The effects of air pollution and meteorological parameters on respiratory morbidity during the summer in São Paulo City


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Received 7 February 2004; accepted 12 August 2004

Abstract

Effects of meteorological variables and air pollutants on child respiratory morbidity are investigated during two consecutive summers (December–March 1992/1993 and 1993/1994) at the Metropolitan Area of São Paulo (MASP), Brazil. The MASP, with almost 17 million inhabitants, is considered the most populous region in South America. Due to warmer temperatures, increased rainfall and consequent low levels of air pollutants during the summer compared to winter, less attention has been paid to epidemiological studies during this season, especially in tropical urban areas such as São Paulo. In the present work, principal component analysis (PCA) is applied to medical end environmental data to identify patterns relating child morbidity, meteorological variables and air pollutants during the summer. The following pollutant concentrations are examined: SO2, inhalable particulate matter (PM10), and O3. The meteorological variables investigated are air temperature, water vapor (water vapor density) and solar radiation. Although low correlation between respiratory morbidity and environmental variables are, in general, observed for the entire dataset, the PCA method indicates that child morbidity is positively associated with O3 for the 1992/1993 summer. This pattern is identified in the third principal component (PC3), which explains about 19% of the total variance of all data in this summer. However, the 1993/1994 summer shows a more complex association between both groups, suggesting stronger ties with meteorological variables. Marked changes in synoptic conditions from the end of January to end of March of the 1993/1994 summer seem to have played an important role in modulating respiratory morbidity. A detailed examination of meteorological conditions in that period indicates that prefrontal (postfrontal), hot (cold) and dry (wet) days favored the observed decrease (increase) of respiratory morbidity.

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Keywords: Principal component analysis; Air pollution; Respiratory diseases; Children morbidity; Atmospheric variables

1. Introduction

Air pollution and its impact on human health have been considered a serious problem in urban areas. Since the beginning of the last century, many events of air pollution have been associated with increase in mortality. Some examples are the Meuse Valley in 1930 (Firket, 1931), Donora in 1948 (Ciocco and Thompson, 1961) and the most famous, London in 1952 (Logan, 1953).

Increase in morality has also been related to non-episodic events of air pollution, even for levels below of the air quality standards (Pope et al. 1992; Schwartz and Dockery, 1992; Bascom et al., 1996). In terms of morbidity, air pollution has been related to a decrease in pulmonary function (Moseholm et al., 1993), increase in respiratory symptoms, attacks of asthma and chronic bronchitis, and school absences (Brabin et al., 1994). White et al. (1994) analyzed these events linking them to high ozone levels.
Pope and Kalkstein (1996) analyzed Utah Valley mortality data using synoptic categorization to account for the weather variability. Their results suggest a statistically robust relationship between cardiopulmonary mortality and PM$_{10}$. These works are also generally linked to wintertime or cold weather conditions.

On the other hand, Chestnut et al. (1998) examined mortality for summertime associated with hot-weather episodes and reported estimates of average hot-weather-related mortality in 44 U.S. metropolitan areas. Their results indicate the existence of geographic patterns: the highest hot-weather-related mortality rates are in northern metropolitan areas, although the average summer temperatures are higher in the southern metropolitan areas. The authors also show that the variability in minimum daily summer temperatures may be one of the most important factors for the hot-weather-related mortality rates. In addition, this study also suggests that the availability of air conditioning, standards of living and housing quality contributed to differences in hot-weather-related mortality.

Kalkstein (1991) evaluated the climatic impact on cardiovascular mortality due to high summer temperatures and air pollution during 10 years in St. Louis (USA) using cluster analysis and principal component analysis. This study indicated a distinction between pollution-induced mortality and weather-induced mortality. The author also showed that 1 out of 10 summer air masses categories found in St. Louis related above mean mortality to consecutive days with hot and oppressive temperature. Kalkstein (1998) emphasized the importance of the links between heat waves and health and proposed some criteria for warning systems. In another research, Smoyer et al. (2000) presented the relationships during summertime between extreme weather and high pollution episodes (ozone and total suspended particles) and mortality for Birmingham (Alabama) and Philadelphia (Pennsylvania). They showed strong relationships between summer weather and mortality, while the role of the pollution was less clear.

Significant associations between air pollution and mortality in children have been also observed in São Paulo (Böhm et al., 1989; Saldiva et al., 1992; Lemos et al., 1996), the focus of the present study. Similar relationships have been found with regard to morbidity (Braga et al., 2000), especially during the wintertime.

The metropolitan São Paulo climate is classified as subtropical, according to Köppen classification, with summer mean daily temperature between 21 and 23 °C (December–March). This region is also under influence of the South America monsoon regime such that approximately 70% of the total annual rainfall (1300 mm) occurs from October to March (e.g. Liebmann et al., 2001). One important characteristic of the summer monsoon regime in São Paulo is the presence of stationary systems responsible for persistent rainfall and cloudiness (Carvalho et al., 2004). Although cold outbreaks caused by the penetration of extra-tropical (polar) masses are uncommon during the summer season, some significant drop in temperature is occasionally observed during the passage of extra-tropical (polar) anticyclones. Such environmental situations can modulate pollutant concentrations and together with temperature and humidity variations may affect human health, particularly for children and elderly people.

The objective of the present paper is to examine the role of weather and air pollutants in increasing child respiratory morbidity during the summer in São Paulo. Principal component analysis is used with the purpose of identifying distinct patterns of respiratory morbidity that occur in this region and the relative importance of meteorological variables and pollutant concentrations. Periods with significant above/below average seasonal respiratory morbidity are also examined in detail along with variations of weather and pollutant concentrations.

2. Data

In this study, we use daily records of respiratory admissions of children younger than 13 years old in 80 hospitals in two periods: December 22, 1992 to March 20, 1993 and December 22, 1993 to March 20, 1994. The Health State Secretary provided these data. Those hospitals are located in distinct regions over the metropolitan area of São Paulo (MASP) and receive support from the public health system. Thus, our sample is mostly representative of the poorest segment of the population that does not have private medical care assistance. Respiratory hospital admissions are classified according to the 9th International Convention of Diseases.

Daily records of PM$_{10}$, SO$_2$ and O$_3$ are obtained from the State Air Pollution Controlling Agency (CETESB). Pollutant concentrations are obtained from 24-h average (starting at 4:00 P.M. of the preceding day) for SO$_2$ (eight stations) and PM$_{10}$ (eight stations). O$_3$ data are the daily maximum from eight stations. The spatial distribution of the stations is shown in Fig. 1.

Daily mean air temperature (TMEAN—°C), daily mean water vapor density (WMEAN—g m$^{-3}$) and solar radiation (RAD—W m$^{-2}$) used in the PCA analyses are obtained from Parque Estadual das Fontes do Ipiranga meteorological station (Fig. 1), which is considered representative of the MASP. Three-day moving average is applied to meteorological and pollutant variables as suggested in Braga et al. (2000). This is an assumption to take into account the average time-lag between the beginning of the respiratory disease and child morbidity in hospitals. It is important to notice that the moving average was applied to the entire dataset, except RM. The RM data are normalized for the period to account for the decrease of morbidity during weekends and holidays.

The synoptic conditions were obtained from NCEP reanalysis and Brazilian Marine Charts from the chosen...
period. The air pressure values were used in the statistical analysis in order to classify the synoptic categories in three distinct categories: stationary precipitating systems (typical from the monsoon regime in this region) which maintain precipitation and temperature relatively uniform, extratropical anticyclones (important for abrupt changes in temperature and, therefore, for child morbidity) and subtropical anticyclones (which characterize warm and dry periods).

To examine relationships between synoptic weather variations and child morbidity, we also used outgoing long-wave radiation (OLR) daily anomalies (the annual and semi-annual cycles are removed) with 2.5° × 2.5° latitude and longitude spatial resolution. The OLR is a satellite product provided by the Climate Diagnostic Center, National Oceanic and Atmospheric Administration (CDC/NOAA). The OLR anomalies are used as a proxy in tropical areas with low topography to investigate the presence of cloud and precipitation. Negative (positive) OLR anomalies are related to the presence of cloudiness (clear skies) and are likely related to enhancement (suppression) of precipitation. Further details about the interpretation of OLR fields will be discussed in the next sessions.

3. Methodology

3.1. Principal component analysis (PCA)

PCA is a multivariate technique in which a number of related variables are transformed in a smaller set of uncorrelated variables. The technique rewrites the original data matrix into a new set of principal components (hereafter PC) that are linearly independent and ordered by the amount of the variance of the original data they explain (e.g. Jackson, 1991). The advantage of using PC is that the PC method finds a new set of uncorrelated variables that describe the principal variability or joint behavior of the dataset. Geometrically, this new set of variables represents a principal axis rotation of the original coordinate axes of the variables around their mean. It is essentially this process that allows finding patterns of correlation between the new axe and the original variables, not promptly identified in the analysis of the correlation matrix (Jackson, 1991).

In the present work, PCA is applied with the purpose of investigating patterns of variability relating RM, air pollution and meteorological variables and separating them in distinct independent factors. The input data for the PCA
is therefore a time series represented by the correlation matrix:

\[ M_x = \begin{bmatrix}
    x_{11} & x_{12} & \cdots & x_{1p} \\
    x_{21} & x_{22} & \cdots & x_{2p} \\
    \vdots & \vdots & \ddots & \vdots \\
    x_{m1} & x_{m2} & \cdots & x_{mp}
\end{bmatrix} \]

where \( x_{ij} \) are the normalized variables. The number of variables \( p \) is equal to 7 (RM, RAD, TMEAN, WMEAN, SO2, PM10, and O3) and the number of events \( m \) is equal to 99 (i.e., the number of days in each summer). The \( M_x \), yields \( p \) eigenvalues \( \lambda_j \), each one being related to a corresponding eigenvector with \( p \) elements. They represent a new base such that each PC explains the variance according to the respective eigenvalue.

4. Results and discussion

4.1. Synoptic overview

The 1992/1993 summer presents an average temperature of 21.6 °C, slightly colder than the 1993/1994 summer, with average temperature ~22.3 °C. Both summers can be considered within one standard deviation from the climatological mean monthly temperatures (21.8 ± 0.5 °C, December to March) from the last 30 years (1973–2002). It is important to recall that summer daily variability of meteorological variables, such as air temperature and humidity, are less pronounced comparatively to the winter period. Fig. 2 shows the frequency of synoptic events based on the Brazilian Marine synoptic charts. It indicates higher frequency of anticyclones during the 1993/1994 comparatively to the previous one (Fig. 2). It is important to recall that summer daily variability of meteorological variables, such as air temperature and humidity, are less pronounced comparatively to the winter period.

4.2. The 1992/1993 summer

The PC coefficients obtained for the 1992/1993 summer are shown in Table 1. These coefficients (hereafter referred to as weights) can be interpreted as the correlation of each PC with each of the original variables. For PC1, which explains ~29% of total variance, the air pollutants (SO2 and PM10) and weather variables (TMEAN and WMEAN) are strongly associated whereas the respiratory morbidity (RM) presents a very low positive weight (0.05). The PC2, which explains ~27% of total variance, shows RAD (0.94) associated with O3 (0.63). On the other hand, the PC3, which explains ~17% of the total variance, indicates that RM has a high weight on this component (0.81) with a positive association with O3 (0.37) and negative with TMEAN (0.47) and WMEAN (0.26). The increase of RM in association with decrease of water vapor density and temperature indicates the influence of atmospheric conditions for child morbidity. Nevertheless, the PC3 for the 1992/1993 summer suggests that the tropospheric O3 played a more important role in increasing child RM than any other pollutant or atmospheric variable considered here. This is consistent with recent studies (Wang et al., 2003; Varotsos et al., 2003) that pointed out the key importance of tropospheric O3 levels and spatial distribution for human health. It is worth mentioning that the tropospheric O3 has high temporal variability during the summer months in São Paulo (Massambani and Andrade, 1994).

4.3. The 1993/1994 summer

Table 2 presents the PC weights for the 1993/1994 summer, which indicate some remarkable differences in relation to the 1992/1993 summer. For instance, the PC1, which explains ~31% of the total variance, shows a strong negative association between RM (−0.73) and TMEAN (0.71) and water vapor density (0.88). The relatively higher frequency of extra-tropical anticyclones during this summer comparatively to the previous one (Fig. 2) is likely the cause of the stronger negative association between RM and TMEAN. The PC2, which explains ~25% of total variance, shows no indication of any significant weight on RM (0.11).
but a strong association between PM10 (0.80) and SO2 (0.92). The PC3, which explains ~18% of total variance, shows a positive association between RAD (−0.97) and O3 (−0.37). The synoptic condition impact during this summer is investigated in the next section.

4.4. The role of synoptic conditions during 1993/1994 summer

To understand the differences of patterns shown in the PC analysis, we examined the time variability of RM (Fig. 3) in the two summers. RM fluctuations are clearly less pronounced during the 1992/1993 (Fig. 3a) than during the 1993/1994 summer (Fig. 3b). For instance, during the 1993/1994 summer, there are two distinct local trends of RM: a negative trend is observed approximately from mid-January 1994 to the beginning of February 1994 followed by a positive trend from mid-February to mid-March 1994 (Fig. 3b).

To examine the role of synoptic conditions on the RM behavior during 1993/1994 summer, we show the time variability of TMEAN, WMEAN and O3 during the period of maximum variability of RM, that is, from January 26 to

Table 2
Principal component analysis for summer 1994, with 3-day moving average (Varimax raw rotation)

<table>
<thead>
<tr>
<th></th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAD</td>
<td>0.02</td>
<td>0.09</td>
<td>−0.97</td>
</tr>
<tr>
<td>TMEAN</td>
<td>0.71</td>
<td>0.40</td>
<td>−0.37</td>
</tr>
<tr>
<td>WMEAN</td>
<td>0.88</td>
<td>0.25</td>
<td>0.09</td>
</tr>
<tr>
<td>SO2</td>
<td>0.01</td>
<td>0.92</td>
<td>0.00</td>
</tr>
<tr>
<td>PM10</td>
<td>0.38</td>
<td>0.80</td>
<td>−0.23</td>
</tr>
<tr>
<td>O3</td>
<td>0.47</td>
<td>−0.06</td>
<td>−0.35</td>
</tr>
<tr>
<td>RM</td>
<td>−0.73</td>
<td>0.11</td>
<td>0.08</td>
</tr>
<tr>
<td>Expl. Var.</td>
<td>2.16±0.32</td>
<td>1.74±0.26</td>
<td>1.27±0.19</td>
</tr>
<tr>
<td>Prp. Totl.</td>
<td>0.31</td>
<td>0.25</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Fig. 3. Respiratory morbidity variability during two summers (December 22–March 20): (a) 1992/1993; (b) 1993/1994.

Fig. 4. Temporal variability of atmospheric parameters and air pollutants for the period with high RM variability (January 26–March 23, 1994): (a) Mean daily air temperature (TMEAN) in °C; (b) inhalable particulate matter (PM10) in g m⁻³; (c) ozone (O3) in ng m⁻³; (d) mean water vapor density in g m⁻³ (WMEAN). A cubic spline fit (heavy continuous line) is adjusted to each time series to show local trends in the period.
March 23 (Fig. 4). The period with negative trend of RM is observed along with a positive trend of TMEAN (Fig. 4a), PM$_{10}$ (Fig. 4b) and O$_3$ (Fig. 4c), and a negative trend of WMEAN (Fig. 4d). This observation suggests that the increase in RM was related to the cooling and humidity increase of the atmosphere due to the passage of a cold front.

To further investigate the hypothesis of the role of weather change on RM variations, the OLR anomalies were averaged for the approximate period with negative RM trend (January 22–February 14; Fig. 5, left) and positive RM trend (February 20–March 20; Fig. 5, right). Negative (positive) OLR anomalies are indicative of the enhancement (suppression) of clouds and precipitation. Therefore, the patterns shown in Fig. 5 (left) indicate that dominant positive OLR anomalies northeastward of MASP and negative southwestward of the area were related to the period with negative RM trend. The pattern of mean OLR anomalies for this period is, therefore, related to dominant warm prefrontal synoptic conditions. The average northwest wind direction during this period is consistent with this observation (not shown). Positive trends of PM$_{10}$ (Fig. 4b) and O$_3$ (Fig. 4c) are probably a consequence of the decrease in precipitation during this period.

On the other hand, the following period with positive RM trend is observed in association with negative trends of TMEAN (Fig. 4a), PM$_{10}$ (Fig. 4b) and O$_3$ (Fig. 4c), and positive trends of WMEAN (Fig. 4d). Average negative OLR anomalies near the MASP (Fig. 5 right) and average southwest to southeast wind directions (not shown) indicate dominant postfrontal synoptic conditions during this period. The negative trends of the air pollutant concentrations seem consistent with the increase of precipitation induced by the passage of a frontal system. The correlation coefficient between TMEAN and RM for the entire period considered in Fig. 4 is equal to $-0.39$ and considered statistically significant at 5% significance level.

5. Conclusions

The investigation of links between respiratory admissions in hospitals in the metropolitan area of Sao Paulo in two consecutive summers and environmental variables suggests the existence of complex and possibly non-linear relationships that can vary significantly from one summer to another.

During the 1992/1993 summer, there is a positive association between O$_3$ and morbidity. This is consistent with previous studies that considered observations for the whole year (i.e., with no seasonal separation) in the Sao Paulo Metropolitan area (Saldiva et al., 1994, 1995; Lin et al., 2003; Pereira et al., 1998) and also with results obtained in other regions of the globe (e.g. White et al., 1994; Smoyer et al., 2000). There is no clear association with other variables such as air temperature and water vapor density.

On the other hand, in the 1993/1994 summer, there are clear, independent and distinct patterns associating RM with temperature and water vapor density, as indicated by the PC analysis. In addition, this summer noticeably shows two opposite trends of RM that evidence the role of synoptic conditions in modulating this variable.

Although in tropical regions during the summer daily variations of temperature are in general less pronounced comparatively to winter, child RM may be dependent on dominant synoptic conditions. Our results indicated that during a summer with smaller contrasts in temperature and water vapor density (e.g. the 1992/1993 summer), links between RM and air pollution (mainly O$_3$) are more likely to be observed. Nonetheless, under significant contrasts of synoptic conditions (e.g. 1993/1994 summer), a stronger relationship between weather variables (air temperature and water vapor density) and RM can occur and the role of pollutants is minimized or unclear. Smoyer et al. (2000) support these results since they present strong relationships between summer weather and mortality, whereas the role of the pollution is less clear.

Acknowledgements

Dr. Gonçalves thanks the support of CAPES and CNPq. Dr. Carvalho acknowledges the financial support of CNPq and FAPESP (Proj. 01-13154-9). Dr. Latorre thanks the financial support of CNPq. The authors thank CETESB, the Brazilian Health State Secretary, the IAG, and CDC/NOAA for providing data.
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