

On the spatial structure and time evolution of Shamal winds over the Arabian Sea- a case study through numerical modeling

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Abstract

Shamal events are extra-tropical weather systems which occur in winter (cold and dry winds) as well as summer (hot and humid winds) with strong northwesterly or northerly winds blowing over the Arabian Peninsula. We have used Weather Research and Forecasting (WRF) model to simulate a major winter shamal event (having duration of 3-5 days), which occurred in 2008 and analyzed the spatial structure and time evolution of shamal winds over the Arabian Sea. The study reveals that horizontally, shamal winds extend upto 14°N and bring out significant changes in the atmospheric temperature - longitudinally from Arabian coast to west coast of India; its vertical extension is upto to approximately 8km near Oman and approximately 3km near Ratnagiri coast. Along the Arabian coast a temperature drop of 12°C is observed and along west coast of India a drop of 5°C. It gets dissipated when northeast monsoon winds dominate. Its speed reduces from 15 m/s (Oman coast) to 9m/s (central Arabian Sea) as it propagates into Arabian Sea. As the present work is limited to a case study, the results are not in any way has a Climatological reference.

Key words: Arabian Sea; shamal winds; numerical modelling; WRF; monsoon; west coast of India.

1. Introduction

The general atmospheric circulation over the Indian Ocean during various seasons reveals the characteristics of different wind systems prevailing over the region. Arabian Sea (AS) is characterized by monsoons in a yearly cycle: southwest (SW) monsoon during June – September and northeast (NE) monsoon during November – February. Winds during SW monsoon are strong, whereas NE monsoon winds are weaker over this region. Synoptic winds are weak during pre-monsoon season (March – May), and hence, localized effects prevail over the AS. For example, the west coast of India is dominated by thermally-driven sea-land breeze circulation during pre-monsoon season (Vethamony et al., 2011; Dhanya et al., 2010; Aparna et al., 2005). Shamal event is a mesoscale atmospheric phenomena which occurs during November-March (winter) as well as June-August (summer) due to dynamic interaction between upper air jet streams and lower tropospheric pressure levels, and is associated with mid-latitude disturbances travelling from the west to the east (Hubert et al., 1983; Perrone, 1981; Ali, 1992). Shamal winds are caused by the presence of a large pressure gradient that develops behind a cold front passage. Upper level subsidence and rapidly building high pressure over Saudi Arabia and Iraq reinforces the low-level northwesterly winds, mainly during December to February. The word ‘shamal’ means ‘north’, according to the Arabic literature. The winds during these events are called shamal winds. The ‘shamal events’ are hereafter referred to as ‘shamals’.

There are a few studies on the onset, duration and strength of the shamal winds over the Arabian Peninsula (Ali, 1994), and their influence on oceanic waves and meteorological conditions over the Arabian/Persian Gulf (Hubert et al., 1983). The shamal winds are strong enough to generate storm surges (El-Sabh and Murty, 1989), oil spills (Murty and El-Sabh, 1985; El-Sabh and Murty, 1988) and dust storms (Perrone, 1979; Walters and Sjoberg, 1988; El-Sabh and Murty, 1988). Based on duration, winter shamals can be divided as those which lasts between 24 and 36 hours (more frequent) and those which lasts between 3 and 5 days (once or twice every year) [Hubert et al., 1983, Perrone, 1981]. Prasad and Patrick (2010) analysed the response of Persian Gulf to a winter Shamal event in 2010. Winter shamals are more significant than the summer shamals with respect to the strength of the wind and associated weather conditions (Perrone, 1981). These are typically strong cold winds ranging upto 20m/s, bringing strong winds to the Arabian Gulf (Lawson, 1971). It has been identified that the winter shamals have significant influence in the northern part of the AS apart from the Arabian Gulf. For

instance, Aboobacker et al (2011) investigated swells generation in the AS due to shamal winds. However, the atmospheric characteristics over the AS during shamals are not yet fully understood. The present study aims at understanding the horizontal and vertical distribution of shamal winds over the AS, their extension along the west coast of India and variations in meteorological parameters such as temperature during shamals. It is worth to note that summer shamals do not affect the entire Arabian Sea or the west coast of India due to the presence of large scale SW monsoon event. The period from 25 January 2008 to 25 February 2008 included three major shamals (having duration of 3-5 days): from 27-29 Jan, 2 - 7 Feb and 20-23 Feb, among which the 2-7 Feb event was the strongest, where the winds were stronger and colder. Moreover, wave data collected along the west coast of India during the above period also showed a clear indication of shamal events (Aboobacker et al., 2011). Hence, the present study is focused on the horizontal and vertical distribution of winter shamal winds in the AS and the variations in air temperature associated with this particular shamal event. Fig 1 shows the study area with the measurement locations.

Figure 1

2. Data and Methodology

Meteorological parameters such as wind (speed and direction) and temperature are measured using Autonomous Weather Station (AWS) of the National Institute of Oceanography (NIO), at Ratnagiri and Goa coasts (see Figure 1 for locations) for every 10-minute interval. The accuracy of AWS is: 0.2 m/s for wind speed in the range 0–60 m/s, 3° for wind direction in the range 0–360° and $\pm 0.15^\circ\text{C}$ for atmospheric temperature in the range 0–45°C. Upper-air sounding observations for the Mumbai and Abu Dhabi regions were obtained from the website <http://weather.uwyo.edu/upperair/sounding.html>. The variations in wind and temperature during shamals have been analyzed and discussed.

Numerical simulations were carried out to generate the atmospheric parameters over the AS using the Weather Research and Forecasting (WRF) model (Shamarock et al., 2008). It is based on fully compressible, non-hydrostatic Euler equations, third order Runge-Kutta integration scheme and Arakawa C grid. The vertical mixing and diffusion was done by Asymmetric Convective Model with non-local upward mixing and local downward mixing (ACM2) scheme (Pleim, 2007) and surface physics by Pleim-Xiu scheme. The simulations employ the SBU-YLIN (Lin and Colle, 2011)

microphysics scheme, and Pleim-Xiu Land Surface Model, Two-layer scheme with vegetation and sub-grid tiling were used. The Rapid Radiative Transfer Model and Dudhia scheme (Skamarock et al., 2008) were used for the longwave and shortwave radiations. The global analysis data from the National Center for Environmental Prediction (NCEP) having a spatial resolution of 1° and a temporal resolution of 6 h has been used to provide the initial and boundary conditions to the model. Terrain data has been taken from the US Geological Survey (USGS) which has a resolution of 0.9km. The model domain extends from 43° E to 85° E and 2° N to 33° N (Figure 1) with spatial resolution of 27km, and the simulations were carried out for a period of one month from 25 January to 25 February of 2008.

3. Results and Discussion

3.1. Model Validation

The simulated wind parameters were validated with the measured AWS wind data of Ratnagiri and the simulated atmospheric temperature with that of Goa (Figure 2). It was found that the simulated u-velocity (zonal component), v-velocity (meridional component), wind speed, wind direction and atmospheric temperature match reasonably well with measurements.

The vertical comparison of simulated and measured (radiosonde) wind speed, wind direction and temperature of the Arabian coast (OMAA Abu Dhabi 54.65° E, 24.53° N) for 1 February 2008 and Indian coast (VABB Mumbai 72.65° E, 19.11° N) for 6 February 2008 showed a good match (Figure 3). These are the closest days, where radiosonde measurements are available at both the coasts during this shamal event. The correlation coefficient, bias and r.m.s. error are 0.7, -0.17 and 1.52, respectively for u-velocity and 0.64, 0.12 and 1.57, respectively for the v-velocity.

Figure 2

Figure 3

3.2. Horizontal distribution of shamal winds

To understand the propagation and horizontal extension of shamal winds, we considered the latitudinal variation of atmospheric temperature, and wind vectors (at 10m height) along four profiles at longitudes: 55° E (p1), 60° E (p2), 65° E (p3) and 70° E (p4) during 25 Jan - 25 Feb 2008 (figure 4). p1 represents the

Arabian Peninsula including the Arabian Gulf, p2 represents the western AS including Gulf of Oman and east coast of Oman, p3 represents the central AS, and p4 represents the eastern AS. When shamals occur, the prevailing NE monsoon wind becomes negligible and the shamal wind (N or NW) dominates. Three major shamals (having a duration of 3-5 days) during the study period have been identified: from 27-29 Jan (s1), 2 - 7 Feb (s2) and 20-23 Feb (s3). The most important event among them is that occurred at s2, where the winds are stronger and colder. The intensity of the winds decreases southward and the wind direction changes from NW to NE due to the dominance of northeast monsoon winds.

Figure 4

There are two distinct temperature patterns-over the land and the sea, respectively. For example, the region between 17°N and 25°N (Figure 4a), north of 26°N (Figure 4b), north of 25°N (Figure 4c) and the region between 21°N and 22.5°N and north of 22.75°N (Figure 4d) represent the land. The diurnal variations in temperature are low over the sea, whereas it is higher over the land. However, the variations during shamals are significant over the sea area, especially at profiles p2, p3 and p4. At p1, the Arabian Gulf is most affected (the wind speeds are very high), but the sea area south of 17°N is least affected by shamals, where NE winds remain throughout the season. Between 17 and 25°N (over the land), during normal condition the night-day temperature typically varies from 17 to 33°C, however, during shamal it drops by about 5 to 11°C. Further north, that is in the Arabian Gulf (25-27°N), a drop of 5°C, which is less compared to the temperature drop in land due to the difference in specific heat capacity of land and sea, is noted during shamals. At p2, the shamal wind has the direction between N (in the northernmost regions) and NW (in the central region). At p3 and p4, the shamal wind direction is NW. The temperature drop in the land area north of 25° N (north of Arabian Sea) is between 8 and 12°C in day-night variation. Over the northern AS, air temperature reduced to 17°C from 23°C, whereas towards the southern AS, the drop in air temperature is decreasing with a minimum drop of < 2 °C at 16 °N latitude. Along the eastern AS profile (p4) , the temperature drop 3-5 °C in day-night over land (Gujarat area) whereas it is 3.5°C over the ocean.

It is evident from figure 4 (d) that the maximum latitudinal extension (southwards) of the shamal winds in the eastern AS is 14°N and can induce a temperature drop of 1.5°C, which indicates that the shamal wind can reach upto the central west coast of India, since the direction is north westerly. The wind measured at Ratnagiri coast (~17°N and temperature measured at Goa coast (~15°N) reveals this fact

(both temperature and winds were not available simultaneously in any one of the stations) (Figure2). The wind speeds are relatively higher and the direction is NW during shamals at these locations. The average shamal wind speed between p1 and p2 is 15 m/s, between p2 and p3 is 11 m/s and between p3 and p4 are 9 m/s. The corresponding propagation times between the profiles are 10 h, 13.5 h and 18 h, respectively.

The northern Arabian Sea (p2 and p3) is cooled by a substantial decrease in air temperature that reach upto 11 to 14°C (Figure 4 b and c) over the ocean. This cooling can significantly affect the air-sea interaction processes, and hence the ocean dynamics. More detailed investigations through in situ observations and ocean modelling can lead to interesting results on air-sea interaction due to shamal event. Even though the shamals are short duration events, they occur every year in multiple numbers, thus affecting the monthly climatology of the northern AS.

Figure 5

NE monsoon winds are least affected in the Arabian Peninsula, and hence, they have limited interaction with shamal winds. It has been found that the NE winds are weaker during January-February, and the shamal winds dominate. As it goes towards the east, the intensity of shamal decreases, conversely, the intensity of NE monsoon winds increases. The general trend in the AS is that the NE winds are merely absent (figure 4) during shamals and retains after the event. It is evident from the wind patterns of profiles p1 to p4 that the longitudinal variations are significant. Even though the shamal patterns exist, the wind speeds and temperature variations are considerably less at p4 (wind speed: 15 to 7m/s; temp: 11 to 5°C) compared to p1. The west coast of India is also influenced by sea-land breeze system, apart from the synoptic SW and NE winds. However, prevailing conditions necessary for the sea breeze generation tend to diminish during shamals primarily due to the decrease in temperature at the offshore regions which decelerate the offshore extension of sea breeze. From figure 5 b during the shamal period the land breeze is suppressed.

3.3. Vertical distribution of Shamal winds

The simulated vertical profiles of wind speed, wind direction and temperature over the Arabian region (figure 3 (a, b and c)) for 1 February 2008 at 0000 h and the Mumbai region (figure 3 (d, e and f)) for 6 February 2008 at 1200 h were compared with observation. The observation shows that the lower and

upper atmospheric winds are stronger over the Arabian region than the Indian coast. For both regions the upper wind directions are northwesterly or westerly which is already reported by Donald in 2001. The decrease in temperature in upper atmosphere due to the adiabatic lapse rate is reproduced in WRF model.

In order to understand the vertical extension of Shamal wind over both the coasts, the Hovmoller diagram (figure 5) for wind direction near the Oman coast (55°E, 26°N) and near Ratnagiri, India (73°E, 17°N) are considered. From figure 5 (a and b) we find that even though the signature of Shamal winds are present, it is difficult to identify its vertical extension since the upper atmospheric winds are also in the westerly or northwesterly direction due to the equatorial high pressure and polar low pressure regions (Donald, 2001). Over the Ratnagiri region, Shamal winds suppressed the land breeze system during the Shamal period (Fig 5b). Since Shamal winds are cold winds and can reduce the atmospheric temperature, we can consider atmospheric temperature profile for studying the vertical extension. For example, at the Oman coast, based on the temperature distribution we can say that the vertical extension of Shamal event (Fig.5c) is approximately 8km. As shamal winds propagate towards the Indian coast, its energy gets dissipated and also its vertical extension gets reduced. For example, at Ratnagiri (Fig.5d) the temperature drop can be seen upto a height of approximately 3km only.

4. Conclusions

The characteristics of Shamal winds are studied using the atmospheric model, WRF by taking a strong winter Shamal event having a period of 3-5 days. The Shamal winds, characterized by strong and northwesterly cold dry winds, propagate to the Arabian Sea and affect the atmospheric conditions along its path. It extends upto 14°N near west coast of India and gets dissipated when dominated by winds of northeast monsoon. Its speed reduced from 15 m/s (Oman coast) to 9m/s (central Arabian Sea) as it propagates to AS; it takes nearly 42 h to reach to its maximum extension near the west coast of India. Along the Indian coast, it interacts with the sea-land breeze system by intensifying the sea breeze and suppressing the land breeze. The cold shamal winds reduce the normal air temperature over land and ocean drastically along its path of propagation. However, it should be noted that, the study is limited to a case study and hence, the southerly extension of the phenomenon and the associated changes in air temperature are not in any way related to Climatological reference. The shamal events may influence

the wind induced circulation, heat flux and stratification in the Arabian Sea and has to be analyzed further.

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Figure captions

Figure 1 Study area. Red dots indicate the measurement locations where the surface and vertical atmospheric parameters are available. OMAA refers to Abu Dhabi airport observation station

and VABB refers to Mumbai airport observation station, respectively.

Figure 2 Timeseries comparison between modeled and AWS measured (a) zonal velocity, (b) meridional velocity, (c) wind speed and (d) wind direction at Ratnagiri and (e) Air temperature at Goa (NIO) for the period 25 January 2008 to 25 February 2008

Figure 3 Comparison between modeled and radiosonde measured vertical profiles of windspeed (a and d), wind direction (b and e), and air temperature (c and f). The upper panel shows the comparison at OMAA Abu Dhabi (see fig.1 for location) for 1 February 2008, 0000 h and the lower panel shows the comparison at VABB Mumbai (see fig.1 for location) for 6 February 2008 , 1200 h

Figure 4 Hovmoller diagram for (a) 55°E (P1), (b) 60°E (P2), (c) 65°E (P3) and (d) 70°E (P4) longitudes

Figure 5 Time series analysis of simulated vertical profiles of wind direction (a and b) and air temperature (c and d) at 55°E, 26°N (a and c) and 73°E, 17°N (b and d)

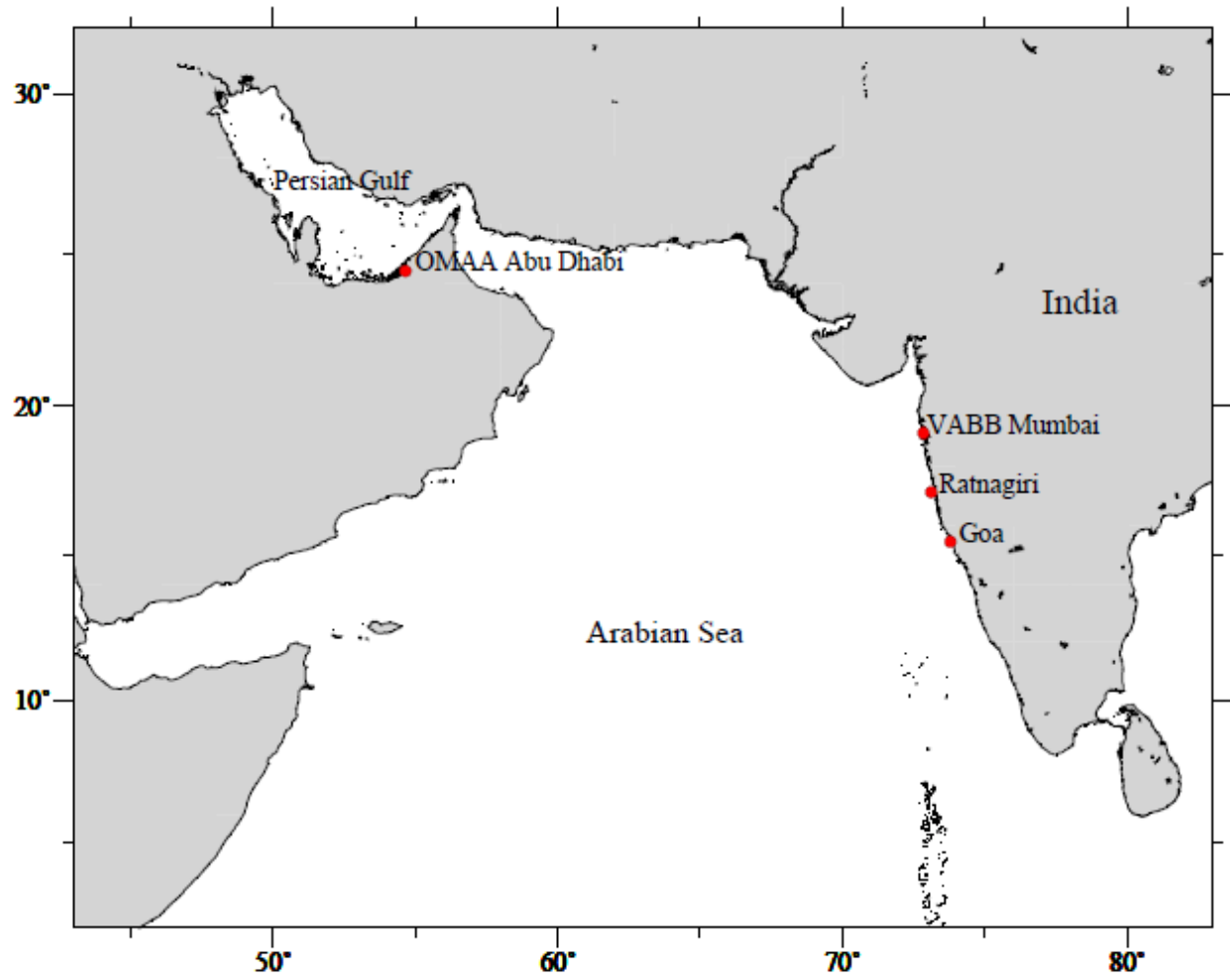


Figure 1

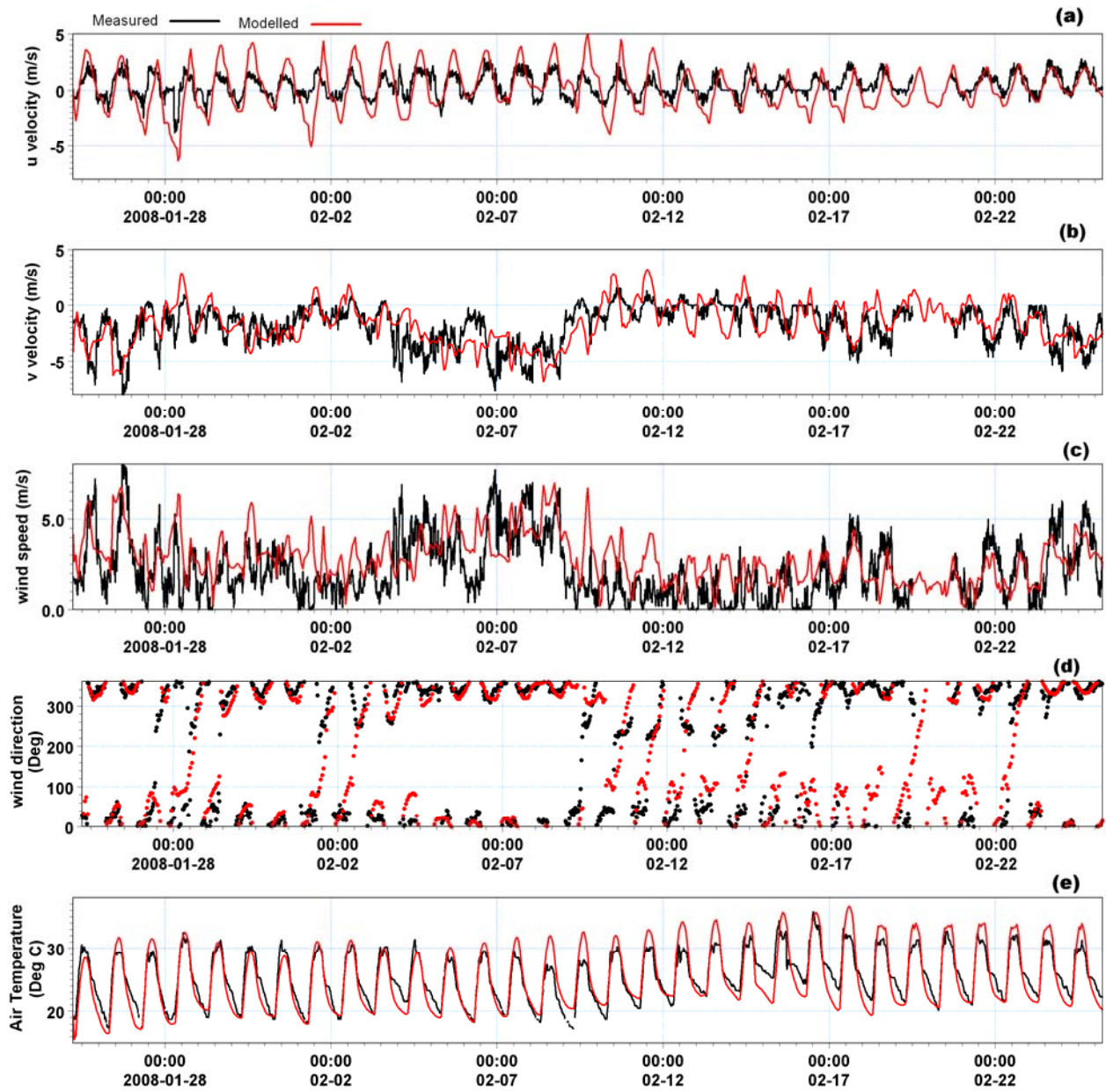


Figure 2

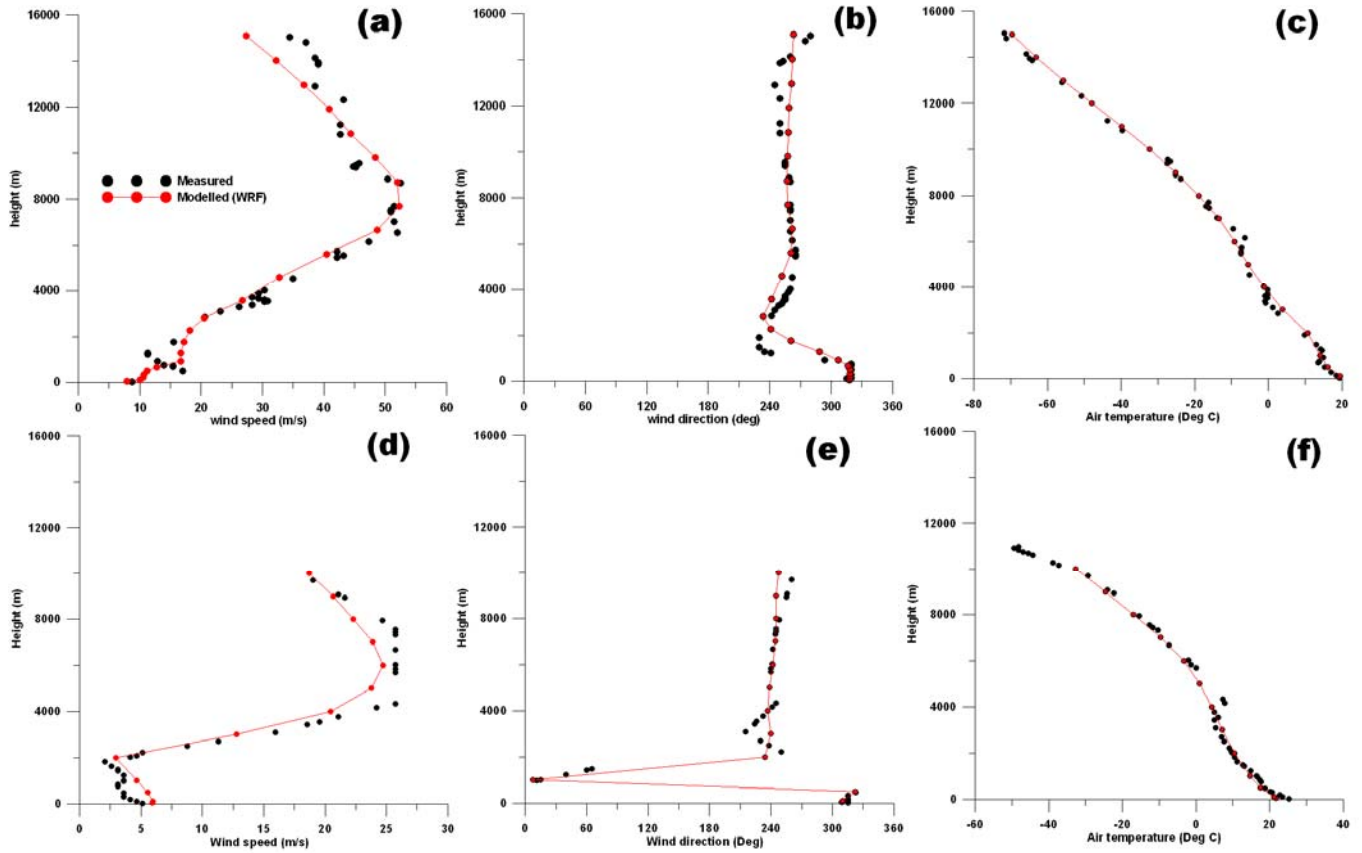


Figure 3

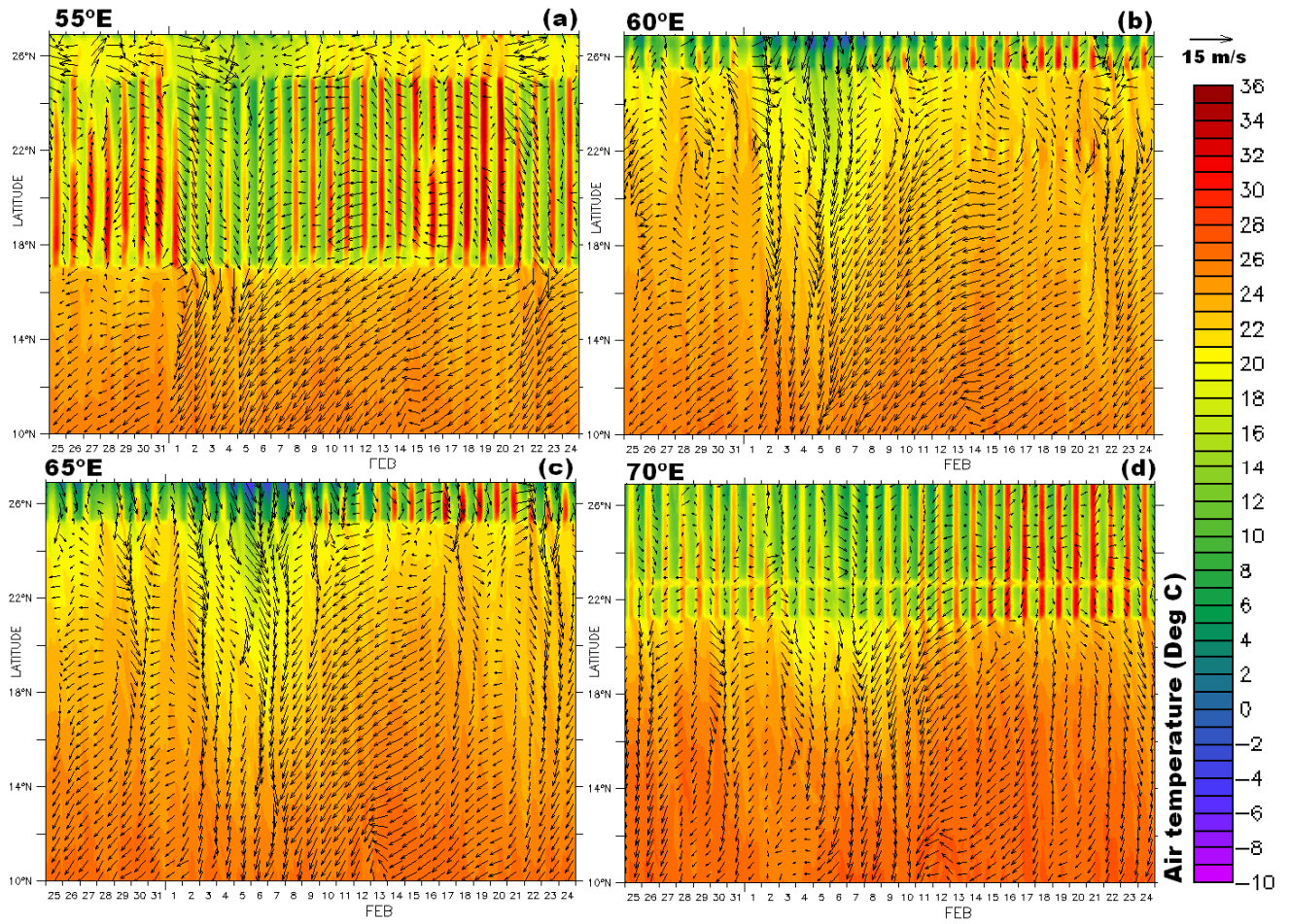


Figure 4

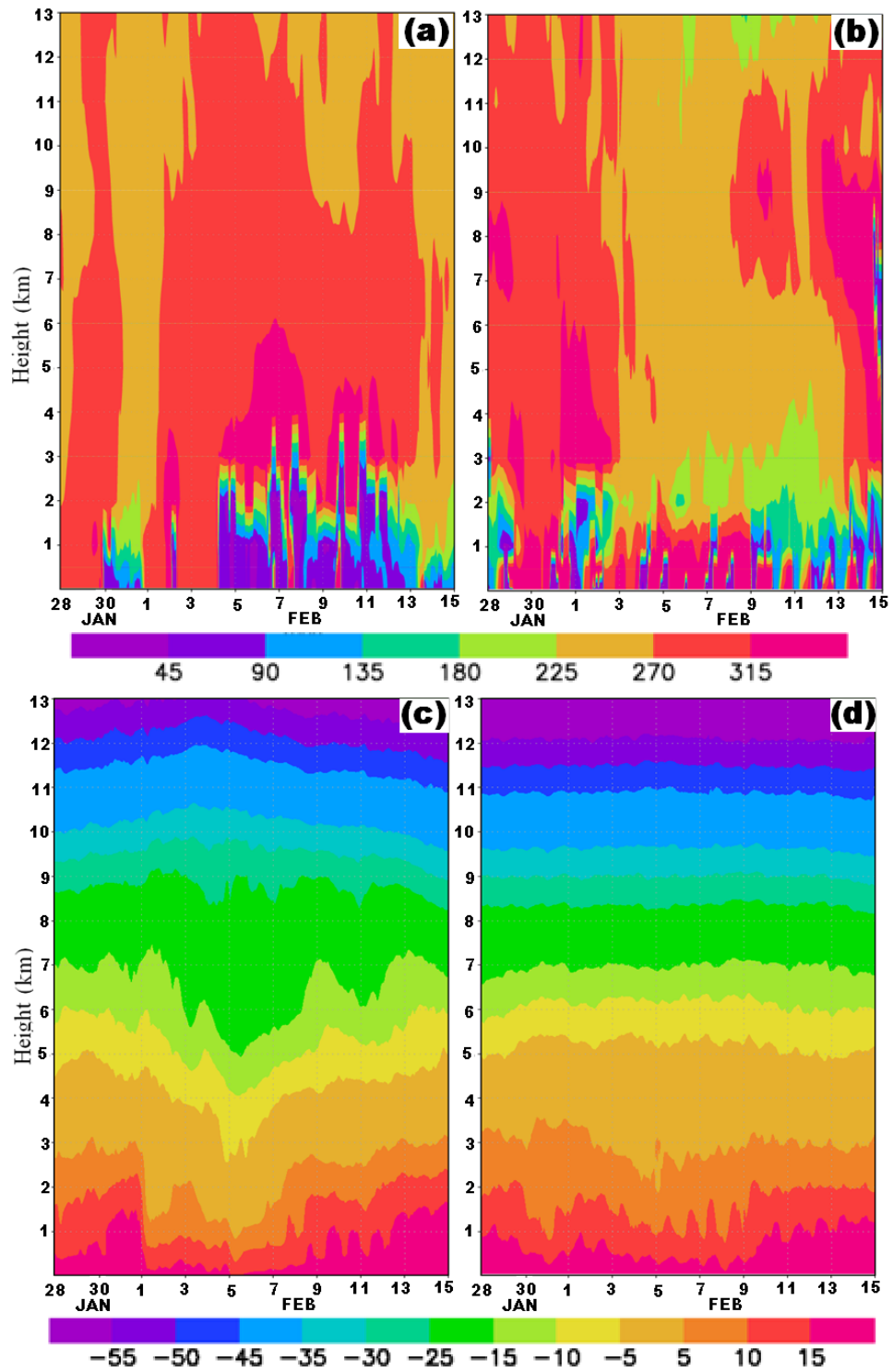


Figure 5