Monsoonal deposition of sea salt and air pollutants over Bombay

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ABSTRACT

Representative sampling of rainwater has been carried out in Greater Bombay and its neighbourhood during the SW monsoon period of 1974. It is estimated that on the average ~200 kg ha^{-1} sea salt is deposited here, each monsoon. A high 'excess' of Ca is observed throughout Bombay, including relatively unpolluted places. The source of this excess is seen to be non-marine. The mean pH, ionic balance and salinity of rainwater has been used to characterise different areas of Bombay in varying degrees of pollution.

1. Introduction

While the knowledge of sea salt deposition over continental regions has great geochemical and climatological significance (Eriksson, 1958; 1960), an idea of the chemical composition of precipitation in and around urban areas could supply useful information on air pollution (Selezneva, 1972). Although considerable concern has been expressed on the rate of industrialization of Indian cities (e.g. Zutshi, 1970; Yennawar et al., 1970), data on air and precipitation are not available on an area-wide and representative scale with the exception of SO_2 in Bombay (Zutshi et al., 1973).

We therefore undertook a study of the composition of rainwater in and around Greater Bombay (area ~300 km^2) during the SW monsoon period of 1974 choosing 4 coastline and 5 inland stations. Three of the stations—Colaba, Bandra and Borivli—on the coastline (≤ 1 km inland) are in Greater Bombay and the remaining station, Tarapur, 70 km to the north of Bombay. The sampling points are located on the map in Fig. 1. Tentative pollutant emission estimates point to the Chembur–Trombay area

Table 1. *Tentative estimates of pollutant emissions in Greater Bombay (Zutshi, 1970)*

Tr = traces; N.K. = not known

	Emissions, kT yr^{-1}					
Source	SO_2	NO_x	Organics	Particulates	H_2S	NH_3
Coal	21.6	4.3	26.0	34.6	1.3	1.3
Gas	0.5	8.5	4.3	0.7	0.7	0.5
Petroleum	0.5	10.4	41.5	1.0	0.5	0.5
Kerosene and diesel oil	13.0	5.3	14.4	0.1	0.1	0.1
Refuse and garbage	5.1	5.1	7.1	7.1	Tr	Tr
Fertilizer operations	12.7	0.7	N.K.	N.K.	N.K.	2.6
Oil refineries	5.4	4.4	3.4	0.7	Tr	Tr
Total	58.8	38.7	96.7	44.2	2.6	5.0
Tons day^{-1}	160	106	265	120	7	14

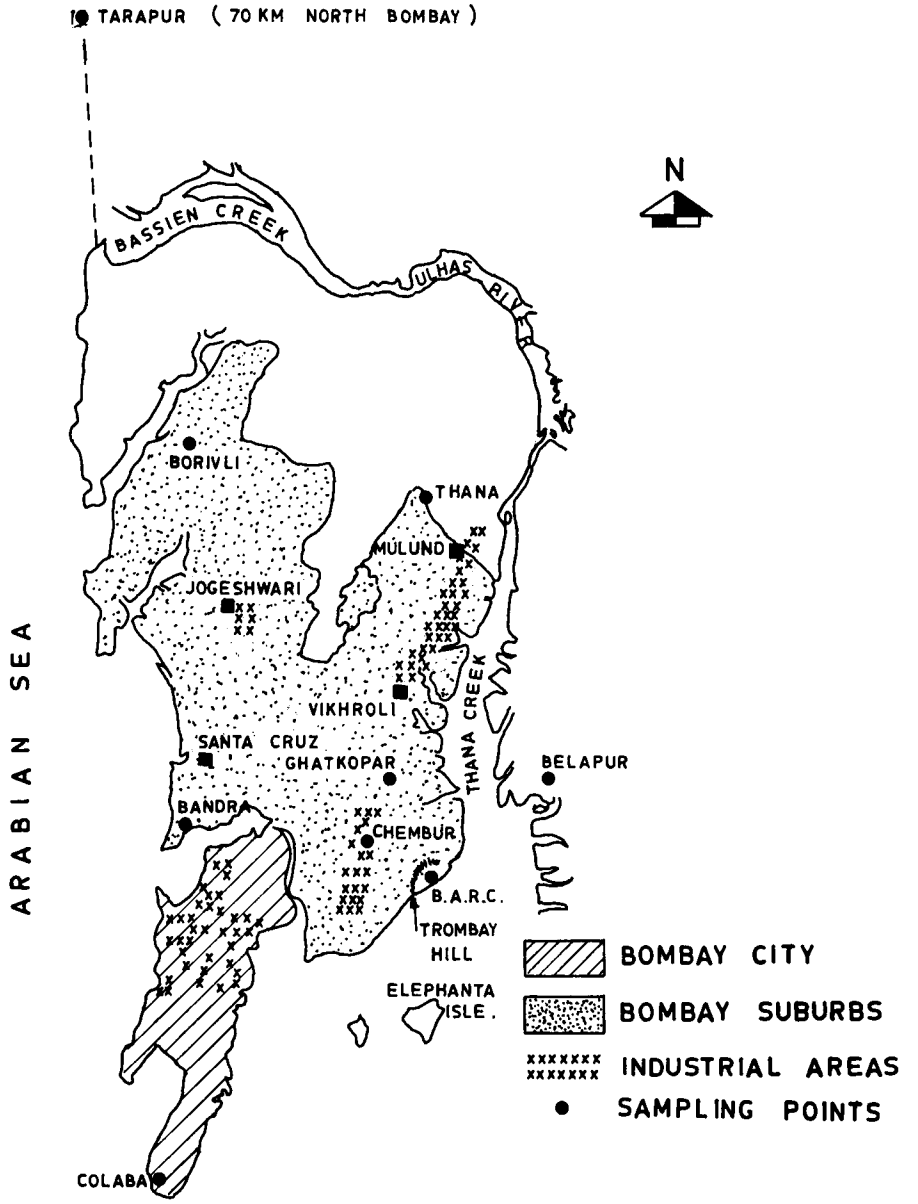

Fig. 1. Map of Greater Bombay (~ 19° N, 73° E).

as the main industrial source of SO_2 and NH_3 within Greater Bombay (Table 1).

Three sampling periods were arbitrarily chosen according to operational convenience. They are June 1–July 10, July 10–August 28 and August 28–October 10, hereafter referred to as periods, I, II and III respectively. Nevertheless they marked the onset, intensification and weakening phases of the monsoon period of 1974 as seen from Figs. 2*a*, 2*b* and 2*c* respectively. Period III was marked by a relatively high incidence of thundercloud activity (Table 2).

2. Sampling and analysis

Rainwater samples were collected into clean, white, all-polythene samplers. Na and K were

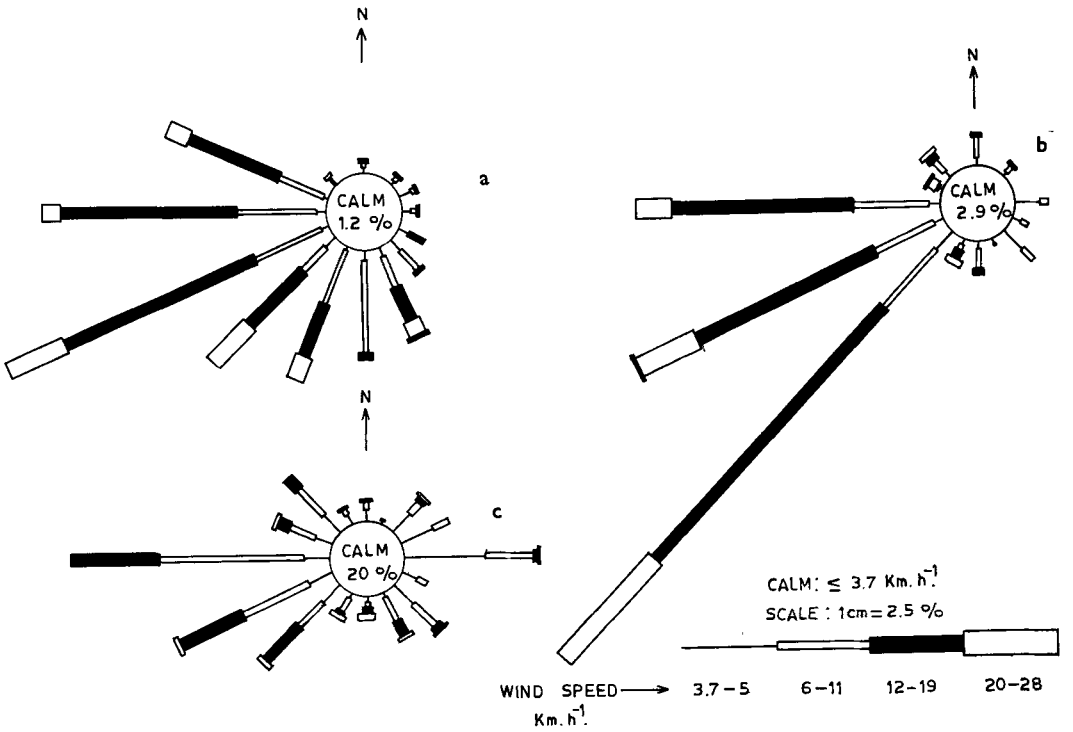

Fig. 2. Wind roses for Santa Cruz, Bombay covering the SW monsoon period, 1974 (hourly wind data through courtesy of India Meteorological Dept., Colaba). (*a*) June 1–July 10 (Period I), (*b*) July 10–August 28 (Period II), and (*c*) August 28–October 10 (Period III).

determined by flame photometry; Ca and Mg by atomic absorption; Cl by mercuric thiocyanate in the presence of Fe^{3+} ion and SO_4 by turbidimetry using $BaCl_2$ crystals. Accuracy of estimation was $\pm 10\%$ for all constituents in the range of concentrations encountered.

3. Results and discussion

(*a*) The weighted mean chemical composition of rainwater for the monsoon period (including period III) is given in Table 3. An unexpected result is the high concentration of Na and Cl on or very near the coastline i.e. at Colaba and Bandra despite respective sampling heights of 25 m and 43 m above m.s.l. there. This is believed to be caused by spurious sea salt particles of spray origin at these rock-laden coastlines where sea waves break roughly. It is therefore suggested that sampling points should be located about 1 km inland at such coasts.

Table 2. *Meteorological data related to sampling periods*

Data: Courtesy India Meteorological Dept., Colaba Observatory

Period	Dates of exposure	Rainy period (%)	Recorded rainfall at Colaba (mm)	Recorded number of days with thundercloud activity at	
				Santa Cruz	Colaba
I	June 1–July 10	17	891	6	3
II	July 10–Aug. 28	17	769	4	1
III	Aug. 28–Oct. 10	8	305	17	15

Table 3. *Weighted mean chemical composition of monsoonal rainwater in and around Greater Bombay, 1974*

Place	Concentration (mg l^{-1})						
	Na	K	Ca	Mg	Cl	SO_4	NH_4
Colaba	3.2	0.1	1.0	0.35	5.5	1.3	0.16
Bandra	3.6	0.45	0.6[a]	0.28	6.1	3.7	0.23
Borivli	2.1	0.10	—	—	3.7	1.8	0.23
Chembur	2.2	1.1	3.1	0.68	5.0	20.2	2.10
Trombay	2.2	0.17	1.3	0.28	3.9	6.8	0.28
Ghatkopar	2.5	0.24	1.5	0.38	4.2	4.4	0.27
Thana	2.5	0.28	1.5	0.38	3.9	5.2	0.34
Belapur	2.0	0.18	1.3	0.36	3.5	4.9	0.24
Tarapur	2.4	0.16	1.4	0.32	4.4	1.3	0.13

[a] Affected by very low value for period I.

Excluding these high values the mean representative concentration of Na is 2.25 mg l^{-1}. Since the mean corrected rainfall over Greater Bombay was found to be 240 cm we have a salt deposition of 180 kg ha^{-1}. Khemani (1974) obtained a Na concentration of ≈ 7 mg l^{-1} at Colaba Observatory during 1972. Since the rainfall that year was only 148 cm, the deposition would have been about 225 kg ha^{-1} if it were corrected for the nearly 50% increase due to the spray component discussed earlier. Correction of an older value by Narayanaswamy (cited by Eriksson, 1958) would give ~ 175 kg ha^{-1} for 1939, the latter value being very similar to that obtained by this author presently. It is therefore probable that about 200 kg ha^{-1} sea salt is deposited in and around Bombay, each monsoon. This value is of similar magnitude as observed in other coastal sites (cf. Eriksson, 1960). The deposition for Ceylon is reported to be near 400 kg ha^{-1} (Eriksson, 1952). Though the representativeness of this value is not known to the present author it is possible that the deposition there may be decisively higher, for, Ceylon has a longer monsoon period than Bombay.

As to other constituents, it is seen from Table 3 that Chembur has the highest concentrations of K, Ca, Mg, SO_4 and NH_4. Excluding this site Mg and NH_4 seem to be fairly uniformly distributed in rainwater within Bombay. Colaba and Tarapur show the lowest SO_4 content as expected while Borivli and Bandra samples indicate some contamination by industrial S from local sources.

(b) Ratios of sea salt constituents

As suggested by the wind patterns (shown in Fig. 2, Sec. 1) it is reasonable to discuss separately, the different ratios of sea salt constituents observed in rainwater samples over periods I and II (June–August) and those obtained during period III (September–October).

(i) *Cl/Na and SO_4/Na (Periods I and II)*

Compared with the Cl/Na ratio in sea water, 1.8, there is generally only a slight net decrease within Bombay but none at Tarapur as seen from the weighted mean values in Table 4*a*. Increase over 1.8 at Chembur is due to an industrial component discussed elsewhere (Sequeira, 1973). A net loss of Cl is generally seen over Bombay during period II, but again none at Tarapur. However, an exclusive sample from Tarapur for July was available and it gave a Cl/Na ratio of 1.65. Since the separation of Cl from sea salt is apparently widespread during July it is to be assumed that this occurs over the marine atmosphere itself. Sadasivan (1973) obtained a Cl/Na ration of ≈ 2 in rainwater collected in July at a rather elevated place (675 m above m.s.l.) about 60 km inland from the west coast. This may be due to the reprecipitation of the gaseous Cl component released from the sea salt aerosols (Eriksson, 1960). However, on a seasonal basis this does not seem to be a significant process as seen by the mean Cl/Na ratios presently obtained. Further the SO_4/Na ratio for Colaba and Tarapur are rather too close to the seawater ratio, 0.25 (Rankama & Sahama, 1950) probably in-

Table 4*a*. *Ratios of sea salt constituents in monsoonal rainwater in and around Greater Bombay, 1974 (periods I and II)*

Mean represents weighted value. * = low values during period I

Place	Period	Cl/ Na/	SO_4/ Na	K/ Na	Ca/ Na	Mg/ Na
Colaba	I	1.8	0.2	*	*	*
	II	1.5	0.4	*	0.5	0.18
	Mean	1.7	0.25	*	*	*
Bandra	I	1.8	0.9	*	*	*
	II	1.6	1.1	0.18	0.3	0.12
	Mean	1.7	1.0	*	*	*
Borivli	I	2.0	1.0	*	*	*
	II	1.6	0.8	0.06	0.5	0.13
	Mean	1.85	0.9	*	*	*
Chembur	I	2.6	14.7	0.54	1.2	0.13
	II	1.9	6.0	0.44	1.4	0.44
	Mean	2.3	11.0	0.5	1.3	0.27
Trombay	I	1.9	2.2	0.13	0.3	0.14
	II	1.6	3.1	0.05	0.7	0.11
	Mean	1.75	2.6	0.09	0.5	0.13
Ghatkopar	I	1.8	2.0	0.13	0.5	0.15
	II	1.7	1.5	0.08	0.6	0.14
	Mean	1.75	1.7	0.10	0.55	0.14
Thana	I	1.9	2.6	0.07	0.6	0.17
	II	1.6	1.6	0.06	0.5	0.14
	Mean	1.7	2.0	0.06	0.5	0.15
Belapur	I	2.3	2.9	0.14	0.9	0.35
	II	1.6	2.0	0.07	0.5	0.12
	Mean	1.9	2.4	0.10	0.7	0.22
Tarapur	I	1.8	0.4	0.07	0.3	0.20
	II	1.8	0.6	0.07	0.6	0.18
	Mean	1.8	0.5	0.07	0.4	0.19
Seawater		1.8	0.25	0.036	0.038	0.12

dicating that SO_2 (originating from oxidation of marine H_2S) is efficiently absorbed over the sea itself. This supports the tentative suggestion that tropical oceans are sinks for SO_2 (Junge, 1972).

(ii) *K/Na ratio*

Seawater has a K/Na ratio of ~0.036. The lowest value obtained by Lodge in the U.S. was 0.075 in regions close to the sea (Rasool, 1973). A similar value is obtained in most places during period II. However, the excess could very well be due to small additions from natural and man-made sources (soil fly-ash).

(iii) *Ca/Na and Mg/Na ratios*

Calcium and Mg belong to the same group in the Periodic Table. While a large excess of Ca is seen, there is hardly any appreciable enrichment of Mg within Bombay. Any systematic role of valency is therefore unlikely as far as the enrichment process is concerned.

The Ca/Na ratio lies mostly between 0.5–0.7 while the same seawater ratio is ~0.038. Khemani's results for Alibag, Colaba and Thana would give values of about 0.5, 0.5 and 0.8 respectively (Khemani, 1974), which are indeed very close to the present ratios. Junge & Werby (1958) attribute high Ca excesses in precipitation in the U.S. to rainout of Ca originating in arid regions. Since our samples were not exposed exclusively during occurence of actual rainfall, we reserve our explanation until further work is carried out. However, some of the excess Ca (probably 10–15%) may be from the sea itself. Tropical seas are supersaturated with respect to $CaCO_3$ (Fairbridge, 1966). Thus Nair et al. (1966) obtained Ca values ranging between 470–1 000 ppm in certain parts of the Arabian Sea, the higher values representing coralline banks.

(iv) *Ratios obtained during period III*

While there is an explicable pattern in the ratios obtained during the periods I and II, a rather random one is found during the weak monsoon period III (Table 4*b*). Both decreases and increases over the Cl/Na ratio in seawater could be observed. There is also a general increase in the SO_4/Na ratio even on the coastline. However, the pH values at the latter places remain almost unaffected, indicating that the excess SO_4 is in the form of a salt

Table 4*b*. *Ratios of sea salt constituents in rainwater in and around Greater Bombay, 1974 (period III: August 28–October 10)*

Place	Cl/ Na	SO_4/ Na	K/ Na	Ca/ Na	Mg/ Na
Colaba	2.1	1.0	—	0.6	0.2
Borivli	Samples lost due to cracking of collectors				
Bandra					
Chembur	2.8	7.9	0.7	1.6	0.2
Trombay	2.0	5.1	0.05	0.7	0.13
Ghatkopar	1.4	2.5	0.11	0.9	0.21
Thana	1.0	3.8	0.43	1.0	0.20
Belapur	1.8	2.3	0.09	0.8	0.17
Tarapur[a]	1.9	2.7	0.56	2.3	2.8
Seawater	1.8	0.25	0.036	0.038	0.13

[a] Likely contamination by vegetable material.

Table 5. *Mean pH, ionic balance and salinity of monsoonal rainwater in and around Greater Bombay, 1974*

Salinity values are normalized to [Na] = 2.2 mg l^{-1}. * = cation excesses observed in case of sample II; sample III lost

Place	pH	Ionic balance (μEq l^{-1})	Salinity (mg l^{-1})
Colaba	6.20	+ 37	8.4
Bandra	6.25	*	10.4
Borivli	6.10	*	—
Chembur	4.85	− 113	34.4
Trombay	4.45	− 48	14.9
Ghatkopar	5.00	+ 30	12.5
Thana	5.20	+ 24	13.1
Belapur	5.20	− 3	11.8
Tarapur	6.15	+ 62	9.4

which does not contribute to pH, for chemical reasons, Na_2SO_4. A close look at the wind pattern during this period explains the above features (Sec. 1). The surface winds during period III were unsteady, the frequency in the SW–W sector had dropped considerably, and the calms increased from ~3% to 20% as compared with period II (Figs. 2*b* and 2*c*). Besides, the clouds that brought rains during this period were mainly cumulonimbus that originated over the hill range some 100 km inland from the west coast and moved towards the coast before dissipation (as seen from the radarscope observations by India Meteorological Department, Santa Cruz airport). Thus the continental traverse of about 100 km prior to dissipation (over Bombay) cause considerable contamination of the clouds by industrial aerosols during period III.

(c) pH, ionic balance and salinity

The weighted mean pH, ionic balance (μEq l^{-1}) and total salinity (mg l^{-1}) for different places have been listed in Table 5. An interesting feature is that the stations close to the coastline show the highest pH, 6.05–6.20 while inland stations have values ranging between 4.45–5.20. The latter range of values is typical of industrial areas (e.g. Okita, 1972). Curiously enough the mean pH for Chembur is 4.85 and is higher than the value for BARC, Trombay. The latter site is, however, situated more or less downwind of industrial Chembur but across a natural barrier, the Trombay hill, 200–300 m high. Concentration of SO_4 on the other hand is distinctly higher at Chembur than at Trombay (as seen earlier in Table 3). Therefore it is only reasonable to believe that reactions of SO_2 on particulate matter and the presence of basic and buffer constituents in the Chembur air cause the higher pH while BARC, Trombay has relatively more filtered air. As to the pH value at BARC, there is considerable evidence. Daily or bidaily samples collected by the author at the same site during 1972 gave pH values ranging from 4.0–4.9 (Sequeira, 1973). Furthermore, the modal value of 182 short term rainwater samples analyzed by Zutshi (1975) lies around a pH of 4.6.

Mostly there is a positive ionic balance observed in Bombay. These were reported to be ~10% of Na in Swedish precipitation (Eriksson, 1960). The present excesses are higher due to a predominant excess of Ca. On the other hand samples from Chembur and Trombay show anion excesses. They also have the lowest pH. These excesses are, therefore, believed to be caused by washout of acidic gases and aerosols. It is the belief of several workers that SO_2 is chief cause of acidic precipitation (Granat, 1972; Okita, 1972). According to Beilke & Georgii (1968) washout of SO_2 forms a significant fraction of the SO_4 in rainwater collected at ground level in urban regions. Indeed the Chembur region accounts for over 50% of the SO_2 emitted by industries in Bombay. The short range variation in pH within Bombay suggests that washout is the main process operative as far as removal of industrial air pollutants is concerned.

The ionic load, i.e. salinity gives a fairly good indication of pollution within the city though in a qualitative sense. It is seen that Chembur has the highest and Colaba the lowest salinity as expected. The value for Chembur directly reflects the dustloads observed there which are much higher than in other parts of Bombay (Yennawar et al., 1970). Other inland stations show distinctly higher values than Colaba or Tarapur, the excesses over the Colaba value being of industrial origin. Belapur has a rather low value probably due to the long passage of air over the Thana creek during monsoon.

From the above discussions one may classify Colaba and Tarapur as 'clean'; Bandra and Borivli as slightly polluted; BARC (Trombay),

Ghatkopar, Belapur and Thana as fairly polluted and Chembur as highly polluted areas in and around Greater Bombay, of course, on a relative basis.

4. Conclusion

The monsoonal sea salt deposition in and around Bombay during 1974 is estimated at ~ 180 kg ha^{-1} and is typical of any other coastal site. Numerous workers have compared the mutual proportions of sea salt constituents in precipitation with those found in seawater and have found positive, negative and no enrichments with respect to Na. These inconsistencies have been reported over the last three decades or so (cf. Glass & Matteson, 1973). The present values suggest that seasonal fractionation referred to above may not be significant during the SW monsoon period.

The magnitude of the 'excess' Ca obtained in rainwater from Bombay cannot be explained by the supersaturation of $CaCO_3$ in tropical sea water and more work is necessary to find out the mainly continental source suggested.

The pH, ionic balance and salinity of rainwater could be successfully used to get a qualitative picture of the state of lower air even over a small coastal industrial area like Bombay when it faces a steady monsoon current.

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МУССОННЫЕ ОТЛОЖЕНИЯ МОРСКОЙ СОЛИ И ЗАГРЯЗНИТЕЛИ ВОЗДУХА НАД БОМБЕЕМ

Во время периода юго-восточного муссона 1974 г. в Большом Бомбее и его окрестностях производились репрезентативные пробы дождевой воды. Оценено, что во время каждого муссона здесь в среднем откладывается порядка 200 *кг/га* морской соли. Во всем Бомбее, включая относительно незагрязненные места, наблюдается большой избыток кальция. Источник этого избытка представляется не морским. Для характеристики различных областей Бомбея по степени загрязнения используется среднее значение pH, ионный баланс и соленость дождевой воды.