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Sea-breeze-initiated rainfall over the east coast of India during the Indian southwest monsoon

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Abstract Sea-breeze-initiated convection and precipitation have been investigated along the east coast of India during the Indian southwest monsoon season. Sea-breeze circulation was observed on approximately 70–80% of days during the summer months (June–August) along the Chennai coast. Average sea-breeze wind speeds are greater at rural locations than in the urban region of Chennai. Sea-breeze circulation was shown to be the dominant mechanism initiating rainfall during the Indian southwest monsoon season. Approximately 80% of the total rainfall observed during the southwest monsoon over Chennai is directly related to convection initiated by sea-breeze circulation.

Keywords Sea breeze · Monsoon · Mesoscale circulation

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1 Introduction

Sea-breeze circulation occurs along coastal regions because of the contrast between surface temperatures over land and water. Temperatures increase more quickly over land than over the ocean during the daytime, because of the greater heat capacity of water. The sea-breeze phenomenon has a direct effect on weather patterns such as daytime temperature and precipitation. Agriculture and local economies are both affected by precipitation caused by the sea breeze along coastal regions. Over half of the global population (3.2 billion) lives within 200 km of the coastline. A large proportion of this population lives in the tropics and middle latitudes, making the sea breeze an important phenomenon to understand. Evolution of the sea breeze is also important when forecasting severe weather events (Blanchard and Lopez 1985) and in the transport of pollution along coastal regions (Rhome et al. 2002).

Several factors affect the strength of the sea breeze and convection resulting from convergence along the sea-breeze front. The shape of the coastline has been shown to affect the amount of inland convergence associated with the sea breeze. Convex coastlines have been shown to enhance inland convergence and increase convective development related to the sea breeze (Pielke 1974; Boybeyi and Raman 1992). McPherson (1970) showed that increased sea-breeze divergence occurs along concave coastlines. Numerical modelling studies of the interaction between the curvature of the coastline and soil moisture variability revealed heavy precipitation occurred along the sea-breeze front near regions of high soil moisture (Baker et al. 2001).

Observational and modelling studies show that mean wind flow is important in determining the intensity of the cumulus convection associated with sea breezes in the summer months (Pielke and Cotton 1977). When the mean low-level wind is in the same direction as the sea breeze, weaker convergence is observed inland along the sea-breeze front (Boybeyi and Raman 1992; Atkins and Wakimoto 1997). Gilliam et al. (2004) showed sea-breeze fronts propagated furthest inland when wind flow was light.

Urban environments near the coast have been shown to affect the timing and evolution of the sea breeze. The horizontal wind speed over Tokyo was increased by 2.3 m s^{-1} relative to the pure sea breeze by the urban heat island (Yoshikado 1992). Numerical modelling has shown that interaction of an urban heat island and the sea-breeze front can result in enhanced convective forcing (Kusaka et al. 2000; Ohashi and Kida 2002). Regions of enhanced vertical motion occur in a convergence zone between the sea-breeze front and the urban heat island circulation (Yoshikado 1994).

Chennai (13.0° N, 80.2° E) is located in the near equatorial coastal region along the east coast of India (Fig. 1a). During the Indian southwest monsoon, which typically extends from June to September, widespread rainfall is observed along the west coast of India and over the northern plains. Large amounts of rain fall along the west coast because of frictional convergence, orographic lift caused by nearby mountains (western Ghats), and the moisture-laden marine air mass advected onshore by the southwest monsoon winds. Monsoon troughs and the development of tropical depressions lead to a large amount of rainfall along the northern plains of India. The southeast coast of India, however, is in a ‘‘rain shadow’’ region during the

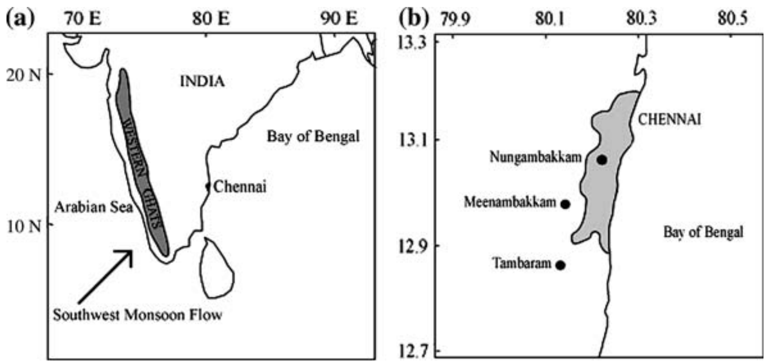

Fig. 1 (**a**) Map showing the location of Chennai along the east coast of India. (**b**) Map showing the locations of Nungambakkam, Meenambakkam, and Tambaram and the city limits of Chennai

Indian southwest monsoon. There are no large-scale weather systems present during the southwest monsoon to cause rainfall over Chennai and the southeast coast. The Indian southwest monsoon is marked by mostly clear skies and warm air temperatures over Chennai. A strong contrast in land and the ocean (Bay of Bengal) surface temperatures is observed along the east coast during the southwest monsoon. Prevailing southwest winds in conjunction with this surface temperature gradient generates conditions for the development of frequent daytime sea-breeze circulations. Numerical modelling of the sea breeze 80 km south of Chennai at Kalpakkam simulated typical onshore wind speeds of 8.3 m s^{-1} and a thermal internal boundary layer extending 18 km inland (Jamima and Lakshminarasimhan 2004). This mesoscale circulation often advances inland with a well-defined frontal feature called the sea-breeze front. Mini-SODAR measurements from Kalpakkam indicate typical positive vertical motion of 2.0–2.5 m s^{-1} along the sea-breeze front during weak synoptic conditions (Prabha et al. 2002). This convergence zone frequently initiates convection along the sea-breeze front and results in significant rainfall along the east coast of India during the southwest monsoon. The objective of the work discussed in this article was to study the frequency of the sea breeze along the east coast of India during the Indian southwest monsoon and the effect of sea-breeze circulation on rainfall variations.

2 Data

Observations of wind speed, wind direction, surface temperature, humidity, and rainfall at Nungambakkam, Meenambakkam, and Tambaram along the east coast of India were used for this study. Locations of the three stations relative to the city of Chennai are shown in Fig. 1b. Data used for the analysis were obtained from the India Meteorological Department (IMD) and the Indian Air Force Meteorological Office. Surface meteorological data from Nungambakkam and Tambaram cover the 11-year period from 1987 to 1997 for the summer monsoon months of June, July, and August. Analysis of meteorological data from the Meenambakkam station covers the period from 1987 to 2003 (except 1999). The Nungambakkam station is approximately 2 km from the coastline whereas Meenambakkam is further inland and is approximately 15 km from the coast. The Tambaram station is located further inland than Meenambakkam. Nungambakkam is well within the urban limits of Chennai, with high buildings present, whereas Meenambakkam and Tambaram are located in more rural settings with a significant decrease in roughness length. Meenambakkam, however, is located downwind of Chennai when the sea-breeze wind direction is easterly and can be affected by flow from the city, thus experiencing the effect of increased surface roughness.

Data at Meenambakkam were available eight times per day starting from 05:30 LT (every 3 h) whereas data for Nungambakkam and Tambaram were available four times per day starting from 05:30 LT. The east coastline of India is oriented at approximately 20° (from the north) as shown in Fig. 1b. We have therefore assumed a sea breeze to occur whenever the wind direction lies between 20° and 200°. Winds from these directions during the daytime are from the Bay of Bengal and caused by sea-breeze circulation.

3 Discussion of results

3.1 Sea breeze

The sea breeze results in a daytime wind shift and an increase in wind speed along the east coast of India. Figure 2 shows the diurnal variation of wind speed (dashed line) and wind direction (solid line) over Meenambakkam caused by the sea breeze on July 2, 1991. This time series of wind speed and direction is representative of typical diurnal variations observed over Chennai during the summer months when the sea breeze is present. Wind direction during the early morning hours was westerly, from approximately 260°, because of the dominant wind direction of the southwest monsoon flow. At approximately 08:00 LT the wind direction began to become more southerly as the sea breeze developed. The wind direction was approximately 140° by 12:00 LT as the sea breeze was well-developed. Southeasterly winds were observed throughout the afternoon until approximately 17:00, when the

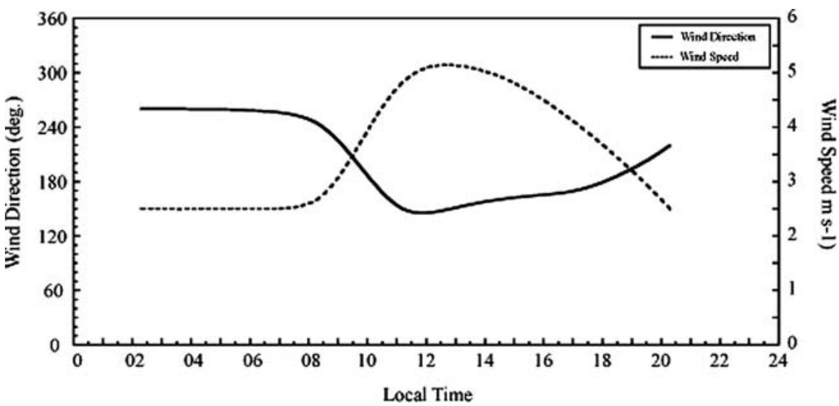

Fig. 2 Diurnal variation of wind speed (*dashed line*) and wind direction (*solid line*) caused by sea breeze on 2 July, 1991, over Meenambakkam

wind direction began to shift to southwesterly as the sea breeze weakened. Wind speeds were approximately 2.5 m s^{-1} until the sea breeze started developing at 08:00 LT. A maximum wind speed of 5.0 m s^{-1} occurred at approximately 13:00 LT when the sea breeze was at peak strength. The wind speed steadily decreased throughout the afternoon until it was approximately 2.6 m s^{-1} by 20:00 LT.

A typical sea-breeze front over Chennai on June 27, 2003, at 15:30 IST, observed by Doppler radar base reflectivity (dBz), is shown in Fig. 3. Inland penetration of the sea-breeze front can be seen in radar imagery as a thin line of weak reflectivity. The presence of a sea-breeze front was observed well inland of the Chennai coast as a narrow line of weak reflectivity around 13–19 dBz. Inland penetration of the sea breeze varied from approximately 20–40 km along the Chennai coast. The sea breeze moved approximately 30 km inland over the urban region of Chennai, whereas to the north of the urban area the sea breeze moved to approximately 40 km inland. This different inland propagation of the sea breeze was a result of the increased roughness of the urban area. Maximum inland penetration of the sea-breeze front typically occurred in the late afternoon at approximately 17:00 LT.

To study the monthly variation of the frequency of occurrence of the sea breeze, the average number of days with a sea breeze for the summer monsoon months

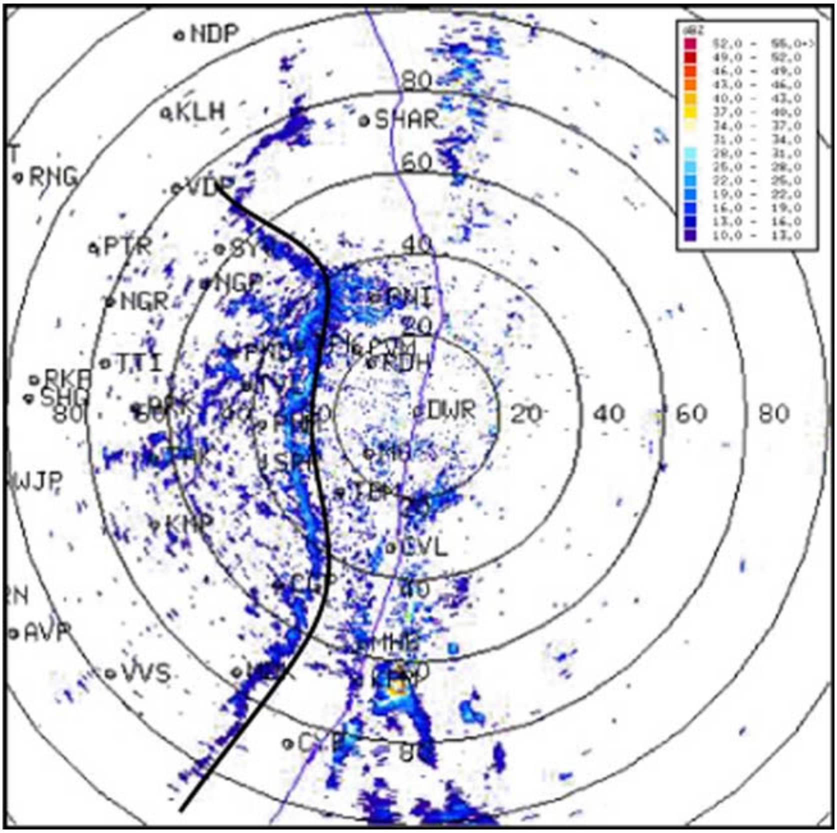

Fig. 3 Doppler radar base reflectivity (dBz) image over Chennai on 27 June, 2003, at 15:30 IST showing the location of a sea-breeze front well inland

along the Chennai coast was determined. The number of days a sea breeze was observed at Meenambakkam during the months of June, July, and August from 1987 to 2003 (except 1999) is shown in Fig. 4a. Daytime onshore wind directions between 20° and 200° during the southwest monsoon were defined as a sea breeze on the basis of alignment with the Chennai coastline. The number of sea-breeze days was, typically, highest in June, an average of 21. The minimum number of sea-breeze days over Chennai in June during the research period was 14, and the maximum was 28. The next highest average number of sea-breeze days during the summer was in July,

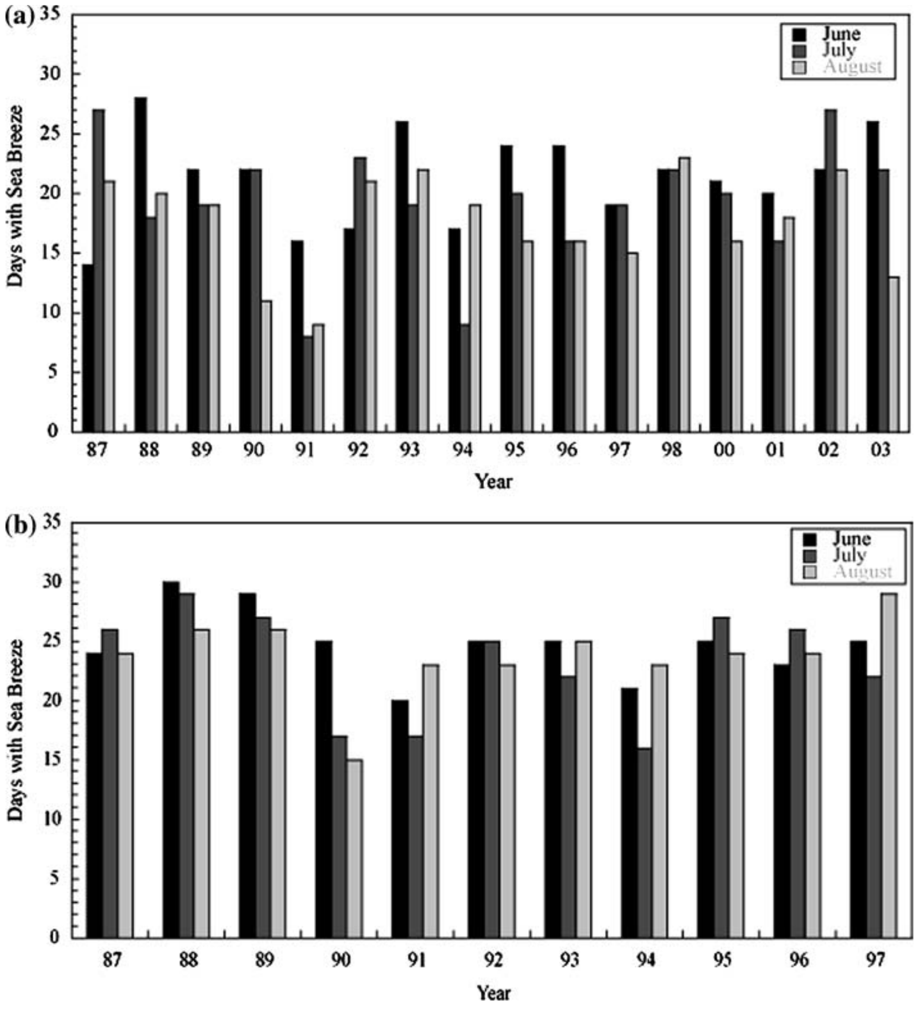

Fig. 4 (**a**) Variation of the number of days with a sea breeze observed over Meenambakkam during June, July, and August over the period 1987–2003 (except 1999). A sea breeze was observed between 58 and 68% of the time during the southwest monsoon over Meenambakkam. (**b**) Variation of the number of days with a sea breeze observed over Tambaram during June, July, and August over the period 1987–1997. Sea breeze was observed between 74% and 83% of the time during the southwest monsoon over Tambaram

with 19. August was observed to have the fewest sea-breeze days during the summer months, with an average of 18. On average for these 16 years a sea breeze was observed over Chennai on 68% of days during June, on 61% of days during July, and on 58% of days during August.

There is also a large inter-annual variation in the number of days with sea breeze over Tambaram. The number of days with a sea breeze observed over Tambaram during June, July, and August for the period 1987–1997 is shown in Fig. 4b. The average number of days with a sea breeze at Tambaram was highest in June, with 25 days. The number of average sea-breeze days occurring during July was similar to June, again with 23 days. August had an almost identical number of sea-breeze days as June and July, with 24 days. On average, a sea breeze occurred on 83% of days during June, 74% of days in July, and 77% of days during August. The percentage of days with a sea breeze over Tambaram was slightly higher than observed over Meenambakkam. One would expect the number of sea-breeze days at these two locations to be the same. This difference may be because of weakening of the winds over and close to the city, because of increased friction.

Average wind speeds in the sea-breeze circulation varied from year to year. The average sea-breeze wind speed during June over Meenambakkam, Nungambakkam, and Tambaram over the period 1987–1997 is shown in Fig. 5a. The highest sea-breeze wind speeds during June were observed over Tambaram, with an average magnitude of 4.6 m s^{-1}. Average sea-breeze winds over Meenambakkam were 3.2 m s^{-1} and over Nungambakkam the average winds were 2.1 m s^{-1}. This variation is consistent with their locations, Nungambakkam being urban, Meenambakkam close to the city, but rural, and Tambaram the more rural of the two. Observed sea-breeze winds were slightly weaker during July (Fig. 5b). The highest average wind speeds during the sea breeze were again observed over Tambaram with a value of 4.4 m s^{-1}. Wind speeds over Meenambakkam decreased to 2.8 m s^{-1} whereas wind speeds over Nungambakkam remained steady at 2.1 m s^{-1}. During August, sea-breeze wind speeds again decreased over Meenambakkam and Tambaram (Fig. 5c). The average sea-breeze wind speed over Meenambakkam during August was 2.6 m s^{-1} and the wind speed over Tambaram fell to 3.9 m s^{-1}. Average wind speed over Nungambakkam increased slightly to 2.3 m s^{-1}, however.

3.2 Sea-breeze-induced rainfall

Amounts of precipitation over Chennai during the summer months seem to be most heavily affected by the daytime sea breeze. Monthly variation of the 50 year (1940–1990) average rainfall observed over Nungambakkam is shown in Fig. 6a. Little rainfall was observed over Chennai from January to April with amounts of precipitation ranging from 15 mm to 30 mm. Northward movement of the inter tropical convergence zone (ITCZ) or the monsoon trough over southern India increased amounts of rainfall to approximately 60 mm during May. Observed rainfall totals in May were slightly higher than in June, probably not because of a stronger sea breeze but rather because May is a monsoon transition month with greater synoptic variability. Increasing amounts of rainfall were observed from June to August despite the absence of any large-scale weather features to produce convection. Most of the rainfall occurring during the summer months over Chennai can only be caused

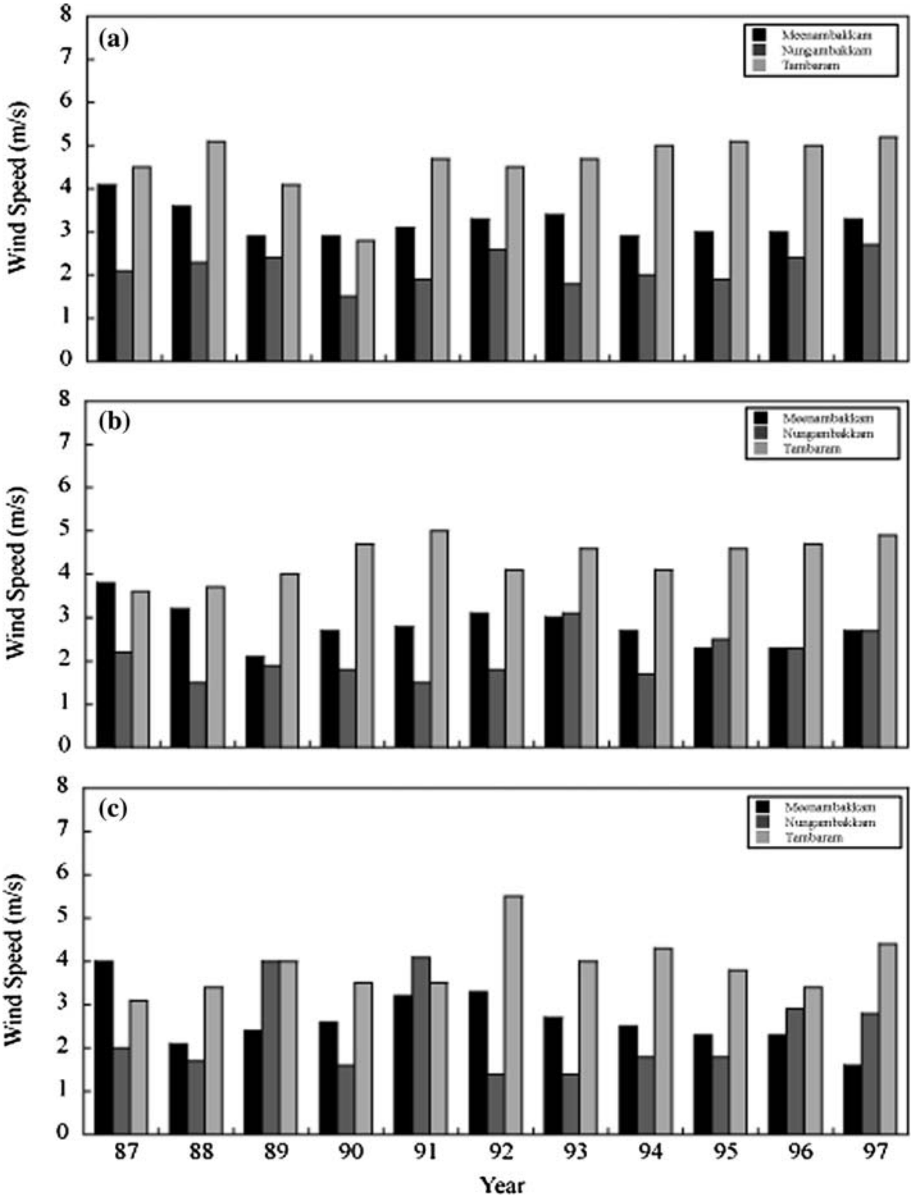

Fig. 5 (**a**) Average wind speed during the sea breeze over Meenambakkam, Nungambakkam, and Tambaram during June in the period 1987–1997. (**b**) Same as (**a**) but for July. (**c**) Same as (**a**) but for August

by sea-breeze circulation. Amounts of rainfall were observed to increase to approximately 270 mm and 330 mm during October and November. This increase in rainfall is because of large-scale effects, for example low-pressure systems, monsoon depressions, and tropical cyclones that form offshore in a highly baroclinic region as the monsoon trough migrates south. In December the rainfall dropped to approximately 150 mm because the monsoon trough moved well to the south.

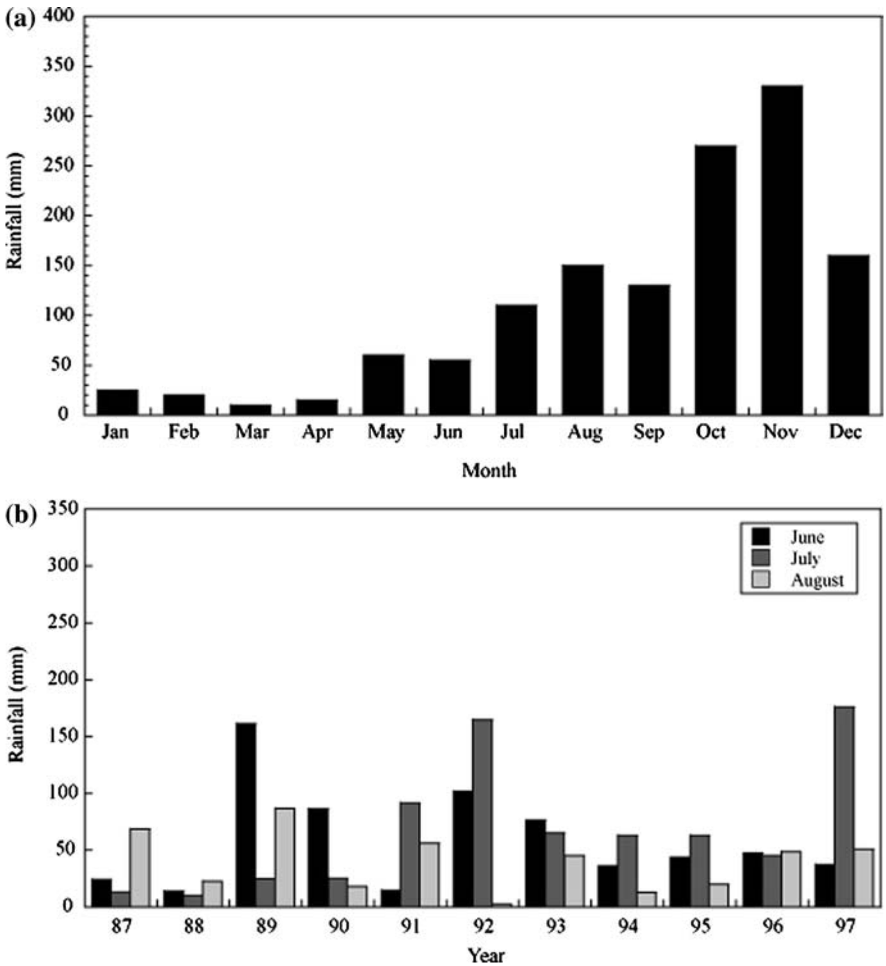

Fig. 6 (**a**) Monthly variation of the 50-year average rainfall over Nungambakkam. The sea breeze is shown to cause a large amount of rainfall during June, July, and August. (**b**) Monthly rainfall during June, July, and August over Nungambakkam during the period 1987–1997

Amounts of rainfall over Nungambakkam in June, July, and August over the period 1987–1997 are shown in Fig. 6b. The average monthly rainfall over Nungambakkam during June was 58 mm and the maximum was 161 mm. Average amounts of rainfall increased slightly to 68 mm during July, when the maximum observed total rainfall was 176 mm. Amounts of rainfall were lowest over Nungambakkam during August, when average monthly rainfall was 39 mm. Maximum rainfall during August was 87 mm and the minimum was 3 mm.

Most of the rainfall along the Chennai coast during the Indian southwest monsoon occurs on days when a well-defined sea-breeze circulation is observed. Total amounts of rainfall (black column) and amounts of rainfall when a sea breeze was observed (gray column) over Meenambakkam for June in the period 1987–2003 (except 1999) are shown in Fig. 7a. Average monthly rainfall for June over Meenambakkam was 66 mm and the average amount of rainfall occurring when

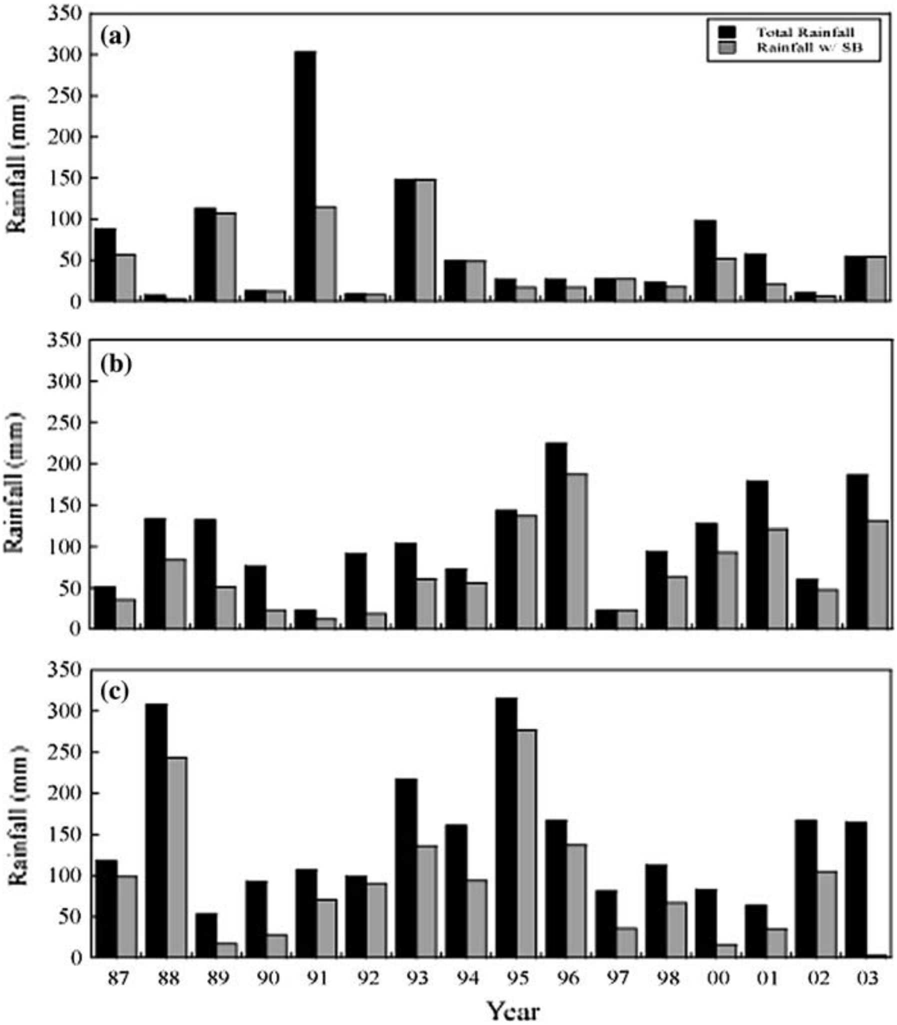

Fig. 7 (**a**) Total rainfall (*black column*) during June over Meenambakkam and rain caused by the sea breeze (*grey column*) during the period 1987–2003 (except 1999). (**b**) same as (**a**) but for July. (**c**) same as (**a**) but for August

there was a sea breeze was 45 mm. On average, the sea breeze is responsible for approximately 70% of the total rainfall over Meenambakkam during June. The rest of the rainfall most probably occurs because of mesoscale convection that forms during breaks in the monsoon and the rare formation of low-pressure systems during this time. Rainfall initiated by thermal instability inland that moves toward the coast might also account for some of the non-sea-breeze-induced rainfall. The average monthly rainfall total over Meenambakkam during July was 108 mm, with 72 mm of the rainfall occurring on days with a sea breeze (Fig. 7b). The sea breeze was responsible for approximately 70% of the rainfall over Meenambakkam during July. Average monthly total rainfall during August was 145 mm, which was much larger than the average rainfall during June and July (Fig. 7c). On average during August approximately 91 mm of rainfall occurred with a sea breeze present, i.e. approximately 63% of total rainfall. This percentage of sea-breeze-initiated rainfall was slightly lower than during June and July.

The effect of the sea breeze on average amounts of rainfall over Tambaram during June, July, and August was also studied. Figure 8a shows total amounts of rainfall over Tambaram in June (black column) and rain occurring when a sea breeze was observed (grey column), during the period 1987–1997. The average June rainfall was 95 mm and the maximum and minimum yearly rainfall during the study period were 217 mm and 3 mm, respectively. On average, 74 mm (or 78%) of the June rainfall occurred on days when a sea breeze was observed. Amounts of rainfall over Tambaram during July were similar to those in June, as shown in Fig. 8b. The average total rainfall during July was 95 mm, the yearly maximum was

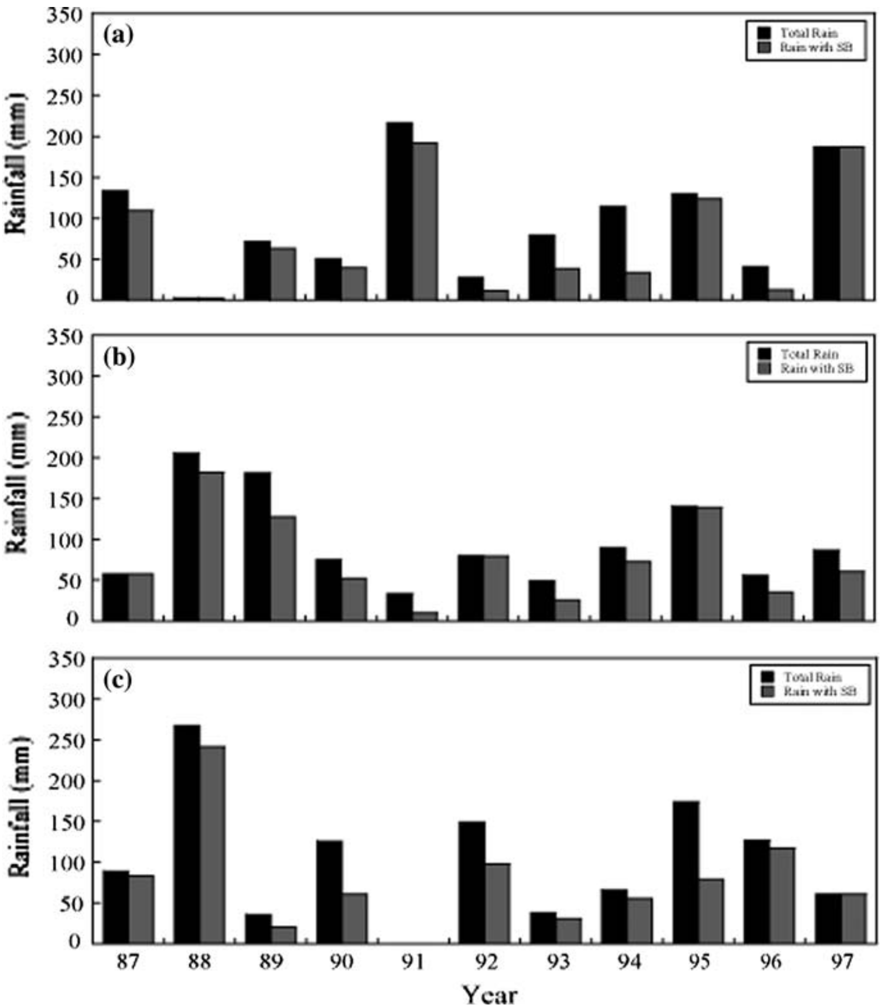

Fig. 8 (**a**) Total rainfall (*black column*) during June over Tambaram and rain caused by the sea breeze (*grey column*) during the period 1987–1997. (**b**) same as (**a**) but for July. (**c**) same as (**a**) but for August

206 mm, and the minimum was 34 mm. Approximately 76 mm of rain (80% of total rain) occurred each year during July when a sea breeze was observed. This percentage is comparable with that observed during June. Average amounts of rainfall increased slightly over Tambaram during August, as shown in Fig. 8c. The average rainfall during July increased to 102 mm. The yearly maximum rainfall during August was 267 mm and the minimum was 36 mm. The amount of rain occurring when a sea breeze was observed dropped to 75% during August. Total amounts of rainfall were almost constant during the summer months over Tambaram and the amount of rain occurring because of the sea breeze was steady at approximately 75%.

4 Conclusions

Well-developed sea-breeze circulation is frequently observed along the east coast of India during the Indian southwest monsoon season. Observations from three locations along the Chennai coast show the sea breeze typically occurs on 75% of days during the summer monsoon months of June to August. Average wind speed during the sea breeze is observed to decrease from June to August. Sea-breeze wind speeds are approximately 1.5 m s^{-1} higher outside Chennai than inside or just downwind of the city. The decrease in wind speed over the urban region of Chennai is directly related to the increase in surface roughness.

The greatest amounts of rainfall over Chennai are observed during the northeast monsoon months of October and November. Chennai also receives a substantial amount of rainfall during the southwest monsoon season, because of sea-breeze circulation. With the monsoon trough far to the north during the southwest monsoon, sea breeze is the dominant mesoscale mechanism for initiating rainfall. The sea breeze is shown to contribute approximately 70–80% of the total rainfall over Chennai during the summer southwest monsoon season. The contribution of the sea breeze to total amounts of rainfall is greater outside the urban region of Chennai, because of the greater intensity of the sea-breeze front.

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