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Investigation of Kelvin-Helmholtz Instability in the boundary layer using Doppler lidar and radiosonde data

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ABSTRACT

Characteristics of Kelvin Helmholtz Instability (KHI) using Doppler wind lidar observation have rarely been reported during the Indian summer monsoon season. In this paper, we present a case study of KHI near planetary boundary layer using Doppler wind lidar and radiosonde measurements at Mahabubnagar, a tropical Indian station. The data was collected during the Integrated Ground Observation Campaign (June–October 2011) under the Cloud Aerosol Interaction and Precipitation Enhancement EXperiment-2011. The continuous wind lidar observation during 10–16 August 2011 shows there is an increase in carrier-to-noise ratio values near planetary boundary layer from 03:00 to 11:00 LT on 13 August; reveals the formation of KHI. There is a strong power bursts pattern corresponding to high turbulence characteristics in the early half of the day. The KHI temporal evolution from initial to dissipating stage is observed with clear variation in the carrier-to-noise ratio values. The observed KHI billows are in the height between ~600 and ~1200 m and lasted for about 7.5 h. The vertical velocity from Doppler lidar measurement shows the presence of updrafts after breaking of KHI in the boundary layer. The presence of strong wind shear, high stability parameter, low Richardson number and high relative humidity during the enhanced carrier-to-noise ratio period indicates the ideal condition for the formation and persistence of this dynamic instability. A typical characteristic of trapped humidity above the KHI billows suggest the presence of strong inversion. A wavelet analysis of 3-dimensional wind components show dominant periodicity of ~45–65 min and the periodicity in vertical wind is more prominent.

1. Introduction

Kelvin-Helmholtz (KH) instability (KHI) is a dynamical instability which forms at the boundary of two fluids with different physical properties (e.g., density) producing velocity shear in horizontal direction. Browning and Watkins (1970) stated, “K-H instability is a form of dynamic instability produced within a hydrostatically stable flow in the presence of sufficiently strong vertical shear”. These instabilities thus generated at the interface of wind shear and stable layer are manifested as waves or “billows”, which are oriented perpendicular to the shear vector. The amplitude of these billows grow and reaches to an extreme point where it starts rolling or breaking eventually into small-scale turbulence flow. This instability occurs either above or below the stratified vertical shear (Muschinski, 1996).

The KHI plays a key role in the formation and dissipation of gravity waves, generation of clear air turbulence, and vertical transport of mass, momentum and atmospheric constituents (Das et al., 2004 and references therein). Most of our understanding of KHI is limited to laboratory experiments and numerical models (Miles and Howard, 1964; Browning et al., 1973; Klostermeyer and Rüster, 1980). KHI can occur in the atmosphere with wavelengths up to a few kilometers. The KHIs were observed in the (1) PBL, (Atlas et al., 1970; Medina and Houze, 2016), (2) free atmosphere as cloud billow in the upper troposphere or near the tropopause (Ludlam, 1967; Browning, 1971; Browning et al., 1973; Klostermeyer and Rüster, 1980; Smith and Jonas, 1996; Bigg, 1997; Das et al., 2004; Ghosh et al., 2004; Das et al., 2008), (3) middle atmosphere (Yamamoto et al., 2003) and (4) upper atmosphere (Sripathi et al., 2003). KH waves were also observed within the clouds of fronts, cumulonimbus anvils, hurricanes, sea breezes and winter storms (e.g. Sha et al., 1991; Chapman and Browning, 1997, 1999; Petre and Verlinde, 2004; Aberson and Halverson, 2006; Geerts and Miao, 2010; Houser and Bluestein, 2011; Zagrodnik et al., 2015).

Measurements from cloud imaging (Ludlam, 1967), high power pulsed radar (Browning and Watkins, 1970), FM-CW radar (Atlas et al.,

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1970), aircraft (Browning et al., 1973), VHF radar (Ghosh et al., 2004; Das et al., 2008), UHF radar (Das et al., 2004) and more recently Doppler weather radar (Medina and Houze, 2016) were used to investigate KHIs. Smith and Jonas (1996) observed several cases of turbulence produced by breaking of KHI in the cirrus cloud from aircraft measurements. Bigg (1997) hypothesized that there is a formation of new particles in the atmosphere due to breaking of KHI. The above studies discussed the KHI characteristics at different altitudes and in different weather conditions. However, the KHI studies were limited over the Indian Summer Monsoon (ISM) region, especially near PBL. A few KHI studies using high resolution radar measurements with simultaneous balloon observations were reported over a tropical Indian station, Gadanki (13.47°N, 79.18°E) (e.g., Das et al., 2004; Ghosh et al., 2004; Sripathi et al., 2003). Das et al. (2004) examined the KHI in the lower troposphere (~3.25 km) under cloudy but no rain condition, where they observed power burst patterns for ~3 h in the radar signal. Over Gadanki, KHI events were reported by Ghosh et al. (2004) in the vicinity of tropopause during clear sky condition, and in the upper atmosphere (~95 km) by Sripathi et al. (2003). These studies confirmed the formation of KHI over the Indian region that extend from PBL to ~100 km altitude.

The present study utilizes the data collected from the Doppler wind lidar (DWL) deployed at Mahabubnagar (16.74°N, 77.99°E, 450 m MSL) during the field campaign, 'Integrated Ground Observational Campaign (IGOC)' under 'Cloud Aerosol Interaction and Precipitation Enhancement EXperiment (CAIPEEX)' program conducted by the Indian Institute of Tropical Meteorology (IITM), Pune. The campaign period was from June to November 2011. Kulkarni et al. (2012) documented the objectives and the preliminary results of CAIPEEX.

Using Doppler lidar observations, Blumen et al. (2001) presented the detailed characteristics of KHI billow in the nighttime boundary layer over Kansas during The Cooperative Atmospheric Surface Exchange Study October 1999 (CASES–99) experiment. They observed the KHI billows at ~200 m height that lasted for about 30 min. Fukao et al. (2011) observed KHI event at ~1.5 km altitude using MU radar data. They listed the KHI observations in terms of mean altitude of the events, wind shear, Richardson number, billow depth, and horizontal wavelength etc., from different remote sensing measurements (e.g., radar and lidar).

In this paper, the characteristics of KHI formed near PBL from DWL measurements are presented. Further, we perform the wavelet analysis to examine the dominant periods in the wind near the boundary layer associated with the KHI. The prevailing background atmospheric conditions are investigated using radiosonde data. The paper is organized as; Sect. 2 provides a brief description of the DWL system and data analysis. Results and discussion are elaborated in Sect. 3. Finally, the results are summarized in Sect. 4.

2. System description and data

The DWL (Model: WindCube–200) was deployed at Mahabubnagar, India and operated during the period from June to October 2011. The DWL consists of the following components: transmitter, receiver and data acquisition and signal processing system. Fig. 1a shows the functional block-diagram of the DWL system and its technical specifications are listed in Table 1. The DWL used in this study is a pulsed lidar operated at near IR wavelength (~1.54 μm) with the pulse energy of ~100 μJ (Ruchith et al., 2014a). The DWL is portable and eye-safe. This lidar works on the heterodyne principle, which relies on the Doppler shift measurement of backscatter signal using aerosols/clouds as tracers. The difference (Δf) between the transmitted (f_t) and backscattered (f_r) frequency is proportional to the radial wind component and is given by

$$\Delta f = f_r - f_t = -2\nu_r/\lambda \quad (1)$$

where, ν_r is wind component (radial velocity) along the Line-Of-Sight (LOS) and λ is lidar wavelength.

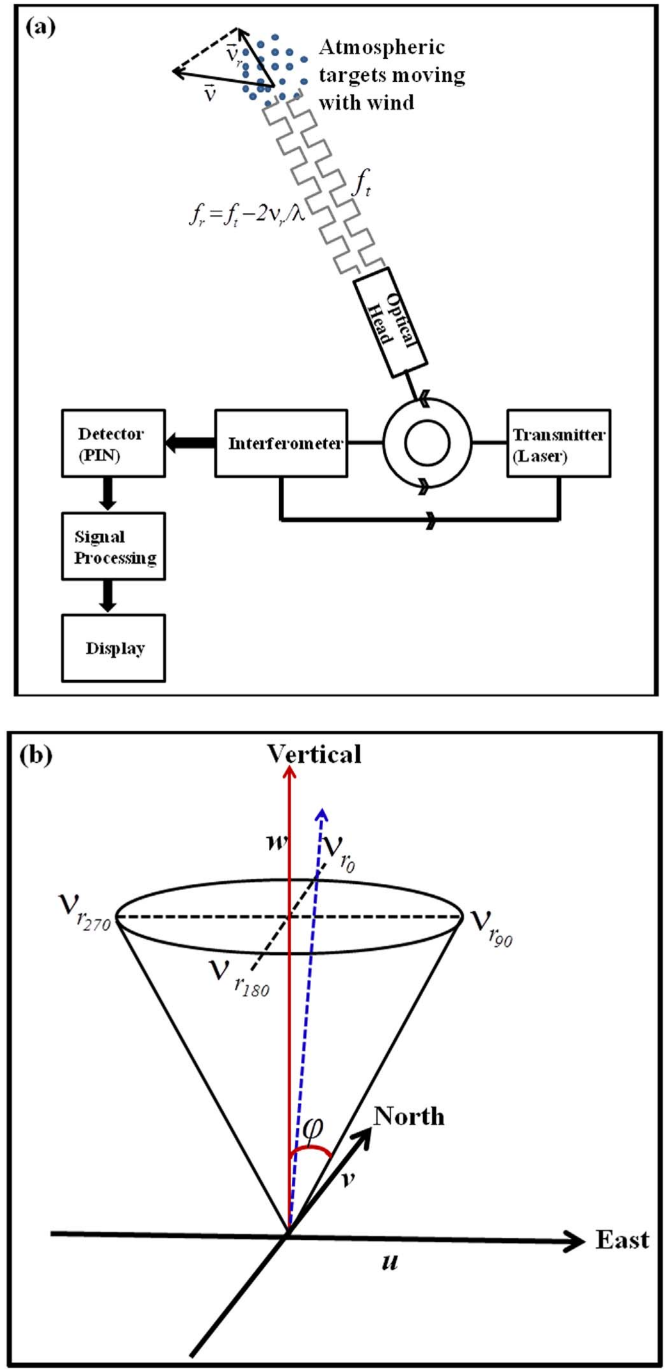

Fig. 1. A schematic (a) block diagram of the Doppler Wind Lidar (DWL) system and (b) scan technique of the vertical and tilted beam in the DWL scan.

As the DWL measures the wind along the axis of lidar laser beam, it needs radial velocity measurements from at least three independent LOS directions to obtain all the three components (zonal, *u*; meridional, *v*; and vertical, *w*) of the wind vector. To achieve this, the DWL has a prism, which deflects the lidar laser beam from the vertical axis. The DWL scans at a cone angle of about 15° at four independent LOS (tilted north, tilted east, tilted south and tilted west), each separated by 90° azimuth as shown in Fig. 1b. The DWL uses 0.3 μs i.e., range resolution of ~50 m with a first useable range gate at 100 m. There are 36,000 pulses per shots for each beam consuming ~12 s accumulation cum processing to get profile in each beam direction. Thus, the entire scan cycle (tilted north, tilted east, tilted south and tilted west) is completed