Salinity of marine aerosols in a Brazilian coastal area—Influence of wind regime

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Received 4 March 2007; received in revised form 28 June 2007; accepted 3 July 2007

Abstract

This paper presents salinity data of marine aerosols in a Brazilian coastal area at sites closer to the shore and discusses the influence of wind regime. Results show that measurements of marine salt deposition are strongly influenced by wind speeds above the critical value of 3.0 m s\textsuperscript{-1}. Although there is no agreement in literature yet as to how much this threshold is, the level of 3.0 m s\textsuperscript{-1} is similar to the one found in a study carried out in Spain. An exponential variation of salt concentration with wind speed is presented in previous published papers. However, in the studied case, another relationship is proposed, which is based on chloride deposition on the wet candle device and wind speeds higher than 3.0 m s\textsuperscript{-1} weighted by the accumulated time in which these wind speeds are observed, what seems to be particularly useful when wind speed ranges around the critical value.

Keywords: Chloride deposition; Marine aerosol; Wet candle; Wind regime; Wind speed

1. Introduction

Marine aerosol is generated either in the ocean or in the surf zone (McKay et al., 1994; Cole et al., 2003\textsuperscript{a}). The bursting of air bubbles at the sea surface, the mechanical disruption of wave crests at higher wind intensities (> 10 m s\textsuperscript{-1}) and the breaking waves motion on the shore are the most prominent physical processes associated with the marine aerosol generation (Erickson et al., 1986; Marks, 1990; Fitzgerald, 1991; Gong et al., 1997).

The production of sea salt aerosol is more effective in the surf zone where marine aerosol drops are more numerous and larger (Fitzgerald, 1991; O’Dowd et al., 1997). Ocean produced aerosol tends to be fine to medium sized (Cole et al., 2003\textsuperscript{a}). Differences of an order of magnitude were observed between the salinity of surf and ocean produced aerosols (McKay et al., 1994). As a consequence of these differences and the settlement effect of salt particles, surf produced aerosol dominates salt concentrations at sites closer to the shore, while the influence of ocean produced aerosol is dominant at greater heights and at further inland zones.
After generation, the marine aerosol droplets rapidly become equilibrated with the environment and, depending on temperature and relative humidity conditions, they can turn into salt solutions or salt crystals (Zezza and Macri, 1995).

Sea salt concentration of marine aerosol is strongly influenced by wind characteristics (Exton et al., 1985; Morcillo et al., 2000). This influence shows higher rates of salinity increase with wind speed for surf produced aerosols than for those produced over the open sea (McKay et al., 1994; Cole et al., 2003a).

After being generated, marine aerosol is transported inland by wind, when salt particles tend to be removed due to effects like the gravitational settling, the deposition onto obstacle surfaces and the scavenging effect by rainfall or snow precipitation (Gong et al., 1997; Feliu et al., 1999; Cole and Paterson, 2004). The gravitational settling is more effective for larger salt particles which remain for a short time in atmosphere. However, stronger winds enable salt particles to cover longer distances before settling. In this way, small-sized aerosols can travel longer distances than coarse aerosols without settling (Kulkarni et al., 1982; Gong et al., 1997; Morcillo et al., 2000; Cole et al., 2003a). The deposition of aerosol particles onto obstacle surfaces, which is influenced by the mean winds, has a strong dependence on the ground roughness as well. This environmental characteristic controls the wind turbulence and thus the aerosol deposition onto surfaces (Cole and Paterson, 2004). The scavenging effect is influenced by the collisions of rain drops or snow crystals onto marine salt particles (Gong et al., 1997).

The relationship between salt concentration of marine aerosol and wind speed is typically represented by an exponential growth function, as shown in Eq. (1), where \( v \) is the wind speed, \( C \) is the salt concentration and \( a \) and \( b \) are constants that conceal other influences (Lovett, 1978; Kulkarni et al., 1982; Exton et al., 1985; Marks, 1990; Gustafsson and Franzen, 1996; Wai and Tanner, 2004).

\[
C = ae^{bv}.
\]  

(1)

Relationships based on Eq. (1) are mainly used at sites dominated by the surf produced aerosol (Exton et al., 1985; McKay et al., 1994; Gustafsson and Franzen, 1996). Applications for sites dominated by ocean produced aerosol are also seen (Lovett, 1978; Marks, 1990). Both approaches can be seen in Table 1 which presents some of these relationships proposed by studies carried out under different environments around the world. These empiric expressions represented by Eq. (1) do not take into account the differences on generation sources and transportation of marine aerosol, as can be seen in a process-based model presented by Cole et al. (2004). However, they are proposed for local applications and have their importance on studying this phenomenon.

Relationships presented in Table 1 show significant variation in the function coefficients. Aspects like differences on source of aerosols, measurement conditions, and local environmental conditions influence these coefficients.

Table 1

<table>
<thead>
<tr>
<th>References</th>
<th>Environment</th>
<th>Condition</th>
<th>Height (m)</th>
<th>Average wind speed range (m s(^{-1}))</th>
<th>Function</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lovett (1978)</td>
<td>Atlantic Ocean (North)</td>
<td>On ships</td>
<td>15</td>
<td>1.8–19.0</td>
<td>( C = 3.0e^{0.20v} )</td>
<td>Higher scatter for low wind speeds</td>
</tr>
<tr>
<td>Kulkarni et al. (1982)</td>
<td>Arabian Sea</td>
<td>Inland (1.8 km)</td>
<td>1.2</td>
<td>2.2–7.2</td>
<td>( C = 5.5e^{0.17v} )</td>
<td>Significant scatter</td>
</tr>
<tr>
<td>Exton et al. (1985)</td>
<td>Atlantic Ocean (North)</td>
<td>(10–270 m)</td>
<td>4</td>
<td>0.8–16.0</td>
<td>( C = 18.5e^{0.13v} )</td>
<td>–</td>
</tr>
<tr>
<td>Marks (1990)</td>
<td>North Sea</td>
<td>Offshore (9 km)</td>
<td>15</td>
<td>0.6–20.0</td>
<td>( C = 13.3e^{0.16v} )</td>
<td>–</td>
</tr>
<tr>
<td>Taylor and Wu (1992)</td>
<td>Atlantic Ocean (North)</td>
<td>Pier</td>
<td>12</td>
<td>7.0–24.0</td>
<td>( C = 1.1e^{0.23v} )</td>
<td>( r^2 = 0.62 )</td>
</tr>
<tr>
<td>McKay et al. (1994)</td>
<td>Atlantic Ocean (North)</td>
<td>Shoreline</td>
<td>8.2</td>
<td>2.5–16.0</td>
<td>( C = 2.40e^{0.15v} )</td>
<td>Higher scatter for low wind speeds</td>
</tr>
<tr>
<td>Gustafsson and Franzen (1996)</td>
<td>North Sea</td>
<td>Inland (1 m)</td>
<td>1.5</td>
<td>7.3–20.7</td>
<td>( C = 0.96e^{0.19v} )</td>
<td>( r^2 = 0.85 )</td>
</tr>
<tr>
<td></td>
<td>Inland (0.5 km)</td>
<td></td>
<td></td>
<td></td>
<td>( C = 0.84e^{0.21v} )</td>
<td>( r^2 = 0.90 )</td>
</tr>
<tr>
<td></td>
<td>Inland (3 km)</td>
<td></td>
<td></td>
<td></td>
<td>( C = 0.38e^{0.38v} )</td>
<td>( r^2 = 0.99 )</td>
</tr>
<tr>
<td>Wai and Tanner (2004)</td>
<td>Pacific Ocean</td>
<td>Inland (residential area)</td>
<td>10</td>
<td>2.8–11.0</td>
<td>( C = 0.64e^{0.17v} )</td>
<td>( r^2 = 0.62 )</td>
</tr>
</tbody>
</table>
devices and techniques used, height from the ground level, land characteristics and prevailing climatic conditions, which certainly change from site to site, may help to explain these differences (Eriksson, 1959; Exton et al., 1985; McKay et al., 1994; Wai and Tanner, 2004; Meira et al., 2006).

Regarding the wind speed influence on sea salt concentration in marine aerosols, aspects like wind speed threshold and wind power have been less studied (Strekalov and Panchenko, 1994; Morcillo et al., 2000).

About the wind speed threshold, few studies report that salt concentrations strongly increase after a certain wind speed level. There is no agreement as to how much this threshold is, although values between 3.0 and 7.1 m s\(^{-1}\) are given (Spiel and De Leeuw, 1996; Piazzola and Despiau, 1997; Morcillo et al., 2000). In a different approach, Exton et al. (1985) observed that the marine aerosol is much stronger wind speed dependent for the larger particles, which agrees with a sharp increase of salt concentrations with wind speed and with the characteristics of surf produced aerosols.

The accumulated time for which the wind speed is within given intervals, what is called in this paper as the duration of wind speeds, is another aspect that plays an important role. A study carried out by Feliu et al. (1999), based on previous Russian results (Strekalov and Panchenko, 1994), shows that the salt measurements present a stronger relationship with the wind power (wind speed multiplied by its duration) than with wind speed alone.

Wind speed threshold, wind power and duration of wind speeds, although being aspects which are less studied, indicate that there are wind speed particularities that may strongly influence salt concentration of marine aerosol. In this paper, the relationship between wind speed characteristics and salt presence in the marine aerosol is discussed, taking into consideration the salinity of marine aerosols in a Brazilian coastal area at sites closer to the shore. A wind speed threshold and the length of time for which a particular range of wind speeds takes place are embodied in this analysis. An alternative relationship between the salinity of marine aerosol and wind speed characteristics is proposed and simultaneously proved at different distances from the sea.

2. Experimental work

Salt presence in marine aerosol and climatic parameters were monitored for at least 17 months, from 2002 to 2003, in the city of João Pessoa, which is located in a tropical region in the northeast of Brazil (Fig. 1).

The salinity of marine aerosols was indirectly appreciated by dry deposition of chlorides using the wet candle technique, according to the American Society for Testing and Materials (ASTM) G-140 (1996). This technique has been successfully used in previous studies (Ambler and Bain, 1955; Mustafa and Yusof, 1994; Morcillo et al., 2000; Cole et al., 2003b) and takes into consideration that most salt particles in marine aerosol are sodium chloride composed.

The chloride deposition, which means the chlorides deposited on a retaining device while marine aerosol is transported inland by wind, was measured at five monitoring stations placed at sites 10, 100, 200, 500 and 1100 m from the sea (Fig. 1), in order to observe if there were differences in the behaviour of the relationships between wind characteristics and salt measurements. The area chosen was as flat as possible, to avoid significant variations in height, and free of obstacles between the shoreline and monitoring stations to reduce the effect of ground roughness in the measured data. At each station, a wet candle device was installed and liquid samples were monthly analysed by potentiometric titration with silver nitrate solution 0.05 M.

The climatic data were collected at the monitoring station 1100 m from the sea (Fig. 1), where a Brazilian Government weather station is located. Continuous daily anemographic sheets, from a universal anemograph, were used to obtain daily and monthly average wind data (wind speed, wind direction and duration of wind speeds). In this case, only marine winds were taken into account. Temperature, relative humidity and rainfall data were also collected at the same weather station, by using a psychrometer and a pluviometer, respectively. The UTC (coordinated universal time) references were followed.

3. Results

A typical behaviour of the climatic parameters temperature, relative humidity and rainfall is presented in Fig. 2. These data represent monthly and yearly averages for temperature and relative humidity measurements taken three times per day (Fig. 2a). As these measurements were taken for at least 17 months, two points are plotted for those cases which had different records. Rainfall data
represent the monthly and yearly accumulated rainfall taken from daily measurements (Fig. 2b). The average data for a period of 30 years, obtained from the Brazilian National Institute of Meteorology database, are also plotted. A similar behaviour is observed for both period data. Along the period in which the measurements were taken, temperature and relative humidity show little variation, with monthly average values roughly ranging from 25 to 28 °C and from 70% to 86%, respectively (Fig. 2a). Periods of heavy rainfall occurred around June, with a big increase in this month (Fig. 2b).

The region chosen for the experimental work is characterised by mild winds. The monthly average values ranged between 2.3 and 3.6 m s\(^{-1}\) (Fig. 3), with low variability within each month and with an increase between August and October. Predominant winds were from the quadrant S–E (Fig. 3). This is typical wind regime behaviour for the studied region.

The chloride deposition data are shown in Fig. 4. There is a clear reduction of salinity in the first meters from the sea, due to the gravitational settling of salt particles and some ground roughness effect (Gustafsson and Franzén, 1996; Feliu et al., 1999; Meira et al., 2006). The variability of the results at each site is not large and can be connected with low wind speed ranges and with low variability of wind characteristics and other climatic parameters over the research period.

4. Discussion

An increase in wind speed results in the aerosol being composed of more and larger particles which are transported inland (McDonald et al., 1982; Fitzgerald, 1991; Gustafsson and Franzén, 1996; Piazzola and Despiau, 1997; Morcillo et al., 2000). This effect is more accentuated for the surf produced aerosol (McKay et al., 1994). In this way, Exton et al. (1985) observed that the volumetric loading of large particles (8–16 \(\mu\)m) can increase around five times more than the volumetric loading of small salt particles (0.1–0.3 \(\mu\)m) when wind speed varies from 1.5 to 18 m s\(^{-1}\). The wind speed effect can be observed in data obtained at monitoring stations. An increase in the chloride deposition rate between two and five times when monthly average wind speed increases from 2.5 to 3.6 m s\(^{-1}\) is observed (Fig. 5a).

Eq. (1) is widely used in literature to represent this relationship (see Table 1). When fitting Eq. (1) to experimental data, although it is possible to see an increase tendency of salt measurements with wind
speed, there are relatively poor correlations and significant scatter (Fig. 5a). This can also be observed in other studies that take into account low wind speed levels (Kulkarni et al., 1982; Taylor and Wu, 1992; Wai and Tanner, 2004), which indicates that there might be a change in the behaviour of the relationship between wind speed and salinity of marine aerosol at low wind speed ranges.

A more detailed analysis of marine salt and wind speed data show that there is a strong increase in chloride deposition with above average wind speed values near 3.0 m s\(^{-1}\) (Fig. 5b). This behaviour agrees with a study carried out in Spain (Morcillo...
et al., 2000), which outlined that above 3.0 m s\(^{-1}\) there is a sharp increase of salt concentrations.

Other studies also comment on this increase tendency (Spiel and De Leeuw, 1996; Piazzola and Despiau, 1997). However, there is no agreement about the wind speed threshold. More research is necessary to clarify if it is possible to set a general wind speed threshold, but it can be outlined that the
influence of wind speed is stronger above a certain level of wind speed and this may be taken into account in aerosol studies. Fig. 6 shows this tendency with data from Spain (Morcillo et al., 2000) and from the present study.

As well as wind speed, the influence of the accumulated time for which the wind speed is within given intervals (duration of wind speed) is another aspect analysed. The role of the duration of wind speeds can be seen in Fig. 7, which represents
the monthly variation of chloride deposition and the accumulated time in which winds stronger than 3.0 m s\(^{-1}\) were recorded, for Brazilian data at 10 m from the sea. A fair similar pattern for both variables can be observed, which is repeated for all analysed distances, despite not being represented in Fig. 7. Similar behaviour was also observed in Spanish study (Morcillo et al., 2000).

Fig. 6. Behaviour of Brazilian and Spanish data for the relationship between chloride deposition on the wet candle device and monthly average wind speed.

Fig. 7. Relationship between chloride deposition on the wet candle device at 10 m from the sea and the accumulated time for which wind speed is above 3.0 m s\(^{-1}\).
This work joined these last two tendencies and tried another relationship between marine salts and wind characteristics, which is represented by Eq. (2) and correlates, in one side, the chloride deposition \( (D) \) and, in the other side, the wind speeds higher than \( 3.0 \text{ m s}^{-1} \) \( (v_3) \), weighted by their duration \( (v_3 t_3 t_i^{-1}) \). This means that wind speeds higher than \( 3.0 \text{ m s}^{-1} \) were multiplied by the length of time that

![Diagram](image-url)

**Fig. 8.** Relationship between chloride deposition on the wet candle device \( (D) \) and wind speeds higher than \( 3.0 \text{ m s}^{-1} \) weighted by their duration \( (v_3 t_3 t_i^{-1}) \), for 10, 100 (a), 200, 500 and 1100 m (b) from the sea.
it took place \( (t_3) \) and divided by the total observation time \( (t) \). A coefficient \( (D_1) \) is incorporated, which represents the chloride deposition correlated with wind speeds lower than 3.0 m s\(^{-1}\).

\[
D = D_1 + ae^{b(t_3/t^-1)}.
\] (2)

For all analysis made here the vectorial components of wind speed were considered, as monitoring stations were placed inland at different distances from the sea. Few studies commented on the dependence of aerosol production upon the relative frequency of wind speeds (Morcillo et al., 2000; Cole et al., 2004), but not in the same way as presented in this work.

Results of fitting Eq. (2) to experimental data show better correlation than in the first case (Fig. 5a). All coefficients of determination increased and there was less scatter than in the previous fitting (Fig. 8). The behaviour observed in Fig. 8 seems to be reasonable considering a study taken under natural conditions and the previous relationships presented in literature. This agrees with previous observations that show a strong increase of salt concentrations when wind speed rises above a certain level and also show that the duration of this particular kind of wind \( (v > 3.0 \text{ m s}^{-1}) \) plays an important role in determining the atmospheric salinity.

Analysing the behaviour of \( D_1 \) connected with the distance from the sea, a sharp decrease in their values can be seen, which is explained by the settlement of salt particles while aerosol is transported inland. In the same way, the \( a \) coefficient also decreases with the distance from the sea, as can be seen in other studies that used Eq. (1) (Gustafsson and Franzen, 1996). On the other hand, the \( b \) coefficient presented low variation. However, a slight increase can be observed at sites further from the sea. This means that the increase tendency of salinity with wind speed is sharper for sites with low sea salt concentrations. This behaviour agrees with Exton et al. (1985) findings which show more volumetric loading for larger salt particles when wind speed increases. Thus, this effect is proportionately more prominent for low salt concentrations. In agreement with these comments, Kulkarni et al. (1982) observed that the \( b \) coefficient indicates the degree of dependence of aerosol salinity on the wind speed.

5. Conclusions

This study shows that there is a wind speed threshold above which there is a sharp increase of salt measurements. For this work, this threshold was around 3.0 m s\(^{-1}\) and agrees with values found by Morcillo et al. (2000) in Spain. This influence is coupled with the duration of wind speeds, which makes the first influence stronger as the duration of this kind of wind increases.

The expression \( D = D_1 + ae^{b(t_3/t^-1)} \), proposed to represent the relationship between marine salts and wind speed, takes into consideration the influence of this particular kind of winds and the correlated accumulated time in which it takes place. As a consequence, the proposed model presented a more accurate behaviour than that with Eq. (1), for the environmental conditions that characterise the studied case. It means an alternative for representing this phenomenon at sites closer to the shore, where the presence of surf produced aerosol is stronger, and seems to be particularly useful when wind speed ranges around the critical value, which corresponds to the case studied in this paper.

Acknowledgements

The authors thank CAPES (A Brazilian government agency for the improvement of graduated professionals) for supporting the Sandwich Doctorate of Gibson R. Meira in Eduardo Torroja Construction Research Institute-IETcc (Spain), thus making possible a reciprocal collaboration between these institutions.

References


