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QUANTIFICATION OF SURFACE GUSTS

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Abstract: Quantification of gust is of prime importance for a variety of applications, including the stability of structures/buildings, generation of turbulence, even rocket launches, when the vehicle is on launch pad. An attempt has been made to quantify the gust in the surface layer using high-resolution tower measurements and the results are presented in this paper**.** In particular, the study focuses on the characteristics of, in terms of their duration, magnitude, height variation and a broad source apportionment of gusts (convective and non-convective).

Keywords: Gust, tower measurements.

1. INTRODUCTION

Gust is a transient phenomenon and traditionally it is regarded as a rapid change in wind from the background wind for a short duration. It has the greatest damaging potential and is regarded as one of the deadliest natural hazards. Quantification of gust is of prime importance for a variety of applications, including the aviation meteorology, wind energy, stability of structures/buildings, generation of turbulence, even rocket launches, when the vehicle is on launch pad. These extreme winds increase the aerodynamic load on structures, both floating bodies like aeroplanes and land-locked wind turbines. Knowledge on gusts is required not only at the time of take-off and landing, but also during the flight (Shi et al., 2015). For wind energy applications, gust information is required at different stages in different ways. It is required to design of the turbines at the time of establishing the plant, which can be obtained from the wind climatology of that region. For planning of operations, long-term wind (and gusts) forecast is highly essential. Short-term forecast of extreme wind gusts are also useful to take precautionary measures from causing enhanced fatigue and breakage of turbines. These hazardous winds typically cause damage to trees and forests by uprooting them. The economic loss is not only due to the loss of timber, but also due to falling of trees on power lines and houses, thereby causing wide range of problems to public (Prahl et al., 2015).

Wind gusts are heavily dependent on upstream terrain conditions (roughness), but are also affected by transitional flow regimes (specifically, changes in terrain and the distance from the upstream terrain change to the measuring device), wind measurement height, stability of the boundary layer, and, potentially, the presence of deep convection (Paulsen and Schroeder 2005). The gust factor, the ratio of gust wind speed to the mean wind speed, decreases with measurement height. The higher the aerodynamic roughness of the surface, the greater is the change. The decrease of the gust factor with height is smaller in unstable than in stable conditions (Suomi 2017).

Storms and cyclones with extreme wind gusts can cause severe damages and loss of property and lives and therefore regarded as one of the lethal natural hazards. So far, the strongest wind gust recorded is 253 miles per hour (mi h^{-1}) or ~113 m s^{-1} on 10 April 1996 during the passage of cyclone Olivia over Barrow Island, Australia. There were several reports with wind gusts exceeding 200 mph (90 m s^{-1}) in the literature and all of them were recorded during the passage of cyclones. Direct surface measurements of wind gusts in tornadoes are rare. A few of them are available in the literature (Blair et al., 2008, Blanchard 2013, Wurman et al., 2013) and all of them show wind gusts in the range of 40-70 m s^{-1}, which is less than that observed in intense cyclones (Smith et al. 2013, Nolan et al. 2017 and references therein). Wind gusts can occur in mature to decaying convective systems. Convective wind gusts are induced by rapidly descending air masses in a thunderstorm or squall line. On impact with the ground the air contained by the downdraft is deflected by the surface and causes the wind gusts.

As seen above, gusts typically occur with intense convective/cloud activity or tornadoes, all can be identified by their visual manifestations. However, terrain differences can also cause steep gradients of surface atmospheric pressure leading to windstorms (Knox et al., 2011, Miller et al., 2016). These meso-scale processes are termed non-convective and may occur without the presence of clouds or precipitation. Non-convective gusts tend to occur over a larger spatial and temporal scales and produce a more homogeneous wind field as compared to winds associated with thunderstorms or tornadoes (Lacke et al., 2007, Ashley and Black 2008, Pryor et al., 2014).

As seen above, one section of researchers define wind gusts based on the maximum wind that it attains, for instance in cyclones, tornadoes, etc. and the other section considers it as a transient phenomenon with wind maximum superimposed on the background wind. The issuance criteria for US's National Weather Service (NWS) (NWS, 2015) wind advisories are based on sustained wind or wind gusts. They issue wind advisory (high wind warning), if wind is in the range of 25-39 (exceeds 40 knots) or wind gusts in the range of 46-57 (exceeds 58 knots). Miller et al. (2016) examined the rationale for choosing the above thresholds for identifying non-convective gusts and tested the applicability of these thresholds in different climatic zones. According to World Meteorological Organization (WMO), GUST is a maximum wind speed of short duration (3 sec) during a sampling interval of 10 min (WMO, 2008). Some other studies used different criteria for wind gusts and sustained wind. Lombardo et al., (2009) identified gusts from automatic weather stations observations by considering 5 s wind gusts in 1 hour observations.

Gusts have been quantified and characterized over different types of surfaces, including the land (Wieringa 1973, Suomi 2017), near the coast and off-shore (Hsu and Blanchard, 2004, Suomi et al., 2013), in complex topography (Meyers et al., 2003, Belusic and Klaic, 2004). Most of the comprehensive studies on gust were carried out in mid latitudes (Wieringa, 1973, Beljaars, 1987, Woetman Nielsen and Petersen, 2001, Brasseur, 2001, Wichers Schreur and Geertsema, 2008, Suomi et al., 2015). A few studies focused on gust factors in tropical and subtropical cyclones (Paulsen and Schroeder 2005). The aim of the present study is to characterize gusts in surface layer, in terms of their duration, magnitude, height variation and a broad source apportionment of gusts (convective and non-convective).

2. DATA AND METHODOLOGY

Since gust is a transient phenomenon, high resolution measurements are needed to identify and characterize it. Wind measurements made at 2, 4, 8, 16, 32 and 50 m at 1 Hz resolution are used for this purpose. Also, the other collocated simultaneous meteorological parameters of temperature, humidity, rainfall, etc. are also used to identify the convective and non-convective events.

2.1. Definitions for surface gust

Though gust is considered as a sudden but brief increase in speed of the wind, there is no unique threshold/definition to identify it in the data. According to U.S. weather observing practice, "gusts are reported when the peak wind speed reaches at least 16 knots and the variation in wind speed between the peaks and lulls is at least 9 knots. The duration of a gust is usually less than 20 seconds". As mentioned WMO identifies it from 2 s average data for gust from 10 min. sustained wind, while Lombardo suggested 5 s gusts in 1 hour sustained wind. Pryor et al. (2014) used a 10 m s^{-1} wind threshold or wind should exceed 95th percentile wind for identifying the gust.

2.2. Identification of surface gust

The threshold used in the present study for gust is somewhat similar to those employed by U.S. Weather Service. The procedure of identifying gust from high-temporal resolution measurements of horizontal wind is demonstrated below in Figure 1.1. To obtain the daily synoptic wind without disturbing the diurnal cycle, the 24 hour data with 1 Hz resolution are subjected to a polynomial fit. Different orders of polynomials were tried and 10th order polynomial is found to work well with the data. Higher than 10th order is found to reduce the gust magnitude, while lower order fits does not represent the data well. The original wind measurements (blue line) and the polynomial fit (pink line) over a time period of 24 hours clearly shows that the 10th order polynomial is working well and also broadly providing the sustained wind, including the diurnal cycle. The gust is identified in the present study, whenever peak wind speed exceeds 8 m s^{-1} and the variation in wind speed between the peaks and lulls exceed 6 m s^{-1}. Figure 1.1 clearly shows a gust at ~16:00 LT, where the wind speed reaches 13.6 m s^{-1} and the wind magnitude is larger than the sustained wind by 12 m s^{-1}.

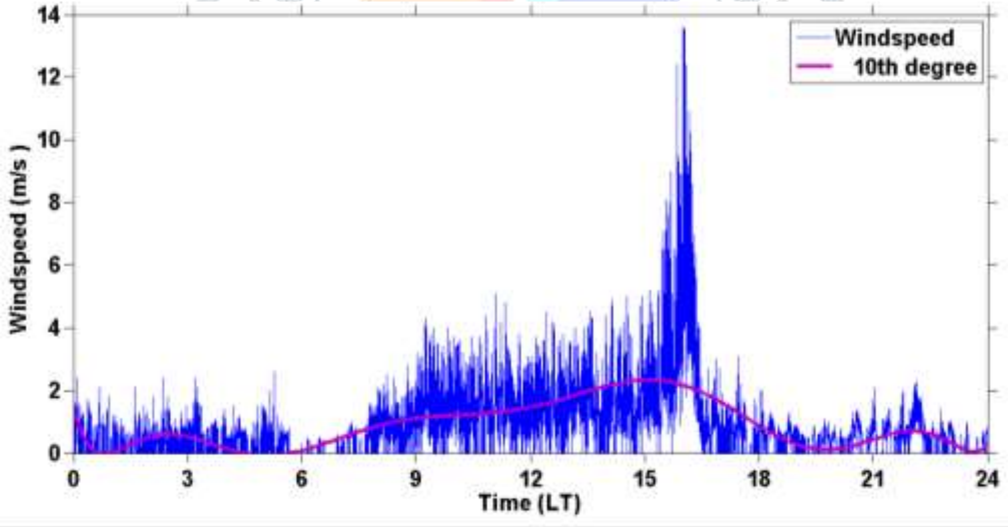


Figure 1.1: Time series of high-resolution winds (blue line) and 10th order polynomial fit to the mean horizontal wind (pink line), depicting the procedure of identifying the gust.

3. RESULTS AND DISCUSSION

This section provides a brief account on the characteristics of gusts (in terms of their duration, magnitude, time of occurrence and height variation) in different seasons.

3.1. Occurrence (duration) statistics

The gust is identified as explained in Section 2.2 and the duration of gust in each event is estimated. Then, the duration of gust is accumulated as a function of month. As the instrumented tower at NARL is having sensors at 2, 4, 8, 16, 32 and 50 m, the gust duration is estimated at each altitude to understand its height variation. The accumulated gust durations at different heights are shown in Figure 1.2 as a function of month. The gust duration is, in general, longer during hottest months, i.e., April - July. Two important observations are noted from this plot. Firstly, the duration of gust increases gradually with height. The duration increases by a factor of 10 from 2 m to 50 m. The horizontal winds are generally weaker near the earth's surface due to surface friction and partly due to canopy. As height increases the surface friction reduces and wind speed increases in a logarithmic fashion with altitude within the surface layer. The maximum wind condition gets satisfied more easily at higher altitudes. Secondly, the peak in duration, which is narrow and confined to May at 2 m has become broad as the height increases. For instance, the peak in duration spreads from April to July at 32 and 50 m. As mentioned above, the gusts at lower heights (2 and 4 m) are mainly associated with thunderstorms that are predominant during April-May. On the other hand, along with gusts other mesoscale flows are also playing a role at higher heights. It is also possible that because of stronger winds at higher heights (due to less surface friction), the events during monsoon months may just be satisfying the thresholds used for the gust in the present study.

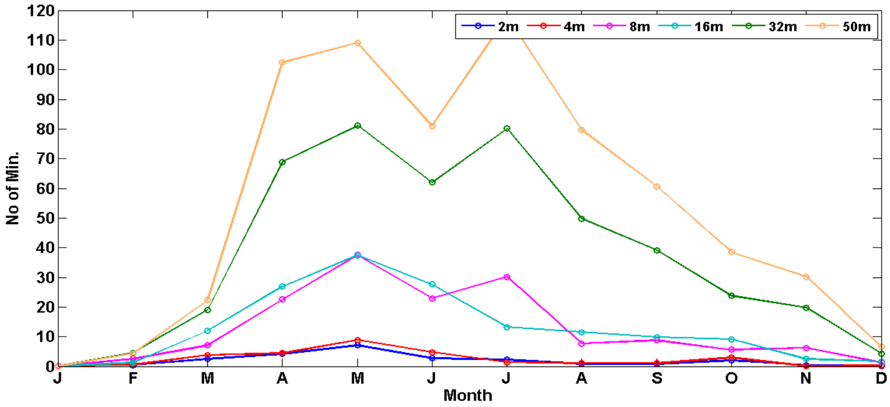
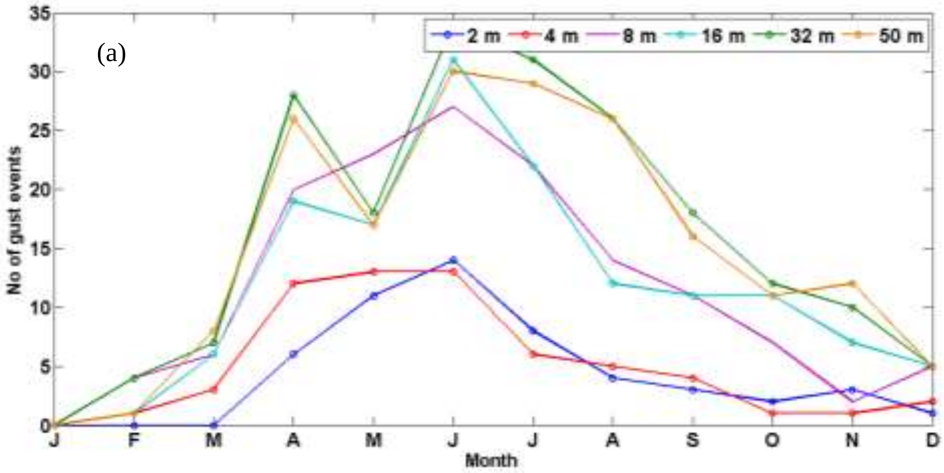


Figure 1.2: Monthly variation of duration of gusts at different heights.

This duration could be due to more gusts or longer gusts or both. To examine this issue, the number of gust events and average duration of gust events (total duration/number of events) are plotted in Figure 1.3. In general, the number of events increases with height in all the months, more so during hotter months. It is not a monotonic increase, but the number is certainly larger at 32 and 50 m than at 2 and 4 m. The number of events is a factor of 4-7 larger at higher heights than at lower heights. The duration of events also increase with height in all the months by a factor of ~5. It means the height variation of the number of events and their duration are responsible for the observed increase in duration with height.

Interestingly, the broad maximum in duration from April to July is due to various reasons. The number of events is smaller in May than in other hotter months, however, the average duration is larger (a factor of 2) than in other months. These longer duration events in May are primarily associated with intense and deep thunderstorms (Saikranthi et al., 2014, Rao et al., 2016). In other hotter months, the gust events are of shorter duration, but large in number and are primarily responsible for longer total duration.



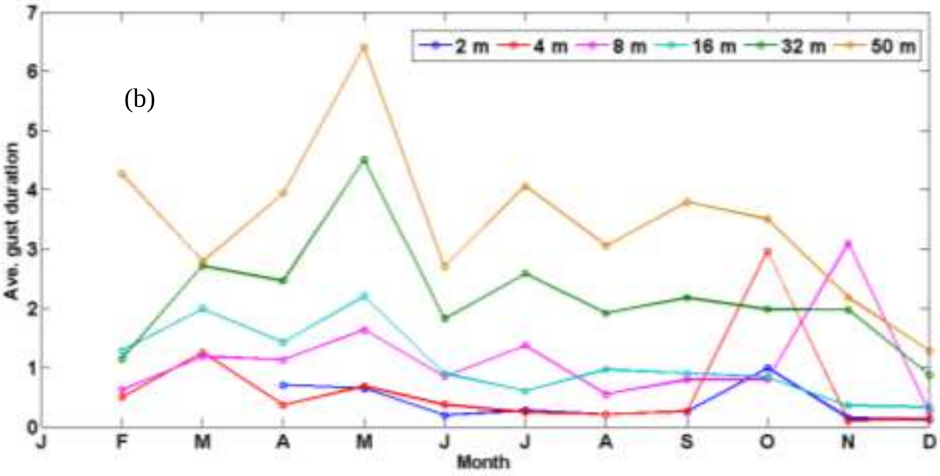


Figure 1.3: Monthly variation of (a) number of wind gust events and (b) average duration of gusts.

3.2. Gust magnitude

To examine the strength of gust magnitude in different months, the maximum wind speed attained by gust in each event is collected and are grouped monthly. The statistics of peak winds (in each event) are shown as box plots as a function of month in Figure 1.4. Three representative heights are selected (4, 16 and 50 m) for studying the height variation. The magnitude of wind speed (at 4, 16 and 50 m) increases slightly with height, from ~10 m s^{-1} at 4 m to ~15 m s^{-1} at 50 m. The even-to-event variability also increases with altitude (as evidenced by the broadening of each box in a month). The magnitude of gust also shows a weak annual cycle with stronger wind gusts during hot months. The magnitude is generally weaker during colder months, except for October. During March-June, temperatures are high at Gadanki and the probability of thunderstorms with strong wind gusts is quite high in these months. Several studies have shown that premonsoon receives majority of its rainfall in the form of convective (Rao et al., 2008, 2016, Saikranti et al., 2014). These studies also have shown that the intensity and vertical extent of convective systems is quite high as evidenced by high rain rate and cloud top height. These strong systems produce strong wind gusts as seen in Figure 1.3.

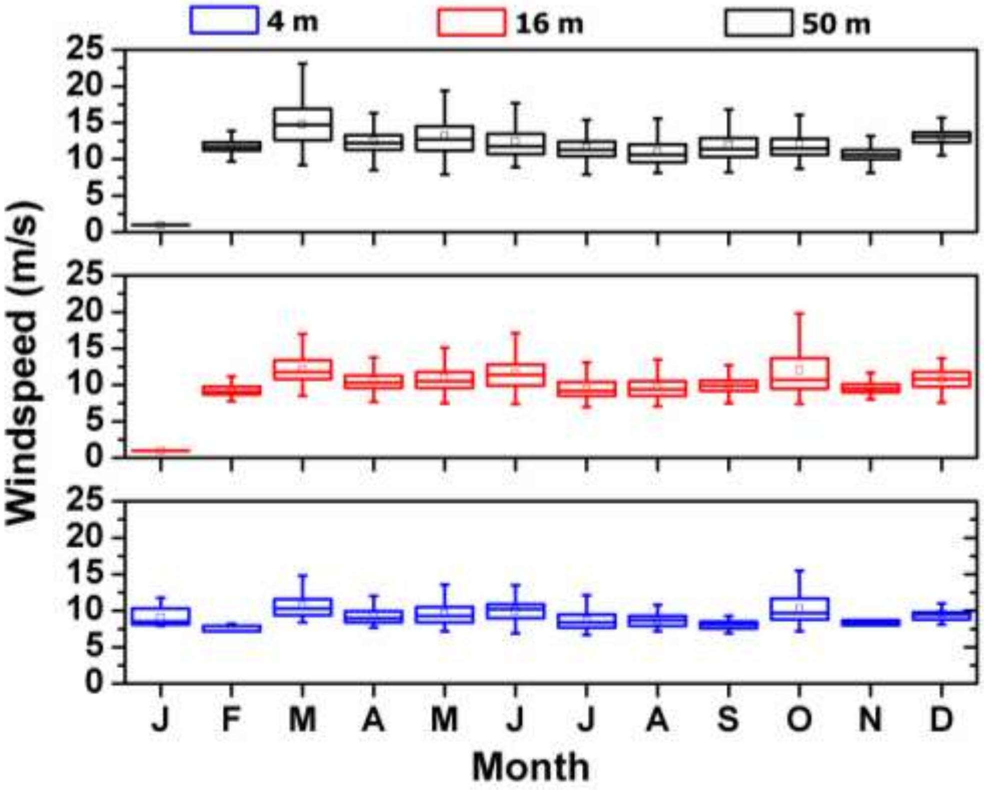


Figure 1.4: The monthly variation of the magnitude of wind gust at three representative heights - 4, 16 and 50 m.

3.3. Diurnal variation in different seasons

To study the diurnal variation of wind gust duration, the duration of each gust event is first segregated based on the start time of gust into hourly bins and all these durations in each hour are added. The accumulated duration of gusts in each hour is shown in Figure 1.5 as a function of season. The duration of gust exhibits clear diurnal and seasonal variations. The duration is longer during noon – early night in all the seasons. As seen in Figure 1.1, generally surface winds also increase in the noon-evening period due to the downward transport of momentum.

The winds due to this turbulent transport generally will have a spiky nature with large variance. However, the amplitude of these oscillations does not generally qualify the thresholds used for gust. The observed gusts, and will be discussed latter, are manifestations of mesoscale flows. The probability of the occurrence of these mesoscale flows (thunderstorms, complex flow in hilly terrain, etc.) is high during the noon-early night and these flows are primarily responsible for the observed diurnal variation of gusts.

The seasonal variation of gust duration is strikingly apparent from Figure 1.4. Maximum duration is observed during premonsoon and monsoon, followed by postmonsoon. Negligible gust duration (due to few events) is observed during the winter. As discussed above, the mesoscale processes (thunderstorm, valley winds, etc.) that generate wind gusts occur predominantly during the hotter months.

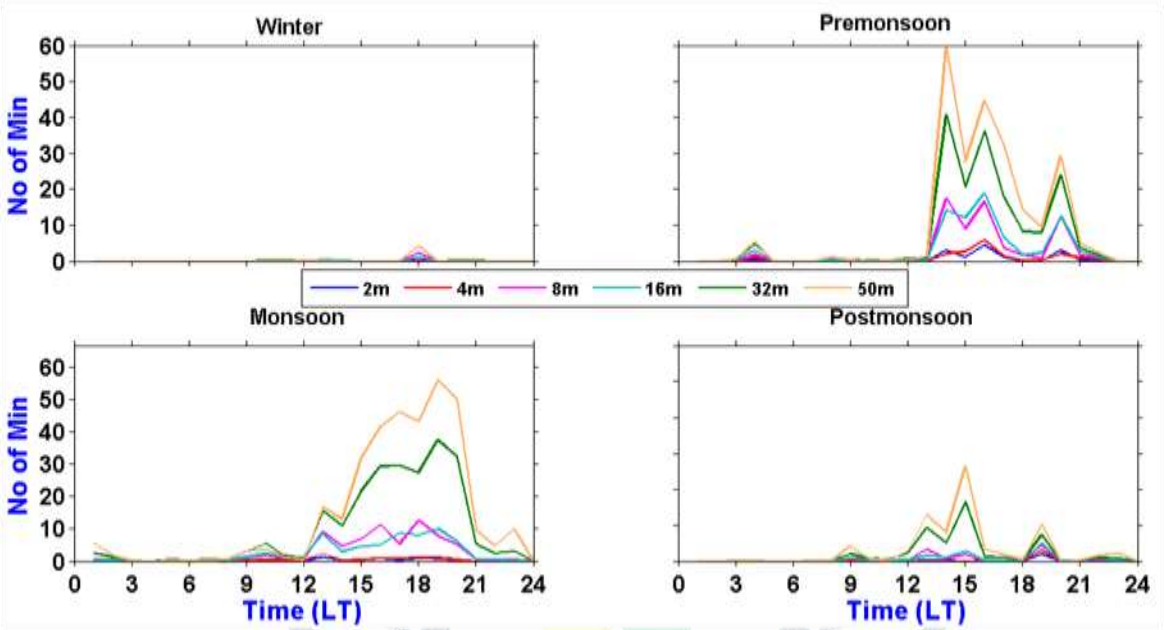


Figure 1.5: Temporal variation of gust duration as a function of the hour of the day and season.

Interestingly, the duration peaks during evening hours in premonsoon, but it peaks a few hours latter (i.e., early night) in the monsoon season. This feature also matches with the seasonal variation in hourly frequency of thunderstorm occurrence. The height variation of gust duration exists in all seasons, except for winter (during which the gust duration itself is very short). Gust duration at higher heights is nearly 10 times that of observed at lower heights in all seasons, similar to Figure 1.2.

4. SOURCES OF GUST

As discussed in the introduction, wind gusts can form due to convective/ thunderstorm and non-convective/non-thunderstorm processes. To understand how much percentage of gusts is of convective (non-convective) origin, the events are segregated in to convective and non-convective categories. The convective days are identified from the changes in meteorological parameters such as temperature, relative humidity, rainfall, etc. Typical examples for convective and non-convective wind gusts and the variation of meteorological parameters during those days are shown in Figure 1.6. One can clearly see a sudden drop in temperature and increase in relative humidity concurrently with a strong enhancement in wind on a thunderstorm day (top panel). Other features of thunderstorm (like meso-high in pressure and rainfall) are also seen on that day. For many events, rainfall was not seen during the gust wind. Doppler Weather Radar (DWR) maps from Chennai indicate the presence of convective clouds north of Gadanki (during premonsoon months). But its outflow reaches Gadanki as wind gust showing all the manifestations of thunderstorm, except rainfall at Gadanki. On a non-thunderstorm day (bottom panel), none of these features, like temperature drop, are seen.

A total of 164 wind gust events (at 50 m) are segregated into convective and non-convective categories, based on the variation of concurrent meteorological parameters. Monthly variation of events associated with convection and other meso-scale flows (other than convection) is shown in Figure 1.7. The number of events associated with convective (118) is quite large compared to non-convective (46) events. In other words, about 72% of events are linked to convective activity. They are the outflows of convection either from overhead convection or those occurred in the vicinity of Gadanki.

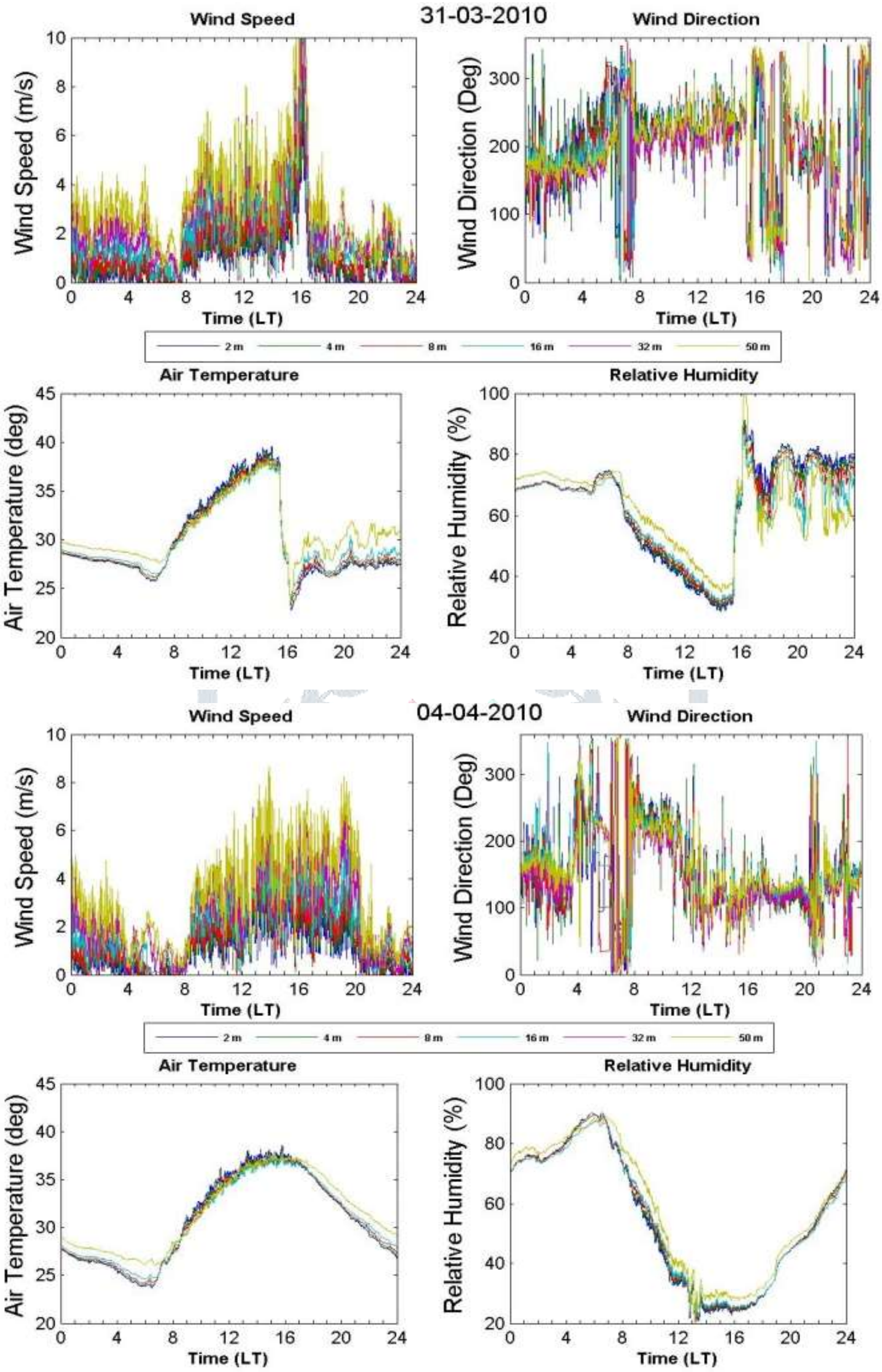


Figure 1.6: Diurnal variation of Wind speed and wind direction during (a) Thunderstorm (top) (b) Non-thunderstorm day (bottom).

The monthly variation of these events reveals that the number of convective gust events is always larger than non-convective events in all months, except for June. During June, both convective and non-convective gust events are nearly equal in number.

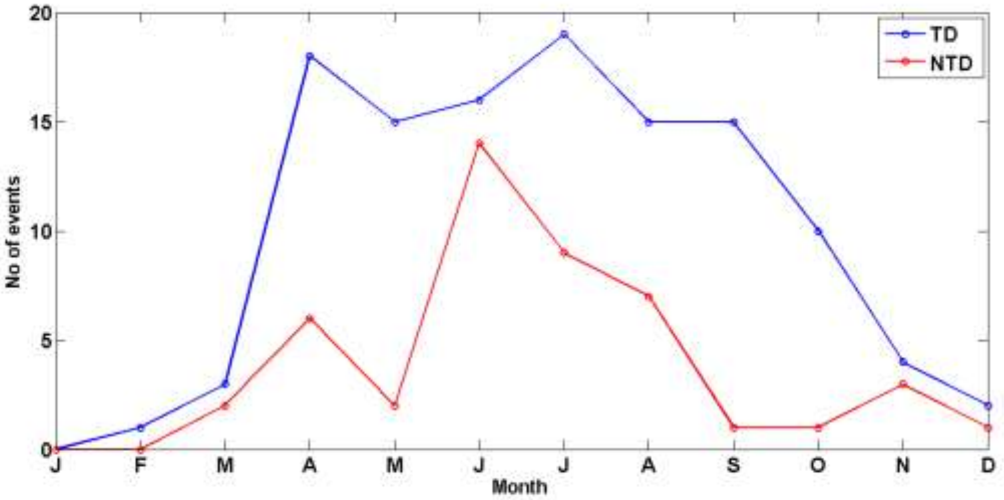


Figure 1.7: Monthly variation of number of convective (or thunderstorm days, TD) and non-convective (non-thunderstorm days, NTD) events.

5. CONCLUSIONS

Employing high-resolution wind measurements made over 2 years at different heights within the surface layer, gusts are characterized (in terms of their occurrence, duration, height variation, diurnal and seasonal variation) over a complex hilly terrain. The literature on wind gust is somewhat confusing. Some researchers consider maximum wind attained during an event as gust, while others look for a brief wind enhancement over a sustained wind. The present study follows the second approach. A 10th order polynomial fit was adopted to obtain the sustained find, as it fits well to the data without biasing the diurnal cycle and magnitude of wind gust. The important results obtained from the study are summarized below.

- ✓ The gust duration increases with height by a factor of 10 from 2m to 50 m, mainly due to the increase in number of events and duration within the event with height. The increase in events and duration is attributed to the lowering of surface friction at higher heights.
- ✓ The duration of gust shows a clear seasonal variation with a broad peak in hotter months of April-July. Though a broad peak is observed in total duration, the reason for longer duration is different for different months. While shorter duration events but large in number are responsible for longer total duration during June-July, a few longer duration events are more predominant during May. The convective storms are stronger and deeper during May and are primarily responsible for the longevity of wind gusts.
- ✓ The magnitude of wind gust shows a small variation with height (increases with height) and month (larger during hotter months). The event to event variability is also larger during hotter months, whereas the gust magnitudes are not only weaker but also exhibit lesser variability between the events during colder months.
- ✓ The diurnal variation of gust duration indicates that they appear more frequently in the noon – early night in all seasons. The sources for wind gusts, like thunderstorms and other mesoscale flows, occur more frequently during that period and are responsible for the observed diurnal variability. Though a broad maximum in duration is observed during the premonsoon and monsoon seasons, the peak occurs at different timings in those seasons. The peak in duration occurs in the evening during the premonsoon, while it occurs a few hours latter during the monsoon.
- ✓ Source apportionment has been done by segregating the events into convective and non-convective categories based on variability in the concurrent meteorological parameters. The analysis reveals that 72% of total gusts are due to convective activity at Gadanki or its vicinity.

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