Assessment of the variability of pollutants concentration over the metropolitan area of São Paulo, Brazil, using the wavelet transform

M. Zeri,1,* V. S. B. Carvalho,2 G. Cunha-Zeri,1 J. F. Oliveira-Júnior,3 G. B. Lyra3 and E. D. Freitas4

1Brazilian Center for Monitoring and Early Warnings of Natural Disasters (CEMADEN), São José dos Campos, Brazil
2Instituto de Recursos Naturais, Universidade Federal de Itajubá, Brazil
3Departamento de Ciências Ambientais, Instituto de Florestas, Universidade Federal Rural do Rio de Janeiro, Seropédica, Brazil
4Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, Brazil

*Correspondence to:
M. Zeri, Brazilian Center for Monitoring and Early Warnings of Natural Disasters (CEMADEN), Estrada Doutor Altino Bondesan, 500 – Eugênio de Mela, 12247–016, São José dos Campos, São Paulo, Brazil. E-mail: marcelo.zeri@cemaden.gov.br

Abstract

The objective of this work was to investigate the mean and variability of a dataset of pollutant concentrations from measurements taken over the metropolitan area of São Paulo city, Brazil. Wavelet analysis was applied to the time series of pollutant concentrations, revealing the strongest harmonics influencing the signals. A mode of variability of 4–8 days was significant until the middle of the last decade and is likely associated with the approach and passage of meteorological systems. A dataset representing the number of frontal systems moving across the state helped to explain the interannual variability during wintertime. Years with fewer frontal systems had higher levels of pollutants in several locations. Weather events such as inversions and the passage of frontal systems influence the concentration of pollutants. Public policies on air quality should focus not only on reducing the long-term exposure of city-dwellers to the negative effects of pollutants but also account for the possible short-term effects of the weather on air quality.

Keywords: air pollution; wavelet analysis; meteorological systems; data analysis; industrial activity

1. Introduction

Air pollution is a common problem in cities around the world, particularly in metropolitan areas (Sharma et al., 1983; deLeon et al., 1996; Schwartz, 1996; Samet et al., 2000; de Miranda et al., 2002; Godoy et al., 2009). The effects of air pollution – such as particulate matter with diameter ≤10 μm (PM10), sulfur dioxide (SO2), carbon monoxide (CO), or ozone (O3) – increase hospitalizations due to respiratory problems, lung cancer trends, acid rain, and the black dust covering building’s façades (Fajersztajn et al., 2013). The effects of air pollution over the metropolitan area of São Paulo (MASP), Brazil, are already linked to impacts on human health (Gonçalves et al., 2005; Cançado et al., 2006), as well as to feedbacks with atmospheric and climatic conditions including composition of aerosols (Castanho and Artaxo, 2001; Bourrote et al., 2005), the urban heat island (UHI) effect, local circulation patterns (Silva Dias and Machado, 1997; Freitas et al., 2007), and mesoscale circulations induced by topography and sea/land breezes (Oliveira et al., 2003). In this work, a dataset of pollutants concentration was analyzed using statistical inference (means and variances) as well as wavelet analysis, to detect the most important modes of variability influencing the levels of pollution. In general, the concentrations have a daily cycle associated with traffic of vehicles or industrial activity.

There is also an annual trend, with a maximum in winter; the cold air makes the atmospheric surface layer shallow and not well mixed, increasing the concentrations. In addition, atmospheric inversions are sometimes observed in winter, when the vertical profile of air temperature makes it impossible to an air parcel to rise due to buoyancy. Here, we used daily averages, thus the daily cycle was filtered out. The wavelets helped to identify harmonics of several days, which contributed to modulate the concentrations beyond the daily cycle. Observed variability in air pollutant concentrations was analyzed in the context of technological changes facing Brazil regarding air quality policies and the use of ethanol as a substitute to gasoline (Goldemberg, 2007). Brazilian federal agencies, such as the Federal Environmental Council – CONAMA, and state agencies continue to study environmental quality, establish pollutant concentration standards, and operate pollution monitoring networks. These agencies also enforce the use of new technologies to help reduce pollutant emissions, such as catalytic converters which chemically catalyze reactions to oxidize or reduce toxic pollutants into less toxic products and are required by CONAMA to be installed in all new cars from 1997 onwards. Additional examples that public policies decisions have on pollutants concentrations can be found in Andrade et al. (2015) and Carvalho et al. (2015). The oil crisis in the 1970s also had a significant impact on technology in...
Brazil. The rising prices of gasoline compelled the federal government to implement an ethanol fuel industry for road transportation guaranteeing a supply of ethanol from sugarcane coupled with the auto industry building vehicles to run on the new fuel (Goldemberg, 2007). Currently, ethanol-only or flex fuel cars represent nearly 60% of the total vehicle fleet and contribute to 80% of new licensed vehicle in Brazil.

In this work, we report on the variability of pollutants in the MASP using time series of pollutants concentrations measured over 22 stations. The objective here was not a comprehensive study of annual or daily cycles or causes and effects of public policies, which was described in other studies (Salvo and Geiger, 2014; Andrade et al., 2015; Carvalho et al., 2015), but to complement the analysis in those studies by applying wavelet decomposition to the time series of pollutants concentrations.

2. Site and data

The MASP is located in São Paulo state (Figure 1), southeastern Brazil. The territorial area of MASP is of 7944 km², while the urbanized area covers 2139 km², including many cities which are adjacent to the border of São Paulo city (thick black line in bottom panel). For this study, cities outside the limits of MASP were also included, such as São José dos Campos, Cubataó, Sorocaba, Paulínia, and Campinas. The MASP is surrounded by topographical features with altitudes up to 1100 m above sea level, such as the hills of Serra do Mar, to the south, and Serra da Cantareira, to the north. The climate is tropical wet with rainy summers and dry winters (Bourrotte et al., 2005).

During summer, the region is influenced by South Atlantic convergence zone (SACZ) and mesoscale convective systems (MCS), which typically cause thunderstorms before sunset and nighttime fog (Silva Dias and Machado, 1997; Castanho and Artaxo, 2001; Freitas et al., 2007). During winter, the reduction in rainfall and the occurrence of thermal inversions in the atmospheric boundary layer (ABL) contribute to higher concentrations of SO₂, CO, and PM₁₀ (Angevine et al., 1998; Martins et al., 2004; Barbaro et al., 2014). The dispersion of pollutants in this region is influenced by sea breeze and by valley-mountain circulations, due to the proximity to both the coast and the mountain range that runs parallel to the Atlantic Ocean known as Serra do Mar (Silva Dias and Machado, 1997; Oliveira et al., 2003; Carvalho et al., 2012). In addition, circulations associated with the UHI effect contribute to the general dispersion of pollutants (Freitas et al., 2007). Similar to other metropolitan areas of the world, emissions by industrial activity and vehicle traffic are the main source of anthropogenic pollutants in the MASP (Castanho and Artaxo, 2001).

Pollutant concentration datasets were obtained from the São Paulo Environmental Agency (CETESB) from stations primarily located within the urban perimeter.
Most of the air quality stations used in this study are influenced by vehicle or/and industrial emissions with exception of the Ibirapuera station (Figures S2(e) and S5, Supporting Information), which is located in a park. Stations located outside the MASP, such as Campinas, Sorocaba, and São José dos Campos, had historically lower concentrations for some pollutants. Information regarding the number of licensed vehicles and the size of the ethanol fleet were obtained from the Brazilian Sugarcane Industry Association (UNICA).

The dataset of pollutants concentration from each station included hourly records on PM$_{10}$, O$_3$, CO, and SO$_2$, averaged in this work over 8- or 24-h windows, as recommend by World Health Organization (WHO) standards. In recent years, many studies have addressed both the variability, annual cycle, daily and weekday patterns (Carvalho et al., 2015), and relationships of ethanol prices and public policies on this variability (Salvo and Geiger, 2014; Andrade et al., 2015). In this work, we chose to work only with CO and SO$_2$, because they presented the highest change from 1996 to 2012 and also had continuous time series of concentrations which were suitable for wavelet analysis. Results on O$_3$ and PM$_{10}$ are shown in Figures S1–S12 of Supporting Information.

To help explain some peaks in mean monthly concentrations from year to year, data on the number of frontal systems reaching the coast and the countryside were obtained from Climanálise (Climanalise, 2005). These data were plotted together with the monthly concentrations in Figures 2 and 3.

3. Methodology

Data analysis consisted of statistical inferences on time series of concentrations, such as averages, and also correlations with time, to give support to observed trends in pollutant concentrations. In general, wintertime is characterized by less mixing of pollutants, due to colder temperatures and the proximity of the South Atlantic Subtropical Anticyclone. To better identify interannual trends in concentrations, averages were calculated for both July (winter) and January (summer). This procedure enhances the long-term trends because annual maxima (and minima) are compared together. Because of the nature of the annual cycle, with a strong peak during winter but low concentration during summer, yearly averages tend to weaken the maxima, masking the effects of frontal systems on air pollution. It should be noted that not all pollutants were measured at all stations.
The full dataset was presented in Figures S1–S4 together with standards for each pollutant following the WHO or CONAMA. The standards used were 9 ppm for CO (maximum 8-h moving average), 150 µg m\(^{-3}\) for PM\(_{10}\) (24-h mean), 100 µg m\(^{-3}\) for O\(_3\) (maximum 8-h moving average), and 20 µg m\(^{-3}\) for SO\(_2\), (24-h mean). The standards for PM\(_{10}\) and CO were established by CONAMA.

The time series of pollutant concentrations were analyzed using wavelet analysis, a technique that enables the most important frequencies influencing the variability of a signal to be inferred (Daubechies, 1992; Torrence and Compo, 1998). Although Fourier analysis can also be used to identify the most important harmonics in time series, wavelets make it possible to locate in time the influence of harmonics which are not stationary. In recent years, wavelet analysis has been used in many studies of geophysical data, such as river levels, turbulence over plant canopies, and pollutant concentrations (Collineau and Brunet, 1993; Sá et al., 1998; Terradellas et al., 2005; Zeri et al., 2011). The wavelet decomposition works similar to a spectrum, separating the harmonics in a signal while assigning a ‘wavelet power’ to them, which is proportional to the overall variance. The most important harmonics will be the ones with high wavelet power. Mathematically, the wavelet power is calculated from the convolution of a function (the wavelet mother) with portions of the signal. The wavelet mother chosen for this study was the Morlet (wavenumber 6), because it was shown to be appropriate to identify the variability of climatological data (Torrence and Compo, 1998). Wavelet analysis requires continuous time series. For this reason, gaps in the data were filled using linear interpolation. Because the wavelet power is calculated locally, the influence of interpolated gaps is easily identified in the scalograms. The wavelet power shown in the scalograms of Figures 5 and 6 (and Figures S1–S12) was calculated as the squared modulus of the wavelet coefficients, having units of signal variance.

4. Results, discussion, and conclusions

The concentration of some pollutants over the MASP is well below the standards (WHO) while others have been continuously surpassing the safe limits. The concentration of CO reached more than the limit of 9 ppm only in the beginning of the period analyzed here (1996–1997), except for two stations that are influenced heavily by heavy vehicle traffic (Congonhas and Cerqueira César). From 2004 to 2011, only 2 or 3 events of CO higher than
9 ppm were observed (Figure S1). For PM$_{10}$ (Figure S2), even wintertime peaks have been below the safe limit of 150 $\mu$g m$^{-3}$. The only station that deviated from these results is Cubatão (Figure S2(d)), where average concentrations are rarely below 70 $\mu$g m$^{-3}$. Cubatão has intense industrial activity associated with its chemical and petrochemical complex, and as a result it has the highest levels of pollution in the dataset. This is also reflected in the concentrations of SO$_2$ (Figure S3), with both stations in Cubatão frequently showing SO$_2$ above the 20 $\mu$g m$^{-3}$ limit. Finally, O$_3$ has been increasing in several stations and frequently reaching over the limit of 100 $\mu$g m$^{-3}$, creating concerns associated with this damaging pollutant (Figure S4).

The monthly averaged concentrations of CO and SO$_2$ (Figures 2 and 3) presented strong interannual variability, with peaks following minima and vice versa. The wintertime concentrations of SO$_2$ (Figure 3(a)) peaked in several cities in 2006 and later in 2008 with different amplitudes. These peaks and valleys during wintertime were also observed for other pollutants, including PM$_{10}$ (Figure S3) and O$_3$ (Figure S6). The number of frontal systems reaching the coast and the countryside (bars) helps to explain this variability. In general, a frontal system brings rainfall for several days, washing out pollutants from the air. Indeed, July of 2006 and 2008 had the lowest number of frontal systems and the highest values of mean monthly pollution concentration. The monthly concentrations of PM$_{10}$ decreased for January (Figure S5(b)) and are approximately constant when averaged for July (wintertime), responding strongly only to months with lower rainfall (lower number of frontal systems, Figure S5(a)).

Overall, a decrease in CO and SO$_2$ concentrations from 1996 to 2011 is evident for most of the stations. However, the decreasing trend is stronger for July (Figures 2(a) and 3(a)). For some locations (Osasco, Cerqueira César), CO decreased by about 50% from 1996 to 2011 while the station near the airport of Congonhas, a site strongly influenced by vehicles emissions, decreased from 4.7 to 1.5 ppm in the period, a change of almost 70%. Similar changes were observed for SO$_2$ (Figure 3), with largest reductions observed in winter compared to summer. For PM$_{10}$ and O$_3$ (Figures S5 and S6), a decreasing trend was observed only for summer in PM$_{10}$ (from 1996 to 2002). This trend could be associated with public policies enforced to reduce vehicular emissions (Carvalho et al., 2015).

On the other hand, the summertime concentration of O$_3$ has been increasing (Figure S6) since 2007, which could be associated with the increasing fleet of vehicles using ethanol, producing more precursors to O$_3$ formation, particularly aldehydes (Salvo and Geiger, 2014).
The wintertime concentrations for CO and SO$_2$ were averaged for all locations for each year (Figure 4), revealing three significant results: (1) three phases are evident for CO: a sharp decrease in average concentration from 1996 to 1998, followed by a steady phase, and another decrease by 2006–2007, (2) both average and spatial variability (indicated by lower error bars) in CO among stations separated by 100s of kilometers were lower at the end of the period, (3) in the 2000s, SO$_2$ concentration decreased from 2004 to 2005 and later from 2008 to 2009. The different phases observed in the two topmost panels (Figure 4) were likely associated with the changes in policies of air pollution (until ∼2005) and later by the widespread adoption of ethanol cars, discussed in more details by Andrade et al. (2015) and Carvalho et al. (2015). Here, we present some data of ethanol use (Figure 4(b) and (c)) to give context to the changes observed in the time series of pollutants. The decrease in concentrations of CO and SO$_2$ after 2004 was likely influenced by the increasing number ethanol fueled cars, which pollute less CO and SO$_2$, licensed each year (data for whole country), coupled with an increase in ethanol production in the state of São Paulo – which is responsible for more than 60% of ethanol production in Brazil (Goldemberg, 2007). Overall, the ethanol fleet increased from 20% in 2005 to 60% in 2011. The true causation, however, of the reductions observed in the data goes beyond the scope of this paper. To accomplish this, a detailed analysis of sources of pollutants over temporal and spatial scales is required.

The wavelet decomposition revealed the strongest and statistically significant harmonics or temporal scales from 1996 to 2011 (SO$_2$ measured at Congonhas airport, Figure 5, and at São Caetano do Sul, Figure 6. Other examples were included in Figures S1–S12.). As expected, the annual cycle is strong and significant, between 256 and 512 days of duration. Because the series are composed of daily averages, the influence of the diurnal cycle is not shown. However, the contours between 4 and 8 days are present from the start of the period until ∼2006–2007. This indicates that the concentrations are likely modulated in those scales by precipitation, horizontal advection, stability of the ABL, the solar radiation at the surface, or other effects. The results in Figures S7–S12 show...
a mixture of trends for some pollutants and cities. While the 4–8 days harmonic became less prevalent in Figures S7–S9, it was still strong and frequent for PM$_{10}$ (Figures S10–S12), modulating the high variance observed until 2011. The same result was found in another study for the city of Rio de Janeiro (Zeri et al., 2011). This variability was associated with the passage of frontal systems, which have a similar duration when they occur in the southeastern region of Brazil. While the dataset for Rio de Janeiro limited to 2 years, the longer time series of pollutants presented here made it possible to register a sudden change in the influence of this harmonic of 4–8 days of duration, becoming non-statistically significant after 2006–2007. The disappearance of this harmonic suggests a much weaker influence of the meteorological systems that reach the region, at least in time scales of several days, beyond the daily cycles. The daily cycle would still be influenced by the evolution of air temperature, humidity and wind speed, cycles influence by solar energy as well as by anthropogenic factors, such as traffic and industrial activity. In addition, the temporal resolution of this analysis (daily averages) makes it impossible to infer on short-lived spikes in concentrations (hours), beyond the acceptable limits determined by air quality agencies.

The patterns identified in the wavelet analysis are a result of the modulation of the variance by the harmonics. When the variance is reduced, the modulation loses significance and the patterns disappear from the wavelet plots. The reduction in both daily averages and variances of SO$_2$ and CO concentrations is obvious from the plots in Figures S1 and S4, with the exception of SO$_2$ in Cubatão panels S4(c) and S4(d). The sources of pollutants differ between locations, causing great differences in averages and variances between stations separated by a few kilometers. For example, São Caetano do Sul and Congonhas are separated by ~15 km, but the variance observed in the signal of SO$_2$ reduced from 2005 to 2006, in Congonhas, and later from 2007 to 2008, in São Caetano do Sul. As a result, the modulation with periods of 4–8 days identified by the wavelet lasted longer in São Caetano do Sul. Thus, the variance in the signals is a result of local sources and not induced by the harmonics. Finally, the harmonic of 4–8 days could be associated with low-pressure systems, as evidenced by the number of frontal systems reaching the state during July in Figures 2 and 3, or high pressure systems, leading to lower temperatures and reduced turbulent mixing, increasing concentrations of pollutants. A more detailed analysis using continuous meteorological data near the
stations should make a clear distinction between both influences.

Low levels of pollutants should be a target of public policies so that the MASP, and cities in general, become more resilient to the influence of meteorological systems on air quality. The consequence of ideal public policies is a reduction in the vulnerability of city dwellers to the presence of meteorological systems that disturb the lower atmosphere for days, trapping pollutants during cold inversions or spreading – by turbulence – dust deposited over the ground. Wavelet analysis is a helpful tool that identifies the harmonics in time series of pollutants. Future work using finer temporal resolutions (hours) should explore other harmonics associated with human or industrial activity, such as patterns of traffic of cars or industrial activity.

Acknowledgements

The authors are grateful to CETESB for sharing the dataset of pollutants; data can be accessed at http://ar.cetesb.sp.gov.br/qualar. The authors acknowledge the helpful comments from three anonymous reviewers as well as the assistance of C. J. Bernacchi with the language.

Supporting information

The following supporting information is available:

Figure S1. Time series of concentrations of CO (ppm). The standard of 99 ppm (maximum 8-h moving average) is marked with the dashed line.

Figure S2. Time series of concentrations of PM$_{10}$ ($\mu$m$^{-3}$). The standard of 150 $\mu$m$^{-3}$ (24-h mean) is marked with the dashed line.

Figure S3. Time series of concentrations of $O_3$ ($\mu$m$^{-3}$). The standard of 100 $\mu$m$^{-3}$ (maximum 8-h moving average) is marked with the dashed line.

Figure S4. Time series of concentrations of SO$_2$ ($\mu$m$^{-3}$). The standard of 20 $\mu$m$^{-3}$ (24-h mean) is marked with the dashed line.

Figure S5. Evolution of monthly averages of PM$_{10}$ ($\mu$g m$^{-3}$) from 1996 to 2011. Top: July and bottom: January. Bars denote the number of frontal systems reaching the coast (deep blue) and the countryside (light blue).

Figure S6. Evolution of monthly averages of $O_3$ ($\mu$m$^{-3}$) from 1996 to 2011. Top: July and bottom: January. Bars denote the number of frontal systems reaching the coast (deep blue) and the countryside (light blue).

Figure S7. Top: time series of the concentration of CO (ppm) for the station Congonhas; bottom: wavelet decomposition for the time series. The color scale is proportional to the series variance while bold contours enclose regions where the wavelet power is statistically significant, when compared to a random noise.

Figure S8. Top: time series of the concentration of CO (ppm) for the station São Caetano do Sul; bottom: wavelet decomposition for the time series. The color scale is proportional to the series variance while bold contours enclose regions where the wavelet power is statistically significant, when compared to a random noise.

Figure S9. Top: time series of the concentration of PM$_{10}$ ($\mu$g m$^{-3}$) for the station Congonhas; bottom: wavelet decomposition for the time series. The color scale is proportional to the series variance while bold contours enclose regions where the wavelet power is statistically significant, when compared to a random noise.

Figure S10. Top: time series of the concentration of PM$_{10}$ ($\mu$g m$^{-3}$) for the station São Caetano do Sul; bottom: wavelet decomposition for the time series. The color scale is proportional to the series variance while bold contours enclose regions where the wavelet power is statistically significant, when compared to a random noise.

Figure S11. Top: time series of the concentration of SO$_2$ ($\mu$g m$^{-3}$) for the station Cubatão; bottom: wavelet decomposition for the time series. The color scale is proportional to the series variance while bold contours enclose regions where the wavelet power is statistically significant, when compared to a random noise.

References

Andrade MF, Ynoue RY, Freitas ED, Todesco E, Vara Vela A, Ibarra S, Martins LD, Martins JA, Carvalho VSB. 2015. Air quality forecasting system for Southeastern Brazil. Frontiers in Environmental Science 3: 9, doi: 10.3389/fenvs.2015.00009

Angevine WM, Grimsdell AW, Hartten LM, Delany AC. 1998. The flatland boundary layer experiments. Bulletin of the American Meteorological Society 79: 419–431, doi: 10.1175/1520-0477(1998)079<0419:TBFLEx>2.0.CO;2.

Barbato E, de Arellano JV-G, Ouwersloot HG, Schröter JS, Donovan DP, Krol MC. 2014. Aerosols in the convective boundary layer: shortwave radiation effects on the coupled land-atmosphere system. Journal of Geophysical Research, [Atmospheres] 119: 5845–5863, doi: 10.1002/2013JD021237.

Bourrot C, Porti M-C, Taniguchi S, Bicó M, Bolza CE, Lotufo PA. 2005. A wintertime study of PAHs in fine and coarse aerosols in São Paulo city, Brazil. Atmospheric Environment 39: 3799–3811, doi: 10.1016/j.atmosenv.2005.02.054.

Cançado JED, Saldia PH, Pereira LAA, Lara LBL, Artaxo P, Martinelli LA, Arbex MA, Zanobetti A, Braga ALF. 2006. The impact of sugar cane-burning emissions on the respiratory system of children and the elderly. Environmental Health Perspectives 114: 725–729.

Carvalho VSB, Freitas ED, Mazzoli CR, Andrade MF. 2012. Avaliação da influência de condições meteorológicas na ocorrência e manutenção de um episódio prolongado com altas concentrações de ozônio sobre a região metropolitana de São Paulo. Revista Brasileira de Meteorologia 27: 463–474, doi: 10.1590/S0102-7786201200400009.

Carvalho VSB, Freitas ED, Martins LD, Martins JA, Mazzoli CR, Andrade MF. 2015. Air quality status and trends over the metropolitan area of São Paulo, Brazil as a result of emission control policies. Environmental Science & Policy 47: 68–79, doi: 10.1016/j.envsci.2014.11.001.

Castanho ADA, Artaxo P. 2001. Wintertime and summertime São Paulo aerosol source apportionment study. Atmospheric Environment 35: 4889–4902, doi: 10.1016/S1352-2310(01)00357-0.

Climanalise. 2005. Produtos Climanalise INPE/CPTEC. http://www.cptec.inpe.br/products/climanalise/ (accessed 3 March 2011).
Collineau S, Brunet Y. 1993. Detection of turbulent coherent motions in a forest canopy. Part I. Wavelet analysis. Boundary-Layer Meteorology 65: 357–379.

Daubechies I. 1992. Ten Lectures on Wavelets, Vol. 61. Society for Industrial and Applied Mathematics: Philadelphia, PA, 377 pp.

Fajersztajn L, Veras M, Barrozo LV, Saldiva P. 2013. Air pollution: a potentially modifiable risk factor for lung cancer. Nature Reviews Cancer 13: 674–678, doi: 10.1038/nrc3572.

Freitas E, Rozoff C, Cotton W, Dias PS. 2007. Interactions of an urban heat island and sea-breeze circulations during winter over the metropolitan area of São Paulo, Brazil. Boundary-Layer Meteorology 122: 43–65, doi: 10.1007/s10546-006-9091-3

Godoy MLDP, Godoy JM, Roldão LA, Soluri DS, Donagemma RA. 2009. Coarse and fine aerosol source apportionment in Rio de Janeiro, Brazil. Atmospheric Environment 43: 2366–2374, doi: 10.1016/j.atmosenv.2008.12.046.

Goldemberg J. 2007. Ethanol for a sustainable energy future. Science 315: 808–810.

Gonçalves FLT, Carvalho LMV, Conde FC, Latorre M, Saldiva PHN, Braga ALF. 2005. The effects of air pollution and meteorological parameters on respiratory morbidity during the summer in Sao Paulo City. Environment International 31: 343–349.

de Leon AP, Anderson HR, Bland JM, Strachan DP, Bower J. 1996. Effects of air pollution on daily hospital admissions for respiratory disease in London between 1987–88 and 1991–92. Journal of Epidemiology and Community Health 50: S63–S70.

Martins MHKB, Anazia R, Guardani MLG, Lacava CIV, Romano J, Silva SR. 2004. Evolution of air quality in the Sao Paulo Metropolitan Area and its relation with public policies. International Journal of Environment and Pollution 22: 430–440, doi: 10.1504/IJEP.2004.005679

de Miranda RM, de Fátima Andrade M, Worobiec A, Grieken RV. 2002. Characterisation of aerosol particles in the São Paulo Metropolitan Area. Atmospheric Environment 36: 345–352, doi: 10.1016/S1352-2310(01)00363-6

Oliveira AP, Bornstein RD, Soares J. 2003. Annual and diurnal wind patterns in the city of São Paulo. Water, Air and Soil Pollution: Focus 3: 3–15, doi: 10.1023/a:1026090103764

Sá LDA, Sambatti SMB, Galvao GP. 1998. Applying the Morlet wavelet in a study of variability of the level of Paraguay River at Ladario, MS. Pesquisa Agropecuaria Brasileira 33: 1775–1785.

Salvo A, Geiger FM. 2014. Reduction in local ozone levels in urban Sao Paulo due to a shift from ethanol to gasoline use. Nature Geoscience 7: 450–458, doi: 10.1038/Ngeo2144

Samet JM, Dominici F, Curriero FC, Coursac I, Zeger SL. 2000. Fine particulate air pollution and mortality in 20 US Cities, 1987–1994. New England Journal of Medicine 343: 1742–1749, doi: 10.1056/Nejm200012143432401

Schwartz J. 1996. Air pollution and hospital admissions for respiratory disease. Epidemiology 7: 20–28.

Sharma VP, Arora HC, Gupta RK. 1983. Atmospheric pollution studies at Kanpur – suspended particulate matter. Atmospheric Environment 17: 1307–1313, doi: 10.1016/0004-6981(83)90405-5

Silva Dias MF, Machado AJ. 1997. The role of local circulations in summertime convective development and nocturnal fog in São Paulo, Brazil. Boundary-Layer Meteorology 82: 135–157, doi: 10.1023/A:1000241602661

Terradellas E, Soler MR, Ferreres E, Bravo M. 2005. Analysis of oscillations in the stable atmospheric boundary layer using wavelet methods. Boundary-Layer Meteorology 114: 489–518, doi: 10.1007/S10546-004-1293-Y

Torrence C, Compo GP. 1998. A practical guide to wavelet analysis. Bulletin of the American Meteorological Society 79: 61–78, doi: 10.1175/1520-0477(1998)079<0061:Agwta>2.0.co;2

Zeri M, Oliveira JF, Lyra GB. 2011. Spatiotemporal analysis of particulate matter, sulfur dioxide and carbon monoxide concentrations over the city of Rio de Janeiro, Brazil. Meteorology and Atmospheric Physics 113: 139–152, doi: 10.1007/s00703-011-0153-9