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Observation and numerical simulation of submesoscale motions within sea breeze over a tropical coastal site: A case study

P.T. Rakesh[a,*], B.S. Sandeepan[b], R. Venkatesan[a], R. Baskaran[a]

[a] Indira Gandhi Centre for Atomic Research, HBNI, Kalpakkam, Tamil Nadu, India
[b] Texas A & M University at Qatar, Mechanical Engineering, Qatar

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ABSTRACT

Submesoscale motions observed using SODAR and fast response anemometer data during sea breeze hours are studied. SODAR data indicates the presence of waves with period ~30 min during the sea breeze hours. The observations are further verified by spectral analysis of sonic anemometer data using wavelet and FFT techniques. The analysis confirms that there are waves with periods of ~30 min present throughout the sea breeze hours with varying intensity. The observed waves are simulated using high-resolution WRF-ARW model using the MYJ planetary boundary layer scheme. The conditions of occurrence of such motions are briefly discussed. It is also found that these motions are caused by horizontal convective rolls within the sea breeze layer.

1. Introduction

Generally, coastal sites experience mesoscale sea breeze wind circulations, gravity waves and vortices due to the horizontal heterogeneity of the terrain. Many in the past have studied the sea - land breeze structure and fronts (Simpson, 1987, Plant and Keith, 2007; Helmis et al., 1987; Ogawa et al., 1986; Prakash et al., 1992; Dailey and Fovell, 1999; Miller et al., 2003; Puygrenier et al., 2005; Federico et al., 2010; Rani et al., 2010; Robinson et al., 2013; Comin et al., 2015). In the recent past, due to advancement in numerical modeling and observation techniques, the studies focused on the turbulence structure at the interface between the land and sea breezes. Prakash et al. (1992, 1993) studied the spectral characteristics of the boundary layer and sea breeze front over a coastal area, Thumba situated on the western coast of south India. Their study shows the existence of a six-minute wave during the passage of the front. A few researchers have also pointed out the existence of coherent structures within the sea breeze layer (Sha et al., 1993; Hadi et al., 2000; Lapworth, 2000; Plant and Keith, 2007, Li et al., 2013). Based on the time and space scales of these structures, they can be classified as submesoscale motions. Submesoscale motions are defined as those small scale motions having periodicities larger than the boundary layer turbulence scale and smaller than the scale resolved by meso timescale (Mahrt, 1999). Typically, submesoscale motion falls in the space scale of a few hundreds of meters and timescale of a couple of tens of minutes. A visual manifestation of these can be seen in the clouds as cells, streets and brush like patterns (Scorer, 1990). In general, these structures are not important from the weather point of view, but could have an impact on the atmospheric dispersion of pollutants (Simpson and Britter, 1980; Buckley and Kurzeja, 1997; Aouizerats et al., 2010; Sandeepan et al., 2013).

Submesoscale motions have been studied by many authors in the past. There are many reasons reported for the occurrence of such motions (Etling, 1990). A few of the causes of submeso motions are gravity waves and vortices with horizontal or vertical axis. Satyanarayana et al. (2014) observed roll structures using Mesosphere-Stratosphere-Troposphere (MST) radar at Gadanki, India before thunderstorm. An attempt was made to simulate the roll vortices using two-dimensional models by Hartmann et al. (1997) based on the observed homogeneity in the direction of the mean wind. Roll and cell structures are also simulated using large eddy and high-resolution modeling techniques (Moeng and Sullivan, 1994; Khanna and Brasseur, 1998; Antonelli and Rotunno, 2007; Liu and Sang, 2011). Cloud street structures or Horizontal Convective Rolls (HCR) have been studied using high-resolution three-dimensional models (Tian and Ramanathan, 2003; Miao and Chen, 2008) and condition for the occurrence of such structures with respect to stability parameter, Z_i/L has been put forward. Fesquet et al. (2009) using wavelet transforms showed that under all stability conditions, these coherent structures show universal properties which are independent of the terrain features, the frequency of occurrence, duration and time separation of the coherent structures and their relative contribution to the total fluxes (momentum and heat).

The objective of the present study is to analyze SODAR and sonic anemometer data to identify the submesoscale waves within the sea breeze in a tropical coastal environment. The observed waves are

* Corresponding author at: Radiological Safety Division, Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, India.
E-mail address: ptr@igcar.gov.in (P.T. Rakesh).

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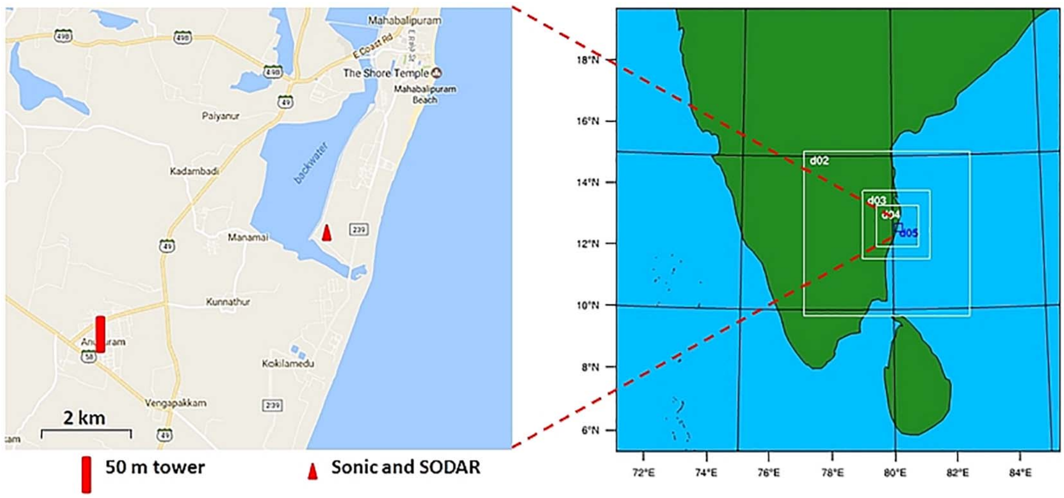

Fig. 1. Sitemap and simulation domain (right) with the location of tower, SODAR, sonic anemometer etc. (Courtesy: Google Maps).

subsequently simulated using an operational mesoscale weather model, Weather Research Forecast (WRF) in high spatial resolution so that the condition under which they take place could be elucidated. Section 2 introduces the site, data and the configuration of the numerical model, WRF. Section 3 describes the results of FFT and wavelet analysis using tower, sonic anemometer data and the results of numerical simulations. The conclusion of the study is given in Section 4.

2. Description of the site, data and configuration of the numerical model

Kalpakkam is located on the eastern coast of the Southern Indian peninsula at 12°34′28″ N latitude and 80°10′27″ E longitude, 80 km south of Chennai. The terrain is plain and gently sloping about l0 m above mean sea level (m.s.l). The coastline is linear and runs along the SSW-NNE direction. The site map and measurement locations together with the simulation domain are shown in Fig. 1.

Sea breeze – land breeze wind circulation occurs almost 80% of the year. Measurements of wind speed, direction, air temperature and relative humidity are made at five levels, i.e. at 2 m, 8 m, 16 m, 32 m and 50 m from a tall meteorological tower. Data are sampled at every 1 s, averaged for 10 min and archived. A sonic anemometer (R.M. Young Ltd.) installed at 10 m above ground level on the tower is used for fast response measurements with a sampling rate of 10 Hz. A phased array Doppler SODAR located nearby is used to identify the vertical structure of the turbulence. The SODAR and the tower are installed at about 1 km and 5 km respectively away from the coast. A water body shown on the western side of the SODAR is a shallow backwater which remains dry in summer months. The SODAR is operated with a frequency of 1800 Hz with 180 ms pulse width. The output consists of three Cartesian components of the wind and their respective standard deviations averaged over 15 min at height intervals of 20 m up to a vertical range of about 500 m.

Fig. 2 shows hourly wind velocity averaged over each month of the year 2009. The data is taken from 8 m level measurement from the 50 m tower. For example, the hourly mean wind velocity at the 0th hour of each day for 31 days is averaged in the month of January and is shown as a vector in the lowest left place in the figure. The arrows stacked one above the other corresponds to the progressive hours, Indian Standard Time (IST) of the day indicated in the y-axis. As the time of the day progresses in January, the weak wind from the NE direction backs into a very weak land breeze from the NW at about 4 h. Sea breeze sets at 10 h which persists up to midnight.

The nearest grid point surface wind data for the monthly mean from National Center for Environmental Prediction (NCEP) during 2009 are shown at the top of the Fig. 2 as black arrows (synoptic wind). This data indicates the prevailing large-scale wind velocity as it is sampled and refitted to a grid resolution of 1° latitude and longitude. The arrow of the large-scale wind shows an onshore flow during six months i.e. November, December, January, February, March, April and offshore during the other six months. In June, synoptic wind becomes strong coinciding with the onset of Southwest monsoon and continues in the westerly direction until October. In November, with the beginning of the winter monsoon, wind direction shifts to Northeast. Below this synoptic wind arrow, the other arrows in the figure show the monthly averaged local wind for each hour of the day from the tower data. The large scale wind data along with the tower data of the same period helps to understand the diurnal wind pattern at the given site. The hourly profile of wind velocity clearly shows a local land breeze in the morning hours up to 1000 IST (IST; GMT + 0530) and sea breeze in the afternoon hours. The onset of the sea breeze is early approximately at 1000 IST during winter months due to weak and aiding large-scale wind and at 1400 IST during the summer Southwest monsoon months with the strong opposing large scale wind. Thus sea breezes of varying strength are noticed almost 80% of the days in a year.

In order to simulate the sea breeze wind and turbulence in detail, a high-resolution mesoscale model WRF-ARW is utilized. The WRF model is an Numerical Weather Prediction (NWP) model that solves the compressible non-hydrostatic Euler equations in flux form on a mass-based terrain-following vertical coordinate system. It solves prognostic equations for variables such as the horizontal and vertical wind components, various microphysical quantities, and the perturbation potential temperature, geopotential, and surface pressure of dry air. It is a fully compressible, non-hydrostatic model. The model uses the Runge–Kutta 3rd order time integration scheme and the 2nd to 6th order advection schemes in both horizontal and vertical directions. A complete description of the WRF modeling system is contained in Skamarock et al. (2008).

In the present study, WRF is used in high resolution, in a nested configuration of five domains with a grid size ratio of 1:3:3:3:3 (Fig. 1), the grid resolution of the master domain is 27 km and that of the innermost domain is 0.333 km. The domain dimensions and the number of grid cells for each domain are given in Table 1.

The terrain data used for the innermost domain is obtained from the USGS in 30 s resolution and for land use class, Moderate Resolution Imaging Spectroradiometer (MODIS) data which has a spatial resolution of 30 s is used. The Mellor-Yamada-Janjic (MYJ scheme (Mellor and Yamada, 1982) is used as the boundary layer scheme in this case. The other physical parameterization schemes used in all model domains include Janjic Eta Monin–Obukhov surface layer scheme, Dudhia