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The speed and some other features of the sea-breeze front at Madras

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ABSTRACT. The speed with which the sea breeze advances inland at Madras under various meteorological conditions and its dependence on the time of onset and depth of penetration are discussed in this paper, utilising the records for the years 1945 and 1946 of autographic instruments at three stations located at different distances from the coast. A velocity of 10-15 mph, a southsoutheasterly direction of the resultant wind, the months April to September and a time of onset during the early afternoon are favoured most by the sea breeze at Madras. The average speed of the sea-breeze front is found to be 3-7 mph. It is accelerated with depth of penetration inland independently of the wind speed. It varies with the hour of onset of the sea-breeze, being lowest during the epoch of maximum temperature. The variation of the ratio of the speed inland to that near the coast with time of onset and direction of the on-shore wind is investigated. The results are explained on the basis of the temperature gradient and its variation with distance inland. The mean temperature drop and vapour pressure rise caused by the sea-breeze for different times of incidence and magnitudes of wind velocity in the various months have also been studied. The changes are maximum in the proximity of the epoch of maximum temperature and in the month of July in the year. The results of this study would help in anticipating with sufficient accuracy and sufficiently in advance for aviation needs the time of onset of the sea-breeze and the accompanying meteorological changes at the airfield at Meenambakkam, given the time of incidence and the direction of the on-shore wind earlier at a point closer to the coast.

1. Introduction

It is well-known that the surface winds at a coastal station are characterised by well-marked sea and land breezes. Of these, the sea-breeze is relatively stronger and especially pronounced in the tropics during the summer months with some of the characteristics of a cold front. In India, Ramanathan (1931) was the earliest to investigate the speed of the sea-breeze front in his paper on the structure of the sea-breeze at Poona. Ramdas (1932) has studied the sea-breeze at Karachi, but his investigation was necessarily confined to the period October to March as, during the summer months, the prevailing wind blows continuously from the sea, giving rise to a permanent sea-breeze. Roy (1941) has investigated the structure of the sea-breeze at Madras, which, being located on the east coast of the Peninsula, displays well-marked sea-breeze during the summer part of the year. Analysing the data of the two years February 1938 to January 1940, Roy has determined the frequencies of occurrence of sea-breeze during the different hours of the day and of temperature falls and humidity rises of different orders caused by the advent of the sea-breeze. He has also studied the thickness of the sea-breeze and the indication provided by the strength of the westerly component at the higher levels of the early or late onset of the sea-breeze. Hatcher and Sawyer (1947) have investigated the structure of the sea-breeze at Madras with the help of aeroplane ascent data at different points normal to the coastline during April and May 1945, with particular reference to the temperature and water vapour gradients associated with radio ducts. Craig and others (1945) have studied the sea-breeze in the Massachusetts Bay and constructed sea breeze cross-sections from psychrometric measurements.

A knowledge of the shift in the wind direction and change in its velocity caused by the onset of sea-breeze and the dependence of these variations on its time of onset is of practical value at an aerodrome station on the

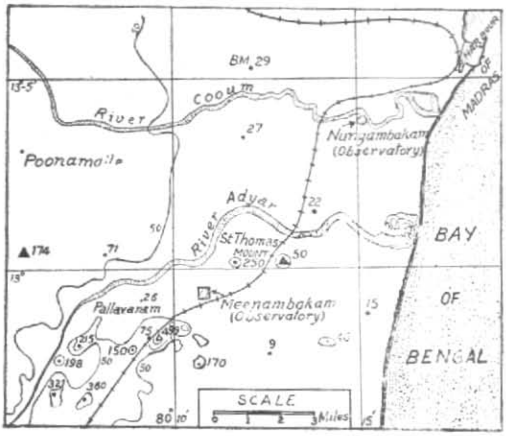

Fig. 1. Map of Madras coast and neighbourhood

coast like Madras, with frequent landings and take-off during the afternoon demanding accurate forecasts of the surface wind. The temperature and humidity changes caused by the sea-breeze under varied conditions are also of much meteorological interest. The object of this paper is limited to a study and discussion of these aspects of the sea-breeze at Madras.

2. Data analysed

In a study of this nature, it is necessary to have two or more observing stations equipped with autographic instruments at and away from the coast. There is a D. P. T. Anemograph at the Madras Harbour almost on the coastline. Another D. P. T. Anemograph was located at the old Madras Observatory site at Nungambakkam till 1951, at a perpendicular distance of 2·6 miles from the coastline. The Meenambakkam observatory near the aerodrome, situated at a distance* of 5·98 miles from the coast as the crow flies, was started in 1943. A topographical map showing the location of these observatories is given in Fig. 1. The effects of the sea-breeze at these three stations were studied on each day of the two years 1945 and 1946. Data of the sea-breeze from the anemographs at the Harbour and Nungambakkam and the temperature and humidity changes caused by the advent of the sea-breeze as manifested by the thermograph and hygrograph at the latter place in these two years were catalogued. There were 252 occasions of sea-breeze during the period of study when the influence of the sea-breeze was noticeably felt at all these stations. As the primary object of this study is to examine the speed of the sea-breeze front and the meteorological changes caused by its advent, only those significant cases of the sea-breeze have been taken into account when there was unmistakable evidence of the occurrence of the sea-breeze at all the three stations and the mean wind speed at the Harbour and Nungambakkam exceeded 5 mph. There were 174 such cases during the years 1945 and 1946.

TABLE 1

No. of occasions of sea-breeze of different speeds(mph) during the years 1945 and 1946

Month	0–4	5–9	10–14	15 and above	All speeds
Apr	18	4	9	1	32
May	12	5	21	11	49
Jun	11	6	30	4	51
Jul	10	9	12	5	36
Aug	17	11	13	0	41
Sep	2	14	12	1	29
Oct	8	2	4	0	14
Total (Apr-Oct)	78	51	101	22	252

3. Frequencies of occasions of sea-breeze of varying speeds

Roy has computed the average number of cases of sea-breeze in the different months, based on the data of the two years February 1938 to January 1940. His results cover winds of all speeds. From the point of view of aviation, the shift in direction and the speed of the surface wind after the incidence of sea-breeze is of considerable practical significance. In Table 1 is shown the distribution of the 252 cases of sea-breeze during the years 1945 and 1946, with different ranges of wind speed.

*These distances have been measured from the topographical map of "Madras City and Environs" (Scale 3·3″=1 mile) published by the Madras Survey Department

TABLE 2

No. of occasions of winds from different points of compass due to onset of sea-breeze at different times

Duration (*hrs*)	NNE	NE	ENE	E	ESE	SE	SSE	S	All points of compass
1000—1159	0	0	0	6	6	7	20	1	40
1200—1359	0	0	1	12	8	5	24	6	56
1400—1559	1	2	2	3	8	5	25	5	51
1600—1759	0	1	0	2	0	1	12	4	20
1800—2000	0	0	0	1	0	2	1	3	7

The data in this table refer to Nungambakkam as this station is located in between the other two and is, therefore, generally representative of all significant features of the sea-breeze at Madras. The period November to March has been omitted from this table, as there is practically continuous or permanent sea-breeze at Madras during these months.

It is seen from Table 1 that pronounced sea-breeze with an on-shore wind exceeding 15 mph occurs at Madras almost entirely during the months of May, June and July. During these months, the percentage numbers of occasions of wind speed exceeding 10 mph are 65, 65 and 47 respectively. In the rest of the months, the winds were light on a large majority of occasions. The most frequent surface wind speed in the year on the onset of sea-breeze is 10-14 mph, 101 out of 252 cases being of such speed. On most of the occasions in the months of April and October, the sea-breeze is relatively light. It may, therefore, be concluded that the most pronounced sea-breezes occur at Madras during the months May to September, of which the first three months are characterised by the strongest breezes.

4. Distribution of the occasions of sea-breeze with direction and time of onset

The coastline at Madras runs roughly from north by northnortheast to south by southsouthwest. The sea-breeze would, therefore, have a southerly component also at Madras. It is of interest to see the frequency of winds from different points of the compass from NNE to S through E associated with sea-breeze at Madras, for varying times of its incidence. A knowledge of the favoured direction and time of onset of the sea-breeze is also of value in providing guidance for forecasting the surface wind for aviation interests. Frequencies so computed are shown in Table 2, taking into account only the significant cases of winds exceeding 5 mph in speed. These data also relate to the intermediate station at Nungambakkam.

It is at once seen from Table 2 that the most frequent wind direction associated with the sea-breeze at Madras is SSE for all times of onset before sunset. Winds from the NE quadrant (excluding easterly winds) are comparatively rare, only 7 out of 174 occasions being of such winds during the 2 years covered by the study. Again, 62 per cent of all these occasions were of onset of sea-breeze during 1200-1600 hrs. In the light of the results in Tables 1 and 2, it would seem that the months of May, June and July, the direction of SSE, a speed of 10-15 mph and a time of onset during the early afternoon are favoured most by the sea-breeze at Madras.

5. The speed of the sea-breeze front

As mentioned already, little information appears to be available regarding the speed with which the sea-breeze front advances across the coast. In his paper on the sea-breeze at Karachi, Ramdas (1932) gives data of the time intervals elapsing between the times of onset of the sea-breeze at Manora (on the coast south of Karachi) and Drigh Road (about 13½ miles north-east of Manora) on 6 occasions during

TABLE 3

Intervals of time taken (in minutes) and mean speeds of the sea-breeze front from the coast to Meenambakkam

Period (*hrs*)	Direction of the resultant surface wind					
	ENE	E	ESE	SE	SSE	S
1000—1159	..	114 (*3·2*)	109 (*3·3*)	100 (*3·6*)	101 (*3·6*)	130 (*2·8*)
1200—1359	103 (*3·5*)	89 (*4·1*)	59 (*6·1*)	89 (*4·1*)	97 (*3·7*)	94 (*3·8*)
1400—1559	..	118 (*3·1*)	110 (*3·3*)	109 (*3·3*)	75 (*4·5*)	83 (*4·4*)
1600—1759	..	102 (*2·5*)	..	100 (*3·6*)	66 (*5·5*)	112 (*3·2*)
1800—2000	..	60 (*6·0*)	..	50 (*7·2*)	..	68 (*5·3*)

November and December 1930. The wind speed itself was 10 mph in one case and less than that in the rest of the cases. The time intervals for the sea-breeze to cover the distance from Manora to Drigh Road was found to vary from 65 to 303 minutes. This gives for the speed of the sea-breeze front a value varying from 2 to 10 mph. In his study of the sea-breeze at Poona, Ramanathan (1931) mentions that on 3 March 1930, the time of incidence of sea-breeze at Lonavala, 33 miles to the westnorthwest of Poona, was 200 minutes ahead of that at Poona. This gives an average frontal speed of about 10 mph between these two places.

The information available, does not give any insight into the dynamics of the sea-breeze beyond the suggestion that it is possibly lower than the wind speed itself. The strength of the sea-breeze is a function of the contrast in temperature attained by the sea and the adjoining land as a result of insolation and may vary with the depth of penetration inland. The magnitude of such variation might be determined by the time of onset of the sea-breeze. Further, the orientation of the resultant wind might also affect the velocity of the sea-breeze front. It is, therefore, desirable to study the dependence of the velocity of the sea-breeze front on the hour of its commencement and on the direction of the resultant wind.

In what follows, the hour of onset refers to the time of commencement of the sea-breeze at the coastline, as found from the Harbour anemograms. In calculating the speed of the sea-breeze front, it has been assumed that the front advances normal to the coastline and parallel to itself, irrespective of the direction of the surface wind towards its seaward side. Jeffereys (1922) has shown that the sea-breeze is an antitriptic wind, which moves parallel to the pressure or temperature gradient. Such gradients, when caused by insolation would be normal to the coastline. The assumption made in computing the velocity of the sea-breeze front is justified by the fact that the sea-breeze is an anti-triptic wind occurring along a whole length of the coast at about the same time, with the motive force for advancing inland provided by the component of the wind normal to the coastline.

In Table 3 are shown the average intervals of time in minutes elapsing between the times of commencement of the sea-breeze at the coast and its incidence at Meenambakkam, for different directions of the resultant wind. These figures represent the averages for all cases available in each

TABLE 4

Variation of the speed of the sea-breeze front with distance inland

Period (hrs)	Direction of the resultant surface wind									
	E		ESE		SE		SSE		S	
	V_c	V_i	V_c	V_i	V_c	V_i	V_c	V_i	V_c	V_i
1000—1159	2·8	3·5	4·5	2·8	2·9	4·5	3·5	3·7	4·1	2·3
1200—1359	4·5	3·8	4·5	8·9	3·5	5·6	3·5	4·0	2·9	5·2
1400—1559	2·3	4·1	2·7	4·1	3·2	3·6	4·5	5·2	3·2	5·8
1600—1759	3·2	4·1	..	..	4·5	2·8	6·4	5·0	4·1	2·8
1800—2000	16·0	4·1	..	..	8·0	6·8	..	..	6·2	4·7

compartment of the table. The figures in brackets denote the mean speed of the sea-breeze front in miles per hour from the coast to Meenambakkam, taking into account the components of the distances normal to the coast. The period in column 1 denotes the interval of time within which the time of commencement of the sea-breeze at the coast falls.

It is seen from Table 3 that the average speed of the sea-breeze front is small and lies between 3-7 mph. As seen from Table 1, 122 out of 174 cases of sea-breeze yielding the data in Table 3 are winds of speed exceeding 10 mph and the rest of 5-9 mph. The speed of the sea-breeze front is, therefore, about half the wind velocity on its seaward side. It is also seen that the frontal speed reaches the lowest value during the epoch of maximum temperature.

In order to examine the behaviour of the velocity of the sea-breeze front, the intervals of time elapsing between Harbour and Nungambakkam and between the latter place and Meenambakkam and the corresponding speed of the sea-breeze front in between these stations have been computed. The results are reproduced in Table 4. In this table, V_c stands for the average frontal velocity from the coast to Nungambakkam and V_i for that in the interior between Nungambakkam and Meenambakkam. As the number of cases from the NE quadrant was very small to admit of any generalisation, these have been omitted from the table.

The following general inferences may be drawn from the results in Table 4—

(a) In all cases of onset of the sea-breeze during the afternoon, the frontal speed of the sea-breeze is generally 2-6 mph which is much less than the average speed of 10-15 mph of the wind on the seaward side of the front. The frontal speed shoots upto 5-10 mph for cases of post-sunset onset.

(b) In all cases of onset during the afternoon, the coastal speed is lower than that in the interior, suggestive of a possible increase of the frontal speed with depth of penetration inland.

(c) The speed of the front is generally lowest when it is incident near about the epoch of maximum temperature. The minimum speed of advance near the coast is associated with cases of onset at or before the attainment of temperature maximum and in the interior for cases of later onset.

The above results throw some interesting light on the dynamics of the sea-breeze front. The propulsive force for the sea-breeze is provided by the contrast in surface temperatures between the land and the

TABLE 5

Distribution of V_i/V_c with different times and directions

Period (*hrs*)	Direction of the resultant surface wind				
	E	ESE	SE	SSE	S
1000—1159	1·25	0·62	1·55	1·06	0·56
1200—1359	0·84	1·98	1·78	1·14	1·79
1400—1559	1·88	1·52	1·13	1·15	1·81
1600—1759	1·28	..	0·84	0·78	0·68
1800—2000	0·26	..	0·85	..	0·76

sea arising out of unequal absorption of insolation. Once the resistance to its flow near the coast is overcome, the sea-breeze would appear to progress inland with accelerated speed.

5. Gradient of the velocity of the sea-breeze front normal to the coastline

A discussion of the relative speeds of the sea-breeze close to the coast and inland is facilitated by a comparison of the ratios of the speed of the sea-breeze front between Nungambakkam and Meenambakkam to that up to the former place from the coast. These ratios are dispersed in Table 5 with the time of onset and the direction of the resultant wind.

The velocity ratios in Table 5 clearly demonstrate the increased speed acquired by the sea-breeze front with progress inland during the afternoon. The highest velocity ratio generally obtains during the afternoon, especially between 1400-1600 hrs. This implies that there is a steepening temperature gradient from the coast towards the interior during these hours. Thereafter with fall in temperature, the interior would cool down faster than the coastal belt. Such differential cooling would result in a more rapid diminution of the impulse for the influx of the sea-breeze in the interior than near the coast. Hence relatively lower speed of the sea-breeze front in the interior than near the coast, notwithstanding, the increased absolute speed.

If the prevailing westerly wind is completely overcome by the sea-breeze and has no deflective influence on the latter, the surface wind to the seaward side of the sea-breeze front would be easterly. The effect of differential cooling normal to the coast must then be much greater on an easterly wind, as, in such a case, the varying reaction of the component of the prevailing wind to the varying conditions of temperature is almost totally eliminated. If an easterly breeze occurs after sunset, it would get speedily retarded as it moves inland. That this is so is seen from the low value of 0·26 for the velocity ratio for an easterly wind occurring after 1800 hrs.

A pronounced southerly component, on the other hand, would imply a weak sea-breeze and consequently less of momentum for the sea-breeze front. With the diurnal fall in temperature, the relatively greater radiative cooling to the interior would retard the sea-breeze front with a weak easterly component even for an earlier time of onset than in the case of one with a pronounced easterly component. The fact that the interior velocity is smaller than the coastal velocity for breezes from a southeasterly to a southerly direction and that the less the easterly component the less is the velocity ratio or the interior speed of the front, must be thus due to the variation in the strength of the easterly component constituting the sea-breeze.

Cases of onset of the sea-breeze during 1000-1200 hrs do not provide any reliable pointer to the dynamics of the sea-breeze front. It is likely that if the onset of the sea-breeze takes place prematurely before the establishment of sufficient thermal contrast, it may not move in as a well-defined front. The increasing temperature over the land and the increasing turbulence caused thereby might rapidly warm up the sea-breeze air as it moves inland and destroy any boundary that might initially exist between the prevailing wind and the sea-breeze air.

6. Temperature and humidity changes caused by the sea-breeze

Roy (1941) has computed the average number of occasions of temperature fall and humidity rise of different orders from his study of the data of the years, February 1938 to January 1940. It is of interest to examine the mean monthly variation of the magnitude of such changes caused by the sea-breeze. On a preliminary scrutiny of the data collected during the years 1945 and 1946, it has been found that the magnitudes of these changes were about the same, irrespective of the wind speed after the onset of the sea-breeze or the time of its onset. All the 174 significant cases of sea-breeze during the period of study were, therefore, used in computing the monthly averages of falls of temperature and rise of relative humidity shown in Table 6. These changes refer to Meenambakkam, which is 5·98 miles inland normal to the coast and cover a period of 15 minutes after the onset of the sea-breeze.

The mean monthly maximum temperatures are also included in Table 6 for comparison with the magnitudes of the changes caused by the sea-breeze.

It is seen from this table that the average temperature fall and humidity rise caused by the advent of the sea-breeze at Meenambakkam are maximum during the month of July, being 8°F and 28 per cent respectively. On the average, the sea-breeze at Madras causes a temperature drop of 5°F and humidity rise by 22 per cent, the contribution to these deriving mainly from the monsoon period. The sea-breezes of April and October do not produce significant changes, likely to make the onset of the breeze physically felt. In the summer period, April is felt locally to be hotter during the afternoon than May, although May is the hottest month in the year, for the reason that the sense of relief with the onset of sea-breeze in May is much greater due to a relatively higher temperature drop and humidity rise than in the month of April. For the same reason, the monsoon months are not regarded as approaching the earlier months in hotness, although the maximum temperature in these months is of the same order as in April itself.

In order to study the relationship between the mean monthly maximum temperatures and the mean temperature and humidity changes, the data in Table 6 are represented graphically in Figs. 2 and 3. It is seen that there is a striking similarity between the trends revealed by the two curves shown in these figures. There is a certain phase-lag also seen between the curve of monthly maxima and the curves showing the changes associated with the sea-breeze. The explanation for this anomaly may consist in the fact that with the progress of the summer, the cumulative contrast between the land and the sea would tend to increase. The day-to-day thermal contrast would be superposed over this, effectively, causing more intense sea-breezes in July than in May. It is also interesting to note the tendency for a slight levelling up of the temperature curve and the change curves in Figs. 2 and 3 during the months July to September. By July, the cumulative contrast between the land and the sea apparently reaches a maximum. When the stage is reached, the superposed day-to-day thermal contrast asserts itself as the factor that governs the intensity of the sea-breeze caused.

TABLE 6

Monthly averages of temperature fall and relative humidity rise due to onset of sea-breeze

Element	Apr	May	Jun	Jul	Aug	Sep	Oct	Year
Temperature fall (°F)	2	5	7	8	6	5	2	5
Relative humidity rise (%)	14	18	24	28	27	26	13	22
Mean maximum temperature	95·5	101·3	99·6	96·3	94·8	93·9	90·1	92·2

TABLE 7

Average fall of temperature on the onset of the sea breeze

Period (*hrs*)	Direction of the resultant wind					Mean for all directions
	E	ESE	SE	SSE	S	
1000—1159	6	5	..	3	..	4·7
1200—1359	6	6	5	6	4	5·4
1400—1559	5	8	8	7	5	6·6
1600—1759	9	..	9	7	9	8·5
1800—2000	6	..	6	..	7	6·3

TABLE 8

Average rise in aqueous vapour pressure (in mb) on the onset of sea-breeze

Period (*hrs*)	Direction of the resultant wind					Mean for all directions
	E	ESE	SE	SSE	S	
1000—1159	6·0	7·5	5·6	6·8	7·8	7·2
1200—1359	7·5	6·4	11·1	7·5	7·9	8·1
1400—1559	6·3	9·5	8·7	9·3	8·3	8·4
1600—1759	6·1	..	12·1	10·1	4·9	8·3
1800—2000	6·9	..	9·6	5·6	5·7	6·9
1000—2000	6·6	7·8	9·4	7·9	6·9	7·8

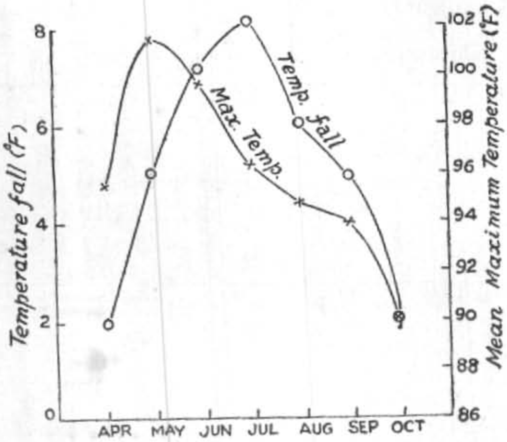

Fig. 2. Monthly variation of temperature fall on the advent of sea breeze and of mean maximum temperature

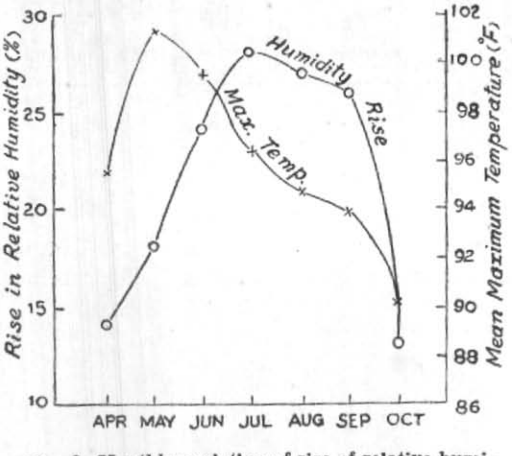

Fig. 3. Monthly variation of rise of relative humidity on the advent of sea breeze and of mean maximum temperature

In passing, it is of interest to mention that the mean May maximum might provide an advance clue to the intensity of the sea-breeze in the succeeding monsoon months. This point, however, would require further examination.

7. Dependence of meteorological changes caused by sea-breeze on the hour of onset and wind direction

The dependence of the magnitude of the mean fall in temperature on the time of incidence of the sea-breeze and the direction of the resultant wind is shown by the data in Table 7. The data in this and the following table are based on all the significant cases of sea-breeze during the years 1945 and 1946.

The striking feature of Table 7 is the gradual increase in the magnitude of the temperature fall caused by a later time of onset of the sea-breeze till the epoch of maximum temperature when it attains the peak value of 8·5°F. In the cases of subsequent onset of the sea-breeze, the temperature fall is less. The trend of the temperature falls does not show any sensible variation with the direction of the resultant wind.

In Table 8 are shown the changes in aqueous vapour pressure caused by the onset of sea-breeze. The figures signify the rise in vapour pressure in mb experienced within a period of 15 minutes, following the onset of the sea-breeze.

The magnitude of rise in vapour pressure on the advent of sea-breeze increases with delay in onset and generally reaches the maximum value of over 8 mb during the epoch of maximum temperature, as in the case of temperature fall. Vapour pressure rise, however, displays significant dependence on the direction of the resultant wind. Leaving aside the cases of premature onset of the sea-breeze before noon, it is seen that the southeasterly sea-breeze is the dampest of all. For the same hour of onset, the vapour pressure rise decreases generally with an increasing southerly component. As a southerly wind implies a pronounced southerly component of the prevailing wind, the moisture content would already be large in the air by the time the sea-breeze sets in. The further rise due to incidence of the sea-breeze would, therefore, be smaller than in the case of winds from the other points of the compass.

8. Conclusions

The sea-breeze at Madras is most pronounced during the months of May, June and July and occurs mostly from the southsoutheasterly direction with a wind speed of 10-15 mph during the early afternoon. It advances as a weak cold front with an average speed of 3-7 mph which is much less than the on-shore wind speed. This frontal speed is lowest when the onset occurs near the epoch of maximum temperature and shoots up to 5-10 mph in cases of post-sunset onset. With depth of penetration, it increases in the afternoon and falls if the onset takes place later. An easterly breeze with little or no component of the prevailing wind in it, is speedily retarded as it moves inland after sunset, while a southerly breeze with a small sea-breeze component is retarded for even an earlier onset. The fall in temperature and rise of aqueous tension caused by the advent of the sea-breeze is maximum for the onset during the epoch of maximum temperature. During the year, the maxima of temperature and humidity changes occur in the month of July and lag by a couple of months behind the maximum of the mean monthly maximum temperatures. The results of this investigation would help in forecasting in sufficient advance for aviation needs the time of onset of the sea-breeze and accompanying temperature and humidity changes at the airfield at Meenambakkam, if the time of onset and the direction of the on-shore wind earlier at a point closer to the coastline are known.

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