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Accuracy and reliability of Chile's National Air Quality Information System for measuring particulate matter: Beta attenuation monitoring issue

Richard Toro A., Claudia Campos, Carolina Molina, Raul G.E. Morales S., Manuel A. Leiva-Guzmán *

Center for Environmental Sciences and Chemistry Department, Faculty of Sciences, University of Chile, Las Palmeras 3425, Ñuñoa, Santiago de Chile, Chile

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ABSTRACT

A critical analysis of Chile's National Air Quality Information System (NAQIS) is presented, focusing on particulate matter (PM) measurement. This paper examines the complexity, availability and reliability of monitoring station information, the implementation of control systems, the quality assurance protocols of the monitoring station data and the reliability of the measurement systems in areas highly polluted by particulate matter. From information available on the NAQIS website, it is possible to confirm that the $PM_{2.5}$ (PM_{10}) data available on the site correspond to 30.8% (69.2%) of the total information available from the monitoring stations. There is a lack of information regarding the measurement systems used to quantify air pollutants, most of the available data registers contain gaps, almost all of the information is categorized as "preliminary information" and neither standard operating procedures (operational and validation) nor assurance audits or quality control of the measurements are reported. In contrast, events that cause saturation of the monitoring detectors located in northern and southern Chile have been observed using beta attenuation monitoring. In these cases, it can only be concluded that the PM content is equal to or greater than the saturation concentration registered by the monitors and that the air quality indexes obtained from these measurements are underestimated. This occurrence has been observed in 12 (20) public and private stations where $PM_{2.5}$ (PM_{10}) is measured. The shortcomings of the NAQIS data have important repercussions for the conclusions obtained from the data and for how the data are used. However, these issues represent opportunities for improving the system to widen its use, incorporate comparison protocols between equipment, install new stations and standardize the control system and quality assurance.

1. Background

In recent decades, a global tendency toward air quality degradation has been observed in several urban areas of the world (Folberth et al., 2014; Parrish et al., 2011; Vallero, 2014), which has been attributed to high concentrations of particulate matter (PM). Of these urban areas, cities such as Sao Paulo, Mexico City, Lima, Buenos Aires and Santiago experience air pollution related to PM (Molina and Molina, 2004; WHO, 2014; Zereini and Wiseman, 2010) that poses a risk to human health (Kampa and Castanas, 2008; Kim et al., 2015; Leiva G et al., 2013). Studies performed by the World Health Organization (WHO) show that air pollution causes cancer in humans; in particular, PM is the air pollutant responsible for the most cases of cancer, especially lung cancer (IARC/WHO, 2013). It was estimated that by the year 2012, 3.7 million people worldwide had died prematurely due to exposure to particles with aerodynamic diameters less than 10 μm (PM_{10}) (WHO, 2014).

In most cities in Chile, there are air quality problems related to the presence of high levels of PM_{10} and $PM_{2.5}$ (particulate matter with an aerodynamic diameter under 2.5 μm) (Díaz-Robles et al., 2011; MMA, 2013). The annual average concentration for PM_{10} and $PM_{2.5}$ exceeds the guidelines established by the WHO for PM_{10} and $PM_{2.5}$, as well as the air quality national standard of Chile, in several cities in Chile (see Fig. 1). Moreover, the official 2011 Report of the State of the Environment in Chile, developed by Chile's Environment Ministry (MMA), highlighted that at least 10 million people (60% of the country's population) are exposed to an average annual concentration of $PM_{2.5}$ higher than the national standard (20 μg m^{-3}) (MMA, 2011). Additionally, it was estimated that at least 4000 deaths every year are caused by chronic exposure to $PM_{2.5}$ (MMA, 2011).

Air quality monitoring stations have been installed in Chile since the 1990s (Morales and Leiva G., 2006; Ulriksen, 1993). Initially, the responsibility for monitoring the air quality was shared by several institutions in the country: the Ministry of Health, the Farming and Livestock Service, the MMA, private companies and NGOs. However, since 1 January 2012 the MMA is solely responsible for the administration and implementation of public stations and networks to monitor the air quality.

* Corresponding author.
E-mail addresses: manleiva@uchile.cl, manleiva@me.com (M.A. Leiva-Guzmán).

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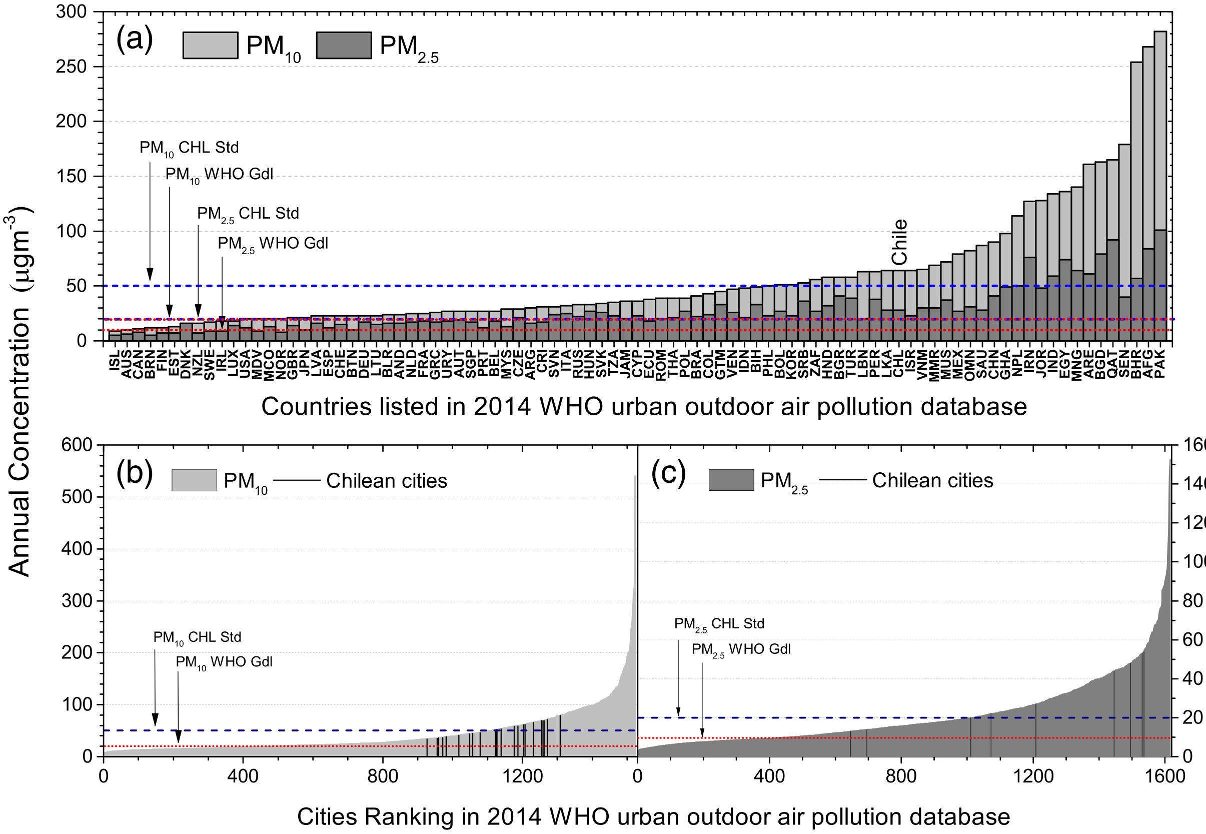


Fig. 1. Ranking of concentrations of particulate matter in different counties (a) and cities around the world for PM_{10} (b) and $PM_{2.5}$ (c) (WHO, 2014). Black line are chilean cities listed in *Database of Atmospheric (outdoor) air pollution in cities*, (WHO, 2014). Blue dash line is a Chilean air quality standard (PM_x Cl STd) and red dot lines is the WHO air quality guideline (PM_x WHO-Gdl).

The air quality information in Chile is obtained from public and private monitoring networks. This information is centralized at the National Air Quality Information System (NAQIS) that is currently managed by the MMA (SINCA, 2015). Through the NAQIS, the MMA, provides viable and reliable access to air quality information, assesses compliance with standards, proposes measures to prevent and control pollution, implements measures to protect public health as specified in the law, provides reliable data for scientific research, optimizes available resources, avoids loss of resources and avoids task duplication (SINCA, 2015).

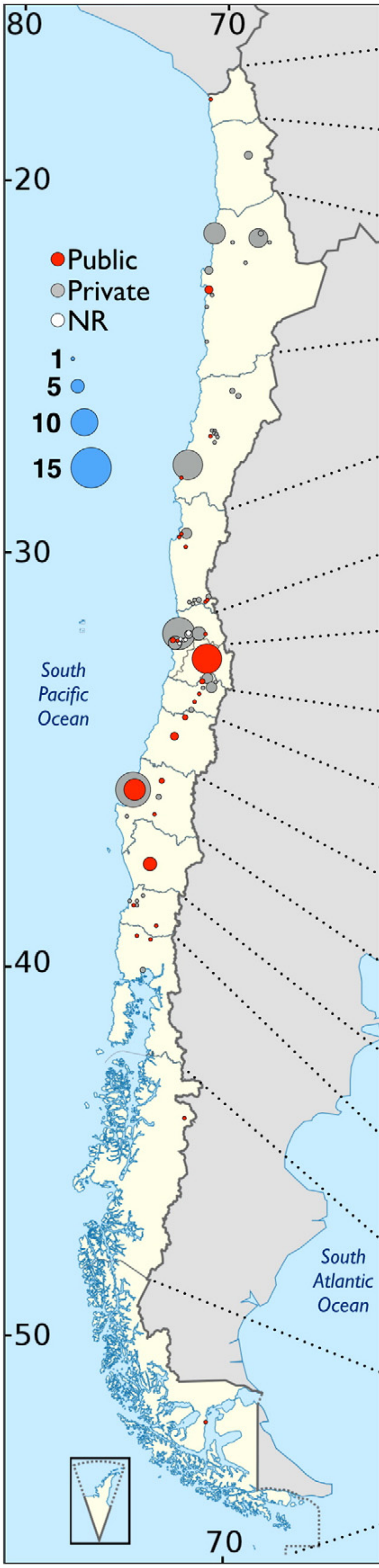
Information about air pollutant concentrations in the environment is available to the public at the NAQIS website (SINCA, 2015). This site is widely used to develop several official reports as well as scientific studies about the state of the air quality, especially regarding PM concentrations. This information has been used in epidemiological studies (Díaz-Robles et al., 2014; Leiva G et al., 2013; Sanhueza et al., 2009), high pollution events forecasting (Cassmassi, 1999; Díaz-Robles et al., 2008; Perez and Reyes, 2006), studies concerning the relation between the chemical and physical compositions of PM (Morales and Leiva G., 2006; Morata et al., 2007; Toro A. et al., 2014), analyses of spatial and temporal trends (Gramsh et al., 2006; Morales and Leiva G., 2006; Toro A. et al., 2014), assessments of the cost and efficacy of prevention and decontamination measures (Silva and Quiroz, 2003; Toro A. et al., 2014). At a governmental level, the reports regarding the state of the air quality in Chile are noteworthy because the government's main objective is the enforcement of regulations, laws or international treaties signed by Chile. Examples of these noteworthy reports include the Official Environment Status Report 2011 (Chapter 1) (MMA, 2011), First Report about the State of the Environment 2013 (MMA, 2013), OECD Environmental Performance Reviews: Chile 2005 (OECD, 2005), and Database of Atmospheric (outdoor) air pollution in cities, 2014 (WHO, 2014).

To properly assess air quality standards, implement prevention and decontamination policies and develop scientific research using the information available at the NAQIS, the information must be reliable (MMA, 2014). For this reason, this paper presents a critical analysis of the information available at the NAQIS. This paper examines the reliability and completeness of the information, the characteristics of the equipment used in the measurements and the implementation of quality assurance and quality control (QA/QC) programs. Additionally, this paper discusses the repercussions of using beta attenuation monitoring (BAM) detectors, which has been proven to underestimate the 24-hour standard in some areas of the country highly polluted with PM_{10} and $PM_{2.5}$, in monitoring networks. Finally, this paper highlights the need for the relevant authorities to implement constant improvements to the NAQIS systems.

2. Materials and methods

2.1. National Air Quality Information System website

The NAQIS can be accessed via a website maintained by the MMA (SINCA, 2015). The information comes from public stations administered by the state (mainly by the MMA) and from private stations operated by private and/or state-owned companies to meet the requirements of environmental regulations (SINCA, 2015). The NAQIS website uses the Airviro software application developed by the Swedish Meteorological and Hydrological Institute (SMHI), Norrköping, Sweden (SMHI, http://www.smhi.se/airviro/). This software assists in handling high volumes of information and connecting with other systems and monitoring networks. The information from public and private monitoring stations is sent to the NAQIS portal (SINCA, 2015).



	N°Stations	$PM_{2.5}$	PM_{10}
XV R. de Arica y Parinacota	1 (1)	1 (1)	0 (0)
I R. de Tarapacá	3 (0)	0 (0)	3 (0)
II R. de Antofagasta	29 (3)	10 (1)	26 (3)
III R. de Atacama	26 (2)	3 (2)	15 (1)
IV R. de Coquimbo	18 (5)	2 (2)	15 (3)
V R. de Valparaíso	36 (4)	9 (4)	31 (3)
RM R. Metropolitana de Santiago	11 (11)	11 (11)	11 (11)
VI R. del Lib. Gral. Bernardo O'Higgins	15 (4)	2 (2)	14 (4)
VII R. del Maule	7 (5)	5 (5)	6 (5)
VIII R. del Bio Bio	32 (16)	14 (14)	28 (13)
IX R. de la Araucanía	4 (4)	3 (3)	4 (4)
XIV Región de Los Rios	6 (2)	2 (2)	6 (2)
X Región de Los Lagos	4 (2)	2 (2)	4 (2)
XI R. Aisén del Gral Carlos Ibáñez del C.	2 (2)	2 (2)	2 (2)
XII R. de Magallanes y de la Antártica Ch.	1 (1)	1 (1)	0 (0)
Total	195 (62)	65 (51)	171 (53)

Fig. 2. Map of Chile with the number of monitoring stations per administrative región (in red the public stations).

Table 1
Summary for stations measuring PM_{10} and $PM_{2.5}$ in Chile's National Air Quality Information System (NAQIS). (a) Number and percentage of monitoring stations (total, public and private) that measure PM_{10} and $PM_{2.5}$; (b) number and percentage of public and private stations have information monitoring of PM_{10} and $PM_{2.5}$; (c) year first record of PM_{10} and $PM_{2.5}$ in public and private stations available; (d) last year's record of PM_{10} and $PM_{2.5}$ in public and private stations monitoring information; (e) number of total years of the duration of the series of average time for monitoring stations reporting data of PM_{10} and $PM_{2.5}$; (f) range of average concentrations of PM_{10} and $PM_{2.5}$ in public and private stations (g) measurement system of PM10 and PM2.5 in public and private stations.

	$PM_{2.5}$		PM_{10}	
	N°	%	N°	%
(a) Category	Total stations availability information (N° stations and %)			
Yes	60	30.8	142	69.2
No	7	3.6	17	10.5
NI	6	3.1	6	4.5
NM	122	62.6	30	15.8
Total	195	100	195	100

		Public stations				Private and public enterprise stations			
		$PM_{2.5}$		PM_{10}		$PM_{2.5}$		PM_{10}	
		N°	%	N°	%	N°	%	N°	%
(b) Category		Data availability (N° stations and %)							
Yes		48	77.4	50	80.6	12	9.4	92	72.4
No		3	4.8	3	4.8	4	3.1	14	11.0
NM		11	17.7	9	14.5	111	87.4	21	16.5
(c) N° years		Total record measurement (N° stations and %)							
0–3.0		32	51.6	24	38.7	10	7.9	24	18.9
3.1–6.0		7	11.3	11	17.7	2	1.6	25	19.7
6.1–9.0		6	9.7	7	11.3	0	0.0	13	10.2
9.1–12		1	1.6	2	3.2	1	0.8	25	19.7
12.1 or more		4	6.5	7	11.3	0	0.0	9	7.1
NI		1	1.6	2	3.2	3	2.4	10	7.9
NM		11	17.7	9	14.5	111	87.4	21	16.5
(d) Year (yyyy)		First available data (N° stations and %)							
1993–1998		–	–	7	20.7	1	0.8	6	4.7
1999–2002		5	8.1	2	6.0	–	–	29	22.8
2003–2004		1	1.6	3	8.9	1	0.8	15	11.8
2005–2006		–	–	1	3.0	1	0.8	16	12.6
2007–2008		21	33.9	13	38.4	9	7.1	10	7.9
2009–2010		8	12.9	10	29.5	1	0.8	6	4.7
2011–2012		11	17.7	9	26.6	–	–	12	9.4
2013–2014		10	16.1	6	17.7	–	–	2	1.6
NM		1	1.6	2	5.9	3	2.4	10	7.9
NI		5	8.1	9	26.6	111	87.4	21	16.5
(e) Year (yyyy)		Last available data (N° stations and %)							
2003–2004		–	–	–	–	–	–	1	0.8
2005–2006		–	–	–	–	–	–	2	1.6
2007–2008		–	–	–	–	–	–	10	7.9
2009–2010		5	8.1	6	9.7	–	–	48	37.8
2011–2013		2	3.2	3	4.8	2	1.6	4	3.1
2013–2014		43	69.4	42	67.7	11	8.7	31	24.4
NM		1	1.6	2	3.2	3	2.4	10	7.9
NI		11	17.7	9	14.5	111	87.4	21	16.5
(f) $PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)	Range of average concentration in availed record measurement (N° stations and %)							
0–20	0–25	9	14.8	1	1.6	8	6.3	10	7.9
21–30	26–50	17	27.9	17	27.4	4	3.1	40	31.5
31–40	51–60	12	19.7	13	21.0	–	–	23	18.1
41–60	61–80	6	9.8	17	27.4	–	–	14	11.0
61–80	81–100	4	6.6	1	1.6	–	–	3	2.4
80>	101>	–	–	1	1.6	–	–	2	1.6
NI		2	3.3	3	4.8	4	3.1	13	10.2
NM		11	18.0	9	14.5	111	87.4	22	17.3
(g) Name		Measurement system							
Beta attenuator particulate		31	50.0	30	48.4	6	4.7	20	15.7
Gravimetry (otros)		2	3.2	2	3.2	5	3.9	25	19.7
Nephelometry		2	3.2	2	3.2	0	0.0	0	0.0
TEOM		0	0.0	1	1.6	0	0.0	5	3.9
NI		16	25.8	18	29.0	5	3.9	56	44.1
Not measured		11	17.7	9	14.5	111	87.4	21	16.5

Yes: Measured and information online; No: measured without information online; NM: not measured; NI: non informed. TEOM: tapered element oscillating microbalance a see Section 2.1.

2.2. Data analysis

As of December 2014, the NAQIS displays information from 195 monitoring stations in Chile (Fig. 2). We obtained the information from each monitoring station directly from the NAQIS website (http://sinca.mma.gob.cl). The following information is available from each station: owner (the person in charge of the station), station operator (the person in charge of station maintenance), location (the region, province, municipality and UTM coordinates), time zone, method of data reception (online or manual), start date of the operation, date of the first and last register, parameters measured, measurement technique used and a time series of the measured data. The available data were stored, viewed, and manipulated in a table using MS-Excel® 2011 for Mac (Microsoft Corporation, Redmond, WA, USA). The descriptive statistical analysis was performed by using the pivot tables tool of MS-Excel® 2011. The graphs of the time series from chosen stations where $PM_{2.5}$ and/or PM_{10} are measured by BAM detectors were plotted using the software Origin v9.5® (OriginLab Corporation, Northampton, MA, USA).

3. Results and discussion

3.1. PM_{10} and $PM_{2.5}$ information sent from monitoring stations to the NAQIS

Fig. 1 shows the distribution of the 195 air quality monitoring stations that send information to the NAQIS (62 public stations, 127 private stations, and 6 unknown). Table 1a and b presents all of the air quality monitoring stations that send information to the NAQIS, including the number of public and private stations. The monitoring stations sending $PM_{2.5}$ and PM_{10} data account for 30.8% (60 stations) and 69.2% (142 stations) of all stations, respectively (Table 1a). It is known that measurements of $PM_{2.5}$ and PM_{10} for 3.6% (7 stations) and 10.5% (17 stations) of all stations, respectively, are not sent to the NAQIS. At 62.6% of the stations (122 stations), $PM_{2.5}$ is not measured. At 15.8% of the stations (30 stations), PM_{10} is not measured. Six stations do not send information for either PM fraction, accounting for 3.1% (4.5%) of the total information available for $PM_{2.5}$ (PM_{10}).

Table 1b shows the ownership data for the monitoring stations: 32% of the stations (62 stations) are public, 65% of the stations are privately owned (127 stations) and ownership information is not available for 6 stations. For public stations, 82.2% (51 stations) measure $PM_{2.5}$ of which 77.4% (48 stations) send the data to the NAQIS. Regarding PM_{10}, 85.4% of public stations (53 stations) measure it and 80.6% (50 stations) send the data to the NAQIS. For private stations, 12.5% (16 stations) measure $PM_{2.5}$ of which 9.4% (12 stations) send the data to the NAQIS. Finally, PM_{10} is measured at 83.4% of the private stations (106 stations) of which 72.4% (92 stations) send the data to the NAQIS. The high percentage of stations not measuring $PM_{2.5}$ can be explained by the fact that Chile did not have a $PM_{2.5}$ standard until 2012 (D.S.N°12, 2011). However, the PM_{10} standard has been in force since 1998 (D.S.N°59, 1998).

3.2. Data availability, type and measurement times

PM_{10} and $PM_{2.5}$ data from the NAQIS are divided into two groups (SINCA, 2015): preliminary data and official data. Preliminary monitoring data correspond to two categories of data: data that have not been validated operationally and were received online automatically and data that have been validated operationally through a validation process performed by the station operator or measurement network. The preliminary data that have not been validated cannot be used to officially verify compliance with the current legislation. The official monitoring data correspond to data previously validated by operators and ratified by the competent authority. For PM_{10}, 72.5% of private monitoring stations (92 stations) send preliminary data, 51.2% (65 stations) send preliminary data that has been validated operationally and 0% (0 stations) send official data. For $PM_{2.5}$, only 10.3% of the stations (12 stations) send preliminary data and 0% (0 stations) send official data. Although the percentage of official data is low, it is common practice to use all data sent to the public NAQIS networks to assess air quality standards and implement exceptional measures to protect the public health, such as restrictions on industrial operations, limits on automobile use and bans on firewood combustion. The lack of official data highlights the existence of deficiencies in the systematization of the information, the validation methods, the assurance procedures and the quality control of the information.

Concerning data availability, Table 1c shows the available data for PM expressed as a time series for the length of the data sent by the stations (the length is obtained by subtracting the date when the first datum was sent to the NAQIS from the date when the last datum was sent). In this regard, not every monitoring station sending information to the NAQIS is currently operational. In 2014, a total of 43 (42) of the 62 public stations sent $PM_{2.5}$ (PM_{10}) data, while a total of only 11 (30) of the 127 private stations sent $PM_{2.5}$ (PM_{10}) data. This result shows that most stations currently sending information to the NAQIS are public; approximately 69% of the public stations send information for both PM fractions, while only 24% (9%) of private stations send PM_{10} ($PM_{2.5}$) information.

3.3. Observed concentrations in the NAQIS data

Primary national air quality standards for $PM_{2.5}$ and PM_{10} are annual averages of 20 μg m^{-3} (D.S.N°12, 2011) and 50 μg m^{-3} (D.S.N°59, 1998), respectively. The ranges of the average concentrations that were sent to the NAQIS by both public and private monitoring stations are presented in Table 1f. For $PM_{2.5}$, the concentrations sent by 9 public stations (14.8%) are less than the Chilean annual standard for air quality. In contrast, 39 public stations (64.0%) measured concentrations greater than the aforementioned standard. Finally, 3.3% of the public stations do not send information, and 18.0% of public stations do not measure $PM_{2.5}$ (Table 1f). Regarding PM_{10}, 29.0% of the public stations (18 stations) reported concentrations less than the Chilean air quality standard. In contrast, 51.6% of the public stations (32 stations) reported concentrations greater than the standard. Finally, 19.3% of the stations do not send information (3 stations) or do not measure PM_{10} concentrations (9 stations). Additionally, the concentrations sent by 16.4% of the public stations (10 stations) are two times greater than the Chilean annual standard, and the concentrations measured at 6.6% of the stations (4 stations) are three times greater than the national standard.

Regarding private stations, 90.5% do not measure $PM_{2.5}$ (111 stations) or do not send $PM_{2.5}$ information (4 stations). Eight of the 12 private stations that measure $PM_{2.5}$ report concentrations less than the national standard. However, these results are not representative of national air quality due to the small number of private stations that measure $PM_{2.5}$. The situation is completely different in the case of PM_{10} because 39.4% of the 127 stations (50 stations) report results less than the Chilean national standard. The concentrations reported by 33.1% of the stations (42 stations) are greater than the annual standard. For PM_{10}, 10.2% of the stations (13 stations) do not send information and 17.3% (22 stations) do take measurements. Notably, concentrations greater than 101 μg m^{-3} were measured at 2 stations.

3.4. QA/QC at the monitoring stations

The information provided by the monitoring stations is considered to be valid for assessing compliance with the air quality regulations provided that these stations are included in the category of Representative Monitoring Stations (RMS) (DTO-N°61, 2008). Inclusion in this category is determined by a resolution adopted by the MMA. Once a monitoring station is included in the RMS category, the information provided by the station owner must comply with the requirements specified in "Regulations for air pollution measurement stations" (DTO-N°61, 2008) regarding inspections, maintenance and calibration of the equipment and the data validation procedure performed by the station operator. Once these requirements are met, the information obtained by the monitoring station can be used to verify compliance with the air quality standards. Finally, the competent environmental authority verifies whether the information sent by the station owner meets the requirements of the standards. According to the information provided by the NAQIS, 39.5% of the monitoring stations (77 stations) that measure PM_{10} and 4.6% of the

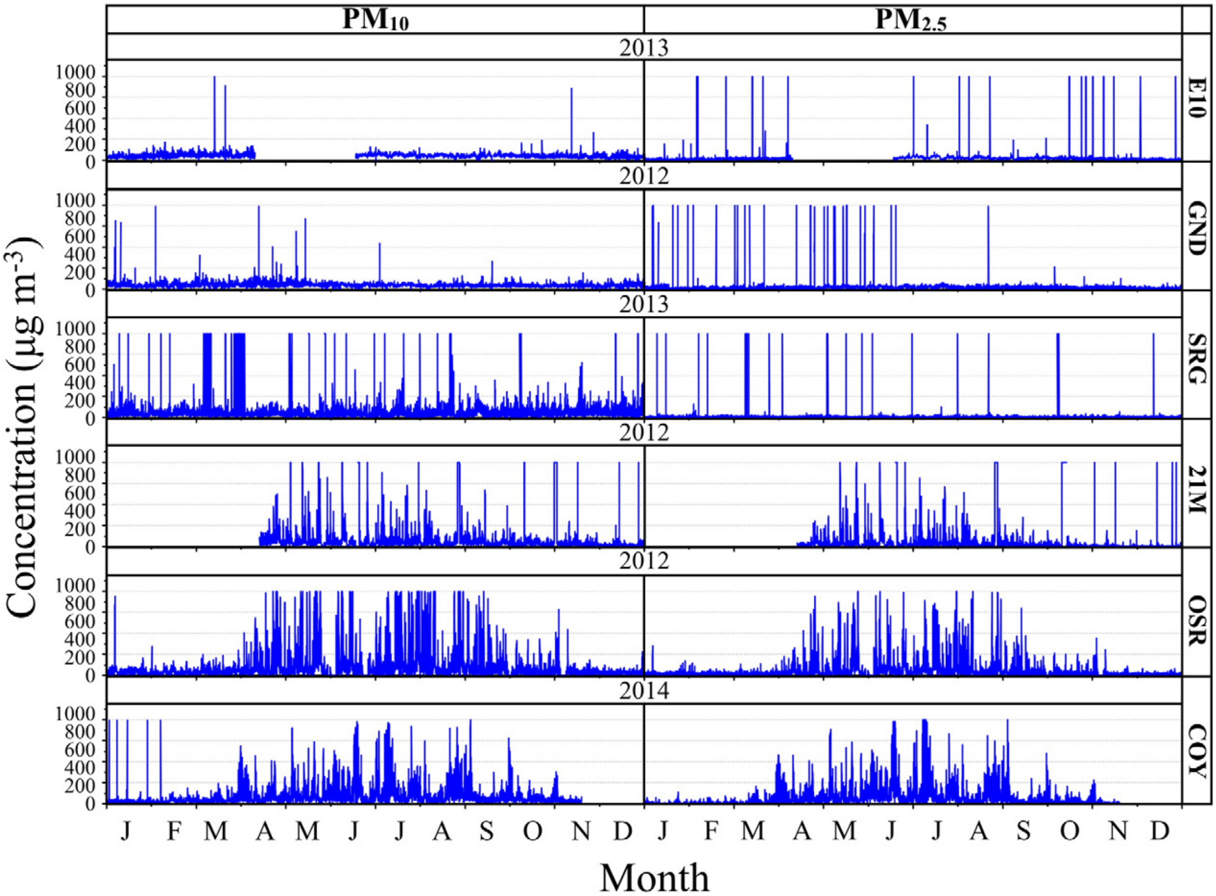


Fig. 3. Time series of hourly PM_{10} and $PM_{2.5}$ concentrations obtained at the E10, GND, SRG, 21M, OSR and COY stations for a complete calendar year.

stations (9 stations) that measure $PM_{2.5}$ are included in the RMS category. The majority of these stations are public stations.

The MMA implementing the ISO/IEC 17025 (ISO-9001, 2008) QA/QC systems at public monitoring stations. A QA/QC system has been implemented by the Air Quality Division of the Air Quality Monitoring Network Department at 4 of the 11 monitoring stations located only in the Metropolitan Region (MACAM network). These stations are the only public stations under the supervision of the MMA, which manages their operation and maintenance. Although the remaining public stations in Chile are the property of the MMA, their operation and maintenance are delegated to private companies through public tender. According to information obtained from the websites of public and private monitoring stations that send information to the NAQIS, at least 50% of operators hold an ISO 9001:2008 accreditation (ISO-9001, 2008). However, it was not possible to determine the extent and validity of the aforementioned accreditation. Moreover, holding this accreditation is not compulsory.

However, it should be compulsory for owners and monitoring station operators to have a unified QA/QC system (ISO/IEC 17025) that ensures measurement quality through audits. It is suggested by the authors that the MMA should implement a system in conjunction with other institutions, such as the National Institute of Normalization (INN), to ensure the comparability and traceability of the measurements nationally (Leiva, 2006). Such a system should use the existing laboratory infrastructure and national standards of mass, temperature, relative humidity, pressure and flow to trace the necessary measurements of particle concentrations in the atmosphere. Another option is to use standards that are traceable to other international institutions, such as the National Institute of Standards and Technology (NIST). An good example of the QA/QC system applied to Air Quality Monitoring Network is provided by the United States Environmental Protection Agency (EPA), which through protocols ensures the traceability and comparability of measurements made at different monitoring networks in charge (EPA, 2008, 2015).

3.5. PM measurement systems and beta attenuation monitoring issue

During 2012 and 2013, the MMA established a strategic priority to extend the monitoring coverage of PM (primarily $PM_{2.5}$) to cities with more than 100,000 inhabitants. In this period, the number of public stations measuring $PM_{2.5}$ (PM_{10}) increased to 21 (15) (Table 1).

The distribution of stations in relation to the measurement method used for $PM_{2.5}$ and PM_{10} at public and private stations is shown in Table 1g. The table shows that 50% of public stations (31 stations) where $PM_{2.5}$ is measured and 48.4% of public stations (30 stations) where PM_{10} is measured use beta attenuation monitoring (BAM). Only 3.2% of the stations use gravimetry (GRAV) and nephelometry (NEPH) to measure PM_{10} and $PM_{2.5}$, respectively. The stations that use tapered element oscillating microbalance (TEOM) systems to measure particles do not send information to the NAQIS, with the exception of one that sends information for PM_{10}. However, according to firsthand knowledge, this type of monitor is used by 11 stations in the monitoring network of the Santiago metropolitan area to measure $PM_{2.5}$ and PM_{10}. For $PM_{2.5}$, 4.7%, 3.9%, 0% and 0% of private stations use BAM, GRAV, NEPH and TEOM measurement methods, respectively. For PM_{10}, 15.7%, 19.7%, 0% and 3.9% of private stations use BAM, GRAV, NEPH and TEOM measurement methods, respectively.

In a recent study, the $PM_{2.5}$ content in air was obtained at 3 air monitoring stations in Taiwan by using a simultaneously dichotomous sampler (gravimetric method) and BAM (Liu et al., 2013). The results show that the concentrations obtained by BAM were always higher than those obtained by the dichotomous samplers. The differences between the concentrations registered by these two methods ranged from 19 to 58%. There are several factors that explain this discrepancy, such as the aerosol water content, the volatility of the organic fraction and positive measurement errors. This result highlights the importance of carefully selecting the measurement method and implementing protocols to assure the quality and comparability of the measurements (AirPARIF, 2011; AQUILA, 2009; Desauziers, 2004; Engel-Cox et al., 2013).

BAM detectors, in general, are capable of measuring PM in two different concentration ranges: from 0 to 1000 μg m^{-3} (the typical setting) and from 100 to 10,000 μg m^{-3} (BAM, 2015). The brand and model of the equipment used is not shown on the NAQIS website, which makes it difficult to identify the configuration and concentration range used. If a low concentration range is set and the particle concentration in the air is greater than the upper limit of this interval, the detector becomes saturated and the measured concentration corresponds to this upper limit. Fig. 3 shows the hourly measurements of PM_{10} and $PM_{2.5}$ obtained from monitors using BAM for complete calendar years between 2012 and 2014. These data come from the following stations: 3 private monitoring stations (Escuela E-10 (E10), Gendarmería (GND) and Sierra Gorda (SRG)), 3 stations located in the Antofagasta region (northern Chile), the public station 21 de Mayo (21M) located in the Biobío region (southern Chile), the Osorno station (OSR) located in Los Lagos (southern Chile) and the Coyhaique station (COY) located in the Aysén del General Carlos Ibáñez del Campo region (southern Chile). The highest concentration obtained at all of these stations for both particle fractions is 1000 μm m^{-3}, which corresponds to the saturation level of the detectors. Stations E10, GND and SRG, located in northern Chile, are affected by emissions from thermoelectric power plants and mining activities. In these locations, no seasonal variability is observed and low concentrations alternate with sudden increases in concentrations that correspond to the saturation level of the detector. In contrast, stations 21M, OSR and COY, located in southern Chile, are affected by emissions from firewood combustion (normally used for residential heating). These stations are located in areas where temperature inversions occur between April and September. For this reason, during critical episodes of pollution caused by particles during the cold season, the BAM detectors become saturated.

Fig. 4 shows the time series of hourly concentrations and the 24-hour moving averages for PM_{10} and $PM_{2.5}$ obtained from BAM detectors during a critical month for each station. The maximum hourly concentration is 1000 μg m^{-3} for periods lasting between 1 and 7 h at the E10 and GND stations. At the SRG station, the saturation of the detector was observed for periods lasting between 1 and 18 h; whereas, at the 21M station a critical event caused the saturation of the detector for 40 h. In these cases, it can only be concluded that the particle concentration is equal to or greater than the saturation concentration measured by the BAM detectors, and, as a consequence, the 24-hour moving average is underestimated (air quality index to compare registers with daily standards). This effect can be observed in the time series plotted in red in Fig. 3. The same concept applies to $PM_{2.5}$ (PM_{10}) measured at 19 (16) public stations and $PM_{2.5}$ (PM_{10}) measured at 3 (4) private stations.

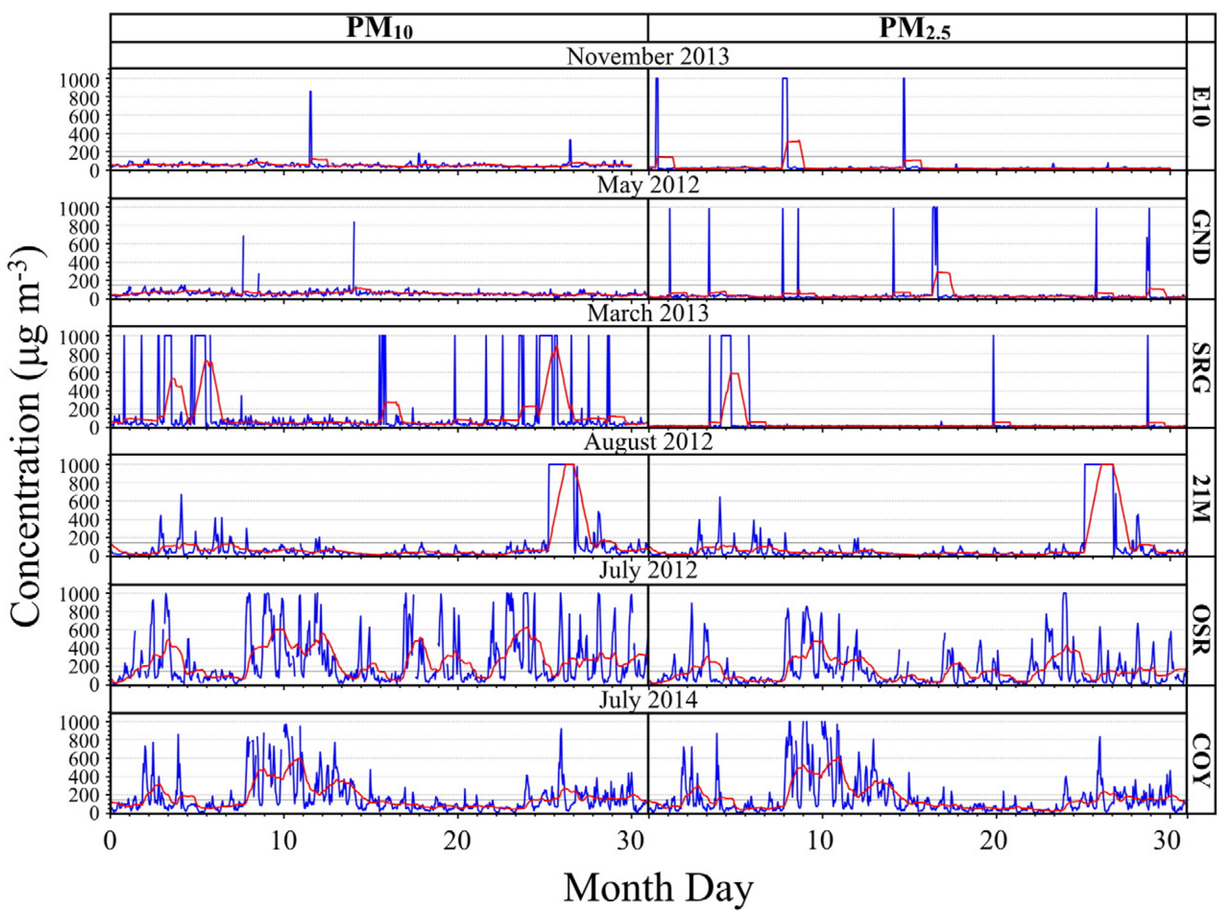


Fig. 4. Time series of hourly concentrations and 24-hour moving averages for PM_{10} and $PM_{2.5}$ obtained from BAM detectors during a critical month for the E10, GND, SRG, 21M, OSR and COY stations. (Doted line is Chilean air quality national standard 150 μg m^{-3} 24-h average).

The situations illustrated in Figs. 3 and 4 make evident the need to implement new protocols in the NAQIS for the installation and operation of the air quality monitoring stations in Chile. It will be necessary to hire personnel, institute training programs, improve the protocols for installing new monitoring stations and modernize existing stations to control the analytical quality of the measurements and the monitoring process. These requirements are especially relevant when considering that only 30% of the stations are part of the national $PM_{2.5}$ network. For this reason, it will be necessary to install a large amount of equipment in upcoming years. This installation should be performed by following protocols that allow for a comparison between measurement methods and avoid loss of information and/or underestimations in the PM concentrations, as previously discussed.

4. Recommendations

The information available from the NAQIS is incomplete and inexact in some cases. There is a lack of information regarding the measurement systems used to quantify the air pollutants, the coordinates of some monitoring stations are incorrect, many parts of the data registers contain gaps, almost all of the information is considered preliminary data and neither validation standard operating procedures nor assurance audits and quality control of the measurements are provided. This lack of information can lead to errors in national and international air quality reports, which are used to determine the urban and industrial areas affected by atmospheric pollution in Chile and to assess the procedures and measures taken to improve and manage the air quality in polluted areas.

The steps taken by the MMA to increase the coverage of the national monitoring network are positive. However, only 30.8% (69.2%) of the stations send information about $PM_{2.5}$ (PM_{10}). In contrast, only 11 (30) of the 127 private stations send information about $PM_{2.5}$ (PM_{10}). These figures highlight the need to increase the network coverage, especially for $PM_{2.5}$. For this reason, existing stations will be modernized and new stations will be installed in upcoming years. This task should be performed by following proper protocols for installing air quality monitoring stations and verifying the equivalence between measurement methods. Several organizations, such as the World Meteorological Organization and United States Environmental Protection Agency, use QA/QC systems in their air quality monitoring networks that could be adopted by the MMA.

The agreement signed by the Air Quality Division of the Air Quality Monitoring Network Department of the MMA and its Canadian counterpart in 2012 is progress toward improving the QA/QC systems of the national air quality networks, particularly the MACAM network. However, it is necessary to strengthen the MMA by increasing the number of human, technological and economic resources so that it can implement a national training program for operators, users and authorities. These additional resources are also needed for periodic audits to enforce QA/QC protocols at new and existing monitoring networks that send information to the NAQIS.

The problems described in this study, such as the underestimation of PM concentrations measured by BAM detectors, show the need for protocols for comparing different types of equipment, installing new monitoring stations and implementing QA/QC systems for the air quality monitoring networks. These improvements represent the most efficient way of obtaining reliable and representative air quality information that can be compared with the information available from different cities, countries, networks, measurement systems and operators and owners of monitoring stations.

Conflict of interest

The authors declare that they have no conflict of interest.

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