FURTHER WORK ON FORECASTING SMALLPOX EPIDEMICS IN INDIA AND BRITISH TROPICAL COUNTRIES BASED ON PREVIOUS CLIMATIC DATA

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(With 3 Figures and 2 Maps in the Text)

In 1926 I recorded a comprehensive study of sixty years of smallpox data in India in relation to climatic data with maps and diagrams. The key to the problem was furnished by Fig. 1 (here reproduced for convenience of reference) which showed the average monthly smallpox deaths per 100,000 for the eight provinces of India in relationship to the monthly average rainfalls, mean temperatures, the relative and the absolute humidity or aqueous vapour tension. In the seven provinces which receive a large part of their total annual rainfall from the South-West monsoon in June to October, which coincides with the maximum yearly absolute humidity, there is a regular great fall during those months in incidence of smallpox to a low annual minimum rate. In Madras alone, which receives a large part of the annual rainfall from the North-East monsoon in October to December, when the absolute humidity is declining, there is no material fall in smallpox in June to October and no very

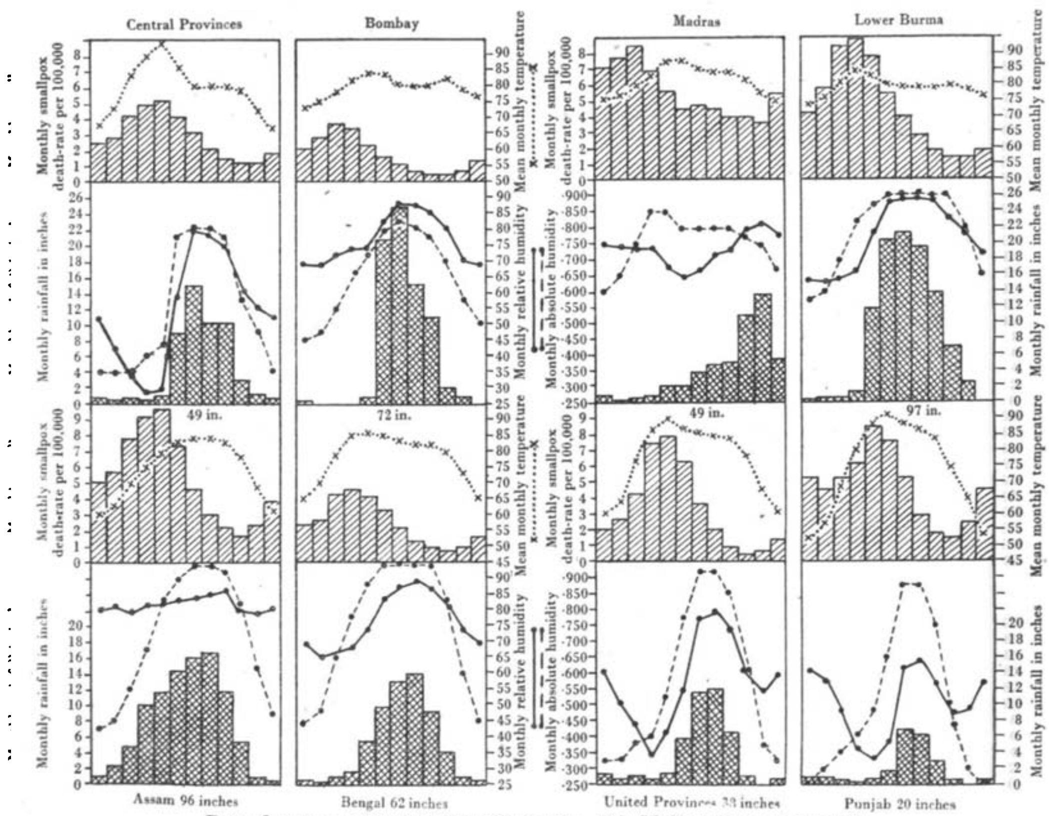

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Fig. 1. Average monthly smallpox death-rate, rainfall, temperature and humidity.

low annual minimum season. In that province alone there is a moderate annual decline of the disease April to June in close relationship with the highest monthly absolute humidity in April and May.

A map in the original paper shows the annual incidence of smallpox in thirty-eight divisions of India, together with inset maps of the annual rainfall and the absolute humidity in July at the height of the South-West monsoon. This brings out the striking fact that the highest smallpox annual rates occur in south-east Madras and in the far distant North-West Frontier Province. It is therefore significant that the only climatic feature common to those two areas is exceptionally low South-West monsoon absolute humidities. Further, smallpox incidence decreases steadily as we proceed from the very high monsoon absolute humidity area of Bengal to the north-west through the United Provinces and the Punjab to the North-West Frontier Province with steadily decreasing monsoon absolute humidities. A relatively high rate in Oudh is explained by vaccination having for long been backward in that area.

I therefore concluded that the annual high South-West monsoon absolute humidities exert a strong restraining influence on the spread of smallpox infection.

It is also worthy of note that a study of the monthly incidence of the mild elastrin type of smallpox in England in 1921–7, which I recorded in 1928*b*, showed in each year that the highest incidence was in the month after the lowest absolute humidity and the lowest incidence in the month after the highest absolute humidity of the year.

A table in my original memoir of the annual provincial smallpox death-rates from 1875 to 1904 brings out the additional fact that not only does the annual incidence increase in the northern provinces of India with the decrease in the South-West monsoon absolute humidities but the degrees of the yearly variations increase in the same areas. Thus in Bengal the annual death-rate in those thirty years never rose above 0·77, but rates of from 2·0 to over 4·0 per mille are not rare in the United Provinces, the Punjab (including the North-West Frontier Province in the earlier years) and also in the Central Provinces. In relation to this incidence it is in those provinces that the greatest failures of the monsoon rains occur, accompanied by exceptionally low monsoon absolute humidities favouring the prevalence of smallpox and inhibiting to some extent the regular great decline of the disease during the monsoon period.

For example, diagram III of my memoir shows that a 50 % deficiency in the monsoon rainfall in 1904 in Bombay resulted in the October annual minimum monthly smallpox death-rate remaining about seven times as high as is usual at that season. The regular annual rise in November and December of that year went on to an epidemic from December 1904 to June 1905 with a maximum of about seven times the average figure.

Charts were next worked out for each province to show the annual smallpox incidence, the annual rainfall and the average monthly absolute humidity during the critical months of the monsoon or the autumn months before the early cold weather seasonal increase of smallpox for several decades. Reference must be made to my 1926 memoir for these, but the results may be summarized here. In the provinces above-mentioned, in which the greatest epidemics of smallpox occur, about four-fifths of them followed immediately on low rainfall and low absolute humidity in relation to the previous monsoon, so they could have been accurately forecasted on the lines indicated. Exceptionally low absolute humidity immediately after a severe epidemic may fail to produce a further epidemic, presumably owing to exhaustion of susceptible material; and several years of high monsoon absolute humidity may be followed by increased smallpox, apparently due to accumulation of susceptible material.

The next step was to put my conclusions to a severe and practical test by publishing in the *Indian Medical Gazette* the incidence forecasts of smallpox (as well as of cholera and plague) for the different provinces of India, based on the meteorological data of the immediately preceding monsoon periods which I was able to obtain in good time when Medical Adviser at the India Office. The results of these were reported in my presidential address to the Royal Society of Tropical Medicine in 1933.

It so happened that in all four years the monsoon was well distributed and consequently very unfavourable for forecasts. Only in the North-West Frontier Province in 1932 was there a serious deficiency of the monsoon rains and the absolute humidity; and in this instance an epidemic was correctly forecast. Further, absolute humidities much above the average in 1931 enabled me correctly to forecast low smallpox incidence in India in 1932. In two of the four years average monsoon data were followed by the absence of epidemic prevalence as expected. Thus the first three forecasts were more correct than I expected in years of good monsoons. In those for the last year, 1933, good 1932 monsoon rains led me not to expect much increase over the average rates except in the north-west of India, where increased prevalence took place, but the increases were greater than I had anticipated.

In my 1926 paper I only dealt with provincial smallpox data. In a comprehensive study of cholera and climate made at the same period (1928*c*)

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I found it necessary to study the data for forty-five divisions of India to enable me to make very successful forecasts for fifteen areas of that vast country. During the last twelve months I have made further studies of smallpox and climate in India of a more detailed nature in the hope of clearing up the few exceptional epidemics, especially in the Central Provinces, which I had not been able to explain, with a view to formulating rules for more accurate forecasts in future. I have also studied a large number of colonial medical reports to ascertain if such rules are likely to apply to them as well. These researches form the subject of the present paper.

SATURATION DEFICIENCIES AND SMALLPOX INCIDENCE

In my 1933 address, already mentioned, I reported that in some instances I had found saturation deficiencies a better guide than absolute humidities in forecasting smallpox epidemics. I had also shown (1928*b*) that saturation deficiencies were the most useful data in forecasting epidemics of plague in India. These data are obtained by deducting from the figure of the saturation point of the absolute humidity or aqueous vapour tension at the mean monthly temperature the actual absolute humidity average for the same month. They thus represent the drying power of the atmosphere and high saturation deficiency accompanies low absolute humidity; both are favourable to the further incidence of smallpox. During the winter of 1946–7 I spent several months in working out these data for each province for several decades, but found they ran so closely parallel with the monthly absolute humidity curves that they presented no material advantages over the latter and still failed to account for a small proportion of smallpox epidemics which I had been unable to explain as the result of previous climatic data.

A STUDY OF SMALLPOX EPIDEMICS IN INDIA AS A WHOLE DURING FIVE DECADES IN RELATION TO CLIMATE: INTERPROVINCIAL SPREAD

In the course of a three years' study of cholera epidemics in India (1928*c*) during fifty years divisional data often enabled the spread of the disease from one province to another to be traced. The Central Provinces is particularly liable to such invasions on account of its geographical position and to its being traversed by the main road and railway communications from east to west across this sub-continent. I therefore spent the summer of 1947 in a study of smallpox epidemics in India as a whole, as opposed to my previous studies of each province separately in watertight compartments. When tabulating the yearly divisional smallpox death-rates per mille I made notes from the reports of each year in the hope of finding information regarding possible spread from one province to another. I was not very surprised to find a complete absence of any such references: for from personal experience in the Sanitary or Public Health department of Bengal I was aware that each provincial annual public health report was essentially a watertight department. In fact in several hundred such reports I found only a single reference to the spread of smallpox from an adjacent badly vaccinated Indian state!

I had therefore to make use of a plan I had found invaluable in my studies of cholera epidemics, namely to make maps of the divisional incidence of the disease during the principal epidemics and to enter the provincial epidemic data in tables: the only possible method of dealing with the vast amount of data within a reasonable compass. By this means further light has been thrown on the subject which appears worthy of record in as brief a form as the extent of the material available permits.

First I divided up the period into epidemic and quiescent years. Fig. 2 shows the yearly all-India smallpox rates and vaccinations. It illustrates the epidemic and quiescent periods dealt with below. The epidemic years included those in which smallpox reached epidemic levels in two or more provinces; the quiescent years those in which there was not more than one epidemic area apart from the continuation into a second year from the previous one.

It was necessary to take some arbitrary figure as an 'epidemic level' and I choose a rise to 50 % over the average of the decade; for owing to the decrease in the epidemic levels through the greatly increased efficiency and extent of vaccination shown in a paper of 1945 the later qualification was necessary, especially during the first three decades of the most rapid decline of the disease in India. In order to indicate exceptionally severe epidemics + + after the rate per mille in each province indicates an increase of over 50 % but under 100 % over the average of the decade; likewise + + + indicates an increase of over 100 %. A few entries of + indicate a rise of 33 % to 50 %. In a similar manner monsoon rainfall and absolute humidities of moderate degrees are indicated by − and of exceptionally high degrees by − −; for the actual rainfall deficiencies in inches would be misleading because an annual deficiency of 5 in. in the Punjab would amount to 25 % of the total, whereas in Assam it would only represent a decline of 5 %. The last column in the tables shows the months of epidemic prevalence. Here again an increase in each month over the average smallpox death-rate of 1 in 100,000 is taken as an epidemic level for that decade and province. All these data had to be worked out and I found it of great help to mark in red ink all the months of epidemic prevalence in my tables. The onset of an epidemic is invariably indicated by exceptionally high death-rates for the season in November to January closely following deficient monsoon rains and absolute humidities during the preceding monsoon months of June to October. Occasionally, however, the epidemic rate for the season of the year did not entered, together with the variations from the average of the annual rainfall and of the monthly absolute humidity monsoon or autumn of the previous rains. The months of epidemic level are also shown.

1877–9 SMALLPOX EPIDEMIC

Table 1 includes the relevant data of the two greatest smallpox epidemics since records have been available for all the provinces of India. In both 1878 and 1884 the all-India smallpox death-rate rose to 1·70 per mille, against an average

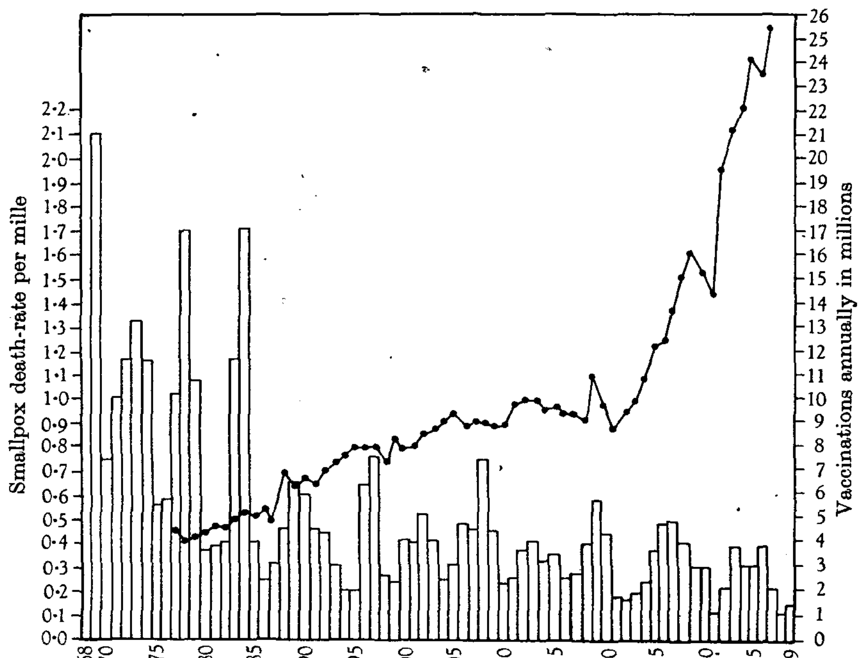

Fig. 2. Smallpox rates per mille and annual vaccinations in millions in British India.

commence until about the following March. The significance of this occurrence will appear in due course. As already mentioned the most serious epidemics continue throughout the year and into the following one, and only cease towards the end of the second year following good monsoon rains. The absolute humidity deficiencies are of greater significance than those of the rainfalls for the simple reason that one-fourth to even one-half (as in Calcutta in September 1900 when boating took place in the main streets) of the annual rainfall may occur within four days; yet the absolute humidity, which is the main factor affecting the future smallpox rate, may actually be deficient in a month of high rainfall.

In Tables 1 and 2 every rise to the epidemic level, as above-defined, during the five decades is

figure of 0·77 for the years 1877–87, and more than twice as high as in any subsequent year. In my 1945 paper I showed that the vaccination department had only recently been organized in some of the provinces and well-vaccinated Bombay had a comparatively low smallpox incidence during this period. Recent studies of the old provincial public health reports have revealed that those high rates were partly due to the spread of the disease by *inoculation*, which was only made illegal towards the end of this period. Hence the great fall in the average yearly all-India death-rate to 0·47 in the following decade of 1888–97.

The tabulated data on the great 1877–9 epidemic will first be dealt with in some detail to bring out the climatic factors related to it. This will enable the operative data in subsequent epidemics to be deduced from the tables without detailed description when they are in accordance with the general rules I have laid down and permit attention to be concentrated on the exceptions to the rule with a view to their elucidation.

In Map 1 of 1877–9 the years of epidemic prevalence are entered in the affected divisions to show the very wide prevalence of smallpox and to indicate the probable lines of spread. The epidemic was associated with one of the greatest monsoon failures, in 1876, since vital statistics became available for British administered India, accompanied by widespread famine and cholera, more especially in the greatest areas of drought in the Madras and Bombay Presidencies, which resulted from extreme deficiency of the monsoon rains in those provinces, with only one-third of the normal rainfall in Madras.

In Bombay the smallpox rate of 0·60 in 1876 rose to 1·69 in 1877 following very low previous monsoon absolute humidity, but with normal monsoon rains in 1877. The epidemic ceased in the last quarter of that year. The worst affected division was the North Deccan with 4·85 deaths per mille, by far the highest rate in my tables for that area.

In Madras the very low monsoon rainfall and absolute humidity of 1876 were followed by a rise in the smallpox mortality from 0·80 to much the highest figure of 3·02 per mille in 1877, with the further result that the epidemic continued during the first ten months of 1878 with a death-rate of 1·90, but ceased after the good winter rains with high absolute humidities.

In the Punjab the monsoon rains were good in 1876, but in 1877 they were only half the average rate and consequently the monsoon absolute

Table 1. *Indian provincial smallpox epidemics*, 1877–99

(1) Year	(2) Province	(3) Deaths per mille	(4) Epidemic prevalence	(5) Previous rainfall	(6) Previous absolute humidity	(7) Months of epidemic prevalence	(8) Remarks
1877	Madras	3·02	+ + +	– –	– –	i.–xii. 1877	—
1878	Madras	1·90	+ +	+ +	+	i.–vi. 1878	Continued from 1877
1877	Bombay	1·69	+ + +	– –	– –	i.–xi. 1877	—
1878	Punjab	2·30	+ + +	– –	– –	x. 1877–xii. 1878	—
1879	Punjab	2·83	+ + +	+ +	+	i.–x. 1879	Continued from 1877
1878	United Provinces	3·99	+ + +	– –	– –	xi. 1877–xii. 1878	—
1878	Central Provinces	2·18	+ + +	–	+ –	iii.–viii. 1878	Spread from Deccan
1879	Central Provinces	3·44	+ + +	+ +	+ +	i.–xii. 1879	Continued from 1878
1879	Bengal	0·32	+ + +	–	+ –	iii.–xii. 1879	—
1880–2	Quiescent						
1883	Madras	1·30	+	+ –	– –	i.–xii. 1883	—
1884	Madras	2·10	+ + +	+ –	–	i. 1884–vii. 1885	—
1883	Bombay	0·81	+ + +	+ –	–	xi. 1882–xii. 1883	—
1884	Bombay	0·88	+ + +	+	+ –	i.–x. 1884	Continued from 1883
1883	United Provinces	3·14	+ + +	– –	– –	xi. 1882–xii. 1883	—
1884	United Provinces	4·59	+ + +	–	– –	i.–ix. 1884	—
1884	Bihar	0·56	+ +	–	?	ii.–vii. 1884	—
1883	Assam	1·36	+ + +	–	?	iii.–x. 1883	—
1884	Assam	1·05	+ +	–	?	i.–x. 1884	—
1885–7	Quiescent						
1888	Central Provinces	1·22	+ +	+	+ –	iii.–xii. 1888	Spread from U.P.
1889	Central Provinces	1·99	+ + +	–	–	i.–viii. 1889	—
1889	United Provinces	1·09	+ +	+	–	i–viii. 1889	—
1890	United Provinces	1·26	+ + +	+	–	i.–xii. 1890	—
1891	Madras	1·40	+ +	– –	–	i.–xii. 1891	—
1892	Madras	1·30	+ +	– –	– –	i.–ix. 1892	—
1893–5	Quiescent						
1895	Central Provinces	0·70	+	+	+	ii.–xii. 1895	Spread from U.P.
1896	Central Provinces	0·82	+ +	–	+	i.–xii. 1896	Continued from 1895
1896	Punjab	2·19	+ + +	– –	– –	x. 1895–xii. 1896	—
1896	United Provinces	0·91	+	–	+ –	iii.–xii. 1896	Spread from Punjab
1897	United Provinces	1·86	+ + +	– –	– –	vii.–x. 1897	—
1898–9	Quiescent						

Column (4): 33–50 % over average of decade, +; 50–100 %, + +; over 100 %, + + +.
Columns (5) and (6): excess, +; average, + –; deficient, –; very deficient, – –.
Column (6): data not available, ?.

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humidity was also very low. Accordingly smallpox rose to an epidemic level in October 1877 and continued very high throughout 1878 to reach 2·30 per mille against 0·70 in the preceding year. As usual in such a severe epidemic it was carried over into and continued high until after normal monsoon rains in 1879, but without reaching quite the epidemic level for that year as a whole.

In the Central Provinces the total rains were in excess, but the monsoon fall was average and the

Table 2. *Indian provincial smallpox epidemics*, 1900–25

(1) Year	(2) Province	(3) Deaths per mille	(4) Epidemic prevalence	(5) Previous rainfall	(6) Previous absolute humidity	(7) Months of epidemic prevalence	(8) Remarks
1900	Madras	0·84	+	−	− −	vi.–xii. 1900	—
1900	Bombay	0·52	+ +	− −	− −	xii. 1899–xii. 1900	—
1900	Central Provinces	0·63	+	− −	− −	ii.–xii. 1900	—
1901	Quiescent						
1902	Assam (South)	1·26	+ + +	− −	?	x. 1901–ix. 1902	—
1902	Bengal	0·73	+ + +	+	+	xii. 1901–xii. 1902	Spread from Orissa
1902	Bihar and Orissa	0·82	+ + +	− −	+ −	i.–xii. 1902	—
1903	United Provinces	0·46	+ +	−	−	iii.–viii. 1903	—
1903	Punjab	0·78	+ +	− −	−	i.–xii. 1903	—
1904	Quiescent						
1905	Bombay	0·92	+ + +	− −	− −	viii. 1904–xii. 1905	—
1905	Central Provinces	0·70	+ +	−	−	ii.–xii. 1905	—
1906	Central Provinces	0·83	+ + +	+	−	i.–viii. 1906	—
1907	United Provinces	1·26	+ +	+ −	+ −	vi.–xii. 1907	? Spread from C.P.
1908	United Provinces	1·26	+ + +	− −	− −	i.–ix. 1908	—
1908	Central Provinces	0·75	+ + +	−	− −	xi. 1907–viii. 1908	—
1908	Bihar	0·91	+ + +	− −	− −	xi. 1907–viii. 1908	—
1909	Bihar	0·66	+ +	− −	− −	xi. 1908–vi. 1909	—
1909	Bengal	0·90	+ + +	− −	−	—	—
1910–11	Quiescent						
1912	Bombay	0·32	+	− −	−	i.–vi. 1912	—
1913	Bombay	0·50	+ +	− −	− −	i.–viii. 1913	—
1912	Punjab	1·57	+ + +	− −	− −	i.–xii. 1912	—
1913	Punjab	2·00	+ + +	−	−	i.–viii. 1913	—
1913	Central Provinces	0·46	+ +	−	− −	i.–vii. 1913	—
1914	United Provinces	0·38	+ +	−	−	i.–vi. 1914	—
1915	Bengal	0·72	+ + +	−	− −	xii. 1914–ix. 1915	—
1916	Quiescent						
1917	Madras	0·90	+ +	−	− −	iii.–xii. 1917	—
1918	Madras	1·50	+ + +	+ −	− −	i.–xii. 1918	—
1919	Madras	1·00	+ +	− −	−	v.–xii. 1919	—
1918	Bombay	0·41	+ +	+ +	+ −	ii.–vi. 1918	Spread from Madras
1919	Central Provinces	0·53	+ + +	− −	− −	xii. 1918–vi. 1919	—
1919	Punjab	0·79	+ + +	− −	− −	xii. 1918–xii. 1919	—
1919	United Provinces	0·23	+ +	−	?	i.–iv. 1919	—
1919	Bengal	0·80	+ + +	− −	− −	i.–viii. 1919	—
1920	Bengal	0·80	+ + +	− −	−	i.–viii. 1920	—
1920	Bihar and Orissa	0·60	+ +	−	−	i.–viii. 1920	—
1921–5	Quiescent						

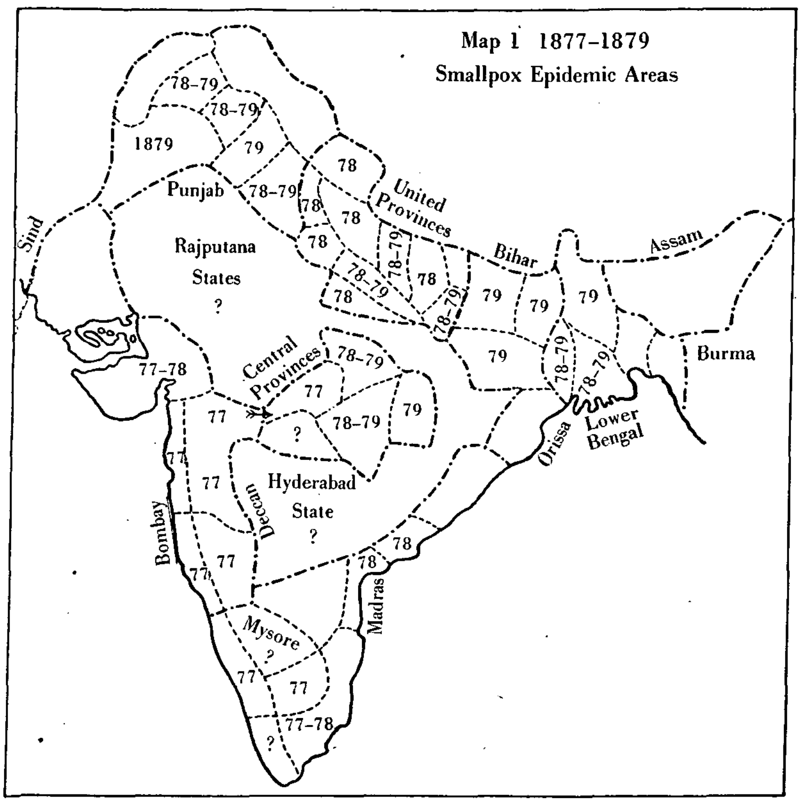
Column (4): 33–50 % over average of decade, +; 50–100 %, + +; over 100 %, + + +.
Columns (5) and (6): excess, +; average, + −; deficient, −; very deficient, − −.
Column (6): data not available, ?.

1879, but ceased in November after normal monsoon rains had been re-established.

In the United Provinces also very low monsoon rains and absolute humidities of 1877 were followed by a rise to the epidemic level in November of that year, which continued throughout 1878 with a rate of 3·99 per mille against 0·84 in the preceding year, monsoon absolute humidity only slightly deficient. Nevertheless, contrary to the general rule, the smallpox death-rate rose from 0·37 per mille in 1877 to the epidemic level of 2·18 in 1878 and to 3·44 in 1879 in spite of high monsoon rains and average absolute humidity in 1878, but fell to only 0·69 in 1880. However, on turning to the months in which the epidemic rise occurred we find, for the first time, that it did not begin very soon after the termination of the monsoon rains in 1877; but the rise was postponed until March 1878, or three to four months later than is found in the case of epidemics following a failure of the monsoon rains.

In the divisional smallpox incidence, as shown in Map 1, we find an explanation of the above events. It has already been mentioned that the worst epidemic of the records occurred in the neglect of vaccination, as did the great Hyderabad Deccan State to the south of the Central Provinces. There are, therefore, very strong reasons for concluding that the 1877–9 smallpox epidemic in the Central Provinces was caused by the spread of the disease from highly infected surrounding areas, beginning, as it did, in the Nerbudda division in 1877 some three months after the very severe outbreak began in the adjacent North Deccan.

In Bengal there was no serious general epidemic during this period, but some of the divisions showed



North Deccan division of Bombay following the failure of the 1876 monsoon rains. That division borders on the north-westerly Nerbudda division of the Central Provinces, which alone showed an epidemic incidence of smallpox in 1877. This epidemic spread to the two central divisions of Jubbulpore and Nagpore in 1878 and to the easterly Chattisgarh division in 1879 as indicated in Map 1. Moreover, in 1878 and 1879 smallpox was epidemic throughout the United Provinces following low monsoon rains as shown in Table 1, including the south-easterly divisions in close connexion across intervening Indian States, which at that period suffered most severely from smallpox owing to the increased smallpox in 1878 and/or 1879 as indicated in Map 1. There was preceding deficient rain in Bihar in 1878 and in Lower Bengal proper in 1879, so it is difficult to say how far these localized outbreaks were due to climatic conditions and how far to spread of the disease from the highly infected eastern divisions of the United Provinces immediately to the west of the Bihar divisions of Bengal.

It will be of interest to recall here that in his sanitary report for the Punjab for 1880 Major H. W. Bellew, I.M.S. (who published a book on the periodicity of cholera epidemics in India), pointed out that during the previous decade 'in each year minimum rainfall is followed by the maximum smallpox mortality. In other words, that rainfall is unfavourable to the prevalence of smallpox, and drought favourable to the development of the disease.' This is the only reference I have found in Indian reports to this relationship, the priority for which should be given to Bellew. He does not, however, refer to absolute humidities, which probably were not available to him at that early date.

To sum up, with the solitary exception of the Central Provinces, all those involved in the great 1877–9 epidemic had suffered from low monsoon rainfalls and absolute humidities immediately before the outbreaks commenced. It would have been strange indeed if they had not spread to the Central Provinces as appears to have been the case. It takes more than the mere drawing of a line on a map demarcating two adjacent provinces to prevent the spread across it of such a disease as smallpox.

QUIESCENT PERIOD OF 1880, 1881 AND 1882

In India as a whole the monsoon rains were over the average in 1879, up to the average in 1880 and once more in excess in 1881. Accordingly the smallpox incidence of 1·70 and 1·07 in 1878 and 1879 fell in 1880, 1881 and 1882 respectively to 0·38, 0·39 and 0·40. Moreover, the only division to show exceptionally high rates in 1880 and 1881 was the Orissa area of Bengal, to which the disease probably spread from the adjacent Burdwan division of Bengal, where the epidemic level had continued from 1879 into 1880. The Jaganath Pilgrimages to Puri in Orissa often spread both smallpox and cholera to that area.

1883–4: SMALLPOX EPIDEMIC

In 1882 the monsoon rains and the accompanying absolute humidities, or both, were deficient in Bombay, Madras, the United Provinces, and in Assam: in accordance with this smallpox rose to epidemic levels at the end of 1882 or the beginning of 1883 as shown in Table 1. In Bombay and in Madras the rainfall was about the average figure, but owing to irregular distribution the operative absolute humidity was very low in Madras and low in Bombay. This is a good example of the greater forecasting value of the humidity than of the monsoon rains. In the case of Madras the absolute humidity alone was again low in 1884, with the result that the smallpox incidence rose still further from 1·30 to 2·10 in the latter year and continued at an epidemic level up to July 1885. The epidemic also continued up to October 1884 in Bombay, but at much the same level as in 1883 in the absence of reduced absolute humidity in 1883.

In the United Provinces the monsoon rains were deficient in both 1882 and 1883 and the absolute deficiency was very low in both years. Accordingly the smallpox rate per mille rose from 0·60 in 1882 to 3·14 in 1883 and reached the record level of 4·59 in 1884 after two successive years of highly favouring climatic conditions.

In Assam the monsoon rains were deficient in both 1882 and 1883 and the smallpox rate of 0·71 in 1882 rose to 1·36 and 1·05 respectively in the two following years.

In the Bihar divisions of Bengal the monsoon rains of 1883 were 40 % below the average, and the smallpox rate rose from 0·12 in 1883 to 0·56 in 1884.

Thus during the 1883–4 epidemic every rise of smallpox to epidemic levels followed immediately after failure of the monsoon rains or the absolute humidities of the previous years in accordance with the rule.

QUIESCENT PERIOD OF 1885, 1886 AND 1887

The monsoon rains were normal in 1884 and 1885 and above the average in 1886; in accordance with which the all-India smallpox death-rates per mille fell from 1·70 in 1884 to 0·40, 0·24 and 0·31 respectively in the three following years: the lowest rates up to that time recorded.

PERIOD OF LESS SEVERE AND EXTENSIVE SMALLPOX EPIDEMICS

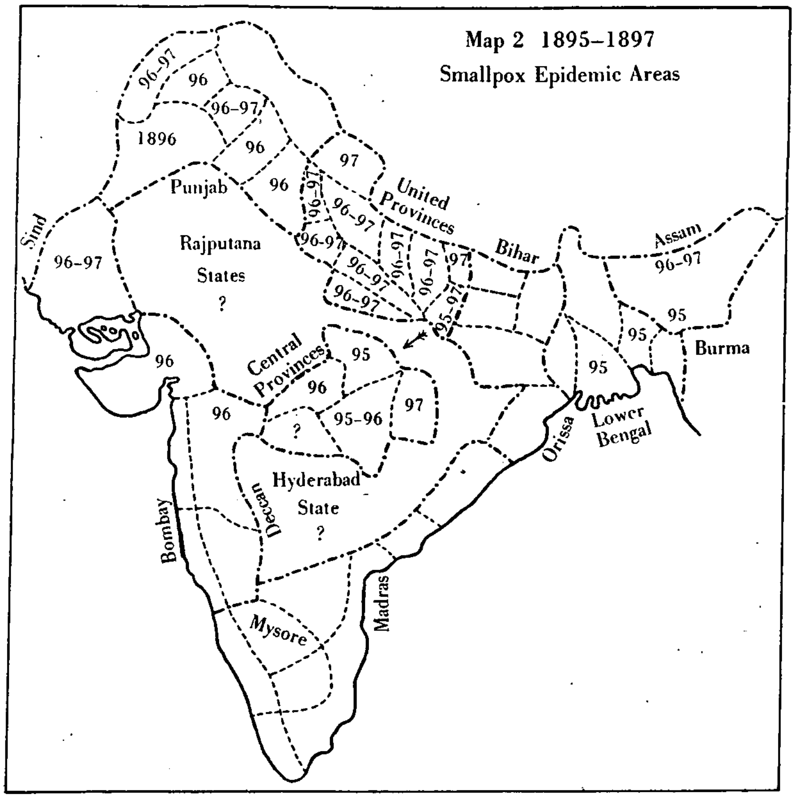
During the next two decades or so from 1888 to 1909 the good effect of the suppression of inoculation against smallpox and an increase of the yearly vaccinations from 5 to 9 millions (see paper of 1945 for illustrative chart) is seen in the remarkable fall from rates of 1·70 per mille for British India as a whole during the two epidemics already described to a maximum of 0·75 in the subsequent decades. Nevertheless, the data in the tables show that the highest rates in 1889, 1897 and 1908 were in each case preceded by weakness of the monsoon rains in India as a whole in the immediately preceding year, and that in nearly every instance the rainfall or the absolute humidity, or both, had been deficient in the very provinces in which the most severe epidemics followed those climatic deficiencies. Several exceptions, however, occurred which are of special interest.

SMALLPOX EPIDEMICS OF 1888–92

It will be seen from the tables that during these five years smallpox deaths only increased in three provinces as a whole to over the epidemic level. With the exception of the Central Provinces in 1888 the previous absolute humidity was low and thus favourable to increased smallpox, although the monsoon rainfall was somewhat high in the United Provinces preceding the outbreaks of 1889 and

1890. This once more was due to irregular distribution of the rainfall and early cessation of the monsoon rains, which reduced the absolute humidity in the critical autumn months to below normal: yet another example of the greater value of the absolute humidity over the rainfall records in making forecasts.

In Madras the epidemic rises of 1891 and 1892 deficient humidity commenced. As we have already seen, this indicates a spread from a neighbouring area, so it is significant that in 1888 smallpox mortality rose in the United Provinces to 0·56 from only 0·19 in the previous year; for the eastern divisions of the United Provinces are in close railway communication with the affected east division of the Central Provinces.



Map 2 1895–1897
Smallpox Epidemic Areas

both followed very low rainfall with reduced absolute humidity according to rule.

The outbreak of smallpox in the Central Provinces in 1888 presents points of exceptional interest. On turning to the divisional data it appears that the epidemic level was only reached in 1888 in the most easterly division of Chattisgarh, where the high incidence of 2·53 per mille was reached, while in the Raipur district the death-rate was no less than 4·41. This divisional outbreak was so severe that it raised the incidence of the whole province to just over the epidemic level. The disease affected all the Central Provinces divisions in 1889 after low absolute humidity had occurred during the previous monsoon period. Moreover, the epidemic level in the Central Provinces was only reached in March 1888; that is, some three or four months after epidemics resulting from previous

QUIESCENT PERIOD 1893, 1894 AND 1895

In these three years no province showed an epidemic rate; in each of the preceding years the monsoon rains had been above the average, once more according to rule. The rates per mille for India as a whole were respectively 0·30, 0·20 and 0·20: the lowest rates for three consecutive years up to this date, which were not equalled for another three decades.

EPIDEMIC OF 1896 AND 1897

In both 1895 and 1896 the monsoon rains were once more deficient in several provinces and were followed by a widespread epidemic in 1896 and 1897, in Northern and Central India, which is illustrated by Map 2. Much the most seriously infected areas were the Punjab in 1896 and the

United Provinces in 1897, with respective rates of 2·19 and 1·86 per mille and an all-India rate in the latter year of 0·75. In both instances there had been exceptionally low previous monsoon rains and absolute humidities.

On the other hand, in the United Provinces in 1896 smallpox rose to 0·91 or just over the epidemic level, but only from March of that year, which indicates spread from the Punjab; for, although the previous monsoon rains were rather low, the absolute humidity was almost up to the average rate. It is therefore significant that the most westerly Agra division of the United Provinces, adjacent to the heavily infected Punjab, showed the highest smallpox rate of this or any later period.

The outbreak in the Central Provinces presents another interesting problem with a rise to 0·82 in 1896 in spite of slightly high preceding absolute humidity. This outbreak is shown by the divisional figures to have begun in 1895 in the Jubbulpore and Nagpore divisions only, as indicated in Map 2, but without quite reaching the epidemic level for the province as a whole. On turning to the divisional figures for the adjacent south-east divisions of the United Provinces it appears that in 1895 the Benares division alone showed the epidemic rate of 0·93, and it continued high through 1896 and 1897. This was the probable source of the outbreak in the northern and central divisions of the Central Provinces in 1895, which spread to the other divisions in 1896.

Assam also showed moderate increases of smallpox in 1896 and 1897; both followed early cessation of the previous monsoon rains with lowered absolute humidity in the critical autumn months. The rise continued into the pre-monsoon months of 1898.

QUIESCENT PERIOD 1898 AND 1899

Once more the monsoon rains for India as a whole were above the average in 1897 and 1898 and accordingly the smallpox death-rate per mille fell in 1898 and 1899 respectively to 0·26 and 0·23 per mille.

In 1899 the monsoon rains were extremely short with resulting famine and the worst cholera epidemic since general statistics were available for India. Accordingly very low monsoon absolute humidity in Madras, Bombay and the Central Provinces in the latter part of 1899 was followed by rises of smallpox mortality in 1900 to an epidemic level in each province as shown in Table 2.

Average monsoon rains in 1900 were once more followed by quiescence of smallpox in 1901.

The monsoon rains were again deficient in both 1901 and 1902 in northern India from Assam to the Punjab, and smallpox rose to the epidemic level in the same regions in 1902 and 1903. In Assam the rate was 1·26 per mille in 1902 with the increased incidence only in the southern Surma valley, where the previous monsoon rains had been very low, doubtless with decreased absolute humidity the data of which are not available. An increase in Lower Bengal affected the Burdwan division in spite of normal previous rainfall, but the neighbouring Orissa division to the south had suffered from an isolated outbreak of smallpox during the previous three years and Bihar, immediately to the west of Burdwan, showed a high smallpox rate in 1902 following exceptionally low monsoon rains with a deficiency of over 40 %, so the Burdwan outbreak was nearly certainly due to infection from adjacent highly infected areas.

Epidemic rises in 1903 followed in each case previous low rainfall and humidity as shown in Table 2.

Average monsoon rains in 1903 were followed by quiescence of smallpox in 1904 with a decline in the all-India rate from 0·41 to 0·24.

EPIDEMICS OF 1905–8

The monsoon rains were deficient again in 1904, 1905 and 1907, especially in the last year, and were followed by an all-India smallpox death-rate of 0·75. During 1905–9 comparatively slight epidemic rises occurred in North and Central India and in Bombay as shown in Table 2. In every instance the outbreaks followed previous low rainfall and humidity, except a minor outbreak in the United Provinces in 1907 followed by more widespread prevalence in 1908, as shown in Table 2, so only the latter requires further consideration. In 1907 the increase was limited to two north-western divisions and only reached the epidemic level in June. That suggests spread from an adjacent area, but divisional figures do not support that view, so this small outbreak remains unexplained.

In view of the previous instances of outbreaks in the Central Provinces having been traced to the spread of infection from adjacent ones, in the absence of previous deficiency rains and humidities in the Central Provinces itself, it is worth noting that the epidemic rises in this area in 1905, 1906 and 1908 did follow previous low absolute humidity in accordance with the rule. This is also true of subsequent Central Provinces outbreaks in 1913 and 1919 in Table 2, all of which occurred at a time when the smallpox epidemics in India as a whole had become less severe and widespread and consequently less liable to extend from one province to an adjacent one. It is also significant that these latter outbreaks also commenced just after deficient monsoon rains and two or three months earlier in the season than those above attributed to spread from an adjacent area.

In both 1909 and 1910 the monsoon rains were above the average; accordingly 1910 and 1911 were quiescent years as regards smallpox epidemics, in which the all-India States fell once more to 0·23 and 0·25 respectively.

LOCALIZED EPIDEMICS OF 1912–15

These years are remarkable for the preceding monsoon rains having been normal except for a slight excess in 1913. They are characterized by the all-India smallpox rates having only appreciably exceeded the average of the decade, 0·364, by a moderate rise to 0·41 in 1913. Nevertheless in all seven instances shown in Table 2 the rises to epidemic level were preceded by low absolute humidities, although the disease was seriously epidemic only in the Punjab in 1912 and 1913 following great monsoon rainfall and humidity deficiencies in 1911 and moderate ones in 1912. This indicates that comparatively mild epidemics can also be forecast correctly.

In addition divisional epidemics occurred in the Orissa division of Bengal and in the Assam Valley. Both were preceded by low monsoon rain and humidity according to rule. In 1916 smallpox was again quiescent after previous normal monsoon rain.

EPIDEMICS IN 1917–20

In 1916 the South-West monsoon rains were good and the smallpox rates were very low in all seven provinces affected by it. Only in Madras did the disease just exceed the epidemic level; the outbreak here was preceded by low North-East monsoon rains and absolute humidity. This outbreak reached a higher level in 1918 and continued through much of 1919; both these years had been preceded by low autumn and early winter absolute humidity.

In 1918 the monsoon rains were materially deficient in India as a whole and in 1919 the all-India smallpox rate rose from 0·39 in the previous year to 0·57 to reach the highest rate in any year since 1908, and to attain to epidemic levels in five provinces as shown in Table 2. In every one of these the previous monsoon rains had been deficient and the absolute humidity was also low in Madras, the Central Provinces and the Punjab. It was probably also deficient in the United Provinces, but unfortunately the data for the critical months are wanting in the tables kindly supplied to me by the Indian Meteorological Office. In the remaining province of Bengal the 1918 monsoon rains showed the exceptionally great deficiency of 20 in. accompanied by low absolute humidity: both recurred in 1919 with a continuance of high smallpox mortality in 1920 unprecedented in my tables.

There remains to be considered the exceptional case of an increase to just over epidemic level in Bombay in 1918, in spite of previous very heavy monsoon rain and nearly average autumn absolute humidity. It will be seen from the table that the rise commenced rather late in February 1918 and it only involved the Bombay-Deccan divisions. As smallpox was epidemic in the adjacent Madras-Deccan in 1917 and 1918, so it must also almost certainly have been present in the huge Hyderabad State immediately to the east of the Bombay-Deccan (although data are not available to test this), and therefore it is almost certain that Bombay was invaded by smallpox from those adjacent areas.

Bihar and Orissa in 1920 showed epidemic prevalence following previous low monsoon rain and humidity.

It is especially noteworthy that during the twenty-one years of scattered, comparatively mild epidemics of smallpox from 1905 to 1920, out of twenty-six entries in Table 2 the epidemic level was only reached in two without previous deficient rain and humidity; namely, in the United Provinces in 1907 and in Bombay in 1918. In both the epidemic level was only slightly exceeded and in both there is evidence that the disease spread from adjacent epidemic areas.

QUIESCENT PERIOD 1921–5

There followed the longest and most striking quiescent period of the five years 1921–5, with rates per mille for all British India of respectively 0·17, 0·17, 0·18, 0·23 and 0·36 compared with an average of 0·347 for the decade 1918–27. All but the first of these five years were preceded by high or average monsoon rains. 1921 showed a low smallpox death-rate in spite of the 1920 monsoon rains having been deficient—the only such occurrence in the five decades dealt with. This exception followed the occurrence of epidemic levels of smallpox in no less than seven of the eight provinces during the previous two years of 1919 and 1920, which may explain it, although it requires to be borne in mind when making forecasts.

EPIDEMICS OF 1926–9

In 1926 epidemic rates of smallpox occurred in the United Provinces, the Punjab, Bihar and Orissa (which had been separated from Lower Bengal), and in Assam. In a paper of 1930 I recorded data to show that all of them had been preceded by monsoon and autumn low absolute humidities due to deficient or early cessation of the monsoon rains.

In 1927 Bihar and Orissa and Lower Bengal showed epidemic rates after previous low monsoon rains and humidity.

In 1929 smallpox reached the epidemic level in the United Provinces after very low previous monsoon rains and absolute humidity, and in Bombay after low absolute humidity but about normal, though ill-distributed monsoon rains.

FORECASTS OF SMALLPOX INCIDENCE IN INDIA 1930–3

To test my method of forecasting smallpox epidemics in India I obtained from the Meteorological Department the necessary data to enable me to make forecasts for four years and sent them for publication in the *Indian Medical Gazette*, in which the results as they came to hand were also reported. They were summarized in my presidential address to the Royal Society of Tropical Medicine in 1933 and were briefly as follows: In none of the four years dealt with was there any very serious previous failure of the monsoon rains, so forecasts were particularly difficult, but the absence of any major epidemics during the first three years was correctly foretold. Moreover, a high incidence in the Central Provinces in 1930 following low monsoon rains was in accordance with my forecast for that year. In the same year the Bombay-Deccan had a high rate following low absolute humidity at the end of the previous year, too late for my forecast, but it could have been foreseen by the public health authorities on the spot had they made use of my published methods.

On the other hand, my forecast for 1933 was less correct, for although I foretold an increase in the Punjab and the North-West Frontier Province, in both cases it proved to be greater than I had anticipated and in Bombay a moderate increase occurred in place of average to low incidence which I expected, but low incidence was correctly anticipated in the Central Provinces. This last attempt left much to be desired; hence the further study recorded in this paper.

EXCEPTIONS IN WHICH LOW MONSOON RAIN AND HUMIDITY WERE NOT FOLLOWED BY INCREASES OF SMALLPOX TO EPIDEMIC LEVELS

An analysis of the five decades records five instances of this occurrence; a remarkably small number.

Table 3. *Low absolute humidity with increased smallpox, but not to 'epidemic levels'*

1899–1900	United Provinces	Rise from 0·07 to 0·28 per mille
1905–6	Punjab	,, 0·25 ,, 0·51 ,,
1910–11	Punjab	,, 0·15 ,, 0·25 ,,
1915–16	Punjab	,, 0·09 ,, 0·15 ,,
1908–9	Bombay Presidency	,, 0·14 ,, 0·27 ,,

Even in these cases there was a material rise in the smallpox following low rain and humidity, but not to the arbitrary 'epidemic levels', which alone are shown in the tables in order to avoid any possible bias in working it out. The data are therefore of value in forecasting a material increase of smallpox incidence, which would allow increased vaccinations to be organized to meet the emergency.

So they are not really exceptions to the general principles governing such forecasts.

In addition, I found two examples in the United Provinces and two in the Central Provinces of low monsoon rains so distributed as not materially to lower the absolute humidities in the crucial autumn and early cold weather months, but which were not followed by epidemic smallpox. They are only illustrations of the greater value of humidity over rainfall data in making forecasts, and are also according to rule.

Lastly, I have found three instances only in which low absolute humidity was not followed by any material increase or change in the smallpox incidence of the succeeding season, contrary to the general rule. These might have led to forecasts of increased smallpox which did not eventuate; but this at least would be a mistake in the right direction and much better than failing to forecast an epidemic which did take place.

SMALLPOX AND CLIMATE IN TROPICAL COUNTRIES OF THE BRITISH EMPIRE

The close relationship between smallpox and climatic conditions in India raises the question whether a similar relationship holds good in other tropical countries with well-marked dry and wet seasons. I therefore searched the annual medical reports of two decades or more of many of our tropical colonies for records of smallpox outbreaks on a scale suitable for my inquiry, and I am much indebted to Dr A. M. Wilson Rae, Medical Adviser to the Colonial Office, for the data on which the following information is based. They include countries in the Northern Hemisphere outside India, Uganda on the Equator and Nyassaland in the Southern Hemisphere. The results are most instructive.

SMALLPOX AND CLIMATE IN JAMAICA

Fig. 3 shows the monthly incidence of smallpox per 100,000 population together with the monthly mean temperature above, and the monthly rainfall, relative and absolute humidity data below; all on similar lines to the Indian data in Fig. 1. The climatic data are the average figures for 1923–7 and the smallpox ones those of the 5318 mild alastrin type of smallpox for the same years, a few cases of which I saw while attending a medical congress in Jamaica in 1924.

It will be seen that the rainfall is low in the first six months of the year except for a moderate rise in May. The monsoon period of heavy rainfall lasts from August to November: one month later than the South-West monsoon in India, during which the absolute humidity rises to its maximum from August to November, by the end of which period the incidence of smallpox falls to its minimum in November; also one month after that in India. The absolute humidity then falls rapidly at the end of the rainy season and remains low from December to March, during which period smallpox rises to its maximum, in a parallel manner to the incidence in India. There is thus the same close relationship between high rainfall and absolute humidity and the annual decline in smallpox and vice versa as in the provinces of India affected by the South-West monsoon rains. On the other hand, there is no such close relationship with either the relative humidity or the mean temperature; once more as in India.

It is worth noting that the Jamaica Medical Report for 1923 records that 'vaccination is a certain preventive of alastrin'. It was not compulsory during the early years of high prevalence, and the prevalence fell rapidly on the introduction of compulsory vaccination in January 1926 from 1108 to 290, 47, 2 and 1 during the following four years.

SMALLPOX AND CLIMATE IN UGANDA

The Uganda data are of special interest on account of the absence in this equatorial area of well-defined dry and wet seasons as shown in Fig. 3 on similar lines to those of other countries dealt with. Moreover, the monthly relative humidity curve shows the remarkably low annual variation of only 2° and the monthly absolute humidity only varies by 0·030 in the whole year: far too little to be expected to exert any material influence on the monthly smallpox incidence, the average monthly rates per 100,000 of which are based on the only available monthly figures of 1920–7 with a total of 1609 cases. These suffice to show that there is no great seasonal fall in the smallpox rate to a low minimum, such as is shown in all the other areas in Figs. 1 and 2 except Madras, which also has no large monsoon fall in the absolute humidity in the absence of any material South-West monsoon rains in the south-east of India. In the Uganda chart increased smallpox is shown in March and April, but this is due to an exceptionally large number of cases in 1921. This does happen to be soon after the comparatively low rainfall in January, but this is probably fortuitous and the rise would most likely be smoothed out if more extensive data were available.

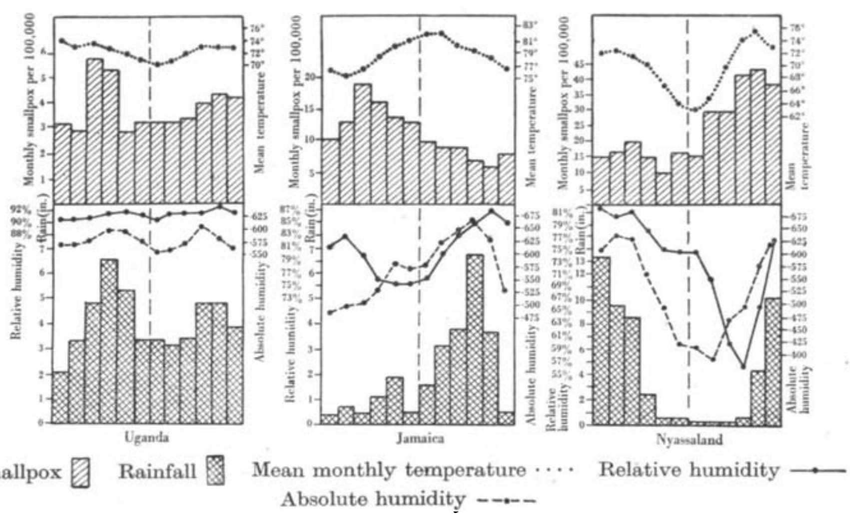


Fig. 3. Average monthly smallpox per 100,000, rainfall, mean temperature, relative and absolute humidity.

Uganda, with no definite dry and wet seasons, and no material monthly variations in the monthly absolute humidity readings, has likewise no constant and clear-cut annual decline in the smallpox incidence to a low minimum, such as occurs in all the tropical areas studied in which the opposite climatic conditions are met with. Uganda thus furnishes a remarkable control area.

SMALLPOX AND CLIMATE IN NYASSALAND

Nyassaland has well-marked dry and wet seasons and correspondingly wide monthly variations of the absolute humidity; but owing to its being in the Southern Hemisphere the seasons are completely reversed as compared with similar climatic data in the Northern Hemisphere. This area therefore furnishes a crucial test regarding the influence of large seasonal variations of the rainfall and absolute humidity on smallpox incidence. A glance at Fig. 2 shows that the seasonal incidence of smallpox is also completely reversed in accordance with my conclusions. It is therefore fortunate that the monthly data supplied to me for 1929–32 inclusive amount to the adequate total of 17,371 cases, the average monthly rates per 100,000 population of which have been charted, together with the monthly climatic data.

In Nyassaland during the six dry cold weather months of May to October the monthly rainfall averages only just over one-third of an inch. In the six wet warm months of November to April, with high absolute humidity, the average rainfall is 8 in. with a maximum of 13 in. in January. As usual during the dry cold months the absolute humidity falls to a low minimum and vice versa. Correspondingly smallpox rises steadily following the low humidity, with the usual lag period of about one month, to reach its maximum in October to December, and then falls steadily in January to May, with the exception of a small rise in March, to reach its minimum in May and it remains low in June and July. In this case the relative humidity curve is very similar to that of the absolute humidity, but with the fall to its minimum rather later.

SMALLPOX AND CLIMATE IN OTHER TROPICAL COUNTRIES

It remains to consider monthly data of smallpox of a limited nature which I found in medical reports of some other tropical countries and have studied in relation to the monthly climatic data for the same areas.

In Ceylon heavy rainfall occurs in April to June and again during the North-East monsoon of October and November. During the first of these wet periods the absolute humidity rises to its maximum and remains rather high up to October. During these wet periods smallpox cases fall to a low minimum. On account of falling temperature in November the absolute humidity declines considerably in that month in spite of high rainfall (just as in the adjoining south-east Madras as shown in Fig. 1) and it reaches its minimum in January and February.

Accordingly smallpox begins to increase in December to reach its maximum in January and February; and the disease falls to a low minimum during the rainy months with high absolute humidity. As far as the available data go this is all according to rule.

At Khartoum in the Anglo-Egyptian Sudan rain is practically absent from November to April, when the absolute humidity is at its minimum. Accordingly, smallpox begins to increase in December to reach its maximum in February and March and it remains fairly high during April and May. A moderate amount of rain falls in May to July and a very high maximum occurs in August, when it may reach 80 in. or more than twice that of the rest of the year. The absolute humidity is at its maximum in July to September and smallpox falls to a very low level during August to November.

The 1919 report for Nigeria states that the natural subsidence of smallpox is always expected and generally realized with the establishment of the rains, but monthly data are not yet available to me.

The above data suffice to prove that in each tropical area dealt with, which has well-defined dry and wet seasons, smallpox incidence falls to a low minimum in relation to high humidity during heavy monsoon rains and vice versa; just as it does in India. My method of forecasting Indian provincial epidemics of smallpox, described in 1926, and amplified in the present paper, is therefore likely to prove of value in other such tropical countries, although there are no such extensive monthly data over several decades available for other tropical parts of the British Empire as there are for India. Smallpox is now very largely a tropical disease, forecasts of increases of which should enable special efforts to be made to extend vaccination with a view to mitigating its ravages.

BACTERIOLOGICAL CONFIRMATION

While the present inquiry was being carried out a paper was published in April 1947 by Prof. A. W. Downie and Dr K. R. Dumbell on 'The survival of variola virus in dried exudate and crusts from smallpox patients'. Twenty-one years ago I had interested a leading bacteriological authority on smallpox in my study of the effects of climatic conditions on the incidence of smallpox, but for want of a reliable method of cultivating the virus nothing came of it. The Liverpool bacteriologists have availed themselves of the method of cultivating smallpox virus in vesicle fluid and crusts on the chorio-allantoic membranes of developing hen's eggs and they found that the virus survived longest when dried and kept in the dark at room temperature, which must have been far below that of the Indian monsoon period. Thus the conditions that favoured the survival of the virus are exactly the opposite to those which I found to be unfavourable to the spread of the infection in India.

In my 1926 paper on smallpox and climate I referred to the work of Newsholme on the influence of dry years in favouring epidemics of rheumatic fever and scarlet fever, and suggested that those

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and other epidemic diseases such as poliomyelitis may be worthy of study in relation to absolute humidity variations. When reading Colonial medical reports I found references to the occurrence in Nigeria of epidemics of cerebro-spinal fever in dry months and their rapid decline with the onset of the rainy season: data which I am now studying. Air-borne diseases in general are worthy of study on the lines of my investigations of the value of climatic variations in relation to the incidence of smallpox, cholera (1928c), plague, leprosy (1923) and pneumonia (1925b), and pulmonary tuberculosis (1925a) in India. The difficulty is to find data of the monthly incidence over a series of years regarding other diseases in tropical and other countries presenting the great monthly and annual variations in the rainfall and humidity necessary for such investigations; but I would suggest that the United States of America present a favourable field for the extension of my work on these lines.

SUMMARY

1. Earlier work on forecasting epidemics of smallpox in India, based on the study of the previous rainfall and humidity, has been confirmed and extended by the present study and a few instances which did not conform to the general rule have been explained as due to the spread of the disease from an adjacent province.

2. An extension of the inquiry to other tropical countries of the British Empire indicates that in tropical countries in general with well-marked dry and wet seasons, the annual decline of smallpox incidence to a low minimum in relation to high absolute humidities during the rainy season is the rule; for it is absent in equatorial Uganda with rains throughout the year, and both the monsoon period and the monthly incidence of smallpox are reversed in such a Southern Hemisphere country as Nyassaland in accordance with the general rule.

3. Where smallpox is endemic in such countries increased prevalence in any year may usually be foreseen by watching the meteorological records in time to control the expected increase to some extent by increased use of vaccination.

4. Other air-borne diseases are worthy of study on similar lines in countries with suitable vital statistics and climatic conditions.

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