A Study on the Influence of Synoptic-Scale Flows on Sea Breeze During Wintertime in the Coastal Zone Near Visakhapatnam, India

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**A study on the influence of synoptic-scale flows on sea breeze during wintertime
in the coastal zone near Visakhapatnam, India**

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Abstract

The present study focuses on the influence of prevailing winds (like onshore, offshore and alongshore) on sea breeze flow over the coastal station Visakhapatnam (17.7°N, 83.3°E). The database consists of sodar observation relative to 58 sea breeze occurred during the winter season (December 2011-February 2012). Results show that the strength of sea breeze are modulated by the large-scale wind flow and show substantial changes between offshore, along-shore and onshore. The role of thermal forcing on the breeze circulation was investigated. Results show that temperature difference between land and sea (ΔT) is larger for offshore and along-shore when compared to that of onshore flow. Results reveal that the vertical velocities show downdrafts and updrafts just before and after the onset of sea breeze. The depth of sea breeze is found to be higher (~220 m) for the offshore than onshore large scale circulation (~160 m). It is found that offshore and alongshore favours the delayed arrival of sea breeze compared to that of onshore. The statistical analysis of sea breeze circulation addressed in this work highlight the distinct behavior in the structure and evolution of sea breeze using high temporal and vertical resolution of sodar observations under different synoptic-scale wind flow. Such statistical results are sparse over the industrialised coastal zones like Visakhapatnam where air pollution is a major concern, as well as for better understanding on the vertical mixing of aerosols and trace gases, and air-pollution dispersal.

1. Introduction

Over the coastal regions, the evolution of the atmospheric boundary layer (ABL) is significantly modulated by the mesoscale circulation systems like land/sea breeze (Simpson et al. 1977). In general, sea breeze are controlled by differences in the sea surface temperature (SST) and land surface air temperature, which is proportional to the pressure difference. Studies have shown that the strength and onset of sea breeze varies with geographical location, depends on several factors such as shape of the coastline, cloud cover, thermal forcing, large-scale wind flow, soil moisture, solar radiation, (Steyn and Kallos 1992; Stull 1998; Miller et al. 2003; Gilliam et al. 2004; Davis et al. 2020). Observations carried out over other coastal locations have shown that the onset of sea breeze (early/delay/normal) depends not only on prevailing background synoptic large-scale winds (like onshore flow, along-shore flow and offshore flow) but also on thermal forcing (e.g., Molina and Chen 2009; Federico et al. 2010).

Associated with the advection of sea breeze, the thermal structure of convective ABL (CABL) is modified with the formation of the thermal internal boundary layer (TIBL) (Kunhikrishnan et al. 1993; Rao and Fuelberg 2000; Anurose et al. 2016). Under weak synoptic-scale wind flow (onshore/offshore) conditions, the evolution of CABL over the coastal region attains peak around noontime with relatively lower CABL heights compared to that of the inland regions (Miller et al. 2003). However, studies have shown that the growth of coastal CABL is controlled by the offshore/onshore flow, the height of CABL are comparable with that of continental regions especially during offshore flow when compared to the onshore flow (Davis et al. 2021). With the passage of sea breeze front, an abrupt transition in the velocity and wind direction within the CABL were reported (Helmis 1987; Chiba 1993; Chiba 1997). The vertical velocities (updraft/downdraft) generated before and after the passage of sea breeze can initiate the development of convective clouds (e.g., Atkins et al. 1995). Also, vertical velocities play a crucial role in diluting the pollutants within the CABL, and quantitative analysis on these are of interest to the air-pollution meteorologists especially the vertical velocities associated by the sea breeze front. However, the magnitude of the vertical velocities and evolution of CABL are controlled by the strength and direction of the sea breeze (Helmis et al. 1987).

The intensity and vertical structure of sea breeze have a profound impact on the increased levels of air pollutants dispersal and the possibility of the re-circulation of pollutant gases by industries near the coastal site (e.g., Kitada 1987; Asimakopoulous et al. 1992; Krishna Moorthy et al. 2003; Niranjan et al. 2004; Augustin et al. 2020).

The role of prevailing background large-scale synoptic wind flow on the evolution of sea breeze structure, its progression and cessation has been studied using numerical models and experimental studies (Estoque 1962; Simpson et al. 1977; Atkins and Wakimoto 1997; Miller et al. 2003; Gilliam et al. 2004; Molina and Chen 2009; Bajamgigni and Steyn 2012; Grachev et al. 2018). Several researchers have reported on the influence of the synoptic flow on the sea breeze flow using sodar observations (Finkelstein et al. 1986; Zhong and Takle 1992; Mastrantonio et al. 1994; Helmis et al. 1995; Chiba 1997; Melas et al. 1998; Kalogiros et al. 1999; Menut et al. 1999; Puygrenier et al. 2005; Federico et al. 2010; Crosman and Horel 2010; 2016).

Over the Indian sub-continent, studies on the sea breeze circulation using Doppler sodar and tower-based measurements (Rao et al. 1981; Singal et al. 1986; Prakash et al. 1992; Kunhikrishnan et al. 1993; Gera and Saxena 1996; Prabha et al. 2002). Recently, using surface-based observations over the coastal station, Visakhapatnam, Kirankumar et al. (2019) highlighted the impact of background prevailing wind flow on the sea breeze characteristics such as occurrence, onset and cessation during different seasons over the site. What is relatively less known over this region is the dynamics (such as vertical velocities, the intensity of wind speed and sea breeze component, depth of sea breeze) within the vertical structure of the sea breeze circulation. This is due to the lack of database with a high temporal and vertical resolution concerning the growth and evolution of sea breeze associated with the prevailing synoptic-scale wind flow. Thus, the aim of the present study is to address this gap and quantify the characteristics of the sea breeze circulation during contrasting synoptic-scale wind flow conditions during the winter season 2011-12. This is carried out using the vertical profiles of Doppler sodar installed over the experimental site Visakhapatnam (17.7°N, 83.3°E; 20 msl). Due to the lack of collocated surface based meteorological data, surface air temperature at 2m, SST were obtained from the ERA Interim reanalysis (Section 3.2).

The present study has significant implications in the studies related to the air pollution, diffusion of trace gases and aerosols etc. Section 2 presents the details on experimental site, instrumentation and database. Section 3, presents the results and discussion on the influence of synoptic-scale winds on the sea breeze by considering three case studies (offshore, alongshore and onshore). A thorough statistical analysis of the phenomena is also presented in this section. Such studies have profound applications and can be useful, for example, addressing the near-surface and vertical distribution of aerosols, and air pollutant dispersal, helpful for the installation of wind power generators in the area and for mitigation measures of the heat island on the coastal town of Visakhapatnam. Finally, conclusions are presented in section 4.

2. Experimental site and background meteorological conditions

The experimental site is located in the Department of Physics, Andhra University, Visakhapatnam which is ~600 m from the eastern coast of the Bay-of-Bengal with the coastline roughly aligned to 45° to 225° (Fig. 1). Thus, breezes arriving at an angle between 45° and 225° are considered as sea breeze and the breezes flowing in other directions are considered as land-breeze (more details on wind flow regimes are presented in section 2.1.1). Hills with an elevation in the range of 500 – 1200 m are located at ~30-50 km northwest of the experimental site. In general, fair-weather conditions with absence of large scale convection prevails during the winter seasons (December to February) and calm winds with dominant northerly/northeasterly prevail during this season. Figure 2 shows the synoptic mean wind pattern at -850 hPa level during winter seasons over the study region (marked with the ‘★’), obtained from the ERA-Interim Reanalysis (Dee et al. 2011) data. From Fig. 2, it is evident that the prevailing wind intensity is low ($<1 \text{ ms}^{-1}$) and pre-dominantly northerly/northeasterly during winter seasons.

2.1 Instrumentation, data, method of analysis

The acoustic sounder or SODAR (Sound Detection And Ranging) is a powerful tool for studying the micro-scale turbulence processes undergoing within the lower atmosphere. The Doppler sodar has the advantage of probing the lower atmosphere with fine temporal and spatial resolution. The monostatic phased-array Doppler sodar system (Make: SAMEER, India) installed at Visakhapatnam can be operated at 1700-2500 Hz with a peak acoustic power of 100 W. This sodar system consisting of an 8x8 array of 52 antenna elements made with piezoelectric transducers. The antenna is used for both transmitting and receiving the signals. Three moments, namely, signal strength, weighted mean Doppler shift, and half-width parameters of the power spectrum are estimated following adaptive moments estimation technique developed for sodar by Anadan et al. (2008). For the present study, the sodar system was operated at a frequency of 1800 Hz, range resolution of 20 m, and inter-pulse period of 6 seconds for probing up to 1000 m. The frequency resolution of discrete frequency spectra is 8.33 Hz. Important specifications of the phased array Doppler sodar are given in Table 1.

Sodar observations during the winter season (December 2011-February 2012) forms the primary database for this study. The data quality is assessed from the signal to noise ratio (SNR) of the sodar signal; the SNR is very poor and irregular during precipitation. The absence of precipitation ensures good data quality during most of the winter period. Extreme care has been taken in the quality check i.e. data recorded during isolated precipitation events, overcast days and incomplete sea breeze circulation days are discarded. The data with a signal to noise ratio (SNR) of $>1 \text{ dB}$ only are considered for deriving the 3-dimensional winds in the present study. This criterion generally limits the upper altitude height of the sodar observation of winds to $<260 \text{ m}$ during most of the day.

Altitude profiles of the zonal (u), meridional (v), vertical (w) winds and SNR derived from the individual soundings (once in 6 seconds) are further averaged for 10 minutes to improve the SNR. Finally, based on the quality of the sodar data, 58 sea breeze days were considered for further analysis.

2.1.1 Synoptic flow regime classification

Due to the variation in the intensity of the synoptic-scale winds and discontinuity in the terrain features (coastal station), the turbulent characteristics of the sea breeze also changes. Following Molina and Chen (2009), in the present study, daily winds derived from the ERA reanalysis at 850 hPa data, were considered as a representative of the low-level synoptic-scale flow regimes to understand the variations in the sea breeze turbulent characteristics associated with the synoptic-scale flow. Referring to the local coastline orientation (Fig. 1), analyses have been done on the three different sets of data classified according to the wind direction as a) offshore wind clockwise ($240.0^\circ - 30.0^\circ$) represents synoptic flow from land to sea, b) onshore wind ($60.0^\circ - 210.0^\circ$) representing the wind flow from sea to land, and c) alongshore wind ($30.0^\circ - 60.0^\circ$) (NE) and ($210.0^\circ - 240.0^\circ$)(SW).

2.1.2. Identification of onset of sea breeze

As specified in Section 2, the Visakhapatnam coastal line is stretched along the direction of $45^\circ-225^\circ$. The wind component normal to the coast is represented as the sea breeze component (SBC) and the following relation is used for the estimation of SBC.

$$SBC = WS * (\sin 225^\circ - WD)$$

Where $WS = \sqrt{u^2 + v^2}$

u - zonal wind (ms^{-1}); v - meridional wind (ms^{-1}) and WD ($^\circ$) is the wind direction. WS (ms^{-1}) is the horizontal wind speed, the positive SBC (m s^{-1}) represents the sea breeze and the negative values represent land breeze.

Various sea breeze criteria were suggested to identify the sea breeze events (Furberg et al. 2002; Steyn and Kallos 1992; Borne et al. 1998; Porson et al. 2007; Molina and Chen 2009). In this study, we adopted an objective selection method as described in Kirankumar et al. (2019) for the identification of onset and cessation of the sea breeze. (i) The sea breeze onset is identified by a distinct shift in the direction of wind across-coast from offshore to onshore. Most importantly, the onshore wind component should last for more than 4 hours (Top panel in Supplementary Material Fig. S.1). (ii) The onset of the sea breeze can also be identified by the change of sign of SBC from negative (offshore) to positive (onshore) (marked by an upward arrow in the bottom panel of Fig. S.1). (iii) The cessation of sea breeze happens when wind direction shifts from onshore to offshore i.e. the sign of SBC shifts from positive (onshore) to negative (offshore) and this continues for more than 4 hours.

3. Results and discussion

3.1. Distribution of winds

Figure 3 shows the wind rose plots recorded from ERA-Interim reanalysis 850 hPa represents the large-scale circulation above the sea breeze circulation. The result shows rather widespread in the wind direction, i.e., about 74%, 7.5% and 18.5%, winds come from offshore, alongshore and onshore respectively (Fig. 3a). Besides the expected higher wind speed at 850 hPa, there is no distinct shift in the wind direction between the daytime and night-time observations (Figs. 3b, c).

Although wind data from the sodar is available at different height levels, to present the statistics of the winds near the surface 60 m data was considered (Figs. 3d-f). The frequency distribution of the seasonal wind observations from sodar at 60 m illustrates the surface coastal flow regime. The winds with low magnitude ($<4 \text{ ms}^{-1}$) distributed mostly in the NW-N direction, whereas the distribution of relatively high wind speed ($>4 \text{ ms}^{-1}$) spread rather wide in the wind direction NE-E-SE (Fig. 3d). Out of the total observed seasonal wind, the frequency distribution of offshore and onshore winds is 62% and 25%, respectively, and remaining 13% is distributed along the coastal line with 12% NE and 1% SW winds. During the daytime, the winds are high ($>4 \text{ ms}^{-1}$) and predominantly NE-E-SE-S with rather widespread. The enhancement in the frequency distribution of onshore winds (49%) during the daytime shows the presence of the sea breeze (Fig. 3e). Noteworthy to mention here, the distribution of offshore winds (33%) indicates the continuance of land breeze due to the delay in the onset of the sea breeze. Remaining 18% of daytime wind flow is distributed along the coastline with 16% from NE and 2% from SW. During the night, the winds are low ($<4 \text{ ms}^{-1}$) and predominantly NW-N-NE. The enhancement in the probability of occurrence of northerly winds suggests the dominance of offshore winds (91%) during the night-time. Remaining 9% of night-time wind flow is distributed between the alongshore (8% (NE)) and 1% onshore winds.

The comparison of wind distribution between ERA at 850 hPa and sodar at 60 m confirms the difference between the circulation at the surface and at the levels above the sea breeze and demonstrates the significance of the local circulations. Following are the important main outcomes: i) The dominance of onshore winds during the daytime and offshore winds during the night-time is well discernible in the sodar data while at 850 hPa the wind direction is rather more spread; b) The daytime onshore wind due to the sea breeze is much more frequent at the surface (49% and 19% at the surface and at 850 hPa respectively); c) The night-time offshore winds due to land breeze, are dominant at the surface (91% and 70% at the surface and at 850 hPa respectively); d) as expected, higher wind speeds are observed at 850 hPa than the surface.

3.2 Role of air-sea temperature contrast

Figure 4 shows the time of onset of sea breeze and its frequency of occurrence under different synoptic conditions during the winter season (December 2011 to February 2012). For this, sodar observations at 60 m height level are considered. From the Fig.4, it can be seen that onset of the time of onset of sea breeze can occur as early as 08:00 IST (IST=GMT+05:30 hrs) and as late as 13:00 IST and most probable time of onset of the sea breeze is in between 09:30 and 10:30 IST (Fig.4b). The present results are in accord with the earlier studies by Sivaramakrishnan and Prakash Rao (1989) and Kirankumar et al. (2019).

Temperature differences between land and sea plays a crucial role in controlling the onset/cessation of sea breeze under weak synoptic-scale wind conditions. Figure 5 shows the mean difference between the sea surface temperature (SST) and surface air temperature observed at (2 m) close to the experimental site under different synoptic wind conditions during December 2011-February 2012. To study the land-ocean temperature contrast, air temperature (at 2 m) over land and SST over the adjoining Bay of Bengal were obtained from ERA Interim Reanalysis (Dee et al. 2011) data with a temporal resolution of 1 hour and grid resolution of $0.25^{\circ} \times 0.25^{\circ}$. Extreme care has been taken in identifying the locations which are closest to the experimental site i.e. over the land (17.75°N , 83.0°E) and over the ocean (17.5°N , 83.25°E). The days considered to generate Fig. 5 are the same as presented in Fig. 4 in order to have uniformity. It is clear from Fig. 5 that the ΔT (temperature differences between land and sea) is positive during daytime indicating that land surface is warmer than adjoining sea and $\Delta T < 0$ during nocturnal period. The onset of sea breeze, can be interpreted by the shift in ΔT from negative to positive, is observed to be around 09:00 IST for onshore cases and around 10:00 IST for offshore and along-shore cases. The peak values of ΔT during offshore, along-shore and onshore are about 5.18, 5.0, and 4.5 $^{\circ}\text{C}$ respectively around 13:00 IST. Irrespective of the synoptic-scale wind flow the temperature differences remained almost stable between 11:00 IST and 14:00 IST before start to decrease. The constant differences is associated with the advection of cool air mass from the adjoined sea. The air temperature over land decreased below adjoined sea surface temperature after 18:00 IST, and ΔT remained negative indicating the dominance of cooling until morning. From Fig. 5 it is observed that the thermal forcing of daytime breeze is larger for offshore and along-shore cases, and minimum for onshore events. Though results are expected, it is noteworthy to mention the presence of stronger thermal forcing during daytime than the night-time over this coastal region. Due to the daytime thermal contrast between the land (warm) and sea (cool) sea breeze flows inland across the coastal region and reverse (land breeze) occurs during night-time.

3.3. Vertical structure of sea breeze under different synoptic conditions

In addition to the thermal contrast of land-sea, prevailing synoptic wind flow also play a major role in modulating the shape of the sea breeze, onset/cessation time of sea breeze and intensity of sea breeze (Prakash et al. 1992; Finklele et al. 1995; Helmis et al. 1995). To investigate this, in this section, of the 58 cases of frontal passages observed in the winter 2011-12, we present three distinct synoptic-scale wind flow cases such as offshore wind (20 December 2011), alongshore wind (04 February 2012) and onshore wind (10 January 2012) observed over the experimental site.

3.3.1. 20 December 2011 (Offshore event)

Figure 6 presents a typical example of offshore flow observed on 20 December 2011. It shows the diurnal variations of the height-time cross-section of 10 minutes averaged signal-noise-ratio (SNR), zonal, meridional, vertical wind, SBC and wind speed. During this day, weak synoptic winds (850 hPa) offshore northwesterlies prevail over the study region (Fig. S.2). Daytime evolution of the CABL due to increase in thermals caused by solar heating of the surface is discernible after ~08:00 IST, which is characterized by an enhanced backscatter is indicated by an increase in SNR at higher altitudes (80-220 m) compared to their night-time values (Fig. 6a). Highest altitude up to which the SNR increases with time during the daytime is ~220 m, above which the diurnal variation of SNR is insignificant. This indicates that the altitude up to which the influence of thermal plumes generated near the surface is felt is <200 m. The time-height variation of SNR is largest and rapid between 08:00-11:30 IST. The above variations show that the CABL height increases from <80 m at 08:00 IST to ~220 m at 10:30 IST during this day. Afterwards, the fluctuations in SNR is noticed until 11:30 IST. The sodar return power shows a significant reduction in the height coverage from 220 m at 10:30 IST to 140 m at 11:00 IST, followed by an increase in the SNR till 11:30 IST, and a continuous, horizontally stratified structure is visible till 13:00 IST. The reduction in the SNR is due to inhibition of large-scale motions with the onset of the sea breeze and the formation of the thermal internal boundary layer (TIBL) (Prakash et al. 1992; Kunhikrishnan et al. 1993; Prabha et al. 2002). On this day, though the sea breeze first arrived around 10:30 IST, it is not well established until 11:30 IST (see Fig. S.1: the offshore case for clarity). The delayed onset of the sea breeze is evident from a noticeable shift from negative to positive in the ΔT (temperature differences between land and sea) around 10:00 IST (Fig. 7). The sodar observations of SNR did not decrease drastically after the onset of sea breeze and remains almost steady till ~13:00 IST, which is followed by a consistent decrease in SNR with time, especially up to ~16:00 IST, indicating the systematic decrease in CABL height associated with the reduction in the intensity of thermals. The time-height variations of SNR attain the typical nocturnal atmospheric boundary layer structure by ~18:00 IST.

The zonal wind shows a significant shift from westerlies to easterlies around 11:30 IST (Fig. 6b), while a gradual reduction in the magnitudes of meridional winds (Fig. 6c) is observed at all altitudes during this period. This feature is seen by a marked shift in the SBC from negative (land breeze) to positive (sea breeze) at all altitudes indicating the onset of sea breeze (Fig. 6e). The onset of sea breeze on this day is almost 1 hr 30 minutes delay compared to the most probable time of onset i.e ~10:00 IST during the winter over the experimental site. The delay in the onset of the sea breeze is characterized by the prevailing strong northwesterly winds observed on this day. As described by Miller et al. (2003), the strong southward components of the background wind over the east coast in northern hemisphere favour the delay in onset of sea breeze (characterized by veering of winds or backdoor sea breeze). The intensity of SBC gradually increases and reaches the maximum value of about 2.5 ms^{-1} at height around 120-140 m during the late afternoon (between 13:00 – 14:00 IST). The present observations corroborate the 2D-model study by Arritt (1993), indicated that for weak offshore synoptic conditions, sea breeze intensifies just after the maximum solar insolation near the coasts. Associated with the onset of sea breeze, vertical velocities undergo significant changes from downdrafts to updrafts before and after the onset (Fig. 6d). At 11:30 IST a downdraft of about 0.15 ms^{-1} is observed up to 80 m, followed by an updraft reaching about 0.3 ms^{-1} , in general, to heights of about 200 m, indicating the convergence of sea breeze front at higher heights (Helmis et al. 1987;1995; Prakash et al. 1992; Chiba, 1993; Stephan et al. 1999). The low values of vertical velocities observed in the present results are due to the averaging time of vertical velocities is about 10 minutes. The noontime maximum wind speed is found to be around 4 ms^{-1} around the 120-140 m height region (Fig. 6f).

3.3.2. 04 February 2012 (Along-shore event)

On the 04 February 2012 (Sunrise at 06:29 IST and sunset at 05:53 IST) early morning low northeasterly synoptic wind conditions prevail over the experimental site (Fig. S.3). The Doppler sodar averaged winds also shows northeasterly winds at all observed heights before and after the sunrise (Figs. 8b,c). As the day progress, the variability in wind speed and direction is observed until 10:30 IST. Later on, the veering of wind (rotates in the clockwise direction) from nocturnal northeasterly (land breeze) to southeasterlies (sea breeze) is seen until later was well established. It is evident from the SBC (Fig. 8e) that the sea breeze onset occurs at ~10:30 IST and the magnitudes of SBC gradually increases and reaches maximum values of around 3 ms^{-1} between 80 and 140 m during 12:00-13:00 IST. The average wind speeds (Fig. 8f) between 120 and 140 m increases from $<2 \text{ ms}^{-1}$ at 10:30 IST (time of onset of the sea breeze) to 5 ms^{-1} at 12:50 IST, while the direction of the wind remains southeasterlies during 10:30 to 17:00 IST. The results are in consistent with that of Atkins and Wakimoto (1997) who showed that, an increase in the sea breeze in the afternoon during parallel flow conditions.

The sodar vertical velocity profiles (Fig. 8d) changes from downdrafts to updrafts before and after the onset. A surge in the updrafts around 10:30 IST is noticed due to the physical wedge of the cool (dense) marine air mass interacting with the warm (lighter) land air mass. The magnitudes of the updrafts are about 0.3 ms^{-1} , extends to a height of about 140 m. These updrafts are responsible for the depth of the sea breeze (Miller et al. 2003). Additionally, sodar vertical velocities show updrafts and downdrafts during the sea breeze, which are due to surface friction and thermal instability caused by the movement of marine air across the land surface. The updraft (+ve) represents the buoyancy generated motion and downdraft (-ve) the compensated regions of negative vertical velocity. These regions are responsible for the transport of fluxes of momentum and energy from the surface. The signal-noise-ratio of sodar data (Fig. 8a), which is an indicative of the backscatter signal corresponding to the fluctuations of thermals, did not show any changes during the time of onset of sea breeze, instead, shows a systematic increase during the evolution of CABL to reach a maximum height of about 220 m at 11:30 IST. The forenoon (11:00 – 12:00 IST) peak values of CABL height over the coastal regions were reported over other regions as well (Zhang et al. 2012; Rajeev et al. 2016; Davis et al. 2021). The SNR in the altitude region below ~180 m remains almost steady during ~12:00 to ~15:00 IST, which is followed by a consistent decrease in SNR with time, especially up to ~17:00 IST at all altitudes above ~100 m. The enhancement of SNR in the lower heights during the sea breeze period may be due to the mechanical turbulence caused due to the formation of TIBL (Helmis et al. 1995).

3.3.3 10 January 2012 (Onshore event)

On the 10 January 2012 (Sunrise at 06:30 IST and sunset at 05:39 IST) weak easterly synoptic flow conditions prevail over the experimental site (Fig. S.4). The Doppler sodar averaged winds also show low WSW wind flow below 100 m before and after the sunrise (Figs. 9(b, c)). The direction of the wind is westerly up to 07:20 IST, which is followed by a gradual change in direction of the wind in anticlockwise (from westerlies to south-easterlies) till ~08:30 IST (see Fig. S.1: onshore wind for clarity). The magnitude of zonal wind shifts from weak westerly to easterly at all altitudes around 08:00 IST (Fig. 9b), while meridional winds (Fig. 9c) increases from weak southerlies ($< 1 \text{ ms}^{-1}$) to strong southerlies ($> 2 \text{ ms}^{-1}$) and attain a maximum value of about 4 ms^{-1} during 12:00-13:00 IST at all altitudes. It is evident from the SBC (Fig. 9d) that the onset of sea breeze occurs at 08:10 IST and the magnitudes of SBC increases during noontime and remains steady till ~15:40 IST. Fig. 7 further confirms that there exists an early onset of sea breeze on this day. After the onset of sea breeze, wind speed (Fig. 9f) shows a gradual increase from till noontime, while the direction of the wind remains more or less remain south easterlies. The intensity of wind speed and SBC observed in this case, are not so strong compared to onshore and

offshore cases. Interesting to mention here that, compared to the offshore and alongshore, the onset of the sea breeze observed on the onshore case is early i.e. around 08:10 IST which is almost 2 hrs before the most probable time of onset during winter. The early onset is due to the presence of prevailing southwesterly which enable the early onset of corkscrew sea breeze (Miller et al. 2003). As pointed out by Miller et al. (2003), the northward component in the northern hemisphere favours the early onset of sea breeze (characterized by anticlockwise rotation of winds or corkscrew sea breeze).

Similar to the other two cases, with the passage of sea breeze, the vertical velocities (Fig. 9d) shift from downdrafts to updrafts in all observed heights. However, the magnitudes of vertical velocities (both up-, and downdrafts) are less during the passage of sea breeze compared to the other two cases. This may be due to the combined effect of weak background wind and sea breeze circulation cell exist on a larger scale (Helmis et al. 1995). The vertical velocities exhibit a systematic up- and downdrafts during the sea breeze period during the onshore case and the range of periodicities is consistent with the earlier studies over the India coastal sites made with sodar measurements (Prabha et al. 2002).

The Doppler sodar SNR (Fig. 9a) which describes the turbulent structure of the low-level boundary layer shows an enhancement below 60-80 m. The enhancement in the backscatter power is due to the mechanical turbulence during night-time and both convective and mechanical turbulence during the daytime. As the day progress, CABL increases and associated sodar backscatter deepens and the strength of SNR increase within this layer and reaches a maximum height of 160 m around 10:00 IST and remains steady around this height till 15:00 IST, thereafter decreases till 17:00 IST. On this day, SNR did not show significant variation in both height coverage and intensity at the time of onset as compared to the alongshore event of 04 February 2012.

3.4. Characteristics of sea breeze front

Figure 10 highlights the impact on the vertical structure of the sea breeze as observed by Doppler sodar under the influence of offshore (top panel), along-shore (middle panel) and onshore (bottom panel). The SBC, vertical velocity and wind speed presented in the figures obtained after carrying out an equivalent day analysis of the above-mentioned wind regimes collected during the study period. From the Figures, it is apparent that the synoptic flow relative to the coast plays a significant role in the modulating the vertical structure and evolution of the sea breeze over the experimental site.

The top panel in Fig. 10 corresponds to the equivalent day analysis of 37 offshore flow cases. The composite analysis of offshore cases shows that the most probable time of onset of sea breeze around 11:00 IST (Fig. 10a). Around the onset of the sea breeze a marked shift in the SBC from negative (land breeze) to positive (sea breeze)

at all observational altitudes (40 – 180 m). After the onset, SBC increases gradually during the day reaches a maximum during the noontime and remain steady till 15:00 IST indicating the passage of the sea breeze front. The averaged vertical velocities (Fig. 10b) show a surge in the updrafts associated with the onset of sea breeze and reach a maximum height up to ~180-200 m, indicating the convergence of the sea breeze front to reach higher heights (Helmis et al. 1995). A systematic up- and downdrafts associated with the passage of the sea breeze is observed. The average of vertical velocity brought out the consistent features of sea breeze structure. Most of the features observed during the individual cases are reproduced indicating the predominant and consistent vertical variations observed during the individual offshore cases. Noteworthy to mention that on almost all individual days there is an existence of downdrafts and updrafts before and after the onset of the sea breeze irrespective of synoptic flow conditions (e.g., Chiba 1993; Helmis et al. 1995). However, vertical velocity varies with the synoptic wind conditions. Stronger up-surge is noticed after the onset of sea breeze for offshore cases compared to the other two cases. The results fit better to the earlier studies (Estoque 1962; Helmis et al. 1987). A noticeable feature seen in Fig. 10c is that wind speed is high ($\sim 4 \text{ ms}^{-1}$) before the onset of sea breeze, slows down to 3 ms^{-1} around the onset time. Afterwards continue to increase as the day progress, reaches higher wind speeds associated with the sea breeze during late noontime, a typical condition of sea breeze characteristics (Pearson 1973; Pielke 1974; Simpson 1994). Turbulence plays an important role in regulating the speed of sea breeze during the daytime (Ogawa et al. 2003), the slow increase in wind speed till early noontime can be ascribed to the presence of turbulence, before accelerating again during late noontime as turbulence diminishes. The cessation of the sea breeze is well identifiable by the reversal in the sign of SBC around 17:00 IST. Strikingly, the cessation occurs first in the lower heights and then aloft, a similar feature observed in other cases also. After cessation, the wind speed decreases below 1.5 ms^{-1} and vertical velocities shows downdrafts.

The middle panel in Fig. 10 shows the Doppler sodar observations of 13 alongshore wind flow. On an average the onset of the sea breeze for along shore events occurs around 10:10 IST seen by a discernable shift in the SBC from negative to positive (Fig. 10d). After the onset, SBC changes significantly both in magnitudes and in heights as the day progress. The averaged vertical velocities (Fig. 10e) show similar features as offshore cases during the sea breeze time. Interestingly, a systematic up- and downdrafts in the vertical velocities with dominant updrafts are noticed and the vertical extent of the sea breeze is below 180 m. Wind speed is very weak before the onset of sea breeze, strengthens during the daytime, associated with sea breeze attains maximum values of about 2.5 ms^{-1} during noontime in between 100 and 180 m height (Fig. 10f). Wind speed is stronger than the other two cases. The wind speed attains minimum during the cessation of sea breeze around 16:30 IST.

The bottom panel in Fig. 10 shows the Doppler sodar observations for 8 onshore wind flow. As observed in individual cases, the mean features also reveal an early onset of sea breeze between 08:30 and 09:00 IST noticed by a shift in the SBC from negative to positive (Fig. 10g). When compared to the other two cases, the onset of the sea breeze is shallow during the onshore case. The intensity of SBC observed to be stronger during noontime compared to other cases indicating the winds aligned perpendicular to the coast i.e. southeasterly. The intensity of SBC is strong ($>2 \text{ ms}^{-1}$) during onshore and alongshore during the afternoon (12:00-13:00 IST). The strengthening of sea breeze occurs when the sea breeze flow and ambient flow are in the same direction. Whereas, the intensity of SBC is relatively less ($<3 \text{ ms}^{-1}$) in offshore case. These results are in agreement with the observations by Atkins and Wakimoto (1987) simulation studies by Gilliam et al. (2004). The late afternoon strengthening of the sea breeze is in agreement with the numerical study of Arritt (1993) as well as observational studies (Atkins and Wakimoto 1997; Gilliam et al. 2004; Molina and Chen 2009). The averaged vertical velocities (Fig. 10h) show similar feature as in the other two cases but the vertical extent of the sea breeze is restricted to 140 m. These observations are in accordance with the simulation results by Gilliam et al. (2004) who reported that the depth of the sea breeze fronts, measured by the level of upward motions of vertical velocity is different between offshore, parallel and onshore flow conditions. The duration of the sea breeze is longer in onshore flow than the other two cases (Sivaramakrishnan and Prakash Rao 1989; Molina and Chen 2009). Interestingly, Fig. 8i shows that very low wind speed is observed before the onset of sea breeze strengthens during the daytime attains maximum values of about 3 ms^{-1} in between 60 – 140 m during noontime. The intensification in the SBC and wind speed is found to be at 120 m height level and not observed near the lower altitudes, probably because of intense mixing of turbulence in the surface layer.

4. Conclusions

The influence of prevailing background winds on the sea breeze over the coastal station Visakhapatnam (17.7°N, 83.3°E) has been investigated using Doppler sodar observations collected during the winter months (December 2011-February 2012). The background wind was obtained from daily ERA-reanalysis at 850 hPa. The prevailing wind regimes were categorized into 3 groups offshore, alongshore and onshore. Total of 58 days of well-defined sea breeze cases are considered in this study. From the selected sea breeze cases of Doppler sodar observations, we focused on the sea breeze features like onset time of sea breeze, its duration, the strength of the sea breeze and its depth under the influence of background wind conditions. Following are the major findings:

- 1) First, existence of sea breeze circulation over the experimental location was revealed by comparing the wind distribution between ERA at 850 hPa and sodar at 60 m. These results demonstrate the significance of the sea breeze in the local circulation.

- 2) Strength of sea breeze are modulated by the large-scale wind flow and show substantial variation between offshore, along-shore and onshore: The strength of sea breeze component (SBC) is strong ($>2 \text{ ms}^{-1}$) during onshore and alongshore during the afternoon (12:00-14:00 IST). Whereas, the strength of SBC is relatively less ($<3 \text{ ms}^{-1}$) in offshore case. During onshore flow cases, the strengthening of sea breeze occurs when the sea breeze flow and ambient flow are in the same direction. Strengthening of the sea breeze in the late afternoon are in agreement with the numerical study of Arritt (1993) as well as observational studies (Atkins and Wakimoto 1997; Gilliam et al. 2004; Molina and Chen 2009).
- 3) The role of thermal forcing on the breeze circulation was investigated: Results show that temperature difference between land and sea (ΔT) is larger for offshore and along-shore when compared to that of onshore flow. Also, it is observed that irrespective of the synoptic-scale wind flow, ΔT remain almost constant between 11:00 IST and 14:00 IST before start to decrease. The constant differences is associated with the advection of cool air mass from the adjoined sea.
- 4) Out of total 58 days of well-defined sea breeze cases observed during winter season, occurrence of offshore flow (37) are more compared to along-shore (13) and less frequent onshore flow cases (8).
- 5) The time of onset of sea breeze can occur as early as 08:00 IST during onshore winds. While for offshore winds, the onset of sea breeze has been observed as late as 12:30 IST. Duration of the sea breeze is less for the offshore case than the onshore case.
- 6) The strength of wind speed at the time of onset is more in offshore flow ($\sim 4 \text{ ms}^{-1}$) and weak for onshore flow ($< 2 \text{ ms}^{-1}$) and alongshore ($<3 \text{ ms}^{-1}$). Furthermore, the depth of the sea breeze is higher ($\sim 220 \text{ m}$) for the offshore than onshore ($\sim 160 \text{ m}$).
- 7) Quantitatively the striking differences between the structures of sea breeze w.r.t. three wind flow is the vertical velocity. The vertical velocities are restricted to lower heights for the onshore flow cases compared to along-shore followed by onshore cases.
- 8) Results show that intensification in the SBC and wind speed is found to be at 120 m height level and not observed near the lower altitudes, probably because of intense mixing of turbulence in the surface layer.

The statistical analysis of sea breeze circulation presented in this work demonstrate the distinct behavior in the structure and evolution of sea breeze (in terms of vertical extent, intensity) using high temporal and vertical resolution of sodar observations under different synoptic-scale wind flow. In this study, the importance of the effect of early and delay onset of sea breeze on the evolution of sea breeze structure are clearly brought out as such results are sparse over the coastal regions. Our observations and findings could aid i) the modelling

community analysing the dynamical aspects of sea breeze circulation, ii) the air pollution meteorologists who are interested in the quantification of vertical velocities under distinct wind flow conditions, iii) for better understanding on the vertical mixing of aerosols and trace gases which have profound importance over the industrialised coastal zones like Visakhapatnam where air pollution is a major concern. To improve the present results, further examination of the database such as inclusion of surface based meteorological data and thermodynamical profiles using balloon ascends are essential. This is especially required to further explanation of vertical extension of sea breeze (which is lacking in the present study). Such studies have not been carried out over this region and the aspects will be addressed in future.

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Data availability: The Doppler sodar data can be acquired from the Space Physics Laboratory by requesting to Dr. Kiran Kumar, e-mail: kirankumar_nvp@vssc.gov.in.

Compliance with ethical standards:

Conflict of interest: The authors declare that they have no conflict of interest.

Code availability: Codes are available on request at kirankumar_nvp@vssc.gov.in

Consent to Participate: The authors declare consent to Participate.

Consent for Publication: The authors declare consent for publication.

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Figure captions:

Figure 1: Schematic diagram illustrating the wind direction for the three flow regimes defined in this study: offshore, alongshore and onshore. The dashed red line shows the sea breeze component (SBC) perpendicular to the coastline ($45^\circ - 225^\circ$)

Figure 2: Spatial variation of seasonal mean wind at the 850 hPa level during December 2011-February 2012 obtained from ERA-Interim reanalysis. The colour scale indicates wind speed and arrows indicate wind direction. Red colour '★' shows the location of the experimental site

Figure 3: Wind roses from ERA-850 hPa and sodar observations at 60 m during December 2011-February 2012

Figure 4: Time of onset of sea breeze and b) histogram of onset of sea breeze under the influence of offshore, along-shore and onshore flow during December 2011 to February 2012

Figure 5: The temperature difference between land and sea surface temperature (obtained from ERA Interim Reanalysis) near to the Visakhapatnam for offshore flow, along-shore and onshore cases observed during winter 2011-12

Figure 6: Time-height cross-sections of (a) signal-noise-ratio, (b) zonal wind, (c) meridional wind, (d) vertical wind, (d) sea breeze component and (e) wind speed observed by Doppler sodar over Visakhapatnam on 20 December 2011 (offshore flow). The vertical arrow indicates the onset of the sea breeze

Figure 7: The temperature difference between land and sea surface temperature (obtained from ERA Interim Reanalysis) near to the Visakhapatnam on 20-December-2011 (offshore), 04-February-2012 (along-shore) and 10-January-2012 (onshore).

Figure 8: Same as Fig. 6, but for the along-shore event observed on 04 February 2012

Figure 9: Same as Fig. 6, but for the onshore flow observed on 10 January 2012

Figure 10: Time-height cross-sections of sea breeze component (a,d,g); vertical velocity (b,e,h) and wind speed (c,f,i) observed by Doppler sodar observations under the influence of offshore (top panel), along-shore (middle panel) and onshore (bottom panel) during winter 2011-12

Table

Table 1 Specifications of the Doppler sodar

601 **Figure 1**

Fig.1 Schematic diagram illustrating the wind direction for the three flow regimes defined in this study: offshore, alongshore and onshore. The dashed red line shows the sea breeze component (SBC) perpendicular to the coastline ($45^{\circ} - 225^{\circ}$)

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610 **Figure 2**

Fig. 2 Spatial variation of seasonal mean wind at the 850 hPa level during December 2011-February 2012 obtained from ERA-Interim reanalysis. The colour scale indicates wind speed and arrows indicate wind direction. Red colour '★' shows the location of the experimental site

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620 **Figure 3**

Fig. 3 Wind roses from ERA-850 hPa and sodar observations at 60 m during December 2011-February 2012

Fig. 4 a) Time of onset of sea breeze and b) histogram of onset of sea breeze under the influence of offshore, alongshore and onshore flow during December 2011 to February 2012.

Figure 5

Fig. 5 The temperature difference between land and sea surface temperature (obtained from ERA Interim Reanalysis) near to the Visakhapatnam for offshore flow, along-shore and onshore cases observed during winter 2011-12

Fig. 6 Time-height cross-sections of (a) signal-noise-ratio, (b) zonal wind, (c) meridional wind, (d) vertical wind, (d) sea breeze component and (e) wind speed observed by Doppler sodar over Visakhapatnam on 20 December 2011 (offshore flow). The vertical arrow indicates the onset of the sea breeze

Fig. 7 The temperature difference between land and sea surface temperature (obtained from ERA Interim Reanalysis) near to the Visakhapatnam on 20-December-2011 (offshore), 04-February-2012 (along-shore) and 10-January-2012 (onshore).

667 **Figure 8**

Fig. 8 Same as Fig. 6, but for the along-shore event observed on 04 February 2012

675 **Figure 9**

Fig. 9 Same as Fig. 6, but for the onshore flow observed on 10 January 2012

Figure 10

Fig. 10 Time-height cross-sections of sea breeze component (a,d,g); vertical velocity (b,e,h) and wind speed (c,f,i) observed by Doppler sodar observations under the influence of offshore (top panel), along-shore (middle panel) and onshore (bottom panel) during winter 2011-12

694 **Table 1:**

695 **Table 1** Specifications of the Doppler sodar

Operating Frequency	1700 Hz to 2500 Hz
No. of elements	52 (8x8)
Acoustic Power	100 W
No. of beams	3 (zenith, north, east)
Beam angle	16°
Pulse width	Programmable
Pulse repetitive frequency	Programmable
Averaging Time	1-60 min
No. of FFT	4096
Transmission type	Reflecting mode
Beamwidth	5
Wind Direction	0-360 degree
Wind Speed	0-30 m s ⁻¹
Wind Speed Accuracy	0.1 m s ⁻¹
Minimum Height	20 m
Maximum Height	1 km
Data Products	Wind components, echogram, time-height plot, wind rose and wind statistics

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Supplementary Figures

Fig. S1 Diurnal variations of wind direction (Top panel) and sea breeze component (bottom panel) observed at 60 m from the Doppler sodar observations on 20 December 2011, 04 February 2012 and 10 January 2012 representative days for offshore wind, along-shore wind and onshore wind cases respectively. The upward arrow marked in the bottom panel represents the time of onset of the sea breeze

Fig. S2 Synoptic circulation pattern at 0, 6, 12 and 18 GMT (0530, 1130, 1730 and 2330 IST at Visakhapatnam) on 20 December 2011, obtained from the ERA Interim reanalysis data.

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Fig. S3 Synoptic circulation pattern at 0, 6, 12 and 18 GMT (0530, 1130, 1730 and 2330 IST at Visakhapatnam) on 4 February 2012, obtained from the ERA-Interim reanalysis data.

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Fig. S4 Synoptic circulation pattern at 0, 6, 12 and 18 GMT (0530, 1130, 1730 and 2330 IST at Visakhapatnam) on 10 January 2012, obtained from the ERA-Interim reanalysis data.

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