	0.44	0.63	0.37	0.37	0.58	0.47	Emerging capabilities
Montevideo	0.84	0.20	0.00	0.91	0.50	0.35	0.66	0.17	0.29	0.37	Limited capabilities
San Salvador	0.36	0.20	0.26	0.32	0.44	0.41	0.45	0.32	0.20	0.32	Limited capabilities
Bucaramanga	0.30	0.00	0.00	0.26	0.28	0.16	0.45	0.24	0.22	0.18	Low capabilities

by CECA dimensions. In general, cities with high CECA scores (0.8–1.0) exhibited strengths in each of the three components, resulting in technically and politically supported long-term integral management plans with ambitious air quality goals. Moreover, they had engaged the private sector through incentives that go beyond the regulations. Another common characteristic of cities with high CECA scores is that they have clear protocols for responding to high pollution episodes and contingency alerts. CECA low scores (0.0–0.4) indicated the need for local efforts in different aspects. Those cities need to improve technical capabilities to understand emissions better and to facilitate the use of air quality models. More data and analyses are needed to improve the potential usage and dissemination of the collected information. A lesson learnt for cities with low CECA scores was the need for institutional and legal framework changes, to start focusing on controlling emission sources rather than only on ambient air monitoring.

Among the studied cities, Mexico City and Santiago had the highest CECA scores. Both cities have an important tradition regarding air pollution, and their management capabilities excel in the three CECA components. These were the only two cities to qualify to the leading capabilities category of the word code, becoming a reference for Latin America in terms of urban AQM capabilities. Sao Paulo ranked in CECA's developing capabilities score range. The city has essential technical capabilities; however, additional efforts are required to improve some specific AQM aspects such as the use of models for decision making and the coordination between regional and local authorities.

Quito, Belo Horizonte, Cali and Manizales were cities ranked in CECA's emerging capabilities word code. Technically, these cities have high scores in air quality measurements dimension and are starting to work on emissions understanding and modelling capabilities. In general, for this group of cities, such work is being conducted together with the process of strengthening other AQM components such as data capabilities. Montevideo, San Salvador (limited capabilities) and Bucaramanga (low capabilities) showed the lowest CECA scores within the studied cities. The AQM context, including the air quality condition, of each of these cities is different, but the three of them have pressing needs to improve technical, data and exploiting capabilities to address local urban air pollution.

4.2. CECA analysis by dimension

Fig. 3 shows CECA average performance grouped by dimensions for the ten pilot cities. Dashed lines in the figure represents 80 and 20 percentiles values for CECA dimensions. These results show the wide range of urban AQM capabilities found among Latin American cities, and it highlights how AQM capabilities are concentrated on monitoring while evidencing that a comprehensive approach is only starting to emerge in the region.

In general, ambient air monitoring is the commonest practice within technical capabilities. Among all CECA dimensions, Air Quality Measurements has the highest average score for the ten studied cities. Assessed cities have monitoring objectives and use standard techniques, but not all make this information public. Lower scores in this dimension were in cities where the number of monitors and their spatial representativeness of the monitoring could improve, together with a strengthening of the quality assurance processes.

In most of the assessed cities there is an incomplete understanding of sources and emissions. Leading cities in this dimension conduct source apportionments analysis, in addition to regular updates of the emissions inventory. As a further step in this dimension, cities are making efforts to determine locally adapted emission factors (primarily for mobile sources), improving the representativeness of the estimates. This dimension is one of the two CECA dimensions with the largest gap between cities (three cities range above 0.8, and four cities below 0.2).

The official use of modeling tools for decision making is still limited. Among all CECA dimensions, Use and Sophistication Level of Modelling Tools has the lowest average score for the ten pilot cities, with only three scoring above 0.5 in this dimension. Cities with high performance in this dimension have robust air quality models that require high-quality data for model input and validation. Consistently, those cities have stronger monitoring and emissions understanding capabilities.

Regarding data capabilities, cities have established procedures for the validation and analysis of air quality and emissions data. Cities with high scores in the Data Validation and Analysis dimension have established procedures for air quality and emissions data validation and analysis, and those are fully documented and audited. The extent of air quality data analysis goes from descriptive indicators and indexes calculations to spatial distributions using interpolation techniques. The Data Usage dimension indicated that its use is often limited to report compliance. Cities with high scores in this dimension (above 0.9) proved to have capabilities to use the information to make technically-supported decisions and have worked together with academia to incorporate these data into impact estimations and the prediction of high

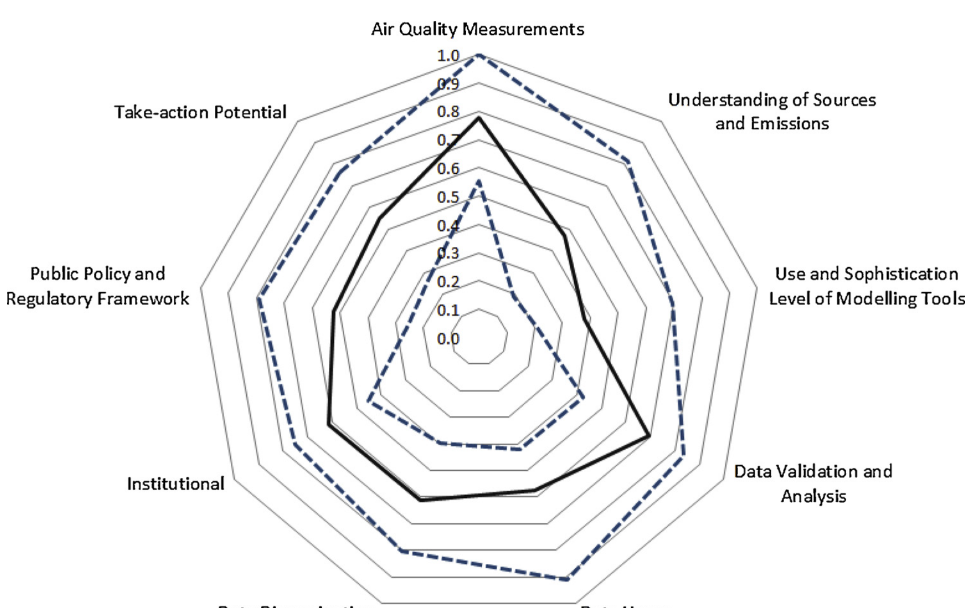

Fig. 3. CECA average performance by dimension for the ten pilot cities (dark line). Dashed lines represent 80 and 20 percentiles for each dimension.

pollution episodes.

Most cities are disseminating air quality and emissions data in the form of annual reports, while few cities have online platforms to follow its air quality conditions in real time. Cities with high performance in this dimension are striving to make the information freely available and easily accessible to the public, focusing on data users' requirements and not only in the needs of the information provider. Several of the assessed cities are part of international sustainability platforms or networks that force authorities to strengthen their air quality and emission data reporting practices.

The results for the Institutional Dimension show that environmental authorities in cities with lower scores lack coordination with authorities from other sectors (e.g., transportation, health, planning). Cities with high performance in this dimension have sufficient AQM staff in number and technical capacities. However, the contractual conditions of the staff in charge of AQM vary in terms of stability, and the salary levels are commonly not competitive on the local job markets.

In terms of public policy and regulatory framework, cities have air quality standards less stringent than the international guidelines (i.e., WHO and European Union guidelines). Only four cities (Mexico City, Santiago, Sao Paulo, Quito) have managed to establish long-term AQM programs and have it in force. Cities with high performance in this dimension have formal command and control mechanisms and have the capabilities to guarantee their compliance. Also, these cities have implemented education programs regarding air pollution causes and impacts.

The cities with the best performance in the Take-action Dimension have a solid political commitment, making AQM visible in city development programs with specific goals and indicators. Those cities have also committed the private sector through incentives to meet the standards and to be a proactive player in local AQM. Community involvement in most cases is reduced to have the citizens informed and with the possibility to give an opinion. Only three of the studied cities have established clear mechanisms for participatory policymaking (Mexico City, Santiago, Sao Paulo).

Cities with high CECA scores exhibited strengths in each of the three components, resulting in technically and politically supported long-term integral management plans with ambitious air quality goals. Moreover, they have engaged the private sector through incentives that go beyond the regulations. Another common characteristic of cities with high CECA scores is that they have clear protocols for responding to high pollution episodes and contingency alerts. CECA low scores indicated the need for local efforts in different aspects. Those cities need to improve technical capabilities to understand emissions better and to facilitate the use of air quality models. More data and analyses are needed to improve the potential usage and dissemination of the collected information. One alert for cities with low CECA scores was the need for institutional and legal framework changes to start focusing on controlling emission sources rather than only on ambient air monitoring.

Fig. 4 shows CECA results and the rate of change for PM_{10} concentration for each of the studied cities. The period of analysis at each city was different, the longest ranging from 2006 to 2016 and the shortest from 2011 to 2016. A positive value in the figure means a reduction in the PM_{10} concentration and the percentage represents the annual rate at which such reduction has occurred. The results of this analysis show a tendency in which the cities with the highest CECA performance show higher reduction rates than the other pilot cites. Although it is necessary to continue exploring this relationship, this analysis begins to show the potential representativeness of CECA as an indicator of the impact of high AQM capabilities on urban air quality improvement.

5. Further discussion

5.1. Good practices and limitations

The possibility of having a score for each CECA dimension (in addition to the single final index value), together with open-end comments and observations made during the city's visits, allowed further qualitative analysis. In Table 7 we list strengths, good practices, limitations and opportunities for urban AQM in the ten pilot cities. A general conclusion is that there is no single strategy for addressing air pollution problems, and Latin American cities need a mix of right policies and actions.

One common good practice among cities with high CECA scores is the understanding and implementation of a comprehensive AQM approach. Such vision facilitates better performances in other AQM dimensions. A recurrent limitation in studied cities is the little interaction and coordination between authorities of different sectors at the local level, and between these with their peers at the regional and national levels. This condition limits the city´s capabilities to act while promoting AQM approach focused exclusively on air quality monitoring.

5.2. Determinants in air quality management

One of the outcomes of this study was the identification of common elements to consider as determinants for a successful urban AQM in Latin American cities. We define a successful city, in terms of good practices in AQM, as one with high technical, data and exploiting capabilities, and which has used those capabilities to implement actions for reducing air pollution. Fig. 5 shows the nine determinants resulting from our analysis. They are arranged as a group of actions that are equally relevant and not directed specifically to environmental authorities.

These nine determinants become a guide for cities where to act in order to promote a more comprehensive AQM vision and to strengthen their capabilities for improving air quality.

Since there is no silver-bullet strategy to reduce air pollution, the prioritization between these actions is relative to the conditions and the state of the urban AQM development of each city.

5.3. CECA opportunities for improvement

CECA is a method to assess and communicate urban AQM capabilities. The Latin American case study presented here shows that CECA is well defined, reliable and useful. However, the assessment and comparative analysis of AQM capabilities is a complex issue that demands continuous review. This means CECA should be an evolving tool, with the flexibility to adjust as needed to reflect particular contexts and expectations. For example, when applying CECA to more developed economies, one suggestion is to revise the reference level on the scoring scale for specific indicators.

Composite indexes combine multidimensional concepts into a single number, presenting methodological limitations when aggregation and standardizing (Klopp and Petretta, 2017; Moreno Pires et al., 2014). CECA uses a geometric aggregation approach to reduce trade-offs between indicators of the different dimensions (high performance in one specific indicator partly compensates a low performance in another one).

Also, scoring methods based on questionnaire answers may be biased depending upon the respondent. CECA methodology, in which we visited each city and conducted personal interviews, allowed us to probe deeper on details regarding the AQM process. Another relevant aspect is that the extent of the visits varied widely among the cities. These differences are related to each city context and experts' availability. For instance, interviews and willingness to share information tend to be better in cities where authorities have more facilities to show and more processes to explain. While this does not directly affect

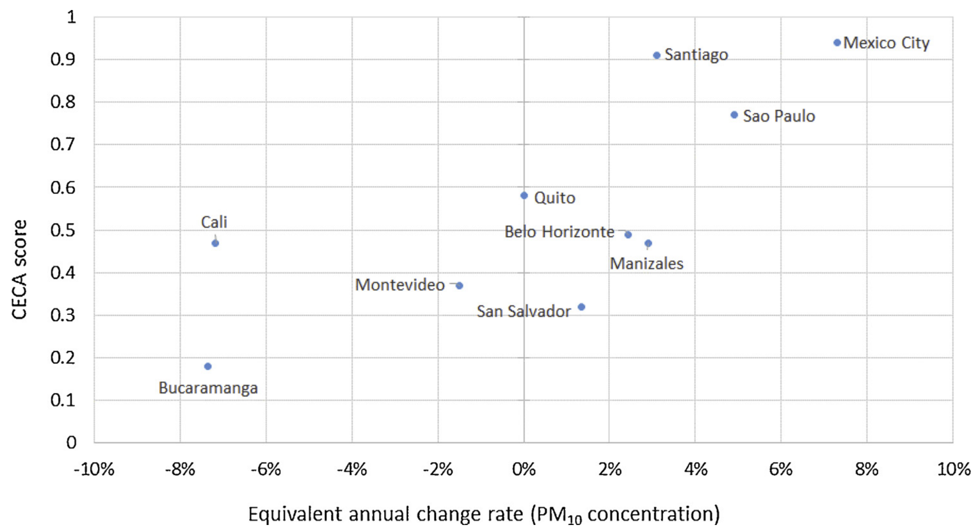

Fig. 4. CECA scores and cities' equivalent annual rate of change in PM_{10} concentration (overall range from 2006 to 2016). Starting year of analysis: 2006 (Mexico City, Santiago, Belo Horizonte and Montevideo); 2010 (Sao Paulo, Quito, Cali, San Salvador; 2011 (Bucaramanga, Manizales).

Table 7
Strengths, good practice, limitations and opportunities.

City[1]	CECA Score	Strengths and Good Practices	Limitations and Opportunities
Mexico City	0.94	• High response capacity to air pollution episodes and contingency alerts. • PROAIRE and its monitoring indicators as long-term AQM tools. • Center Five: an in-house laboratory for instruments calibration and maintenance.	• Promote greater community participation in the definition of air quality goals and as overseers of targets compliance.
Santiago	0.91	• Santiago Respira as a long-term planning instrument and coordination between levels and sectors of governance. • Private sector leadership in clean energy use. • Well-developed compensation system to promote emissions reduction.	• Improve interaction and coordination between environmental and energy sectors to control residential emission sources.
Sao Paulo	0.77	• Formal mechanisms for community participation (i.e., public hearings when licensing new companies). • Solid regional AQM authority (CETESBE), technically supported by experts from academia. • A successful mobile sources technical revision program.	• Need for greater articulation with authorities from other sectors (i.e., public health authorities). • Improve interaction and coordination between regional authority and local authorities.
Quito	0.58	• Technical reliability in air quality monitoring and the practice of reporting information online. Vehicle technical revision program audited.	• Institutional, operational and legal lack of integration with local mobility authority to control the mobile sources.
Belo Horizonte	0.49	• Validation, analysis and reporting air quality data procedures audited by a third party. • Private sector involvement in the operation of the air quality monitoring network through a compensation program.	• Lack of coordination between regional environmental authority (responsible for monitoring) and local authorities. Not a priority in the local public agenda.
Cali	0.47	• Accredited procedures for monitoring and data management. • Important AQM budget, due to an environmental surcharge in the property tax. • Continuous dialogue between local (DAGMA) and regional (CVC) authorities.	• Relatively limited application given to the technical information that is generated. • Lack of formal coordination instances with authorities from other local sectors.
Manizales	0.47	• An official agreement with academia to strengthen technical skills and to generate tools to improve local AQM (i.e., estimation of emissions inventories). • AQM visibility through an inter-institutional air quality board.	• Limited coordination between environmental authorities at local and regional level. • Limited staff in the regional environmental authority (CORPOCALDAS).
Montevideo	0.37	• Regular reporting practices based on available data. Technical understanding of AQM limitations and needs.	• Not a priority in the local public agenda. • Normative void due to the lack of an air quality standard.
San Salvador	0.32	• Leadership from the national environmental authority. Data dissemination through the Environmental Observatory	• Regulatory void for industrial emissions control. No emissions standards for fixed sources.
Bucaramanga	0.18	• Recent agreements with academia to strengthen technical capabilities: emissions inventories and source contribution studies.	• Institutional transition. New metropolitan authority (AMB) opens the door to regional planning.

[1] Cities ordered according to their CECA score (from highest to lowest).

CECA's outcome, in future CECA applications, we recommend that visits to cities be more standardized.

6. Conclusions

This study introduces CECA, a systematic approach to assess and communicate urban AQM capabilities. One of the CECA's main advantages over exiting approaches is the detailed description it provides

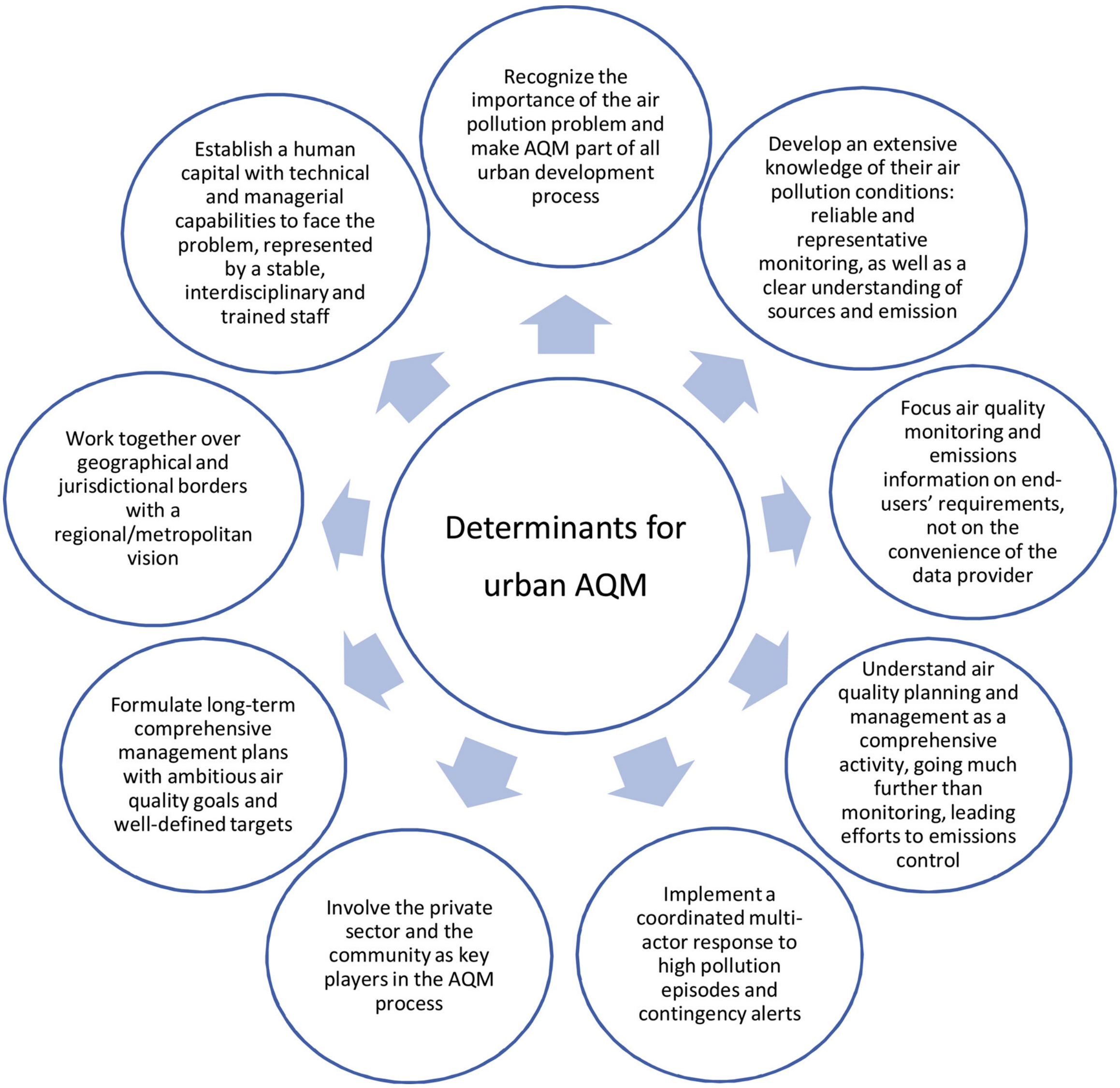

Fig. 5. Determinants of successful urban AQM for Latin American cities.

across nine dimensions, which are determinants for achieving good practices in AQM. This due to the analytical scoring scale defined for each indicator, and to the possibility to get a broader insight on the city's AQM status when administering CECA's questionnaire in person.

CECA application in ten cities in Latin America shows significant differences in AQM aspects across the region, as well as very different states in terms of technical, data and exploiting capabilities. Leading cities, such as Mexico City and Santiago, have in common their effectiveness in integrating technical knowledge into long-term AQM programs, and the strengthening of their institutions and policies to set ambitious air quality goals. At the other side, cities with low and limited capabilities have not prioritized air quality in recent years and have almost exclusively focused on monitoring.

The studied cities coincide the need of having systematic assessment tools to cope with urban air pollution challenges. They recognize in CECA a useful approach to quantitatively describe the capabilities of a city to improve air quality, while fosters a comprehensive view and multisector action at local and national scales. Cities also found the pilot results as a starting point that facilitates the understanding of where to act and an opportunity for benchmarking with other Latin American cities.

Conflict of interest and authorship conformation form

Please check the following as appropriate:

- All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.
- This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.
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