Studies on Wind Characteristics of Thunderstorms

Edmund C C CHOI[1]

Abstract

Small scale (SS) weather systems, e.g. thunderstorm, squall and squall lines are common features of the weather in many places. However the wind characteristics of such systems, especially the low level characteristics at a few hundred metres above ground, are not well understood.

Studies of the wind characteristics of small scale weather systems are reported in the paper. Long term wind characteristics obtained from the analyses of long term wind records from the meteorological stations are presented.

Characteristics in the space and time domains, such as velocity profile, correlation and spectral functions of SS wind systems are studied. Data from two wind stations, one measuring to a height of 20m and the other to a height of 150m are analyzed. Case studies and some preliminary results are presented.

Introduction

Although thunderstorms and other SS weather events are common occurrence in many places, the study of their wind characteristics has not received as much attention as the large scale counter parts. This is partly due to the fact that, in many regions, winds from the larger weather system such as the monsoon, cyclone and typhoon are stronger and more critical to wind loading design. The other reason is the difficulty in tracking down and obtain data for the SS event.

Singapore is situated in the equatorial belt at around 1° north of the equator. There are two monsoon seasons, the north-east monsoon from December to March and the south-west monsoon from June to September. During the inter-monsoon periods, there are frequent occurrences of tropical thunderstorms. Over an area of about 40km by 20Km, there are more than 200 thunderstorms in a year. This makes Singapore an ideal place for the study of SS weather systems.

Extreme wind studies

Studies on extreme wind are carried out using wind data from meteorological stations. The hourly mean wind, 10-minute mean and the 3-second gust speed from Changi (CG) and Tengah (TG) meteorological stations are analyzed. Both stations are located in airfields. While Changi is a big international airport on the eastern side of Singapore Island, Tengah is a smaller airfield towards the western side. The distance from one to the other is no more than 40km. Locations of the two stations are shown in Figure 1.

The data are sorted into large scale (LS) and small scale wind events by looking at the weather report, radar picture, continuous wind record and weather charts. Small scale events such as thunderstorms, heavy rain storms (no thunder heard), or squalls are identified by a sudden sharp change in wind speed (and often also a sudden change in direction) for only a short duration. Classification into SS event instead of thunderstorm has the advantage of including events lasting for a short period but no thunder has been reported. Extreme distributions of the hourly, 10-minute mean winds and the gust speed for Changi (CG) are shown in Figures 2a to 2c. Those for Tengah (TG) are shown in Figures 3a to 3c. The Harris[1] modified BLUE method fitting to v^2 was used in the analysis.

[1] *Professor, School of Civil and Structural Engg., Nanyang Technological University, Nanyang Ave., SINGAPORE*

It is observed that the SS curves are higher than the LS curves for all cases except the Changi hourly mean where the LS curve is higher than the SS curve. This shows that the dominating winds are generated from the small scale events (except Changi hourly). The 3-second gust and the 10-minute mean for SS events are all having higher values than the LS events.

From the figures, the gust factors calculated using the 50-yr return 3-second gust divided by the hourly mean and divided by the 10-minute mean for LS and SS events for the two stations are given as follows.

Gust factor based on hourly mean:

Changi:	LS = 1.95	SS = 2.76
Tengah:	LS = 2.24	SS = 3.12

Gust factor based on 10-minute mean:

Changi:	LS = 1.58	SS = 1.80
Tengah:	LS = 1.64	SS = 1.95

The values for SS, especially those of TG are much higher than the normal values expected for an open air field terrain. This shows that the wind structure of SS events are different from that of the LS events which can normally be described by the boundary layer type of flow.

Tropical thunderstorms

Thunderstorms are common occurrence around the world. There are nearly 2000 thunderstorms in progress at any time over the earth's surface. Every thunderstorm is produced by a cumulonimbus cloud and is always accompanied by lightning and thunder. Although its occurrence is worldwide, the frequency of thunderstorm occurrence varies greatly in different areas. Most thunderstorms are found in tropical regions. A thunderstorm usually lasts no more than one hour and it begins when a parcel of air, either warmer than the surrounding or being pushed up by colder encroaching air such as a cold front, begins to rise. This unstable updraught forms the embryo of the thunderstorm. If the rising air is sufficiently moist, condensation will occur to form cloud droplets. A large amount of moisture condenses and precipitation particles begin to grow as the cell continues to build up. The latent heat released during condensation adds buoyancy to the vapour. The rising air stream form an updraft that is strong enough to keep the water droplets and ice crystals suspended in the clouds. The continuous release of latent heat supplies energy to the system and further accelerates the updraught. At this stage the updraught may have speeds of say 5m/s to 10m/s and sometimes as high as 20-30m/s. As precipitation gathers momentum, the frictional drag induces downdraught. During the mature stage of the thunderstorm, downdraught intensifies. This is the most active period of a thunderstorm with gusty winds and heavy precipitation. The leading edge of the cold air resulting from the downdraft is called the gust front. The gust front is characterized by an abrupt change of temperature, wind speed, and an increased in pressure In severe thunderstorms, the strong downdraft develops into a downburst, which diverges horizontally as an outburst of destructive winds upon reaching the ground. The gust front usually moves ahead of the thunderstorm. Unlike the monsoon wind or even the typhoon wind where the wind moves in the horizontal direction over a substantial stretch of ground, winds from thunderstorm rush vertically down and spread outwards (Figure 4). Thus, the ground roughness has little effect on the wind. The wind characteristics of thunderstorm wind, e.g. the mean wind profile, gust profile, gust factor and turbulence intensity, are expected to be quite different from those of the monsoon winds.

Downburst

Fujita (1985) defined a downburst as "a strong downdraft which induces an outburst of damaging winds on or near the ground". The sizes of downbursts vary from several hundreds of meters to tens of kilometer. The downburst is further sub-divided into macroburst and microburst, depending on their horizontal scale of damaging winds. A macroburst covers an area of more than 4km and its duration usually lasts from 5 to 30 minutes. The damaging winds that could arise are as high as 60m/s. A microburst affects an area less than 4 km and with a duration of less than 10 minutes. The winds associated from the outflows of a microburst are as high as 75m/s.

Case studies

Wind data are obtained from a wind and rain measuring station inside the campus of the University (NTU). The site is about 40m square and located on a small piece of flat land. Towards its west and north is the open space of the sports field. Towards its south, it is also quite open with the land gently sloping downwards and with the general terrain slightly below the site. Towards its east, immediately it is quite open but further upstream there are groups of 12-storey high residential buildings. There are some trees in the northeasterly direction. Wind speeds are measured at five levels using sensitive cup-type anemometers mounted on a 20 metre tall mast at the center of the site. Wind direction sensors are also installed at three levels.

Event 010522:

On the 22nd May 2001, a strong thunderstorm event was recorded by the station. The highest gust speed at 10m was 23.1m/s. Comparing to the extreme gust distributions, this translated to a return period of about 10 years for CG or 5 years for TG.

Close to the wind station, extensive destruction of trees was observed. Many trees were up-rooted and many more were broken at the main trunk immediately above ground level. The path of destruction was observed to be quite narrow, no more than about 50 metre and it ran along a slight curve in the NNW-SSE direction. This line of destruction was no more than one kilometer long. Most of the trees had fallen towards the ENE to ESE directions indicating strong winds were from the western sector. Figure 5 is a photo of the fallen trees.

The highest gust was recorded by the wind station at 11:58:48am. Radar picture just before the highest gust is shown in Figures 6 which was captured at 11:41. It can be seen that the hard echo was directly above the western end of Singapore where the NTU wind station was located.

Plots of wind speed and wind direction are presented in Figures 7a, b and c showing the ½-min mean, gust and direction respectively. High speed recording was triggered at 11:53:18. At that time the 10m, ½-min mean speed was about 5m/s and a gust speed of 8.3m/s. In the next six minutes there was steady increase in wind speed reaching the peak with a mean of 12.3m/s and a gust of 23.1m/s. The next two minutes saw a drastic drop in wind speed with mean dropping to 6m/s and gust to 8m/s. After which there were some severe fluctuations of the wind speed but generally on a decreasing trend. Both mean and gust wind speeds dropped to a very low value at 12:13 and hence onwards they fluctuated around the low value of 2 – 3m/s (other than a small low peak at 12:19). This indicated that, after triggering, the event was all over in less than 20 minutes with the really high wind occurring in only 2 to 3 minutes.

The general wind direction during these 20 minutes was from the northwest. It was also noted that rainfall was first recorded at 12:04 which was about 5 to 6 minutes after the peak gust. This again showed that the gust front moved ahead of the rainfall.

The gust factor calculated using the peak gust and the hourly mean at 10m level gave a very high value of 7.49. Looking at the plots of the wind speed, using the hourly mean as the base probably would not be correct, as the event lasted no more than 20 minutes. Using the peak gust and the highest 10-minute mean at which the peak gust occurred, a gust factor of 2.67 was obtained. This value was much higher than what would be expected of the 10-min gust factor for a sub-urban terrain.

Figures 8a and 8b show the variation with height of the ½-minute mean and the gust speed. From the mean speed profile, it can be observed that before the highest wind, as the wind progressively gets stronger the profiles show the boundary layer type of profile with increasing speed with height. After the highest wind, wind speeds drop quite suddenly. The profiles are more vertical showing less increase of wind speed with height. The gust profile show the same pattern of variations. Another observation is that, during the strongest wind, the gust speeds at 10m, 15m and 20m levels are more less the same. In fact the highest gust speed is at the 15m level and not at the highest level.

During the occasion, the highest gust speeds recorded by the meteorological stations elsewhere in Singapore are given as follows.

Station	Gust speed (m/s)	Wind Direction (degree)
TG	13.4	270
CG	12.4	250
SL	9.3	300
PL	12.9	270

It is interesting to note that TG which is only about 4 km from NTU wind station, recorded a gust speed of only 13.4 m/s. This is only about half that of the value recorded at NTU. This shows that this event, although producing significantly high wind speeds, was very small in size and local in extent.

Case 010222

On 22 February 2000 a thunderstorm event was recorded starting from 14:55:31. The records consist of five 375-seconds time series data that are almost continues within the storm period of an hour. A sequence of radar pictures (Figures 9(a) to 9(c)) shows the development and the movement of the cells during this event. Although there were several cells occurred during this event, at the time of wind recording, it was likely that the wind was the result of the cell directly above NTU. Therefore, this event was interpreted as the effect of a single-cell storm. The radar picture in Figure 9(a) was obtained at 14:33:26 that was before the recording system hit by strong wind. The variations of wind speeds and wind directions with time during this event were shown in Figure 10(a) and the rain intensity shown in Figure 10(b). The rain was recorded at about 5 minutes (15:00:00) after the strong wind hitting the sensors. Therefore, the wind produced during the first record (14:55:31 to 15:01:46) may be interpreted as a gust front (GF) wind. The duration of this gust front wind lasted only a few minutes after which the precipitation hit the station. There after, the remaining wind records were called the outflow (OF). As there were four outflow records, they were called OF-1, OF-2, OF-3, and OF-4. Basically, both the gust front and the outflow winds were the horizontal wind produced by the downdraft after striking the ground. To the observer at a fixed point in space, the first one was experienced before the precipitation and the later was observed after the precipitation hit the sensor. From the radar pictures, the high rainfall intensity (hatch area) could be observed to move passing through the station which was reflected in the rain intensity record. Between 15:10:00 and 15:20:00, the rainfall intensity was gradually increasing. During this time stronger gusts were also observed (OF-2 and OF-3). Although there were fluctuations in the wind directions, the average wind direction during this event was from the west.

Figure 11 shows the normalized spectrum $S(n)/\sigma_u^2$ curves for this event. The curve for non-thunderstorm (NTS) events with the same wind direction is also presented for comparison. It is observed that at the high frequency range of 0.07Hz to 0.5Hz, the energy for TS event during the most intense period is generally several times higher than that of NTS event. This most intense period is OF-3 which was characterized by the heaviest rainfall and might be associated with the strong downdraft. During the passage of the gust front, the $S(n)/\sigma_u^2$ was lower than those of NTS event at most portions. At other stages of the thunderstorm, the $S(n)/\sigma_u^2$ curves within that frequency ranges were comparable with those of NTS event. This phenomenon has also been observed for other thunderstorm events.

Measurements at Tuas Tower

A more comprehensive wind research station was set-up close to the western tip of Singapore (TUAS). The station was within 1km from the coastline towards its west. Five levels of anemometers (35m,)were mounted on a 150 metre tall tower. Three-component ultrasonic high frequency anemometers were used to measure the horizontal as well as vertical wind speeds. At the same five levels, temperature and humidity sensors were also installed. Barometric pressure and rainfall are measured close to the ground. From this wind station, horizontal and vertical wind speeds, wind direction, temperature and humidity, barometric pressure and rainfall are monitored at 100Hz. For normal conditions, the 10-minute statistics (mean, maximum, minimum and standard deviation) are recorded. During high wind conditions, the raw data are also recorded.

Figure 12 shows a typical plot of a thunderstorm event. There was quite a sudden increase in wind speed over a short duration and a sudden change in wind direction. The temperature sensors also recorded a sudden drop in temperature whereas the humidity sensors recorded a gradual increase in humidity. Rainfall was recorded starting at the time at which the change of temperature occurred.

Figure 13 shows plots of the 10-minute mean velocity profile, turbulent intensity profile, gust factor and longitudinal length scale for the 10 minutes of the high wind period.

Discussion and conclusion

Some wind characteristics of thunderstorms are presented in the paper. It is observed that such weather systems, although their size can be very small and their effects very local, can produce significantly high wind speeds. Winds generated from such weather systems can be very turbulent resulting in high turbulent intensities and very high gust factors. The energy components at the frequency range of 0.07 Hz to 0.5 Hz are found to be higher than the large scale wind.

References

1) Choi, E.C.C. (1999). "Extreme wind characteristics over Singapore – an area in the equatorial belt" J. Wind Eng. Ind. Aerodyn., vol. 83, 61-69.
2) Harris, R.I. (1996). "Gumbel re-visited – a new look at extreme value statistics applied to wind speeds" J. Wind Eng. Ind. Aerodyn., vol. 59, 1-22.
3) Fujita, T.T. (1985), "The Downburst – Microburst and Macroburst", Report of Project NIMROD and JAWS.SMRP, University of Chicago, Chicago.
4) Twisdale, L.A. and Vickery, P.J. (1992), "Reasearch on Thunderstorm Wind Design Parameters," Journal of Wind Engineering and Industrial Aerodynamics, No.41-44, pp 545-556.
5) Wallace, J.M., and Hobbs, P.V., (1977), Atmospheric Science – An Introductory Survey, Academic Press Inc., New York.

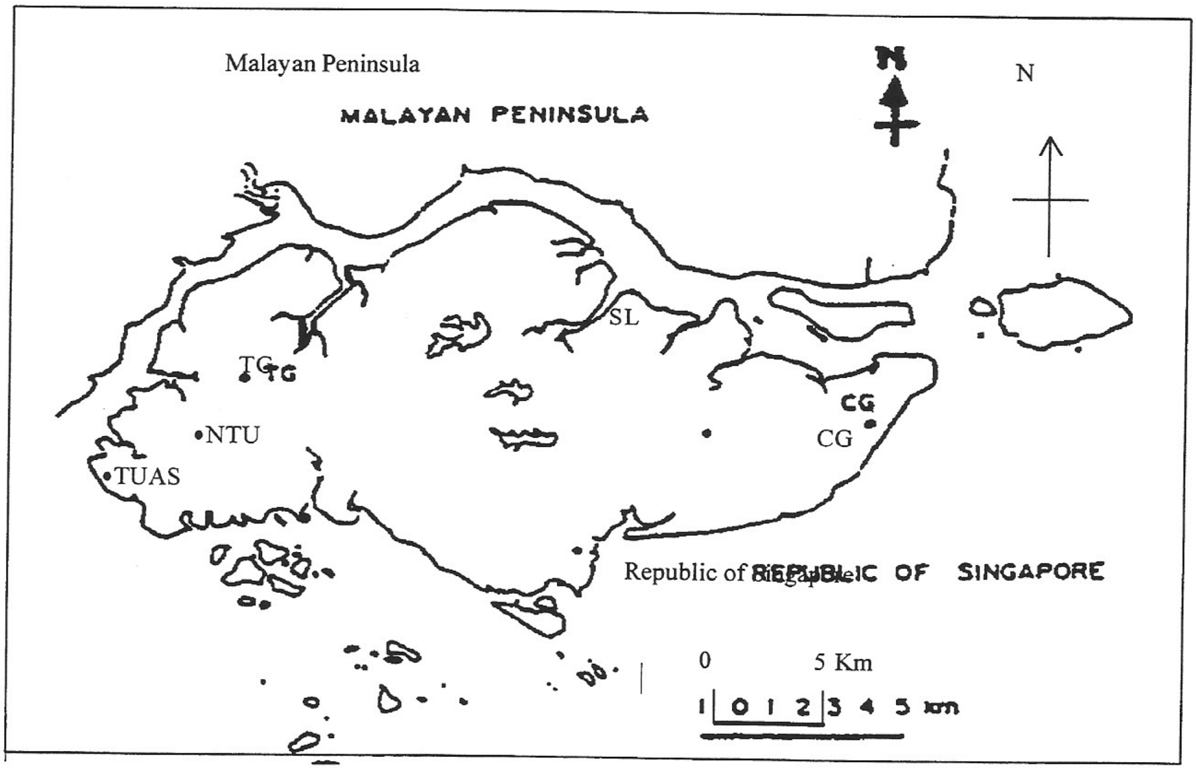


Figure 1. The Location of Changi and Tengah Meteorological Stations.

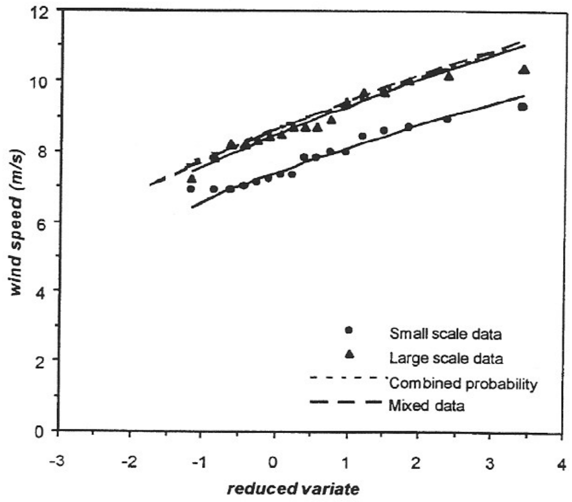


Figure 2a Hourly mean wind for Changi

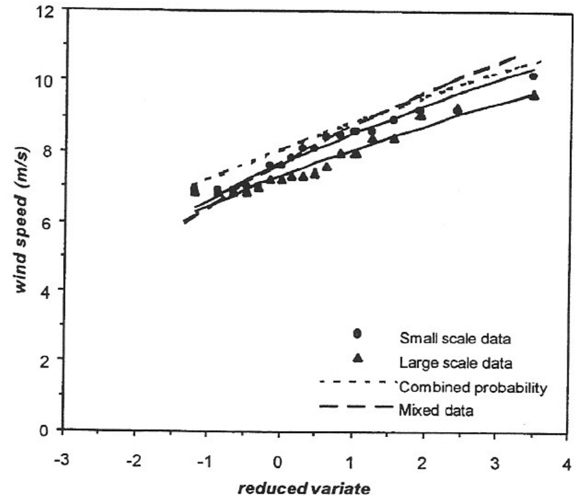


Figure 3a Hourly mean wind for Tengah

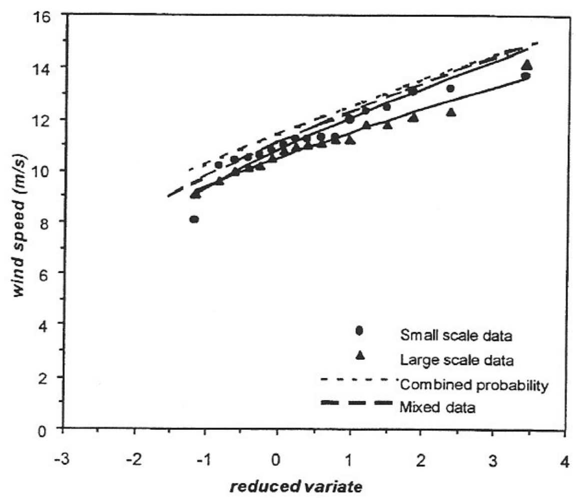


Figure 2b 10-minute mean wind for Changi

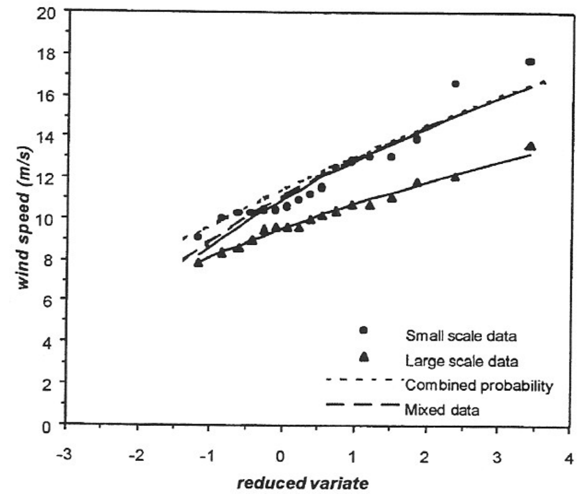


Figure 3b 10-minute mean wind for Tengah

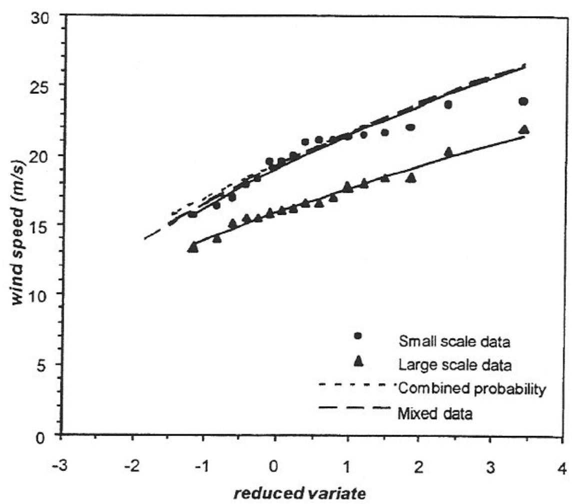


Figure 2c 3-second gust speed for Changi

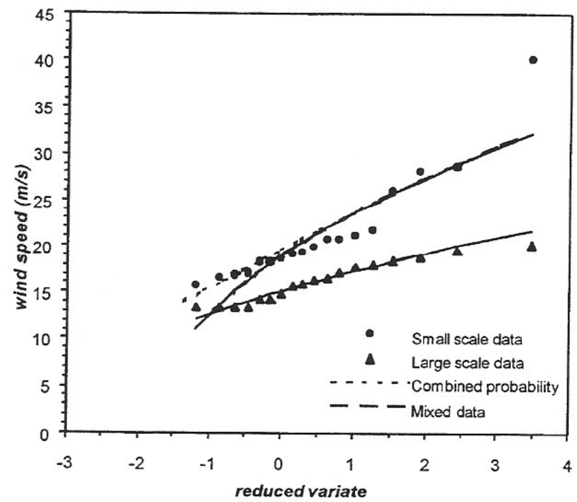


Figure 3c 3-second gust speed for Tengah

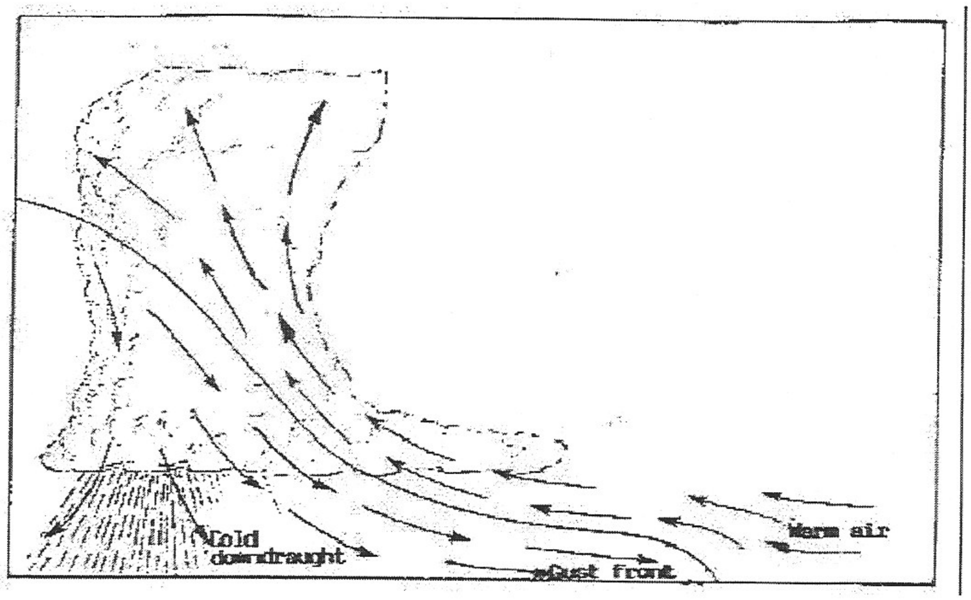


Figure 4 Schematic diagram of a thunderstorm

Figure 5 Fallen trees on 22 May 2001

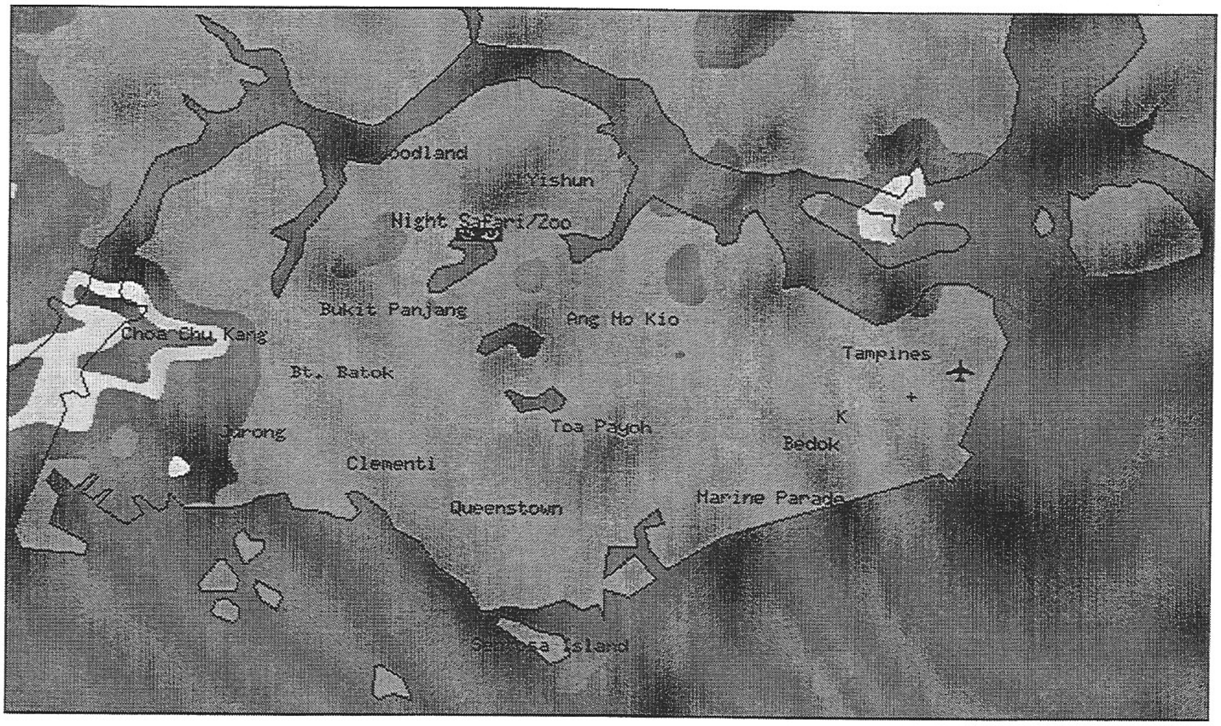
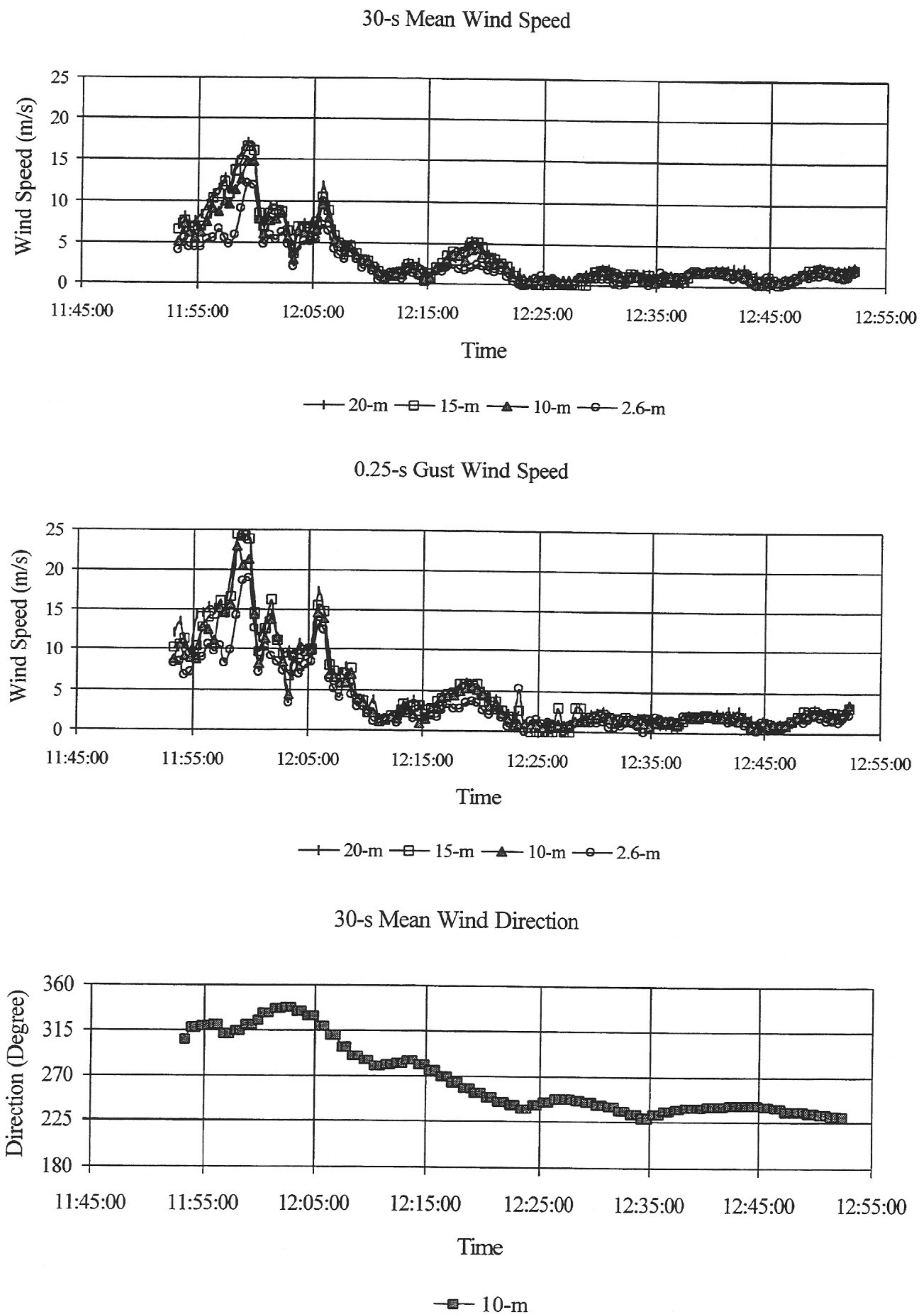
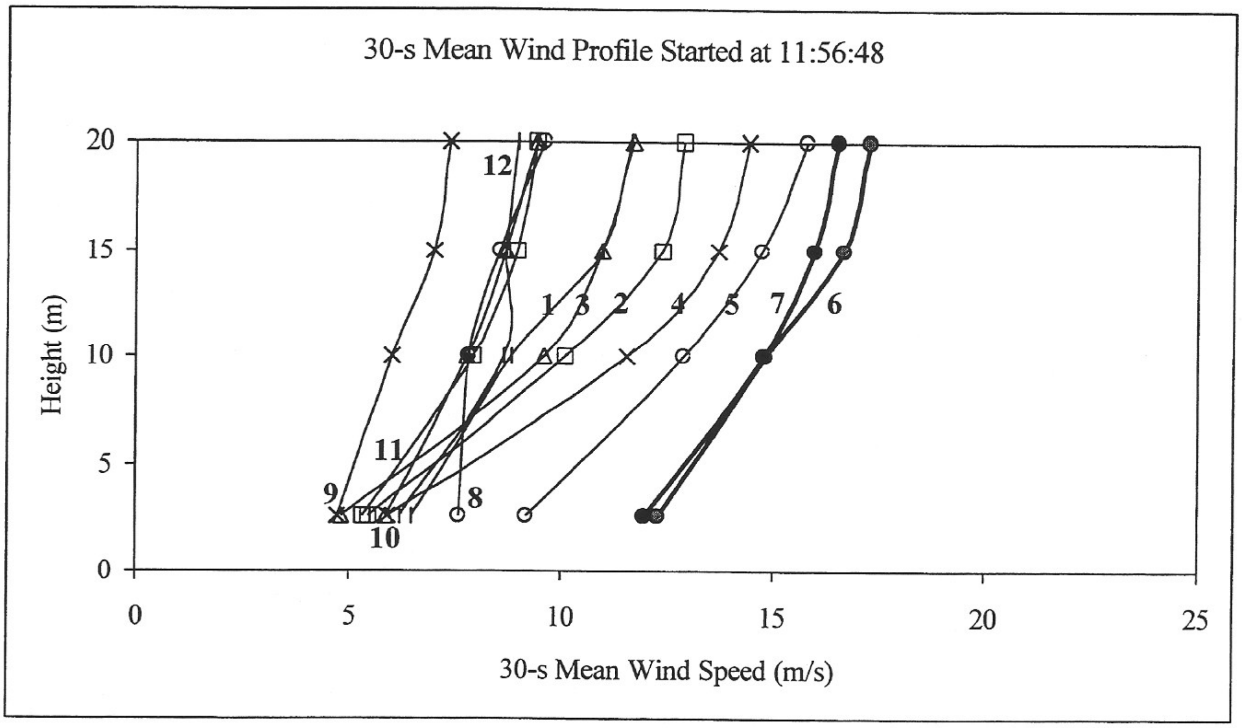
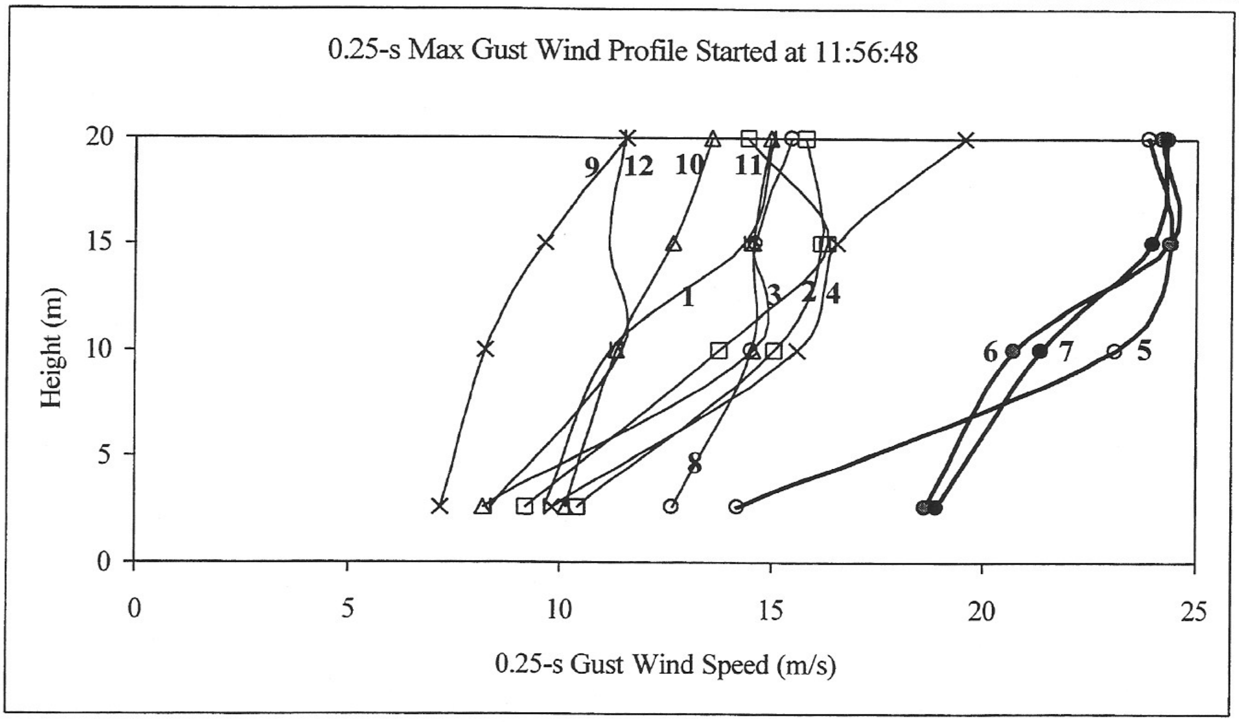


Figure 6 Radar picture at 22/05/01 11:41



Figures 7a, 7b and 7c ½ -minute mean speed, gust speed and mean direction





Figures 8a & 8b ½ -minute mean and gust velocity profiles

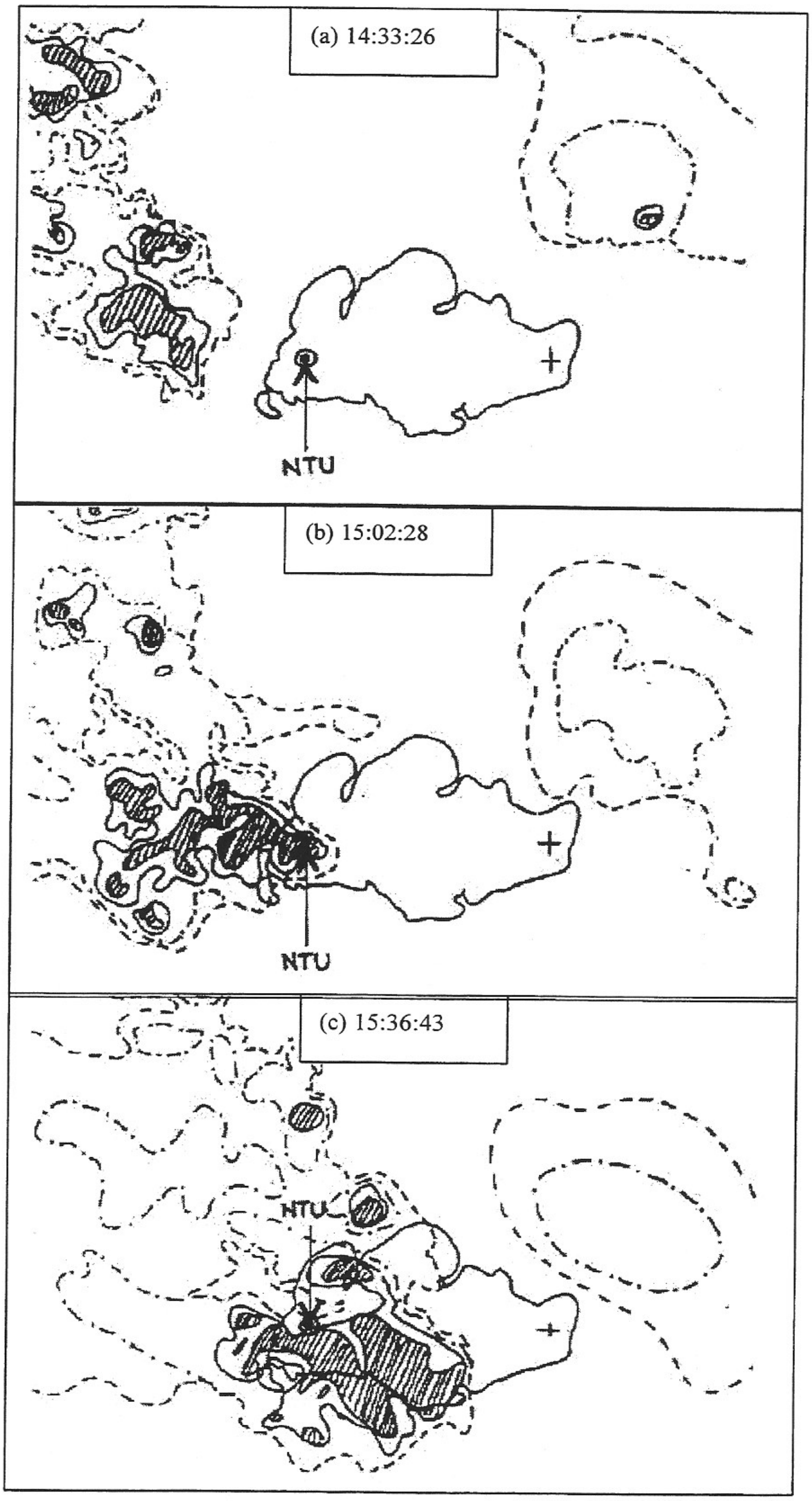
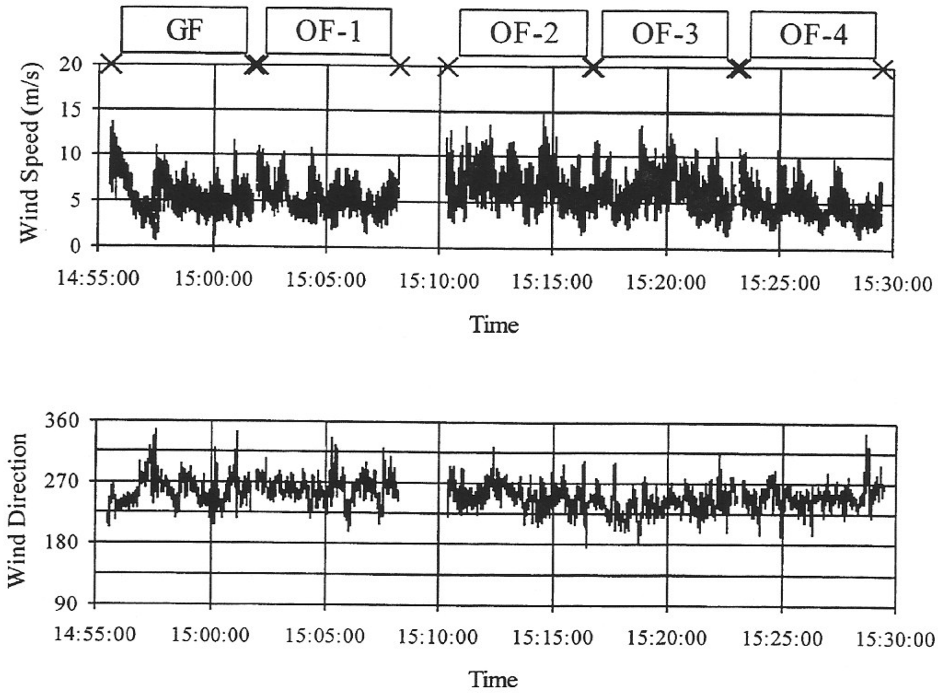
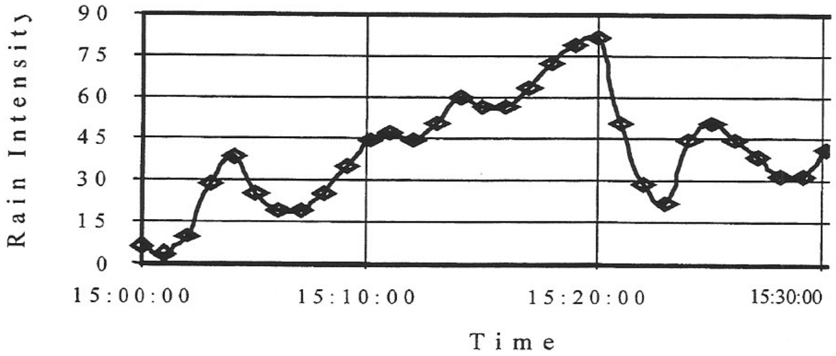


Figure 9. The Evolution and Movement of Thunderstorm Cells Observed by Radar for TS222 event (Hatch: > 40mm/hr, ——: 4 to 40 mm/hr, -·-·-·- : 1 to 4 mm/hr, ----: < 1 mm/hr)



(a) Wind speed and wind direction time-series.



(b) Rainfall intensity.

Figure 10. Variation of wind speed and rainfall intensity during thunderstorm event on 22 February 2000.

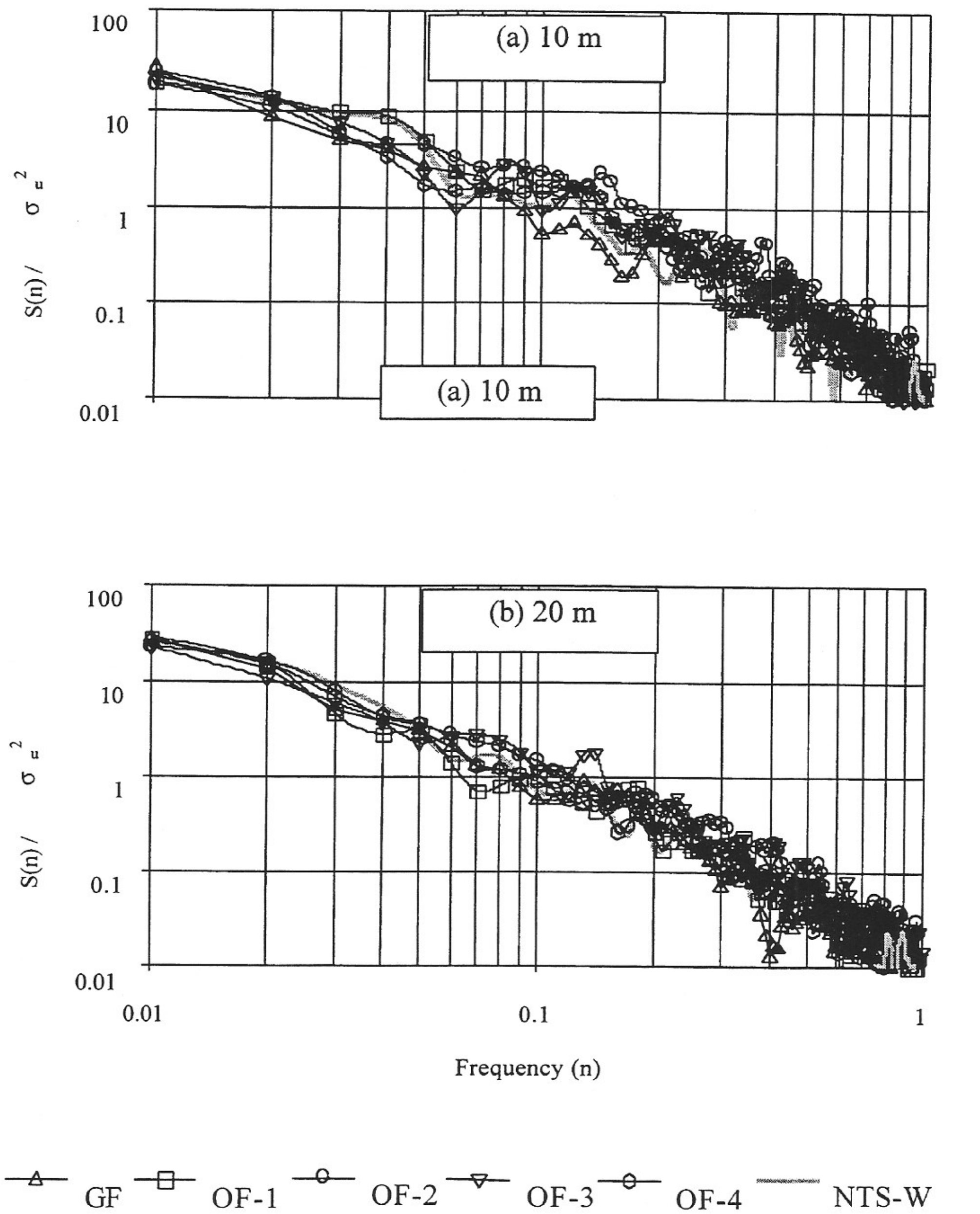


Figure 11. Auto-Spectral Functions during NTS and TS222 events at:
(a) 10 m height (b) 20 m height

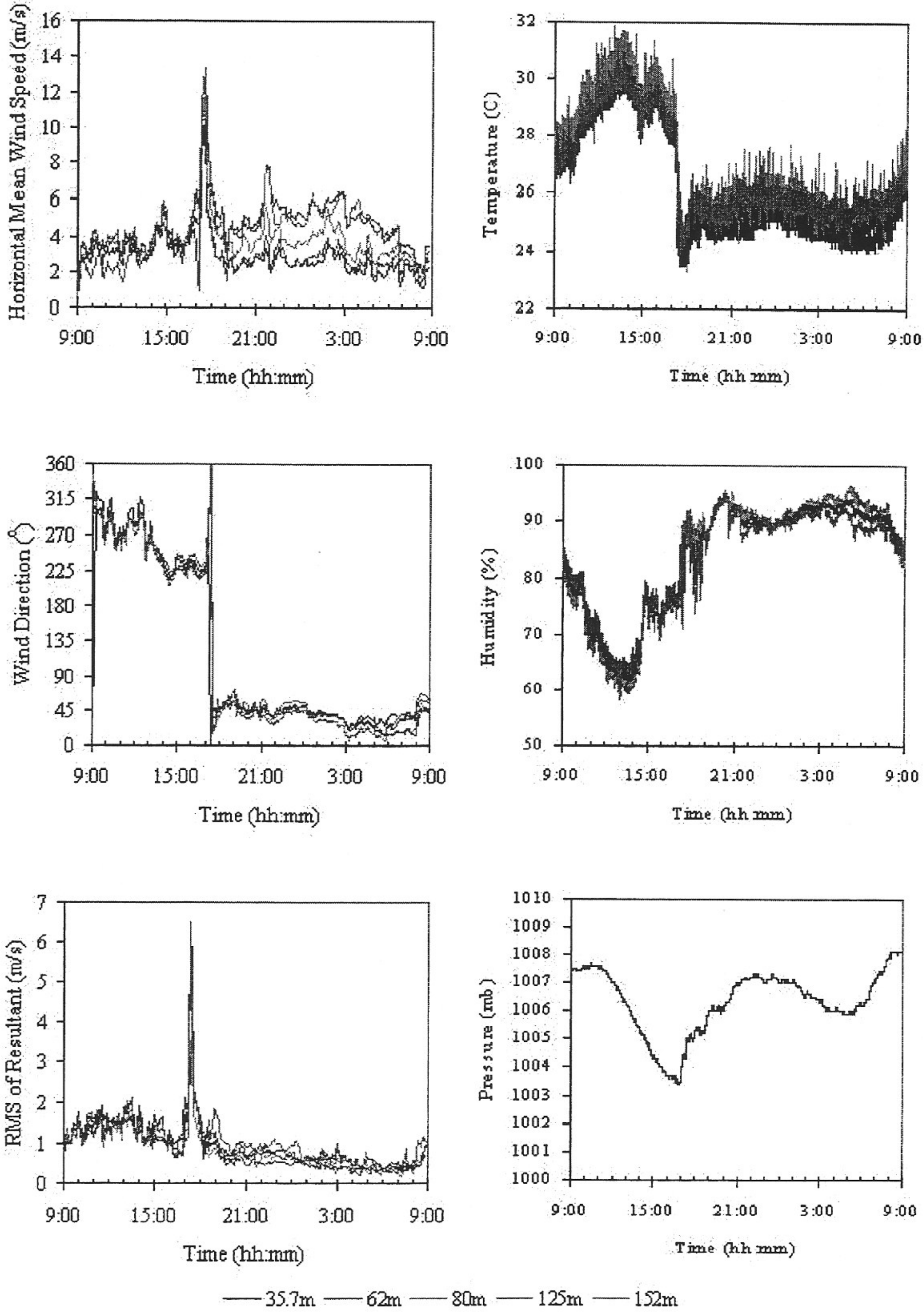


Figure 12 Recordings from the TUAS wind station at 10/12/00

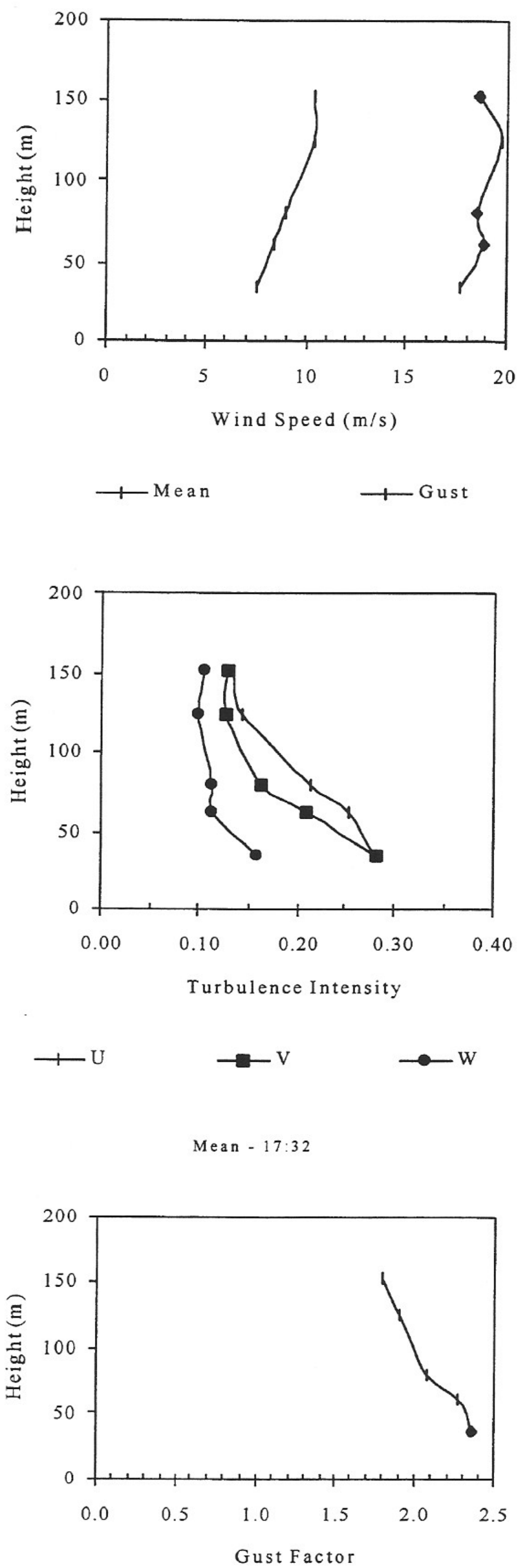


Figure 13a, 13b and 13c Mean and gust profile, turbulent intensity profile and gust factor for the highest 10-minute wind of 10/12/00