LAWRENCE LIVERMORE NATIONAL LABORATORY

UCRL-JRNL-224343

Sea breeze Initiated Rainfall over the east Coast of India during the Indian Southwest Monsoon

M. Simpson, H. Warrior, S. Raman, P. A. Aswathanarayana, U. C. Mohanty, R. Suresh

September 11, 2006

Journal of Natural Hazards

Disclaimer

Sea breeze Initiated Rainfall over the east Coast of India during the Indian Southwest Monsoon

Matthew Simpson, Hari Warrior[1], Sethu Raman, P.A.Aswathanarayana[2], U.C. Mohanty[3], and R. Suresh[4].

Department of Marine, Earth, and Atmospheric Sciences
North Carolina State University, Raleigh, NC 27695-8208, USA
[1] Indian Institute of Technology, Kharagpur, India
[2] Indian Institute of Technology, Chennai, India
[3] Indian Institute of Technology, New Dehli, India
[4] India Meteorological Department, Chennai, India

18 April 2006

Abstract. Sea breeze initiated convection and precipitation is investigated along the east coast of India during the Indian southwest monsoon season. The sea breeze circulations are observed approximately 70 to 80% of the days during the summer months (June to August) along the Chennai coast. Observations of average sea breeze wind speeds are stronger at a rural location as compared to the wind speeds observed inside the urban region of Chennai. The sea breeze circulation is shown to be the dominant mechanism for initiating rainfall during the Indian southwest monsoon season. Roughly 80% of the total rainfall observed during the southwest monsoon over Chennai is directly related to the convection initiated by sea breeze circulation.

Keywords: Sea breeze, Monsoon, Mesoscale circulation

1. Introduction

Sea breeze circulations occur along coastal regions due to the contrast between surface temperatures over land and water. Temperatures increase at a faster rate over land than over the ocean during the daytime due to the 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 influenced 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 portion of this population lives in the tropics and mid latitudes making the sea breeze an important phenomenon to understand. Evolution of the sea breeze is also important in forecasting severe weather events (Blanchard and Lopez 1985) and the transport of pollution along coastal regions (Rhome *et al.* 2002).

Several factors influence the strength of the sea breeze and convection resulting from convergence along the sea breeze front. 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 modeling 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 modeling studies show the mean wind flow is important in determining the intensity of the cumulus convection associated with sea breezes on 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 to propagate furthest inland when light wind flow regimes are present.

Urban environments near the coast have been shown to influence 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 modeling has shown that the 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 as shown in Figure 1a. During the Indian southwest monsoon, which typically extends from June to September, wide-spread rainfall is observed along the west coast of India and over the northern plains. Large amounts of rain are observed along the west coast due to 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 cause a large amount of rainfall along the northern plains of India. However, the southeast coast of India is in a “rain shadow” region during the 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 the 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 modeling 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 to 2.5 m s^{-1} along the sea breeze front during weak synoptic conditions (Prabha *et al*. 2002). Frequently, this convergence zone initiates convection along the sea breeze front and produces significant rainfall along the east coast of India during the southwest monsoon. Objective of this paper is to study the frequency of the sea breeze along the east coast of India during the Indian southwest monsoon and the effect of the sea breeze circulation on rainfall variations.

2. Data

Observations of wind speed, wind direction, surface temperature, humidity, and rainfall from 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 if Figure 1b. Data used for the analysis were obtained from the India Meteorological Department (IMD) and Indian Air Force Meteorological Office. Surface meteorological data from Nungambakkam and Tambaram cover the eleven 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 (excluding 1999). The Nungambakkam station is about 2 km from the coastline, while Meenambakkam is further inland and is about 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, while Meenambakkam and Tambaram are located in more rural settings with a significant decrease in roughness length. However, Meenambakkam is located downwind of Chennai when the sea breeze wind direction is easterly and can be influenced by the 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 three hours), while the data for Nungambakkam and Tambaram were available four times per day starting from 05:30 LT. The east coastline of India is oriented at about 20° (from the north) as shown earlier in Figure 1(b). Therefore, we have 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 caused by sea breeze circulation.

3. Discussion of Results

3.1 Sea breeze

Influence of the sea breeze results in a daytime wind shift and increase in wind speed along the east coast of India. The diurnal variation of wind speed (dashed line) and wind direction (solid line) over Meenambakkam caused by the sea breeze on 2 July 1991 is shown in Figure 2. This time series of wind speed and direction is representative of the typical diurnal variations observed over Chennai during the summer months when sea breeze is present. Wind direction during the early morning hours was westerly, from around 260° due to the dominant wind direction of the southwest monsoon flow. Around 08:00 LT, the wind direction begins to become more southerly as the sea breeze develops. The wind direction was around 140° by 12:00 LT as the sea breeze is well developed. Southeasterly winds were observed throughout the afternoon until around 17:00, when the wind direction begins to shift to southwesterly as the sea breeze weakens. Wind speeds were about 2.5 m s^{-1} until the sea breeze starts developing at 08:00 LT. A maximum wind speed of 5.0 m s^{-1} occurred around 13:00 LT when the sea breeze was at peak strength. The wind speed steadily decreased throughout the afternoon until it was around 2.6 m s^{-1} by 20:00 LT.

A typical sea breeze front over Chennai on 27 June 2003 at 15:30 IST observed by Doppler radar base reflectivity (dBz) is shown in Figure 3. Inland penetration of the sea breeze front can be seen in radar imagery as a thin line of weak reflectivity. Presence of a sea breeze front was observed well inland of the Chennai coast as a narrow line of weak reflectivity around 13 to 19 dBz. Inland penetration of the sea breeze varied from around 20 to 40 km along the Chennai coast. The sea breeze moved around 30 km inland over the urban region of Chennai, while to the north of the urban area, the sea breeze moved to around 40 km inland. Difference in the inland propagation of the sea breeze was influenced by increased roughness of the urban area. Maximum inland penetration of the sea breeze front typically occurs in the late afternoon around 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 along the Chennai coast was determined. The number of days that a sea breeze was observed at Meenambakkam for the months of June, July and August from 1987 to 2003 (excluding 1999) are shown in Figure 4(a). Daytime onshore wind directions between 20° to 200° during the southwest monsoon were defined as a sea breeze based on the alignment of the Chennai coastline. June typically had the highest number of sea breeze days with an average of 21 days. Minimum number of June sea breeze days over Chennai during the research period was 14 days while the maximum number was 28 days. July had the next highest average number of sea breeze days during the summer with 19 days. August was observed to have the fewest of sea breeze days during the summer months with an average value of 18 days. On average, there was a sea breeze observed over Chennai 68% of the days during June, 61% of the days during July, and 58% of the days during August for these 16 years.

There is also a large inter annual variation in the number of days with sea breeze over Tambaram. Number of days with a sea breeze observed over Tambaram during June, July, and August for the period of 1987 to 1997 is shown in Figure 4(b). 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 with 23 days. August had a near identical number of sea breeze days as June and July with 24 days with a sea breeze observed. On average, a sea breeze occurred on 83% of the days during June, 74% of the days in July, and 77% of the 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 theses two locations to be the same. This difference may be due to the weakening of the winds over and close to the city due to 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 of 1987 to 1997 is shown in Figure 5a. 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 most rural of the two. Observed sea breeze winds were slightly weaker during July (Figure 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} while wind speeds over Nungambakkam remained steady at 2.1 m s^{-1}. During August, sea breeze wind speeds again decreased over Meenambakkam and Tambaram (Figure 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}. However, the average wind speed over Nungambakkam increased slightly since July to 2.3 m s^{-1}.

3. 2 Sea breeze induced rainfall

Precipitation amounts over Chennai during the summer months appear to be most heavily influenced by the day time sea breeze. Monthly variation of the fifty year (1940 - 1990) average rainfall observed over Nungambakkam is shown in Figure 6(a). Little rainfall was observed over Chennai from January to April with precipitation amounts ranging from 15 to 30 mm. Northward movement of the inter tropical convergence zone (ITCZ) or the monsoon trough over southern India increases rainfall amounts to around 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 May is a monsoon transition month with greater synoptic variability. Increasing rainfall amounts were observed from June to August despite the absence of any large scale weather features to produce convection. The majority of rainfall occurring during the summer months over Chennai can only be caused by the sea breeze circulations. Rainfall amounts were observed to increase to around 270 mm and 330 mm during October and November. This increase in rainfall is due to large scale effects such as low pressure systems, monsoon depressions and tropical cyclones that form offshore in a highly baroclinic region as the monsoon trough migrates south. December experienced a drop in rainfall to around 150 mm as the monsoon trough has moved well to the south.

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

Majority 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 rainfall amounts (black column) and rainfall amounts when a sea breeze was observed (grey column) over Meenambakkam for June over the period of 1987 to 2003 (excluding 1999) are shown in Figure 7a. Average monthly rainfall for June over Meenambakkam was 66 mm and the average amount of rainfall occurring when there was a sea breeze is 45 mm. On average, the sea breeze accounts for about 70% of the total rainfall observed over Meenambakkam during June. Rest of the rainfall most likely occurs due to 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 towards the coast may also account for a portion 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 (Figure 7b). The sea breeze was responsible for roughly 70% of the rainfall observed over Meenambakkam during July. Average monthly total rainfall during August was 145 mm, which was much larger than average rainfall observed during June and July (Figure 7c). Around 91 mm of rainfall occurred on average during August with a sea breeze present accounting for around 63% of the total rainfall. This percentage of sea breeze initiated rainfall was slightly lower than observed during June and July.

Influence of the sea breeze on average rainfall amounts over Tambaram during June, July, and August was also studied. June total rainfall amounts (black column) and rain occurring when a sea breeze is observed (grey column) during the period 1987 to 1997 over Tambaram are shown in Figure 8a. The average June rainfall was 95 mm while the maximum and minimum yearly rainfall during the study period was 217 and 3 mm, respectively. On average, 74 mm (or 78%) of the June rainfall occurred on days when a sea breeze was observed. Rainfall amounts over Tambaram during July are similar to those in June as shown in Figure 8b. The average total rainfall during July was 95 mm, while the yearly maximum was 206 mm and the minimum was 34 mm. Around 76 mm of rain (80% of total rain) occurred each year during July when a sea breeze was observed. This percentage is comparable to what is observed during June. Average rainfall amounts increased slightly over Tambaram during August as shown in Figure 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. Percentage of rain occurring when a sea breeze was observed dropped to 75% during August. Total rainfall amounts were near constant during the summer months over Tambaram and the percentage of rain occurring due to the sea breeze held steady at around 75%.

4. Conclusions

A 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 75% of the days during the summer monsoon months of June to August. Average wind speed during the sea breeze is observed to decrease from June through August. Observations of sea breeze wind speeds are higher by around 1.5 m s^{-1} outside of Chennai as compared to 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 rainfall amounts 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 due to the sea breeze circulations. With the monsoon trough well 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 to 80% of the total rainfall over Chennai during the summer southwest monsoon season. Contribution of the sea breeze to total rainfall amounts is higher outside of the urban region of Chennai due to greater intensity of the sea breeze front.

Acknowledgements. This work was supported by the Atmospheric Sciences Division, National Science Foundation under grant ATM – 0233780.

This work was performed under the auspices of the U. S. Department of Energy by University of California, Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

References

Atkins, N., and R. Wakimoto, 1997: Influence of the synoptic-scale flow on sea breezes observed during CaPE. *Mon. Wea. Rev*., 125, 2112-2130.

Baker, R., L. Barry, A. Boone, W.K. Tao, and J. Simpson, 2001: The influence of soil moisture, coastline curvature, and land-breeze circulations on sea-breeze initiated precipitation, J. Hydromet., 193-211.

Blanchard, D., and R. Lopez, 1985: Spatial patterns of convection in south Florida, *Mon. Wea. Rev*, 113, 1282-1299.

Boybeyi, Z., and S. Raman, 1992: A three-dimensional numerical sensitivity study of convection over the Florida peninsula. *Bound. Layer Meteor*., 60, 325-359.

Gilliam, R., S. Raman, D.V. Niyogi, 2004: Observational and numerical study on the influence of large-scale flow direction and coastline shape on sea-breeze evolution. *Bound. Layer Meteor*., 111, 275 – 300.

Jamima, P. and J. Lakshminarasimhan, 2004: Numerical simulation of sea breeze characteristics observed at tropical coastal site, Kalpakkam. *Earth Planet. Sci*., 113, 197-209.

Kusaka, H., F. Kimura, H. Hirakuchi, and M. Mitzutori, 2000: The effects of land use alteration on the sea breeze and daytime heat island in the Tokyo metropolitan area. *J. Meteorol. Soc. Japan.*, 78, 405-420.

McPherson, R.D., 1970: A numerical study of the effect of a coastal irregularity on the sea breeze. *J. Appl. Meteor*., 9, 767-777.

Ohashi, Y., and H. Kida, 2002: Local circulations developed in the vicinity of both coastal and inland urban areas: Numerical study with a mesoscale atmospheric model. *J. Appl. Meteorol.*, 41, 30-45.

Pielke, R., 1974: A three-dimensional numerical model of the sea breezes over south Florida. *Mon. Wea. Rev*., 102, 115-139.

Pielke, R.A and W.R.Cotton, 1977: A mesoscale analysis over South Florida for a high rainfall event, Mon. Wea.Rev, 105, 343-362,

Prabha, T.V., R. Venkatesan, E.M. Radlgruber, G. Rengarajan, and N. Jayanthi, 2002: Thermal internal boundary layer characteristics at a tropical coastal site as observed by a mini-SODAR under varying synoptic conditions, *Earth Planet. Sci.*, 111, 63-77.

Rhome. J., D. Niyogi, and S. Raman, 2002: Assessing seasonal transport and deposition of agricultural emissions in eastern North Carolina, USA, *Pure Appl. Geophys*, 160, 117-141.

Yoshikado, H., 1992: Numerical study of the daytime urban effect and its interaction with the sea breeze. J. Appl. Meteor., 31, 1146-1164.

Yoshikado, H., 1994: Interaction of the sea breeze with the urban heat islands of different sizes and locations. J. Meteor. Soc. Japan, 72, 139-142.

Figure Captions

Figure 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.

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

Figure 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.

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

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

Figure 6. (a) Monthly variation of the fifty-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 to 1997

Figure7. (a) Total rainfall (black column) during June over Meenambakkam and rain caused by the sea breeze (grey column) during the period 1987 to 2003 (excluding 1999). (b) same as (a) but for July. (c) same as (a) but for August.

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

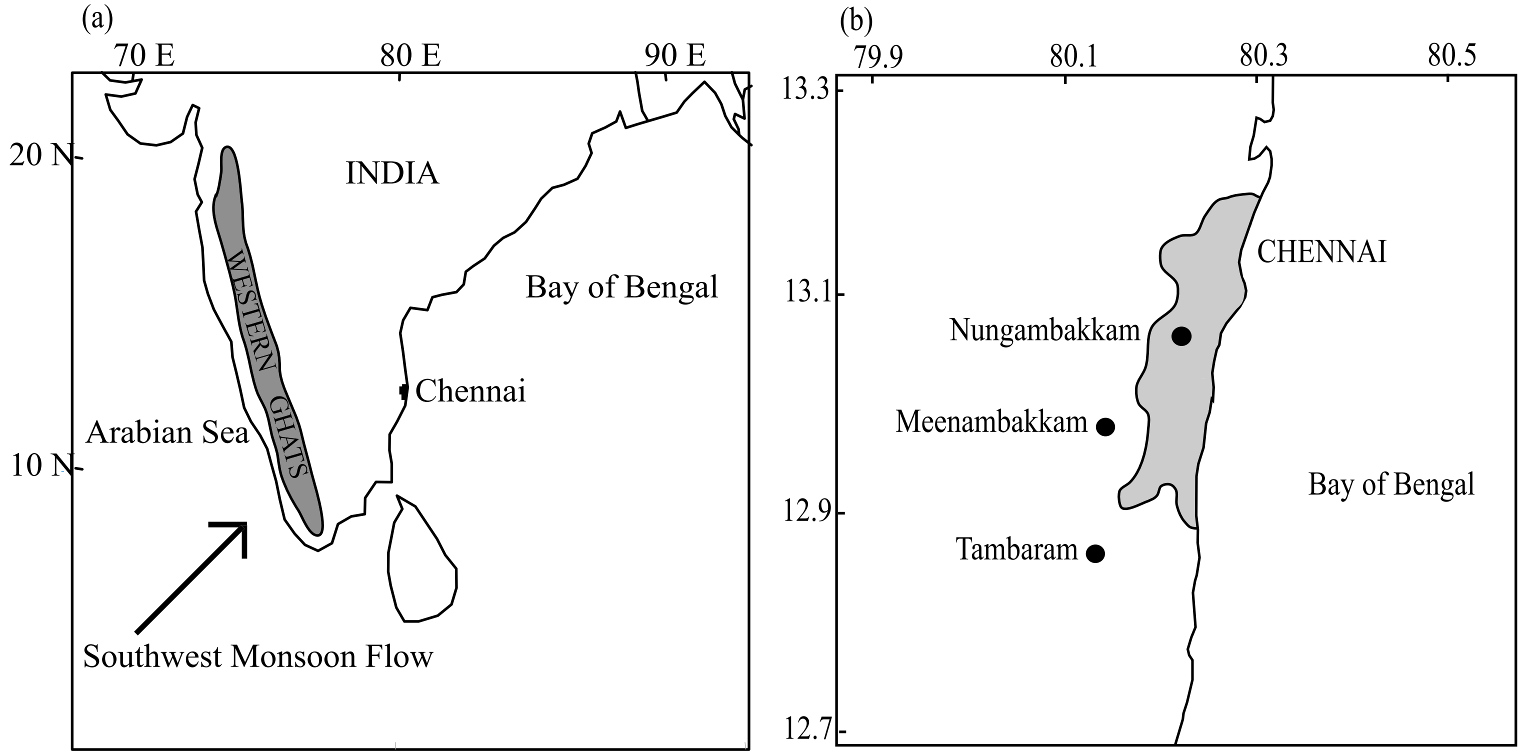

Figure 1. (a) Map showing the location of Chennai along the east coast of India and the dominant wind flow during the Indian Southwest Monsoon. (b) Map of Chennai city limits and locations of Nungambakkam, Meenambakkam, and Tambaram.

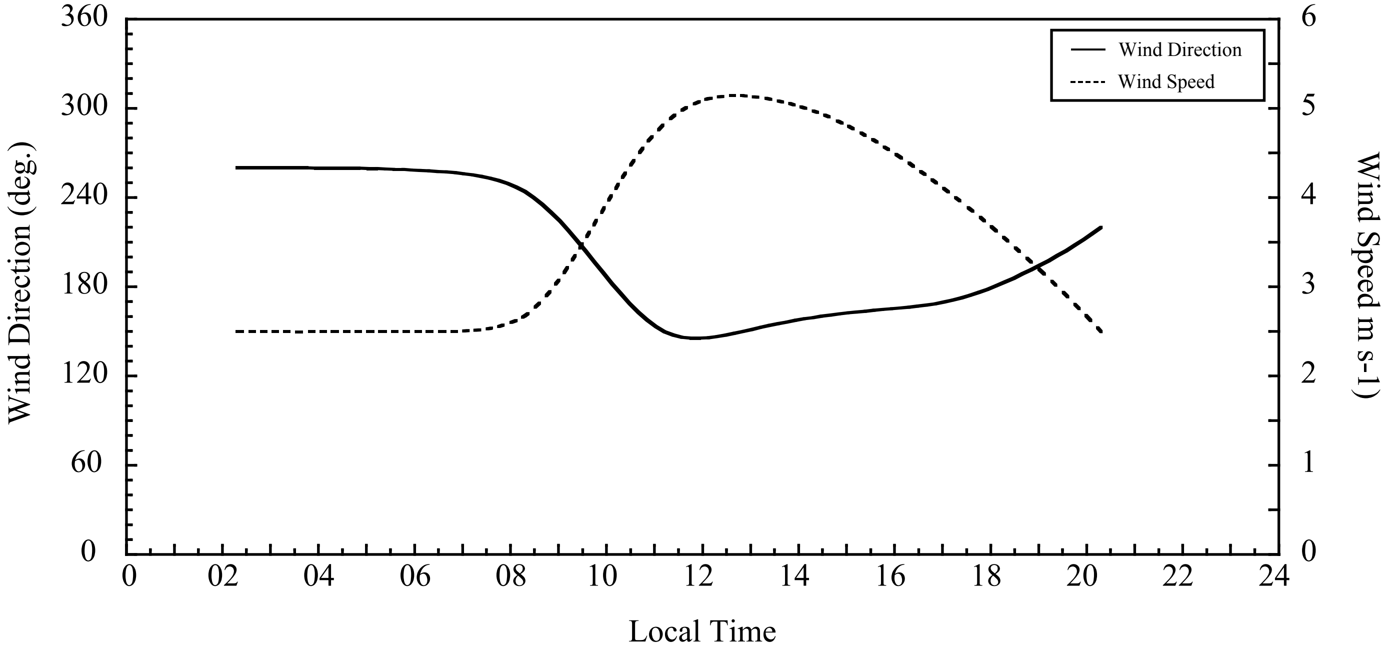

Figure 2. Typical diurnal variation of wind direction (solid line) and wind speed (dashed line) on 2 July 1991 over Meenambakkam.

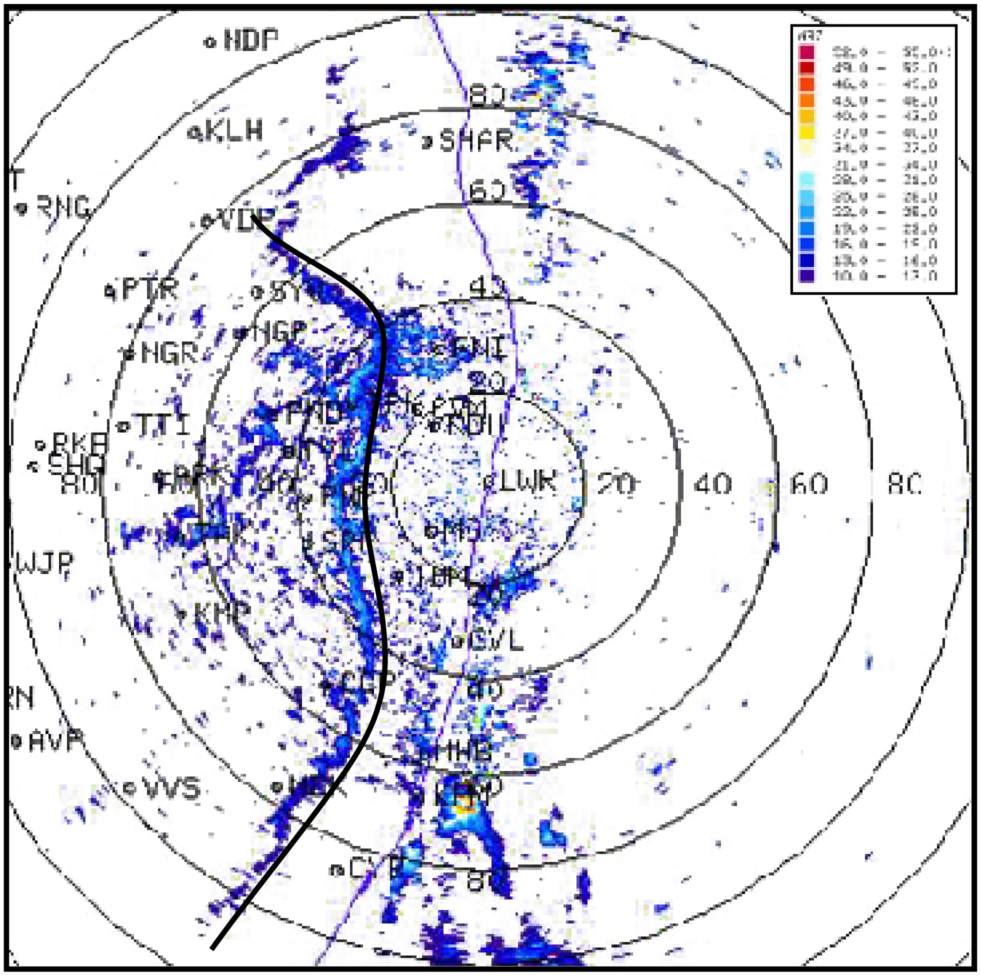

Figure 3. Doppler Weather Radar (DWR) imagery from site located along the coast of Chennai showing the location of the sea breeze front on 27 June 2003 at 15:30 IST .

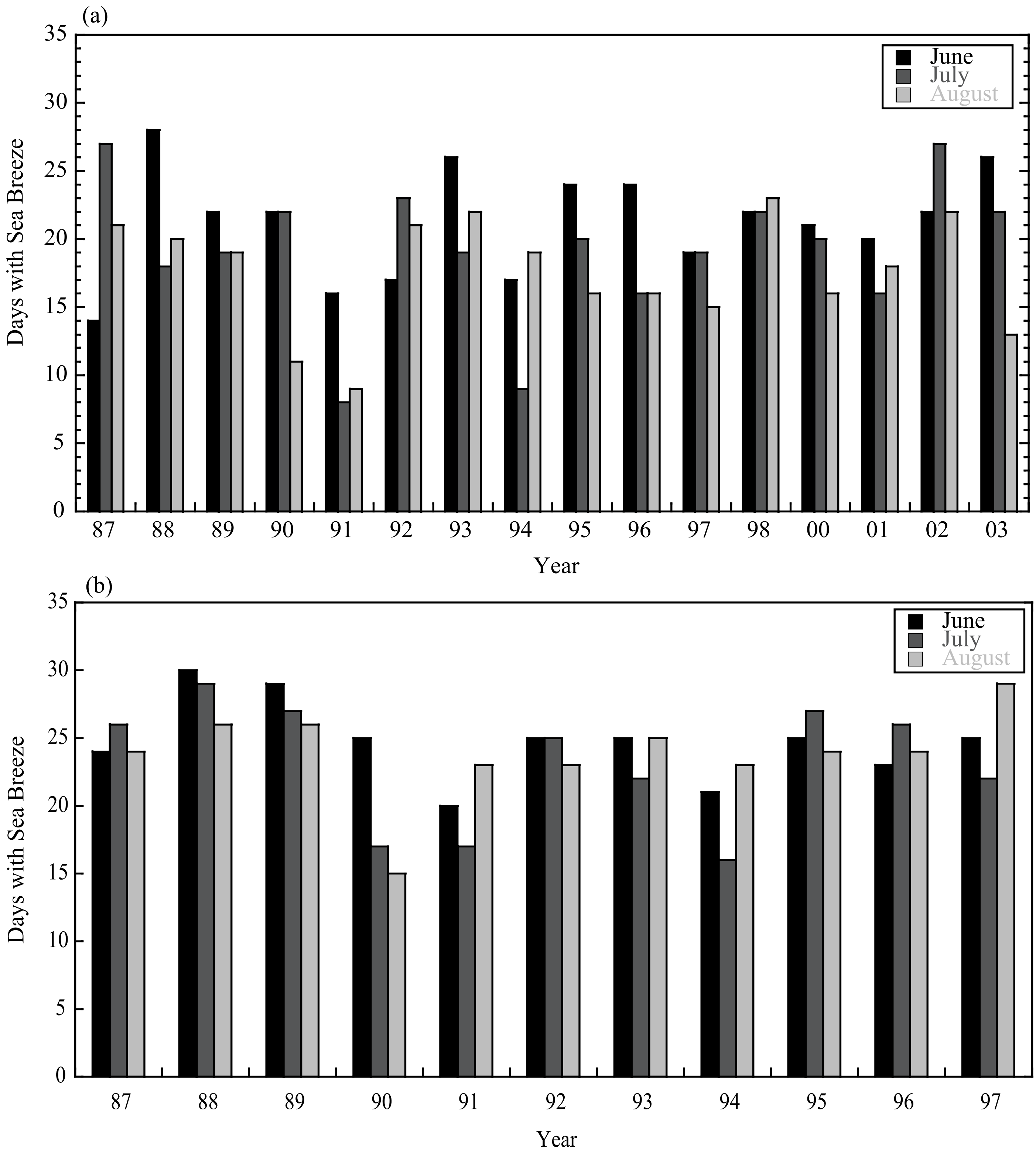

Figure 4. (a) Number of sea breeze days observed over Meenambakkam during June, July, and August over the period from 1987 to 2003 (excluding 1999). (b) Number of days with a sea breeze observed during June, July, and August over Tambaram during the period 1987 to 1997. June had on average 25 days with a sea breeze, July had 23 days, and August had 24 days with a sea breeze.

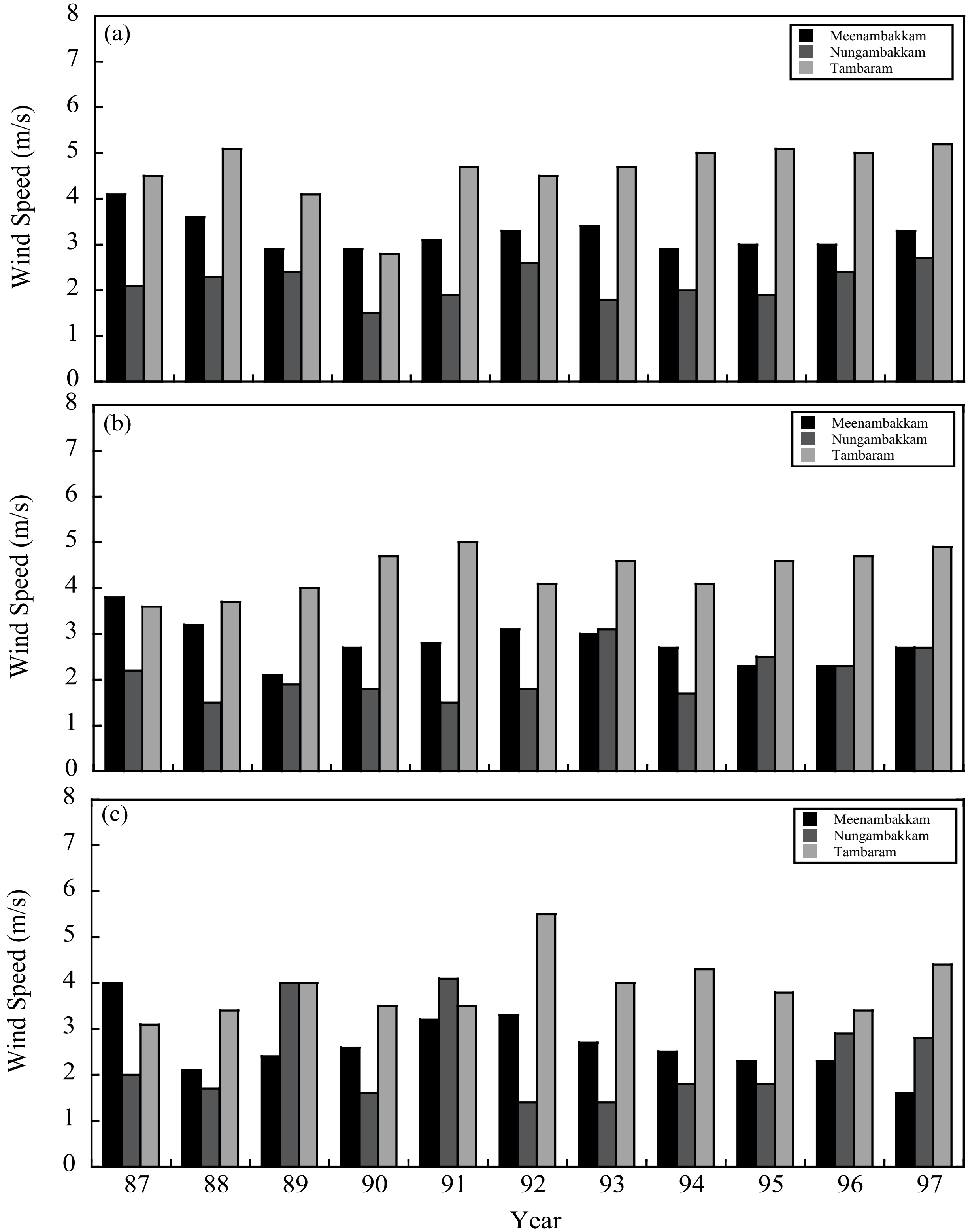

Figure 5. (a) Average wind speed during June over Meenambakkam, Nungambakkam, and Tambaram over the period 1978 to 1997. (b) same as (a) but for July. (c) same as (a) but for August.

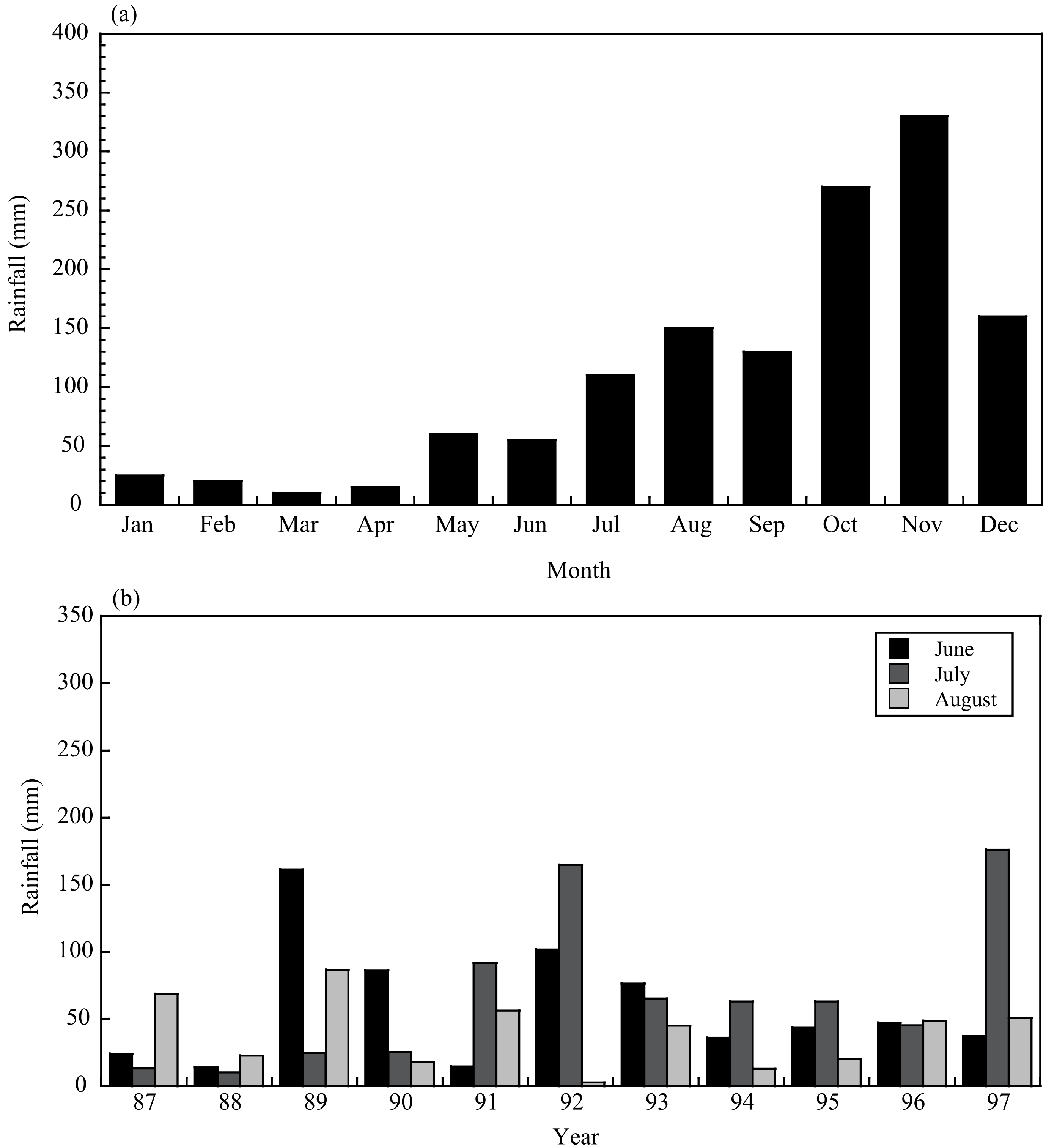

Figure 6. (a) Monthly variation of the fifty - year average rainfall over Nungambakkam. (b) Monthly rainfall totals over Nungambakkam for June, July, and August during the period of 1987 to 1997.

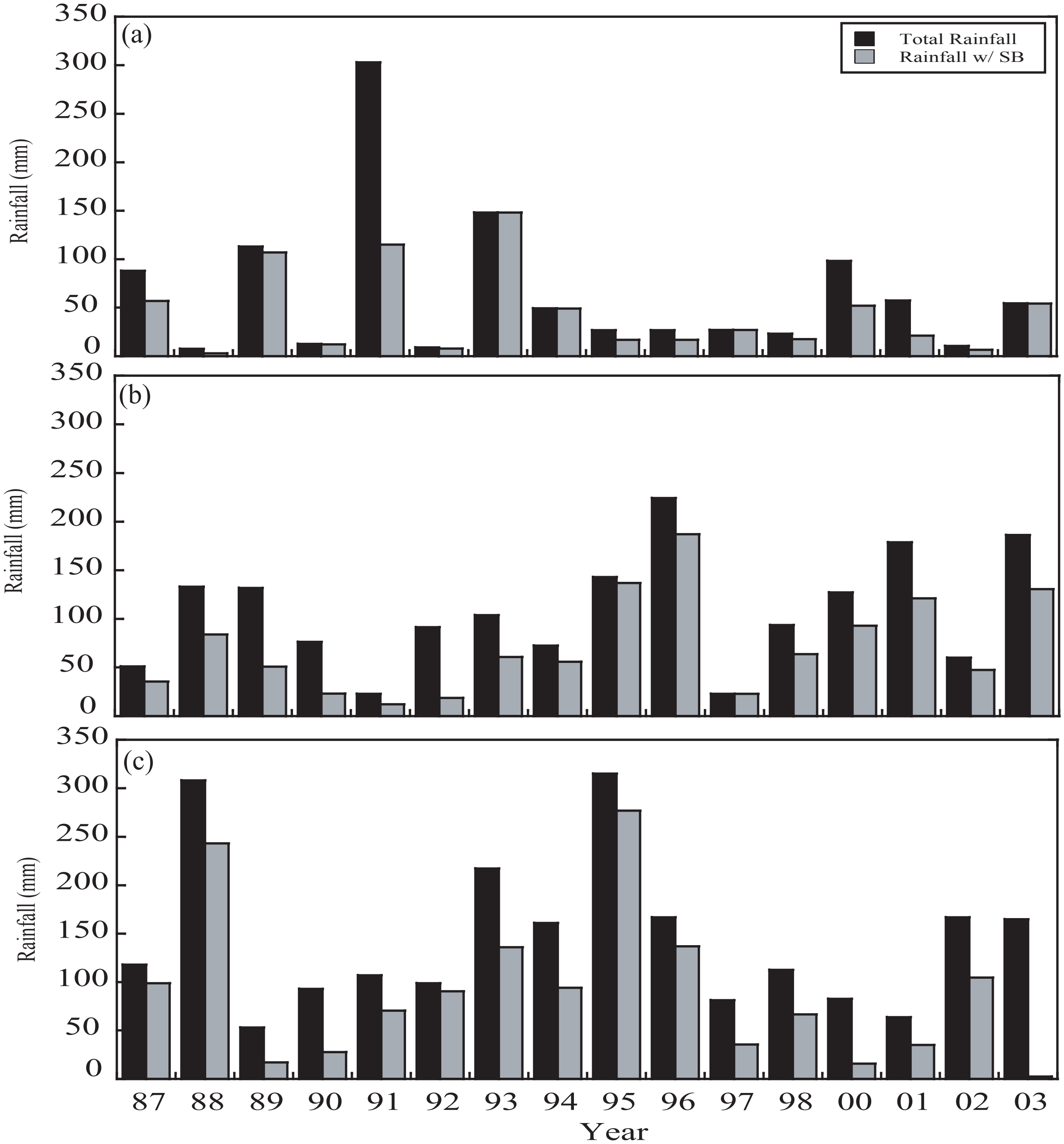

Figure 7. (a) Total June rainfall observed over Meenambakkam in solid black column and rainfall on days with an observed sea breeze in gray column (b) Same as (a) for July. (c) Same as (a) but for August.

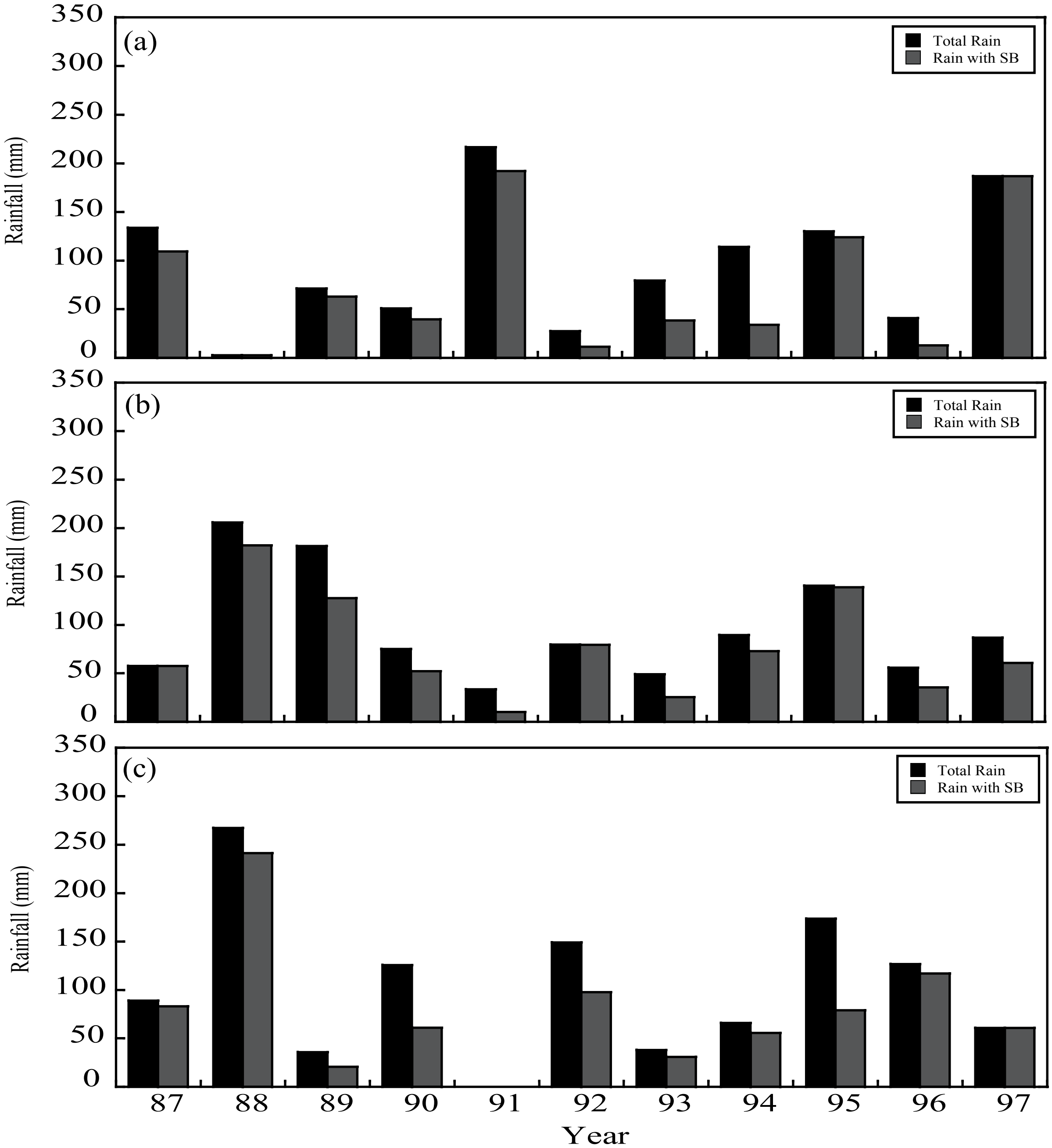

Figure 8. (a) Total rainfall (black) and rainfall with a sea breeze observed (grey) over Tambaram during June from 1987 to 1997. (b) Same as (a) but for July. (c) Same as (a) but for August.