Fog, Temperature and Air Quality Over the Metropolitan Area of São Paulo: a Trend Analysis from 1998 to 2018

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Received: 29 July 2020 / Accepted: 9 October 2020 / Published online: 21 October 2020
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Abstract This study investigates the long-term development of fog occurrences in the Metropolitan Area of São Paulo (MASP). Specifically, it analyzes the roles of meteorological and air quality parameters as potential drivers for fog formation. A dataset reaching back to the year 1933 shows that the overall trends of the annual fog occurrences (AFO) coincide with those of the annual mean temperature. Air quality data have been available since 1998, allowing us to perform a statistical analysis of the contributions of meteorology and air quality to AFO for the period from 1998 to 2018. The logistic regression model shows that the binary dependent variable (daily fog occurrence, FO) is explained by its independent predictors PM₁₀, relative humidity (rH), and daily minimum temperature (T_{min}), in that order. FO was not found to be significantly influenced by atmospheric pressure (aP) and nitrogen oxides (NO_x). While the influence of SO₂ was minor and associated with less confidence, it was negative. Potential causes for these surprising results are discussed. We conclude that the parameters PM₁₀, rH, and T_{min} are significant drivers of fog formation in the MASP, whereby the total

explanatory power of the drivers for the dichotomous variable FO is 16%.

Keywords Air quality · Particulate matter · Climate change · Urban heat island · Logistic regression model

1 Introduction

The Metropolitan Area of São Paulo (MASP) is one of the largest urban agglomerations in South America and is considered to be the most important socioeconomic region in the southeast of Brazil. The area of the MASP extends over 7945 km², and its estimated population of 21.5 million citizens is distributed over 39 conurbated municipalities, including São Paulo City, which is the most densely built and populated city (over 8000 inhabitants km²) in the country (EMPLASA 2017).

The MASP lies close to the Tropic of Capricorn (23° 33' S, 46° 39' W), 80 km from the Atlantic Ocean, on a plateau at an altitude between 700 and 1000 m above mean sea level (MSL). Its climate is classified as humid subtropical (Cwa according to the Köppen scale) and characterized as having humid summer and dry winter seasons (Peel et al. 2007). The local weather is strongly influenced by sea and land breezes, by topographic features, and by interactions with urban heat island (UHI) effects (Vemado et al. 2016).

A meteorological phenomenon that is especially relevant for cities is fog, as incidences of fog directly affect ground, air, and sea transport by impairing the visibility and thus raising the likelihood of accidents

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(Vasconcellos et al. 2018). Fog is a meteorological phenomenon defined by conditions of horizontal visibility below 1 km on the ground as caused by hydrometeors (WMO 2017). Fog, which is a cloud with ground contact, typically has a liquid water content of $0.1\text{--}0.2\text{ g m}^{-3}$ and droplet sizes around $10\text{-}\mu\text{m}$ diameters. In comparison to elevated clouds, fog is usually much more concentrated with respect to air pollutants, because particulate and gaseous emissions from the surface have a more direct impact on fog chemistry than on the chemistry of higher clouds (Seinfeld and Pandis 2006).

Moreover, fog droplets interact directly with the incoming solar radiation, on the one hand through reflection, which increases the albedo, and on the other hand through absorption, which results in heating and increased latent heat fluxes within the fog layer (Boucher et al. 2013). Therefore, fog impacts the local climate. For example, Hartmann et al. (2013) state that the decline in the frequency of fog events in European cities has led to an increase in direct solar radiation at the ground and may, thus, be partially responsible for increased local warming effects.

In the time period between 1933 and 2008, the frequency of fog in the MASP was observed to decrease (Gonçalves et al. 2008). Thus, the goal of the current study is to prove whether the observed trend continued from 2008 through 2018, and, more importantly, determine what caused the observed overall trend. Gonçalves et al. (2008) suggested that regional warming led to the observed decrease of fog. Similarly, Da Rocha et al. (2015) also argue that regional processes account for the occurrence of fog in the MASP, but they suspect radiative rather than advective processes. However, other studies have suggested that both global warming and an increase in air quality have been driving observed decreases in fog at various sites worldwide, including the MASP (Vautard et al. 2009; Klemm and Lin 2016). Therefore, for the MASP, we will analyze the trends of fog in conjunction with the trends of meteorological and air quality parameters.

The main source of air pollutants in the MASP is street-traffic tailpipe emissions, caused by the city's over 7 million vehicles. Other sources are aviation, wood burning emissions from restaurants, construction and demolition, recovery and maintenance of outdoor road surfaces, domestic waste burning, as well as advection of pollutants from distant industrial activities, from biomass burning in peripheral urban areas, and from distant fires in the São Paulo State, Central Brazil,

and the Amazon rainforest (Kumar et al. 2016). The Environmental Agency of São Paulo (Companhia Ambiental do Estado de São Paulo - CETESB) has monitored the MASP's air quality and traffic emissions since 1998, and in the last decade, several studies have concluded that although the vehicle fleet has increased by more than 100%, most vehicular emission levels have decreased due to a series of implemented laws and regulations for tailpipe emissions and fuel blends (CETESB 2016; Silveira et al. 2015).

We will apply statistical modeling to develop an overview of whether fog formation is influenced by the air pollutants SO_2 , NO_x , and PM_{10} (acting as potential cloud condensation nuclei) as well as by the daily minimum temperature ($T_{\min}$), relative humidity (rH), and atmospheric pressure (aP). We make use of air quality data retrieved by CETESB and meteorological data provided from the Institute for Astronomy and Geophysics from the University of São Paulo (IAG/USP).

2 Material and Methods

We employed two different datasets covering two different research periods. Dataset_1 covers the 86-year period from 1933 until 2018. It contains the annual mean air temperature (AMT) and the annual fog occurrence (AFO). Both the air temperature and the fog occurrence were continuously measured, and the respective data were extracted from the database of the IAG/USP.

The second dataset (Dataset_2) covers the 21-year period from 1998 through 2018. The period for Dataset_2 is much shorter than that of Dataset_1, but it contains, in addition to AMT and AFO, air quality data (SO_2 , NO_x , and PM_{10}) as routinely monitored by CETESB and further meteorological data (rH, aP) as provided by the IAG/USP.

2.1 Meteorological Data

The meteorological data (air temperature, relative humidity, atmospheric pressure, fog occurrence) were measured by the IAG/USP at their site on the Água Funda Park, 800 m above MSL and at $23^\circ 39' 05.2''\text{ S}$, $46^\circ 37' 23.4''\text{ W}$. The area itself (almost 750 ha) and its surroundings, especially the vegetation, did not change much since the 1930's. Dataset_1 was used to compare trends of AMT with trends of AFO in order to provide

insight into the development of the two parameters over a very long time period. A similar study by Gonçalves et al. (2008) on the same dataset, though for a shorter period, documented an increase of AMT and a synchronous decrease of AFO.

For the analysis of Dataset_2, we also employed the dew point temperature to calculate the relative humidity. Overall, the daily minimum air temperature ($T_{\min}$), the daily mean relative humidity (rH), and the daily mean atmospheric pressure (aP) were used to analyze potential correlations with fog occurrence and air quality parameters. Daily data on fog occurrence (FO) was available as a binary-coded variable. The variable describes whether, on a given day, a fog occurrence was sighted or not (yes = 1; no = 0).

2.2 Air Quality Data

Data on air quality from 1998 until 2018 was downloaded directly from the São Paulo State Government's (CETESB) website and added to Dataset_2. The dataset is quality checked according to the new state air quality standards established by State Decree No. 59.113 from 2013-04-23 (CETESB 2016). Based on hourly data, we calculated the daily medians of the concentrations of SO_2 , NO_x , and PM_{10} , as measured by 26 automatically monitoring stations in the MASP (Table 1). These stations are scattered through the most densely populated areas of the MASP, strategically installed in areas of heavy traffic and close to public places such as schools, hospitals, and parks, respectively (Fig. 1). We trust that the median of these stations is the best estimate of the overall air pollution in the MASP at a given time. To use either one single station or a group of stations would introduce issues such as missing data, gap filling, and potential overrepresentation of specific station types over others.

The monitoring of the parameters started mostly in 1998, and there is no inconsistency in the dataset. Specifically, there is no gap in the air pollutants' time series, because there was no malfunction of all stations at the same time and the median could be computed for each time step. The $\text{PM}_{2.5}$ concentration was not used in this analysis because there are very large gaps (up to over 5 years) in the data set.

2.3 Data Analysis

Analysis of Dataset_1 is descriptive in nature, as we investigated temporal trends of AMT and AFO from 1933 through 2018 over the MASP. One aim of our study was to determine whether the corresponding trends of the two parameters continued or changed since 2008.

The analysis of Dataset_2 was focused on studying the importance of meteorological and air quality parameters as drivers of fog formation in the MASP. We employed binary logistic regressions, in which the emergence of a dependent, binary variable is linked with several predictor variables. The dichotomous parameter FO was defined as the dependent variable. The meteorological parameters ($T_{\min}$, rH, aP) along with the air quality parameters (SO_2 , NO_x , PM_{10}) were metrically scaled and processed as centered, standardized, independent variables acting as predictors in our model. We employed the "Enter" mode as our analysis method, meaning that all independent variables are analyzed equally, without discarding variables that exceed the significance level ($p = 0.05$).

2.4 Logistic Regression

The equation of the multivariate binary logistic regression is generally defined as follows:

$$P(Y) = \frac{e^{B_0 + B_1 * X_1 + B_2 * X_2 + B_n * X_n}}{1 + e^{B_0 + B_1 * X_1 + B_2 * X_2 + B_n * X_n}} \quad (1)$$

with P being the probability with values between 0 and 1. A statistical model can be formulated using Eq. 1, the predictors X_n (first column in Table 2), and the variables B_n (second column in Table 2) to predict the probability of fog occurrence. For the statistical significance (p value) of the predictors (column "Sig." in Table 2), the critical value was defined as $p \geq 0.05$.

3 Results and Discussion

3.1 Results Dataset_1 (1933–2018)

Figure 2 shows the time series of the annual mean air temperature (AMT) and the annual fog occurrence (AFO) in the period from 1933 through 2018. It clearly depicts an increase of the AMT and a decrease of the

Fig. 1 Section of Southern Brazil with the metropolitan area of São Paulo (MASP, bold white boundary line). CETESB stations are indicated with their numbers (Table 1). The blue dot with “M” shows the IAG/USP monitoring site. Sources: Esri, DigitalGlobe,

GeoEye, Earthstar geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, IBGE, CETESB, DataGeo and the GID User Community

AFO over this period. The lowest AMT (16.8 °C) was registered in 1933. Since then, a rather homogeneous increase of AMT was observed. Exceptionally high temperatures were recorded in 2002 (20.4 °C) and in 2015 (20.3 °C). The linear trend of AMT over the entire time period is $d\text{AMT}/dt = 0.0356 \text{ }^{\circ}\text{C year}^{-1}$; the coefficient of determination is $R^2 = 0.794$.

The AFO time series are much less homogeneous than that of AMT. For example, there is a period of rather high AFO (> 158) from 1973 through 1979 with its local maximum of 207 in 1978. Nevertheless, an overall decrease of AFO is evident since its first registration in 1933. The presumption of a linear trend for the entire timeline yields a yearly decrease of $d\text{AFO}/dt = -1.159 \text{ year}^{-1}$ ($R^2 = 0.4356$). The 95% confidence interval of the slope $d\text{AFO}/dt$ is between -1.446 year^{-1} and -0.873 year^{-1} , the overall decrease of fog occurrence thus convincing.

The results of Dataset_1 exhibit a continuation of the trends previously described by Gonçalves

et al. (2008). While the AMT continues its upward trend, the AFO continues to drop. The reasons for both trends in Dataset_1 are most likely related to global climate change and regional land use change, especially deforestation and urbanization. The almost tenfold growth of the population since the 1930s (Brazilian Institute of Geography and Statistics (IBGE) 2011) was accompanied by an increase in impervious surface area in the MASP (Freitas et al. 2007). This led to a change of the runoff regime and to a change of the meso- and microclimates in the MASP, specifically to the formation of urban heat islands (UHI) (Vemado et al. 2016). In addition, anomalies in the sea surface temperature (SST) of the Atlantic Ocean have been mentioned as potential drivers of the increase of AMT and the decrease of AFO (Gonçalves et al. 2008). Given the positive trend of the AMT in the MASP, it will likely continue to increase, and AFO trends will continue to decrease.

Table 1 CETESB stations in the metropolitan area of São Paulo, monitored pollutants, and launch dates

	Station name	PM ₁₀	NO _x	SO ₂	Launch date
1	Capão Redondo	X	X	—	01.09.2012
2	Carapicuíba	X	X	—	27.02.2012
3	Cerqueira César	X	X	X	01.01.1998
4	Cid.UniversitáriaUSP-Ipen	—	X	—	01.01.1998
5	Congonhas	X	X	X	01.01.1998
6	Diadema	X	—	—	01.01.1998
7	Guarulhos-Paço Municipal	X	X	—	27.02.2012
8	Ibirapuera	*	X	*	03.01.1998
9	Interlagos	X	X	X	27.02.2012
10	Itaim Paulista	X	X	—	03.07.2012
11	Itaquera	*	*	—	09.08.2007
12	Marg.Tietê-Ponte dos Remédios	X	X	X	01.09.2012
13	Mauá	X	X	—	01.01.1998
14	Mooca	X	—	—	03.01.1998
15	Nossa Senhora do Ó	X	—	—	01.01.1998
16	Osasco	X	X	X	01.01.1998
17	Parelheiros	X	X	—	
18	Parque D. Pedro II	X	X	*	01.11.2004
29	Pinheiros	X	X	X	01.09.1999
20	S. André-Capuava	X	—	—	01.01.1998
21	S. André-Paço Municipal	X	—	—	23.06.2009
22	S. Bernardo-Centro	—	X	—	02.04.2014
23	Santana	X	—	—	01.01.1998
24	Santo Amaro	X	—	—	09.06.2009
25	São Caetano do Sul	X	X	X	13.12.2007
26	Taboão da Serra	X	X	—	01.01.1998

(X) Monitored parameter.

(*) Deactivated monitoring. Historic data only.

(—) Not monitored parameter.

Data source: CETESB air quality monitoring network [2000–2018] (<http://www.cetesb.sp.gov.br/ar/qualidade-do-ar/32-qualar>)**Table 2** Result of the logistic regression

Predictors = X _n	B	S.E.	Sig.
T _{min}	− 0.382	0.033	0.000
aP	0.021	0.030	0.483
rH	0.587	0.039	0.000
PM ₁₀	0.828	0.053	0.000
NO _x	− 0.018	0.044	0.678
SO ₂	− 0.117	0.039	0.003
Constant	− 1.628	0.035	0.000

Yet, long-term countermeasures have been proposed. For example, planting suitable trees in the streets may lead to ground shading, cultivating green areas will enhance evapotranspiration, and installing solar panels on facades will help absorb radiation to convert it into electric energy (Johansson et al. 2013). In general, it appears that the local governments have set their focus on climate change mitigation measures. The municipality of São Paulo was the first city of Brazil to establish a “Climate Law” to comply with the goals of the UNFCCC (Prefeitura da Cidade de São Paulo 2012). This law was sharpened in 2018, setting measures to reduce greenhouse gas emissions from the public

Fig. 2 Annual mean temperature (black) and annual fog occurrence (blue) in the MASP from 1933 through 2018. Dotted lines show linear trends

transport sector as well as from public waste management (Prefeitura da Cidade de São Paulo 2018). In the third quarter of 2019, the council of São Paulo ratified the “Plan of Climatic Action”, the main strategy of which is to operate the city in line with the commitments of in the Paris Agreement (Prefeitura da Cidade de São Paulo 2020). Considering the socioeconomic influence of the municipality of São Paulo in the MASP, surrounding municipalities will likely follow its example.

3.2 Results Dataset_2 (1998–2018)

Figure 3 shows the annual median concentrations of the air pollutants PM_{10} , NO_x , and SO_2 between 1998 and 2018 in the MASP. The median concentrations exhibit a pronounced decreasing trend. The highest median of SO_2 occurred in 2000 at about $42 \mu g m^{-3}$, while the lowest ($5.2 \mu g m^{-3}$) was recorded from 2015 through 2018; the negative linear trend of SO_2 is $dSO_2/dt = -1.980 \mu g m^{-3} year^{-1}$ ($R^2 = 0.8927$).

Regarding NO_x , its highest median concentration ($59 \mu g m^{-3}$) was registered in 2001 and its lowest concentration ($19 \mu g m^{-3}$) in 2018; the negative linear trend is $dNO_x/dt = -1.812 \mu g m^{-3} year^{-1}$ ($R^2 = 0.856$). The highest median concentration of PM_{10} ($43 \mu g m^{-3}$) was recorded in 1998, whereas the lowest concentration ($22 \mu g m^{-3}$) occurred in 2017; its negative linear trend is $dPM_{10}/dt = -0.957 \mu g m^{-3} year^{-1}$ ($R^2 = 0.808$). Sulfur dioxide shows the strongest negative trend, followed by the trends of NO_x and PM_{10} .

According to CETESB, since industrial growth was limited the main source of atmospheric pollutants in the MASP has been vehicle emissions (78% of NO_x , 43% of SO_x , and 40% of PM) (Andrade et al. 2015; Kumar

et al. 2016; Nogueira et al. 2015; Vara-Vela et al. 2016). Although the vehicular fleet and the fuels in use have increased by more than 100% within the last decade, and although it is expected to further grow by about $6\% year^{-1}$, the air quality has improved following the implementation of a series of emission control measures enforced by the local and federal governments since the 1980s (Carvalho et al. 2015; Pérez-Martínez et al. 2015; Silveira et al. 2015). The Program for the Control of Vehicular Emission (PROCONVE-L) was introduced in 1986 for light-duty vehicles (LDV). Further on, PROCONVE-P was enacted in 1990 for heavy-duty vehicles (HDV). After the first phase of PROCONVE-L (from 1988 through 1991), a total emission reduction of about 70% was realized, even though the emission standards for HDV only became legally effective in 1994. In 2002, a new law (Resolution CONAMA 315/2002 from the Brazilian Environmental Council) established more strict tailpipe emission standards (Lucon and Goldemberg 2010), followed by PROMOT in 2003, which was another important piece of legislation with the objectives of controlling motorcycles’ emissions and complementing the PROCONVE program (MMA 2013). Those laws and other conditions in Brazil stimulated vehicle manufacturers and the Brazilian market to introduce advanced, cleaner vehicles and fuels, which led to a considerable improvement of air quality (Noronha et al. 2016).

3.2.1 SO_2

The atmospheric concentration of SO_2 decreased mainly due to a reduction of the sulfur content of vehicular and industrial fuels (Silveira et al. 2015). Regulations to

Fig. 3 Annual median concentrations of PM_{10} , NO_x , and SO_2 in the MASP for the period 1998–2018

enforce the reduction of sulfur content in fuels were first implemented in the late 1970s, first affecting industrial sites and later on also vehicle emissions (Kumar et al. 2016).

The sulfur content in diesel fuel is a special case in Brazil. Before the introduction of the CONAMA 315-Resolution in 2002, diesel fuel blends contained between 500 and 2000 $mg\ kg^{-1}$ of sulfur. When the resolution came into effect in 2003, the national oil company Petrobras, which is the main producer of fossil fuels in the country, did not immediately supply the market with the mandatory S50-diesel fuel (= diesel with 50 $mg\ kg^{-1}$ of sulfur). They argued that they only had to follow a prior regulation by the Agência Nacional do Petróleo (ANP), the Brazilian National Oil Agency. Subsequently, the Federal State of São Paulo filed a lawsuit against Petrobras and ANP and eventually enforced them to provide S50-diesel to the Brazilian market starting in 2003 (Lucon and Goldemberg 2010). This process could explain the abrupt decrease of the SO_2 concentration in air after 2004 (Fig. 3).

However, as HDVs remained a major source of SO_2 and other pollutants, the local government took further action in 2008 and prohibited HDV traffic in the central sections of the MASP (Kumar et al. 2016). As the outcome was, again, considered to be unsatisfactory, a new phase of PROCONVE was implemented, so that starting in 2012, S10-diesel has to be provided to the market (Lucon and Goldemberg 2010).

3.2.2 NO_x

The NO_x -emissions also decreased due to the control policies described above and due to improvements of

vehicle technology. In the first phase of PROCONVE-L (L-1), between the years 1988 and 1991, technological innovations (i.e., the introduction of three-way catalytic converters) led to the reduction of exhaust gases, which diminished NO_x emissions. Later, the fourth phase of PROCONVE-L (L-4, from 2005 till 2008) focused on reducing ozone precursor compounds, hydrocarbons and NO_x through new technologies in vehicles (i.e., optimized combustion chamber, electronic and increased pressure fuel injection). In the fifth phase (L-5 from 2009 through 2013), the emission policies were further sharpened. As a result, the NO_x emissions were reduced to 48% and 42% for LDVs and HDVs, respectively. However, regarding vehicular emissions from HDVs, PROCONVE-P aided by the reduction of NO_x emissions especially in its fifth and sixth phases (P-5, from 2003 to 2008 and P-6, from 2009 to 2011) (Nogueira et al. 2015).

3.2.3 PM_{10}

Important contributors to the PM_{10} mass concentration are primary, natural aerosol particles such as dust and sea salt. Further, over 40% of the respective particle mass is secondary material which is formed in atmospheric processes from precursor gases. These gases are primarily hydrocarbons that originate largely from vehicle emissions (Vara-Vela et al. 2016). Another traffic-related source is not related to engine exhaust: Resuspension of material from dry roads and abrasion of brakes, tires, and clutches introduces nonexhaust traffic-related particles into the ambient air that contribute to the PM_{10} concentration (Grigoratos and Martini 2014). The respective emissions are estimated to be of

the same magnitude as that of tailpipe emissions. In addition, human food preparation also contributes to the generation of PM₁₀. The MASP hosts a large number of restaurants (mostly pizzerias operating on wood stoves or steakhouses using charcoal ovens), the emissions of which are not under any emission controls (Kumar et al. 2016). A similar situation applies to home cooking and machines used for construction. Although a few respective case studies do exist, the role of anthropogenic emissions, i.e., cooking, construction and airport emissions, to the PM₁₀ concentration and other pollutant levels in the MASP should not be underestimated.

3.2.4 Minimum Temperature, Relative Humidity, and Atmospheric Pressure

Figure 4 shows the annual medians of the daily minimum temperature ($T_{\min}$) and the annual mean of the relative humidity (rH) in the respective period. The lowest annual median of $T_{\min}$ (15.2 °C) was registered in the year 1999, while the maximum (17.8 °C) occurred in 2015. Assuming a linear trend of $T_{\min}$ since 1998, its slope is positive ($dT_{\min}/dt = 0.0084 \text{ °C year}^{-1}$, $R^2 = 0.0069$). The lowest annual median (71%) of rH was in the year 2007, the highest (85%) was recorded in 1999. Since 1998, rH decreases on average. Accepting a linear negative trend for rH, its slope is $drH/dt = -0.1395\% \text{ year}^{-1}$, $R^2 = 0.054$. A negative trend of aP (not shown in detail) has also been detected ($daP/dt = -0.2331 \text{ hPa year}^{-1}$, $R^2 = 0.2775$). The annual medians do exhibit large fluctuations over the years, and they do not correlate with the decrease of AFO.

With respect to our findings from descriptive statistics of Dataset 2, we summarize that the concentrations of PM₁₀, NO_x, and SO₂ decreased between 1998 and 2018, while $T_{\min}$ increased. Note that the relative humidity also decreased. To study these results and their potential impact on AFO in more detail, we performed the statistical analysis of Dataset 2 via logistic regression.

3.3 Results of the Logistic Regression

We performed the logistic regression on SPSS and chose the “Enter” method for further analysis. First, the significance of our regression model is calculated by the Omnibus Test of Model Coefficients. It is equivalent to the chi-square test and provides a statement about the explanatory power of the model. The model

is, according to the chi-square test (chi-square = 747.31; degrees of freedom = 6; significance is $p = 0.000$) significant and, therefore, useful for further analysis. The goodness of fit of the model was calculated on the basis of Nagelkerke’s pseudo R^2 . If a full model predicts the outcome perfectly, then the Nagelkerke’s pseudo $R^2 = 1$ (UCLA - Statistical Consulting Group n.d., last access: 2019-11-23). In our model $R^2_{\text{Nagelkerke}} = 0.164$, which indicates that the model explains only 16.4% of the observed outcome. Further, the model’s relevance is estimated using the effect size f according to Cohen (1992):

$$f = \sqrt{\frac{R^2_{\text{Nagelkerke}}}{1 - R^2_{\text{Nagelkerke}}}} \quad (2)$$

Corresponding to Cohen’s classification system, our model has a strong effect ($f = 0.44$) (Cohen 2009).

Table 2 shows the results of the binary logistic regression. Here, the predictors (X_n) are in the first column, B ’s are the generated coefficients for the predictors and for the constants in the model (Eq. 1), S.E. values in the third column are the standard errors around the coefficients (B), and Sig. in the fourth column is the statistical significance of each coefficient.

The Sig. values of the independent variables, $T_{\min}$, rH, and PM₁₀ are equal zero ($p = 0$), meaning that these parameters are significant predictors of fog occurrence (FO = 1). For SO₂, the significance of 0.003 does not exceed the critical value (defined as $p = 0.05$), meaning that its influence is considered as significant as well, but at a lower level compared to that of the former variables.

The significance levels of aP ($p = 0.483 > 0.05$) and NO_x ($p = 0.678 > 0.05$) exceed the critical value. Their influence on fog formation is very likely of random character. Thus, they are not implemented into the regression Eq. 3 (Bittmann 2015; Zürich 2018). Substituting the B_n values and the X_n values in Eq. 1 with their respective coefficients and significant predictors (Table 2), we arrive at the following equation:

$$P(\text{Fog} = 1) = \frac{e^{-1.628 - 0.382 \cdot T_{\min} + 0.587 \cdot rH + 0.828 \cdot \text{PM}_{10} - 0.117 \cdot \text{SO}_2}}{1 + e^{-1.628 - 0.382 \cdot T_{\min} + 0.587 \cdot rH + 0.828 \cdot \text{PM}_{10} - 0.117 \cdot \text{SO}_2}} \quad (3)$$

The logistic regression model was operated with daily data. Most of the model results (Eq. 3) are conceivable with general meteorological and climatological reasoning. For example, it is obvious that a day with high air humidity rH is more likely to be (or become) a

Fig. 4 Annual medians of daily minimum temperature (red line) and daily mean relative humidity (purple line) in the MASP for the period 1998–2018

foggy day than a drier day. Correspondingly, the driver $T_{\min}$ exhibits a negative coefficient in Eq. 3, meaning that a relatively low daily minimum air temperature fosters the formation of fog. The roles of these meteorological variables as drivers of fog formation is unequivocal, fog cannot form in an air mass that is warm and dry.

The roles of the air pollution parameters are less straightforward when analyzing their influence on fog on a daily basis than it was for the annual averages (section 3.1). For example, a high concentration of SO_2 leads to the formation of large amounts of cloud condensation nuclei (CCN) after gas-phase oxidation of SO_2 to H_2SO_4 . If rH raises, these CCN facilitate the formation of a large number of small fog droplets that effectively scatter light and lead to a strong reduction of the horizontal visibility. In that sense, high SO_2 should be correlated with high FO. However, Eq. 3 shows a contradictory result, i.e., a negative regression between SO_2 and FO ($B = -0.117$; $p = 0.003$). There are two possible reasonings to explain these findings. First, once fog is formed in conjunction with SO_2 as described above, the liquid phase is a further effective sink for SO_2 . It will be completely scavenged from the gas phase and further oxidized to H_2SO_4 . The remaining very small concentrations of gaseous SO_2 in the gas phase cannot be detected any more with conventional analyzers, so that the correlation between SO_2 and FO is disguised. Second, the data base of our analysis is, both spatially and temporally, not perfectly synchronous. While the FO data are collected at one single location, the SO_2 data are averages over the entire MASP. Further, fog may have been detected on a day for only a short time period, while the SO_2 data are averaged over 24-h periods. Such disalignment may lead to statistical misinterpretation.

The PM_{10} concentration shows a positive regression with FO (Eq. 3). This result is reasonable because PM_{10} can be regarded as a proxy for CCN. Although this last statement should be made cautiously in the context of fog formation, because it is not the mass concentration of aerosol particles that defines their efficacy to act as CCN rather than their number concentration, hygroscopicity, and sizes, the effect of PM_{10} on FO is, statistically speaking, rather strong, even on a daily basis (coefficient $B = 0.828$).

The role of NO_x is somewhat between that of SO_2 and PM_{10} . Nitrogen oxides are, under certain conditions, precursors for CCN and thus for the formation of fog, although their efficacy is much lower than that of SO_2 . They cannot be regarded as a proxy for FO as PM_{10} can. Overall, their contribution is not significant ($B = -0.018$; $p = 0.678$).

Our regression model states that aP has no significant contribution to fog formation. We did not further study if the general weather situation, i.e., the presence of high-pressure or low-pressure systems, plays any role in the formation of radiation fog or advected fog. The general picture suggests that the atmospheric pressure is not a significant driver for the overall occurrence of fog also on a yearly basis. Overall, the regression model suggests that high concentrations of particulate matter (PM_{10}) along with the low presence of high relative humidity (rH) and minimal temperatures ($T_{\min}$) have a strong influence on fog formation mechanisms over the MASP. Statistical uncertainties remain. For instance, both goodness of fit ($R^2_{\text{Nagelkerke}} = 0.164$) and effect size ($f = 0.44$) demonstrate the limitation of the explanatory power of the model. Therefore, the interpretation of the results should be exercised with caution.

4 Conclusion

Most of the results of our overview trend analysis for assessing the occurrence of fog in the MASP under the influence of meteorological drivers and air pollution are highly consistent with scientific understanding of fog formation: The decrease of AFO over decades is associated with increasing temperatures and decreasing relative humidity. Ongoing urbanization and the regional imprint of global change are, thus, rather obvious contributors to the observed trend of AFO. This is evident from visual inspection of the longer historical dataset (since 1933) and the shorter dataset (since 1998) as well as from statistical analysis of the latter set.

Further drivers are increasing air quality in the MASP. The annual trends of air quality parameters (Fig. 3) and their synchronicity with AFO (Fig. 2) are striking. The statistical analysis of the shorter data set with a logistic regression partly supports these observations. PM_{10} is the strongest driver of AFO, followed by rH and T_{min} . This indicates that both warming and increasing air quality lead to the decrease of AFO in the MASP.

For PM_{10} , its dominant role is conceivable as it is a proxy for CCN, which are effective drivers for reduced visibility and fog formation whenever rH is very high (Maurer et al. 2019). Statistically, NO_x is not a significant contributor to the AFO trend. This result is not surprising, because nitrogen oxides are only indirectly associated with the formation of PM and CCN. Note, however, that the NO_x decreases together with AFO.

Due to its chemical properties, we expected that increasing levels of SO_2 would contribute positively to fog formation. Figure 3 shows a strong decrease of the yearly SO_2 concentration, which occurs together with the decrease of AFO (Fig. 2), suggesting a positive correlation between these two parameters. The logistic model results, however, do not support this result, even suggests an opposite relation. At this point, it is not unequivocally clear why the logistic regression does not confirm this picture. We speculate that the SO_2 concentration is, in the MASP, more closely related to the formation of haze situations (visibility 1–5 km) with lower humidity associated with radiative processes, while situations of even lower visibility (< 1 km) are mostly associated with humidity advected from the Atlantic Ocean (Da Rocha et al. 2015). Also, there may be a temporal and spatial mismatch between the observation of fog (one location, often one point in time during a

day) and the SO_2 data (daily medians over the entire MASP). The role of SO_2 is, thus, not entirely comprehensible. We speculate that an analysis based on data with better spatial and temporal allocation would change the picture considerably.

The atmospheric pressure (aP) does not contribute significantly to fog formation. Likely, a more detailed analysis of fog occurrence during the various seasons of the year would lead to a different result, because the weather systems in winter lead to a higher fog frequency than those in summer. It has been shown for other regions that changing circulation patterns may lead to changing patterns of fog occurrence (e.g., LaDochy and Witiw 2012).

It is not expected that the drivers we examined can fully explain the formation (or nonformation) of fog. The explanatory power of our model is only 16%. Further note that, strictly speaking, most parameters analyzed in this and other studies are nothing more than proxies of potential drivers of fog formation. Only for the meteorological parameter rH , a direct and causal effect on fog is expected, because fog occurs only at high-enough rH . However, such high rH is rather difficult to measure accurately so that these data are often not reliable. Therefore, the air temperature is an attractive proxy: With increasing temperature and all other conditions being constant, rH decreases. In a similar fashion, SO_2 or NO_x are not at all direct drivers of fog. Only their oxidation and subsequent formation of secondary aerosol particles drives the formation of cloud condensation nuclei (CCN). A larger number of CCN leads, with all other conditions being constant, to a larger number of yet smaller fog droplets. Klemm and Lin (2016) showed that this effect leads to a reduction of the horizontal visibility and thus enforces fog. The PM_{10} concentration, which is measured in São Paulo and many other places, is the only available proxy for CCN in long-term time series. However, the correlation between PM_{10} and CCN is in many cases poor and therefore the PM_{10} concentration is a rather nonspecific proxy for CCN. Given these limitations we are impressed by the strong role PM_{10} plays in driving the formation of fog in the MASP. We conclude that the model performance (goodness of fit $R^2_{Nagelkerke} = 0.164$, effect size $f = 0.44$) is acceptable to provide an overview of the parameters driving fog trends in the MASP.

More detailed analyses in the future should include the seasonality of fog and meteorological conditions. This may help to elucidate the role of regional weather

systems and their dynamics in the context of how climate change drives fog occurrence in the MASP. Further, nonlinear models should be employed. Hůnová et al. (2018, 2020) found for their studies in the Czech Republic that rH, SO₂, NO_x, air temperature and seasonality were explanatory variables for fog trends. However, they also found that the number of stations analyzed and the lengths of the observation periods played important roles, just like the seasonality. Maurer et al. (2019) found for datasets from Taiwan that the influence of PM₁₀ on fog was stronger when the PM₁₀ concentration was lower, while rH was more important in more polluted air masses.

Future datasets should also include the quantification of the horizontal visibility rather than just the dichotomous parameter of presence/absence of fog during a given day. Also, it should be considered to use exclusively hourly air quality data measured at the same times when fog was observed. We also suggest that intensive campaigns should be performed to produce more detailed data on air chemistry, the chemical composition of CCN and fog, and their particle size distributions in order to quantify how local and regional air pollution influence the formation and density of fog.

Acknowledgments This study was supported by a grant from the Brazilian Center of the University of Münster (WWU) to André Cardoso Mühlig, which is gratefully acknowledged. We also thank Celeste Brennecke for language-editing of this manuscript. An anonymous reviewer on a previous version of the manuscript helped to improve it considerably, thank you!

Funding Open Access funding enabled and organized by Projekt DEAL.

Compliance with Ethical Standards

Competing Interest The authors declare that they have no conflict of interest.

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