Rainfall Variations in an Urban Industrial Region

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ABSTRACT

The rainfall data, for the period 1901–69, of three stations in the region downwind of the urban industrial complex at Bombay and of two stations in the nearby non-urban region, have been analyzed. The study has indicated that, with respect to the non-urban region, the region downwind of the urban industrial complex recorded an increase of rainfall by about 15%, significant at less than the 1% level, during 1941–69 which is the period of increased industrialization.

1. Introduction

One important meteorological consequence of atmospheric pollution is its possible influence on rainfall. Urban regions, which are the main sources of pollution, have been cited as recording, based on available worldwide data (Landsberg, 1962), an 11% increase in annual rainfall (Changnon *et al.*, 1971) as compared to rural regions.

The evaluation of the influence of pollution on rainfall presents problems because of the complex effects of the prevailing pollutants on the micro-structure of clouds in the region. While a decrease in rainfall has been noticed over areas where sugar-cane burning is practiced (Warner, 1968), remarkable increases have been reported in the United States in regions downwind of certain pollutant sources, namely, steel mill complexes (Changnon, 1968) and pulp and paper mill complexes (Hobbs *et al.*, 1970). No such effect has, however, been noticed downwind of a steel mill complex in Australia (Ogden, 1969). The probable reasons for the divergent effects reported on precipitation of pollutants from steel mills have been discussed (Changnon, 1971).

While the above studies indicate rainfall variations in regions where pollutants from specific sources are dominant, such studies with respect to urban regions where phenomenal increases in industrial activity have taken place are limited. An attempt is therefore made to look into this aspect with reference to Bombay, which is the second largest city in India, as part of the Institute's program of work on air pollution and rainfall.

2. Locations selected for study

The ability to evaluate, using climatological data, the effect of urban industrial pollution on rainfall is limited. Even limited success rests on the availability, which is not always met with in the case of every metropolis, of 1) suitable locations which could help provide some sort of target-control contrast as is sought in the case of planned cloud seeding experiments, and 2) rainfall data, for those locations, for periods extending well into the past when the levels of pollution in the region would have been decisively less. Long series of rainfall data are available for Alibag (18°38′N, 72°52′E) and Colaba (18°54′N, 72°49′E) which are situated on the west coast and for Pen (18°44′N, 73°06′E), Panvel (18°59′N, 73°07′E) and Kalyan (19°15′N, 73°07′E) which are situated eastward.

The raingages located at Pen, Panvel and Kalyan are maintained by the State (formerly known as Bombay and now as Maharashtra) and the raingage located at Colaba is maintained by the Centre (India Meteorological Department). There are two raingages located at Alibag at two different sites, one being maintained by the State and other by the Centre. As a longer period record is available for the State-maintained raingage (this gage was in existence even prior to 1900 whereas the other one came into existence only in 1929), the data of this gage have been used throughout the analyses. No significant changes took place in the past either in rainfall recording techniques or in raingage instrumentation, at any of the stations.

The stations are shown in Fig. 1. There has been no major industrial activity either in Alibag or in Pen. All such activity has been concentrated only in the area north of Colaba, which together with Colaba, constitutes the city of Bombay and its suburbs. The areas where major industrial establishments, such as refineries, petrochemical complexes, cotton mills, textile factories, synthetic material plants, thermal power stations, etc., have been situated are also shown in this figure.

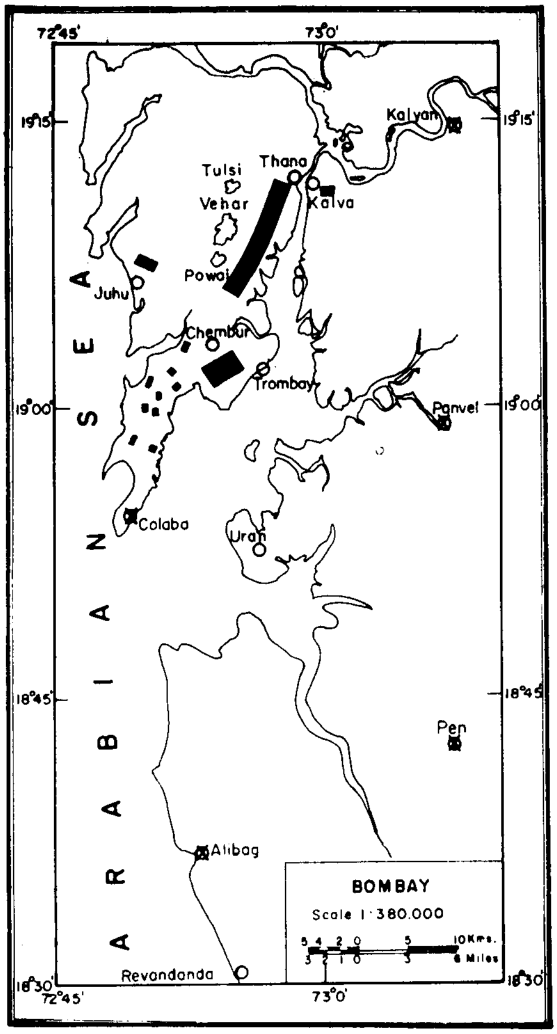

FIG. 1. Locations of non-urban stations, Alibag and Pen, and urban stations, Colaba, Panvel and Kalyan. Solid strips denote locations of major industrial establishments. Lake regions mentioned in text are also shown.

3. Effect, nature and levels of pollution

While the effect of heat and water vapor pollution would tend to destabilize a cloud, particulate pollution could act in either direction depending upon the nature and size distribution of the particulates. The effect of gaseous pollution would perhaps be in the direction of stabilizing a cloud, since certain gases such as sulphur dioxide are nucleogenic (Vohra *et al.*, 1970); it is also known that increasing concentrations of ammonia, nitrogen dioxide, and sulphur dioxide deactivate natural ice-forming aerosols (Georgii, 1960). The net effect of pollution on rainfall is, therefore, unpredictable.

The total amounts of emission of major pollutants from the different fuel sources and industrial establishments in the region under study have been estimated (Zutshi, 1970). These are 708, 160, 14 and 120 tons day^{-1} in the case of carbon monoxide, sulphur dioxide, oxides of nitrogen, ammonia, and particulate matter. The Bombay Municipal Corporation removes more than 2000 tons of refuse and garbage every day of which 20–25% is burnt locally.

4. Target-control contrast

The prevailing wind in the region during the summer monsoon (June to September), which accounts for about 95% of the annual rainfall, is from southwest to west (Table 1). It may reasonably be considered, therefore, that the precipitation recorded at Alibag and Pen is from maritime cumuli, not modified in their microstructure by urban industrial pollutants, the centers of which are located north of the stations at distances $\geqslant 30$ km. The precipitation recorded at Panvel and Kalyan is also from maritime cumuli which, in this case, are likely to have been modified in micro-structure by pollutants picked up in course of their passage downwind over the pollution centers. Colaba is on the southwestern tip of the urban industrial complex and is thus upwind of the pollutant sources; however, as certain pollution sources are in the immediate vicinity of Colaba, it may not be free from industrial pollution. From these considerations it is seen that the non-urban region, Alibag and Pen, serves as a control, and the urban industrial region, Colaba, Panvel and Kalyan, serves as a target in the present study.

5. Phenomenal increase in industrial activity

The percentage of the industries, relative to those existing in 1970, which were established in Bombay and its suburbs at the end of each decade, beginning with the year 1901, is shown in Fig. 2. The information is based on the data made available through the courtesy of the Directorate of Industries, Bombay. The number of industries existing in 1940 increased fivefold by 1970, the steepest rise having taken place during the decade 1951–60.

6. Analysis

a. Decade mean rainfall at different stations

The mean seasonal rainfall during the summer monsoon for each decade, and the percentage variation occurring in each decade with respect to the earliest decade are given in Fig. 3 and Table 2, respectively. In most cases, rainfall in each successive decade following the initial 1901–1910 period increases at both urban and non-urban stations. This feature, which is in conformity with what was reported earlier, namely, that the rainfall of certain west-coast stations has increased during the present century (Koteswaram and Alvi, 1969), does not, by itself, delineate the influence of

TABLE 1. Average upper wind directions and speeds (knots; in parentheses) based on rawinsonde data at Bombay for the period 1954–60 (afternoon).

Height (km)	June	July	August	September
Surface	252 (9.8)	256 (10.8)	264 (8.7)	276 (6.1)
0.3	251 (12.8)	255 (17.5)	261 (15.0)	278 (11.7)
0.6	250 (13.2)	256 (19.0)	260 (16.3)	275 (10.5)
0.9	250 (12.8)	257 (20.4)	262 (17.0)	275 (10.0)
1.5	243 (12.9)	255 (20.2)	261 (17.6)	268 (8.4)
2.1	240 (10.4)	257 (18.8)	258 (16.4)	272 (7.5)

urban industrial pollution on rainfall. But, a few points of interest are to be noted from Table 2. A consistent pattern in the rainfall variation between urban and non-urban stations (with all the urban stations recording higher increases than the non-urban stations) became apparent only over the last three decades, during which period the number of industrial establishments, as already stated, increased fivefold. Also, the increases which were noticed only at the urban stations during the 1951–60 decade (when the steepest rise in the number of industrial establishments took place) attained a high level of statistical significance (less than 1% based on the student t-test). When the data of Table 3 are compared for the two periods 1901–40 and 1941–69, the increases occurring during the latter period at urban stations only are highly significant (less than 1%).

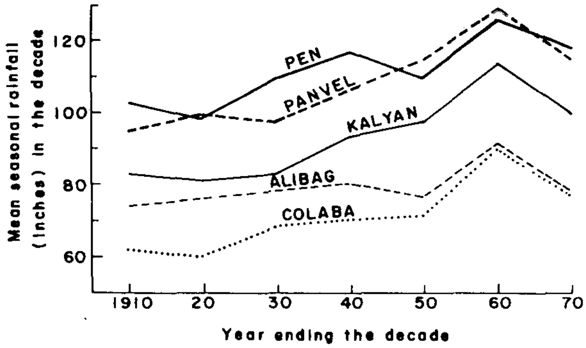

FIG. 3. Decade mean seasonal rainfall at urban stations, Colaba, Panvel and Kalyan, and non-urban stations, Alibag and Pen.

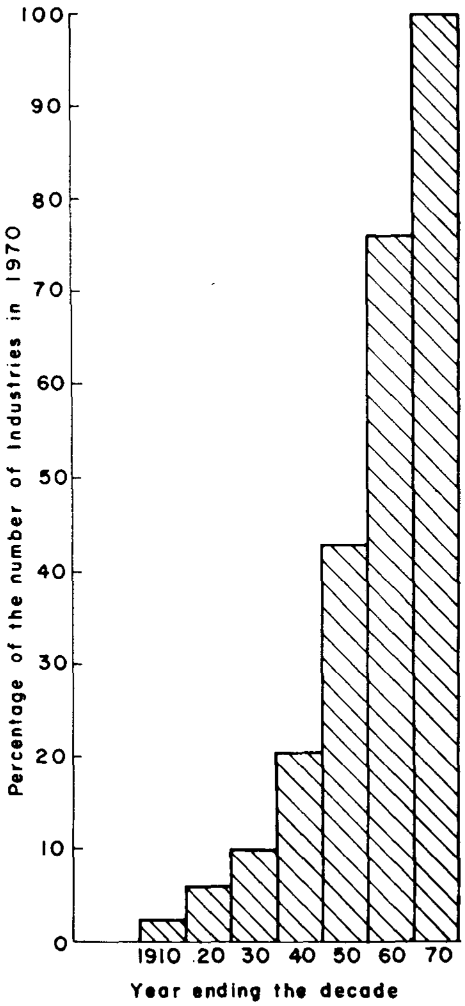

FIG. 2. Decade-wise progress of industrial activity in the Bombay area.

b. Double mass curves

The double mass curve technique which is normally used for testing instrumental and/or exposure errors has been used to examine the influence of urban pollution on rainfall. Application of this technique to the analysis of rainfall data in the present study is considered justified because the correlation between the rainfall values of the stations are fairly high as shown in Table 4, and also because the stations are near

TABLE 2. Percentage change in the mean seasonal rainfall of each decade with respect to that of the earliest decade 1901–10.

Station	Period 1911–20	1921–30	1931–40	1941–50	1951–60	1961–69
Alibag	+2.7	+5.4	+ 8.1	+ 2.7	+23.0	+ 5.4
Pen	−4.8	+5.8	+12.6	+ 5.8	+22.2	+14.6
Colaba	−3.2	+9.7	+12.9	+14.5	+43.5*	+22.6
Panvel	+4.2	+2.1	+11.6	+20.0	+34.7*	+20.0
Kalyan	+2.4	0.0	+12.0	+16.8	+36.1*	+19.3

* Significant at less than the 1% level.

TABLE 3. Mean seasonal rainfall (inches) during two periods and the percentge increase during the second period.

Station	Period 1901–40	1941–69	Percentage increase
Alibag	77.5	81.6	5.3
Pen	106.7	117.4	10.0
Colaba	65.6	78.6	19.8*
Panvel	99.7	118.9	19.3*
Kalyan	85.4	103.3	21.0*

* Significant at less than the 1% level.

TABLE 4. Rainfall correlation coefficients.

Station	With respect to Alibag Period 1901–40	1941–69	With respect to Colaba Period 1901–40	1941–69
Pen	0.73	0.81		
Colaba	0.87	0.86		
Panvel	0.62	0.78	0.63	0.83
Kalyan	0.64	0.72	0.65	0.76

TABLE 5. Mann-Whitney test applied to distributions of rainfall ratios of given station to those of Alibag between the two periods 1901–40 and 1941–1969. *Z* refers to the test statistic.

Station	*Z*	Percentage level of significance
Colaba	2.6	0.5
Panvel	2.7	0.3
Kalyan	2.4	0.8
Pen	0.8	21

enough to be influenced by the same meteorological conditions (the maximum distance, ~50 km, is between Alibag and Kalyan). In preparing the double mass curves, the non-urban station Alibag, which showed minimum variations in rainfall (see Tables 2 and 3) and which, due to its proximity to the coast, is likely to be more free from pollution than the other non-urban station Pen, has been selected as the base station.

Double mass curves have been prepared considering the values of 3-year's mean monsoon rainfall beginning with 1901: these are presented in Figs. 4 and 5. Of the four stations Pen, Panvel, Colaba and Kalyan, all but the first showed considerable departures in rainfall from around 1940–42, indicating increases, as shown by slope changes at points marked by arrows in the figures. The average percentage increases during the 29-year period 1941–69 at Pen, Panvel, Colaba and Kalyan are 4.8, 14.5, 14.1 and 15.8, respectively. The Mann-Whitney test, which is non-parametric, when applied to the distribution of the ratio values of rainfall of each station to the rainfall of Alibag between the two periods 1901–40 and 1941–69, showed that the

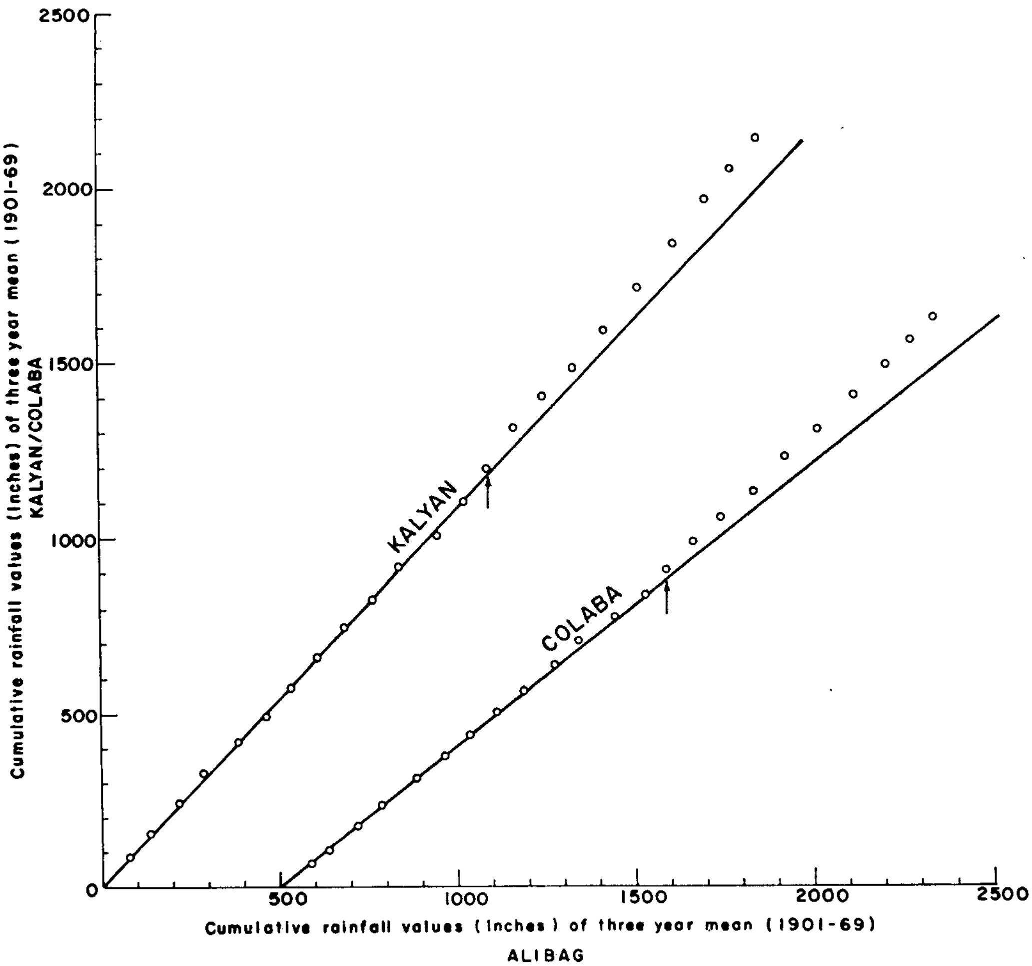

FIG. 4. Double mass curves for urban stations, Kalyan and Colaba, with respect to non-urban base station Alibag. The abscissa is shifted for clarity in the case of Colaba.

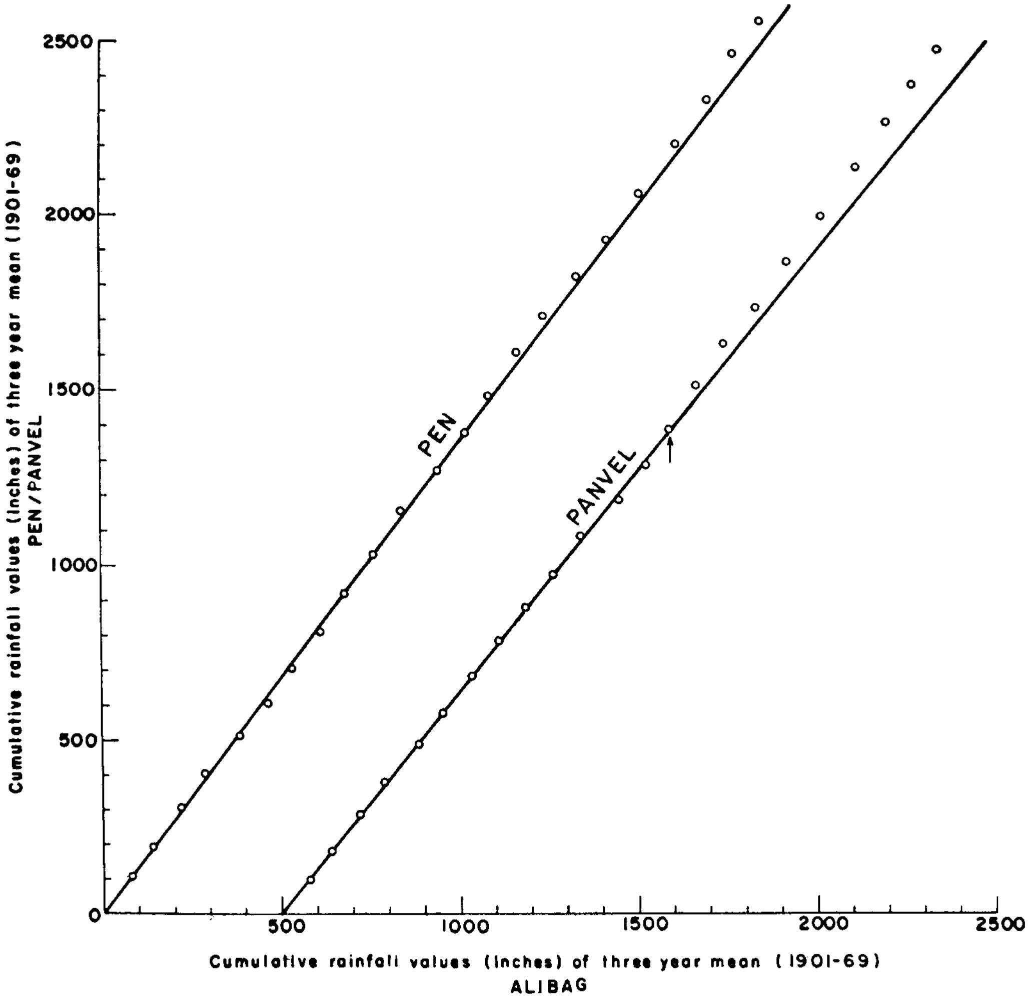

FIG. 5. Double mass curves for non-urban station Pen and urban station Panvel with respect to non-urban base station Alibag. The abscissa is shifted for clarity in the case of Panvel.

departures at the three urban stations are significant at less than 1% level (Table 5). Also, double mass curves prepared, with respect to Alibag, for the lake stations Tulsi, Vehar and Powai situated in the urban region (these curves are not presented), indicated that, from around 1940–42, rainfall at these stations also increased. The average percentage increases for these three stations are 9.9, 7.6 and 10.9, respectively, and are significant at the 5% level according to the Mann-Whitney test.

TABLE 6. The trend index of the ratio of rainfall of each station with that of the non-urban station Alibag. Figures in parentheses represent the estimated significance percentage levels (two-tailed).

Station	Period								
	1901–10	1911–20	1921–30	1931–40	1941–50	1951–60	1961–69	1901–40	1941–69
Pen	0.01 (>90)	−0.81 (44)	−0.15 (>90)	0.06 (>90)	2.22 (6)	−2.82 (2.4)	0.95 (37)	−0.77 (45)	0.19 (85)
Colaba	0.36 (73)	−1.59 (16)	−0.19 (85)	−0.05 (>90)	1.61 (15)	0.11 (>90)	−0.30 (77)	−1.61 (12)	0.03 (>90)
Panvel	−0.31 (76)	−1.11 (30)	0.64 (54)	0.46 (65)	2.07 (7.6)	−2.12 (7)	0.29 (78)	0.39 (70)	0.64 (53)
Kalyan	−0.05 (>90)	−0.80 (45)	1.54 (17)	−0.39 (70)	4.91 (<1)	−0.84 (43)	1.64 (15)	0.10 (>90)	1.05 (30)

c. *Rank correlation with time*

The trend index of the ratio of rainfall of each station with that of Alibag has been calculated for each decade following Woodcock and Jones (1970); the index has also been calculated for each of the two periods 1901–40 and 1941–69. The trend indices and the significance levels resulting are given in Table 6. While there is no consistency in the trend when the values are considered decade-wise, the trend was upward in all cases when the period 1941–69 was compared with 1901–40; the values, however, are not significant.

7. Discussion

The urban stations in the Bombay industrial complex, with respect to nearby non-urban stations, exhibited significant increases in rainfall beginning about 1940–42 (Figs. 4 and 5). As this is also the period which marked the beginning of increased industrialization in the region (Fig. 2), it is considered that one possible factor contributing to the rainfall increases indicated is the increased industrialization. The maximum increase indicated is about 15%. Also, the fact that no consistent and significant trend became discernible in the ratios of rainfall between the urban stations and the non-urban station (Table 6) suggests either or both of the following:

1) The effect of industrialization on rainfall is not entirely dependent on the extent of the industrialization.
2) There have been other factors besides urban industrialization which have been influencing the rainfall.

It is seen, with reference to Alibag, that the station Colaba which is just upwind of the urban industrial complex recorded as much increase in rainfall as the two stations Panvel and Kalyan which are downwind. That there is no noticeable difference in the behavior of the two downwind stations from the behavior of the upwind station is confirmed by the double mass curves presented for Panvel and Kalyan with respect to Colaba (Fig. 6) which indicated no changes in their slopes.

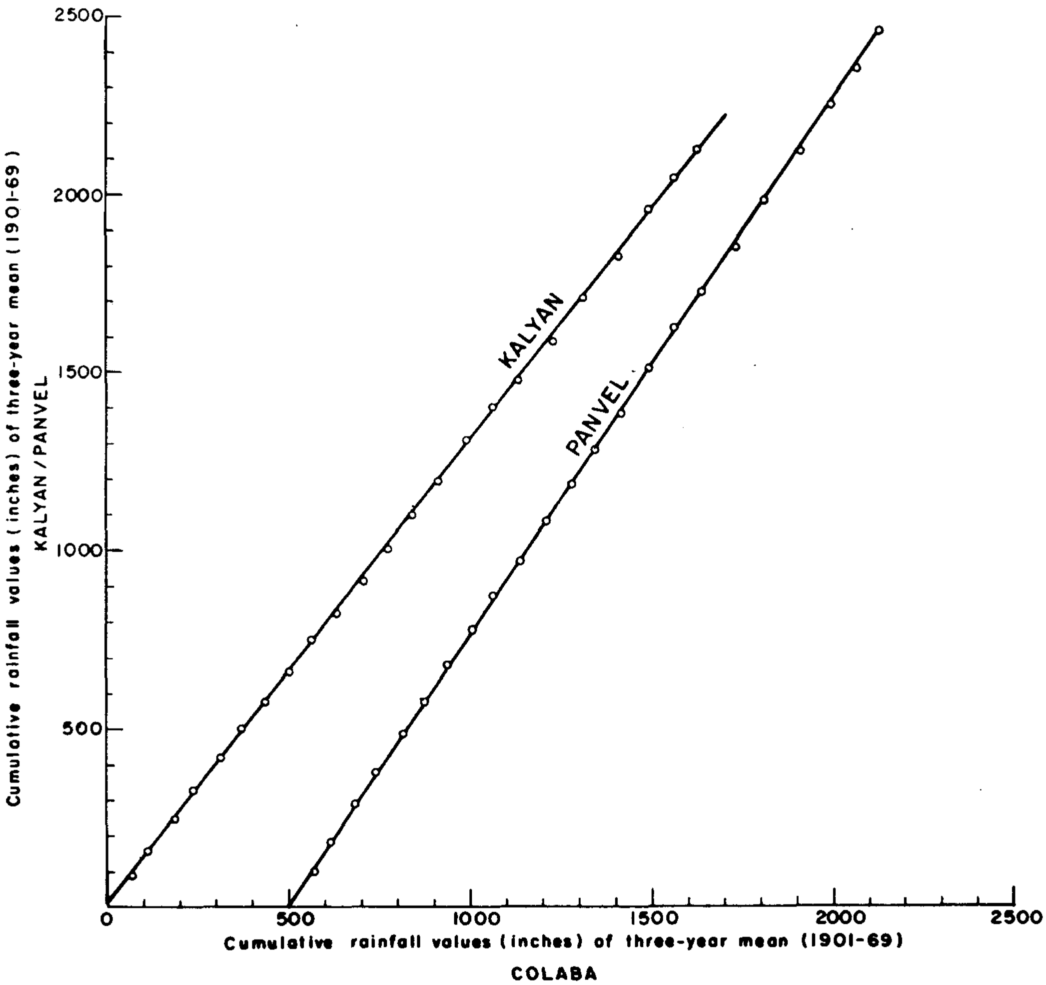

FIG. 6. Double mass curves for downwind urban stations, Kalyan and Panvel, with respect to urban base station Colaba. The abscissa is shifted for clarity in the case of Panvel.

TABLE 7. Values of mean surface temperature (with standard deviations in parentheses).

Period	Amini Devi				Alibag*				Colaba			
	Dec.	Jan.	Feb.	Mar.	Dec.	Jan.	Feb.	Mar.	Dec.	Jan.	Feb.	Mar.
1901–40	80.98 (1.30)	81.08 (1.17)	82.27 (1.30)	83.93 (1.32)	75.38 (1.51)	72.59 (1.30)	73.63 (0.87)	77.35 (1.52)	77.84 (0.87)	75.66 (1.76)	75.87 (1.46)	79.78 (1.27)
1941–65	81.82 (1.26)	82.06 (1.79)	83.33 (1.48)	84.60 (1.33)	75.66 (1.80)	73.46 (1.15)	74.48 (1.67)	78.80 (1.19)	78.84 (1.51)	75.99 (1.68)	77.21 (1.97)	80.46 (1.72)

* Data considered for Alibag are from 1933 which is the first year of data for this station.

This feature, by implication, suggests that clouds precipitating at Colaba also have been influenced by urban industrial pollution. This finding lends support to the reported upwind effects of cloud seeding (Braham and Flueck, 1970).

The inland station Pen, in the non-urban region, also has indicated an increase in rainfall with respect to Alibag (see Table 3); the increase, however, is small, being about 5%, and is not statistically significant.

One important question which arises in the present context is which factors of the urban industrial pollution (gaseous and particulate emission, or heat emission) should be considered as primarily responsible for the observed increases in rainfall, especially in view of the fact that the effect on local rainfall of high urban temperature has been recently demonstrated (Aitkinson, 1971). No data relative to a possible heat island effect in the Bombay region are available to consider the effect of heat emission (thermal pollution). The question of greater importance, however, in the present context is whether temperatures in the Bombay region during the last three decades have shown an increase as compared to the previous four decades which differ from that in the non-urban region. This aspect has been examined, insofar as surface levels are concerned, from monthly mean surface temperatures (using mean values of the maximum and minimum temperatures) of the two west-coast stations Colaba and Alibag and of the island station Amini Devi (11°07′N, 72°44′E). The last mentioned station has also been considered because it may, on account of its geographical location, represent the variations in the thermal conditions of the non-urban region even better than Alibag. As the temperatures in the monsoon months are likely to be affected by the processes of precipitation and cloud cover, the months selected for the purpose are only the dry months December to March. The mean temperature for the three stations referred to above for the periods 1901–40 and 1941–65 are presented in Table 7 (values of standard deviation calculated are given in parentheses). The temperature change at Colaba does not differ from those of either Alibag or Amini Devi. All three stations indicated, in the corresponding months, increases in temperature (some attaining statistical significance) during the later period. Though little can be said from this analysis as to temperature variations at higher levels, the present findings, insofar as the surface temperatures are concerned, do not support the possibility that the suggested rainfall increases in the Bombay region were primarily due to the effect of heat emission.

As has already been mentioned, daily gaseous pollutants emitted in the urban region amounted to some hundreds of tons, and the particulate pollutants a little more than a hundred tons. The effects of these pollutants on the background concentrations of the different types of nuclei, such as cloud condensation, giant hygroscopic, and ice-forming, are, however, not known (no measurements of nuclei concentrations have been made).

It is hoped that heat island and nuclei measurements in the regions under question will help to isolate those factors of the urban industrial complex which are mainly responsible for the indicated increases in rainfall.

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