WEATHER CONDITIONS AT THE POTENTIAL MMA SITE ON MAUNA KEA

Peter J. Napier
NRAO, Socorro
April, 1994

1. INTRODUCTION

In order to design the Millimeter Array (MMA) it will be necessary to have information concerning the meteorological environment on the site. For example, the antennas, phase stable cable systems and heating, ventilation and air conditioning (HVAC) systems must operate correctly over the range of ambient temperature and rate-of-change of temperature experienced on the site. Statistics on wind speed are important in designing the antenna pointing systems and wind direction could be of interest if turbulence from up-wind peaks degrades phase stability. Precipitation information is useful for designing such things as weatherproofing for exposed equipment, site drainage and snow removal requirements.

The potential Millimeter Array (MMA) site on Mt. Mauna Kea on the island of Hawaii is on a sloping plateau on the southeast side of the mountain at an elevation of 3750 m (Holdaway, 1994). Although the weather conditions around the 4200 m summit have been documented (Morrison, 1973), the meteorological conditions at the lower, less exposed site need to be measured. Since the VLBA station on Mauna Kea is located at an elevation of 3720 m, within a few hundred meters horizontally of the MMA site (see Figure 1) the data recorded by the VLBA weather station can be used for this purpose. The VLBA weather station completed its first full year of monitoring on 1 March, 1994. In this report we examine this data and use a severe weather log maintained by the VLBA-MK site technicians to make a first effort at quantifying the weather conditions at the MMA site.

2. THE MEASUREMENTS

The VLBA weather station monitors the seven meteorological quantities shown in Table 1. For the data base reported here all data were sampled and logged into the VLBA monitor database every 512 sec. The raw 512 sec interval data records were processed as follows. Records in which one or more of the seven monitor points were flagged as being of suspect quality by the VLBA monitor and control system were deleted. The remaining data were then binned into 1 hour intervals. 1 hour bins containing less than three 512 sec records, either because records had been deleted or because the VLBA monitor network was out of operation, were deleted. After this editing process 8130 out of the total

8760 (93%) hours in the one year period 3/1/93 - 2/28/94 remained in the data base. 339 out of the 365 (93%) days in the year are represented in the data base. For each one hour period the value reported here is the median value of the 512 second samples in the one hour bin for temperature, dew point, pressure and wind speed. Wind direction selected was that value of wind direction measured at the same time as the median wind sample. For wind peak and precipitation the value reported is the peak value measured during the one hour period. All graphs and distributions were calculated using Lotus 123.

Meteorological Quantity	Sensor Accuracy
Ambient temperature	0.5 °C
Dew point	0.5 °C
Barometric Pressure	0.7 mBar
Wind speed (at sample time)	1%
Wind peak (since previous sample time)	2%
Wind direction (at sample time)	5°
Precipitation (cumulative, reset to zero at UT 24:00, heated to melt snow and ice)	1 mm

Table 1. Meteorological Data Measured by the VLBA Weather Station. Precipitation and pressure are measured at ground level. All other measurements are made at the top of a 10 m tower.

3. TEMPERATURE

A plot of all 8130 hourly median ambient temperatures is shown in Figure 2. The relatively small annual and diurnal temperature variations typical of a tropical island location can be seen in Figure 2. Figure 3 shows the probability distribution for the data in Figure 2. To show how temperature varies diurnally, for each hour of the day Figure 4 shows the temperature averaged over all 339 days. An estimate of rate of change of temperature can be obtained by taking the difference between temperature samples adjacent in time. Figure 5 shows the distribution of rates of change of temperature computed in this way. The principal temperature statistics are shown in Table 2. Note that the average and range of temperatures reported here are in good agreement with long term temperature versus elevation data for Hawaii (pg 64, Armstrong 1983), so it is reasonable to assume that this one year data sample of temperatures is typical for the site.

Average Temperature	6.0 C
Minimum Recorded Temperature	-5.1 C
Maximum Recorded Temperature	16.4 C
Average Diurnal Variation	5 C
Fraction of Time Below Freezing	1.4 %
Maximum Recorded Rate of Temp Change	5.7 C/hr
75,95 Percentile Rate of Temp Change	0.9, 1.9 C/hr

Table 2. Temperature statistics for MK VLBA site, 3/1/93-2/28/94.

4. DEW POINT

The probability of condensation or precipitation increases as the difference between ambient temperature and dewpoint decreases. In Figure 6 we plot all 8130 values of the quantity (hourly median ambient temperature - hourly median dewpoint) and Figure 7 shows the distribution of this data. Figure 7 shows that the site is very dry with ambient temperature being more than 1°C above the dewpoint 96% of the time. Figure 4 shows the average diurnal variation of dewpoint.

5. PRESSURE

Figure 8 is a plot of all 8130 values of barometric pressure versus time. The average pressure is 654 mBar (65% of sea level pressure). Figure 9 shows for each hour of the day the pressure averaged over all 339 days. The 1.5 mBar peak-to-peak sinusoidal variation with a 12 hour period, seen in Figure 9, is the signature of a solar thermally driven atmospheric tide (Lindzen, 1990).

6. WIND

Plots versus time of all 8130 values of hourly median wind speed and hourly peak wind speed are shown in Figures 10 and 11. Cumulative probability distributions for hourly median wind speed and hourly peak wind speed are shown in Figures 12 and 13. Wind statistics are summarized in Table 3. Average diurnal variation of wind is shown in Figure 9. Information on wind direction is given in Figure 14 where each of the 8130 hourly median wind measurements is plotted resolved into its E-W and N-S components (note that the direction recorded and plotted is the direction the wind is blowing FROM). The direction of the dominant wind in Hawaii, the Trade Winds out of the Northeast, do not stand out particularly clearly in Figure 14, presumably because other wind patterns are also significant. Other wind directions to be expected at this site are (pg 65, Armstrong

Quantity	Hourly Median Wind	Hourly Peak Wind
50th Percentile	4.1 m/s	7.2 m/s
75th Percentile	5.9 m/s	9.5 m/s
95th Percentile	8.8 m/s	13.5 m/s
Maximum Value	19.6 m/s	26.8 m/s

Table 3. Wind statistics for MK VLBA site, 3/1/93-2/28/94.

1883): when the tradewinds are absent and there are no storms or fronts the winds will be upslope-downslope which is SE-NW at this location; in the winter a Kona storm will bring southerly winds; in the winter a cold front will be preceded by SW winds and followed by northerly winds. The tradewinds and other dominant wind directions can be seen more clearly in the wind direction probability distributions shown in Figures 15,16,17. The wind direction data in Figures 15-17 are not weighted by wind speed. Wind direction 0° is wind from the north and direction 90° is wind from the east.

The peak recorded wind of 27 m/s (60 mph) is not a suitable specification for structure survival because of the limited one year record and because Hawaii can be hit by hurricanes (although the last tropical storm to hit the Big Island was in 1957, pg 61 Armstrong 1983). The specifications of other structures on the mountain may provide a better guideline. The wind speed at which structural members of the VLBA antenna theoretically reach failure load is 70 m/s (157 mph) at this elevation. This specification was not determined particularly for Mauna Kea but is simply the extrapolation of the sea-level VLBA survival wind of 127 mph (Hvatum, 1986) to the higher elevation. Winds as high as 150 mph have actually been recorded at UKIRT and CFHT on the summit (R. McLaren, UH, private communication, 1994). Structures higher on the mountain use the following survival winds: Keck 145 mph, CFHT 200 mph, SMA 150 mph, Gemini 150 mph.

There is a possibility that both the wind speed and wind direction reported here are influenced by the local terrain in the vicinity of the VLBA weather station and, therefore, are not completely typical of the winds out on the more open MMA site. The local terrain is shown in Figure 1 and is dominated by the VLBA antenna 25 m to the SSE, and volcanic cones in directions S, NW and NNW , at distances of 340 m, 400 m and 960 m respectively and heights above the VLBA site of 60 m, 110 m and 220 m.

7. PRECIPITATION

A plot of daily cumulative precipitation vs time is shown in Figure 18. Most of the precipitation occurs in infrequent, but relatively heavy, storms. The site can occasionally experience extremely heavy driving rain as demonstrated by the 24 July 93 storm which is detailed in Figure 19. During this storm 12.5 cm of rain fell in a period of about 8 hours while the wind was blowing at more than 15 m/s. The peak rain rate during this storm, determined as the steepest slope on the cumulative rainfall plot in Figure 19, is 6.3 cm/hr. This storm washed out the MKO access road at an elevation of 3350 m and trapped the VLBA technicians on the mountain (see Appendix A). This high rainfall rate combined with the high wind speed will require careful design of MMA weatherproofing enclosures. Precipitation statistics are summarized in Table 4. Note that the total annual precipitation for the year is somewhat more than the 51 cm predicted for the site from long term annual rainfall contours for the island (pg 63, Armstrong 1983). Also, the storms were more spasmodic and more intense than usual (Schnell, 1994).

It is encouraging to note that lightning does not appear to be a major threat at the site. There was no lightning damage at the VLBA site and the site technicians did not observe a lightning strike in the vicinity during the year.

Total annual precipitation	62.3 cm
Fraction of total in summer (May-Oct)	48%
Fraction of total in winter (Nov-Apr)	52%
Fraction of days with no precipitation	88%
Fraction of hours with no precipitation	96%
Maximum daily rainfall	12.8 cm
Maximum instantaneous rain rate	6.3 cm/hr

Table 4. Precipitation statistics for VLBA-MK, 3/1/93-2/28/94.

8. WINTER STORMS

To aid in quantifying the bad weather conditions likely to be experienced by the MMA on this site the VLBA site technicians maintain a Severe Weather Log which is reproduced as Appendix A. From this log it can be seen that during the year 5 winter storms occurred, with some of the precipitation in the form of snow and/or ice, on 15 Mar 93, 19 Dec 93, 24 Jan 94, 9-10 Feb 94 and 14-16 Feb 94. Some statistics concerning snow and ice, determined from the log, are given in Table 5. These numbers can only be considered as rough guidelines because of the small number of events. During the storm of 14 Mar 93 5 cm of ice formed on the upwind surfaces of the antenna and other structures. Some of this ice fell from the antenna quadruped guy rods and damaged the dichroic plate at the antenna secondary focus (Figure 20).

Although it is not within the one year data base reported here, the ice storm of 6 Jan 93 will be included because of its severity. During this storm ice up to 12 cm thick formed on all upwind surfaces (Figures 21-24) and ice falling from the quadruped damaged 17 antenna reflector panels, necessitating their replacement. The mechanism of ice formation during these ice storms is identical to the mechanism which causes ice formation on aircraft wings (Schnell, 1994). Supercooled liquid water is carried by the wind onto the structure where it instantly turns to ice on impact. Little information on wind during these ice storms is available because the anemometer usually freezes solid. It is clear that the wind comes out of the SW and W. During the winter storm of 14-16 Feb 94 the wind averaged 14 m/s for sustained periods and had peaks over 20 m/s. A good strategy for the MMA antennas would be to design them to take their survival wind pointing at the horizon. During winter storms they could then be oriented with their backs to the SW so that the ice is kept off of the main reflector surface and the subreflector.

Number of winter storms	5
Number (fraction) of days in winter storm conditions	8 (2%)
Median snowfall during a winter storm	10 cm
Maximum snowfall during a winter storm	20 cm
Ratio of VLBA-MK snowfall to MK-Summit snowfall	25%
Typical ice buildup during ice storm	5 cm
Maximum ice buildup during ice storm	12 cm

Table 5. Winter storm statistics for VLBA-MK, 3/1/93-2/28/94.

9. CONCLUSIONS

Considering its very high altitude, the weather on the Mauna Kea site is, in general, quite moderate. The average diurnal temperature variation of 5 °C and lowest temperature of -5 °C will ease the thermal design of the instrument. The 95th percentile wind of 9 m/s (20 mph) is reasonable for precision pointing of the antenna. The site is reasonably dry with precipitation occurring only 4% of the time. However, when it does rain, the site can experience torrential downpours in driving winds, necessitating careful weatherproofing and drainage design. Winter storms are infrequent with typical snowfalls of only 10 cm (4 in). A major weather-related design challenge will be the protection of the antennas against the severe ice storms which occur once or twice a year.

Weather monitoring of the type reported here should be continued for several more years in order to build up a correct picture of the average weather likely to be experienced at the potential MMA site.

ACKNOWLEDGEMENTS

It is a pleasure to thank D. Hogg and F. Schwab for help with computer programs. The VLBA Site technicians, B. Hancock, M. Prater and T. Sylvester maintain the VLBA-MK Severe Weather Log and J. Oty is thanked for his photographs of antenna icing.

APPENDIX A.

VLBA-MK Severe Weather Log
Reported by VLBA-MK/NRAO
3Mar94

xxJAN93	LBH	Ice Storm (see J. Oty for report documentation).
xxMAR93	LBH	Ice storm, 2" of ice accumulated on Antenna and West Perimeter Fence. "A" Cryo Compressor shut down due to ice accumulation over evaporator.
21JUL93	AHS	Altocumulus clouds packing in, rainy weather with ice forming on antenna, approx. 2" on walkways. Tropical storm FRENANDA approaching.
22JUL93	AHS	Rainy with some snow, road in bad condition. SUMMIT: 3-4" of snow.
24JUL93	AHS	B. Hancock and T. Sylvester trapped at site. Road washed out at 11,000 ft. level. 4.6" of rain in 6 hours. Temperature 33°F. Site is very wet.
13AUG93	AHS	Tropical storm KEONE at 154°W Lon./12.7° N Lat., coast-fine with high winds and rough surf. Site has winds from the NE at 25 MPH, cold but clear.
22SEP93	AHS	Wind from the West at 35 MPH. Rain and hail at site. Thunderclouds surround the island. SUMMIT: 3" of Snow.
29SEP93	AHS	Moderate rain continues at site. Thunderstorm in Hilo.
24NOV93	AHS	Heavy Rains on East side of Island, 10" in 6 hours. Site windy but clear.
16DEC93	AHS	High cirrus clouds moving in from the West. Weather service reports "No Ice Warnings".
18DEC93	AHS	Temperature 32°F, Raining at lower altitudes. Ice and snow conditions approaching.

19DEC93	AHS	6" of snow fell in 4 hours, ½" of ice with 4" of snow in Dish. Temperatures are below 32°F. SUMMIT: Has 1 ft. of snow with 2-4 ft. drifts.
23JAN94	LBH	Cold front moving over islands.
24JAN94	LBH	8" of snow at site, Dish is clean due to wetness of the snow and observation in progress. Temperature 34°F, Snow falling at a rate of 1" per hour. Road was closed at HP (9,000 ft. level) to all traffic. SUMMIT: 2 ft. of Snow with 4-6 ft. drifts.
25JAN94	LBH	Road open at 13:00 hours.
09FEB94	MAP	09:30 hours; Temperature 31°F (-0.9°C), light snow fall, Winds 3 MPH from ESE (114°), BPress 650.0mb Dew Point -1.0, thunderstorms over the island, flash flood warnings for the East side of the island. Unstable air mass over island for the next 24 hours. Light snow (1") from the previous night.
10FEB94	MAP	Sporadic light Hail Flurries from the morning to afternoon. 14:30 hours; Temperature 0.3°C, Dew Point 0.1 with winds at 6 mph from the West. Snow falling at a rate of 1" per hour.
14FEB94	LBH	Ice, snow and rain, the road is closed. Winds at 35 MPH with gusts up to 45 MPH from the East (280°).
15FEB94	LBH	Ice, snow and rain, the road is closed to the public. On site to inspect antenna - All OK. 14:00 hours; Snowing at a rate of 1" per hour, with 2" of snow on the ground.
16FEB94	MAP	Temperature 36°F, Winds 20 MPH, 3-4" of snow/slush mix on the ground. Rain and snow mix from 09:00-15:00 hours. Road is closed all day to public. SUMMIT: 3-4 ft. of snow with 6 ft. drifts. OAHU: Had 11" of rain which broke a 100 year record.
17FEB94	MAP	Temperatures are warming, overcast with fog. Road open to public at mid-day. SUMMIT: Still has snow with 6 ft. drifts.

REFERENCES

Armstrong, R.W. (Editor), *Atlas of Hawaii - 2nd Edition*, Univ Hawaii Press, 1983.

Holdaway, M., "Preliminary MMA Configurations for Mauna Kea", MMA Memo No. 111, March, 1994.

Hvatum, H., "Wind", memo to Ludwig Oster, NSF, 29 May 1986.

Lindzen, R.S., *Dynamics in Atmospheric Physics*, Chapter 9 - Atmospheric Tides, Cambridge University Press, 1990.

Morrison, D., Murphy, B.E., Cruikshank, D.P., Sinton, W. M., and Martin, T.Z., "Evaluation of Mauna Kea, Hawaii, as an Observatory Site", P.A.S.P., vol 85, pp 255-267, 1973.

Schnell, R. (Director of Mauna Loa High Altitude Observatory), private communication, 1994.

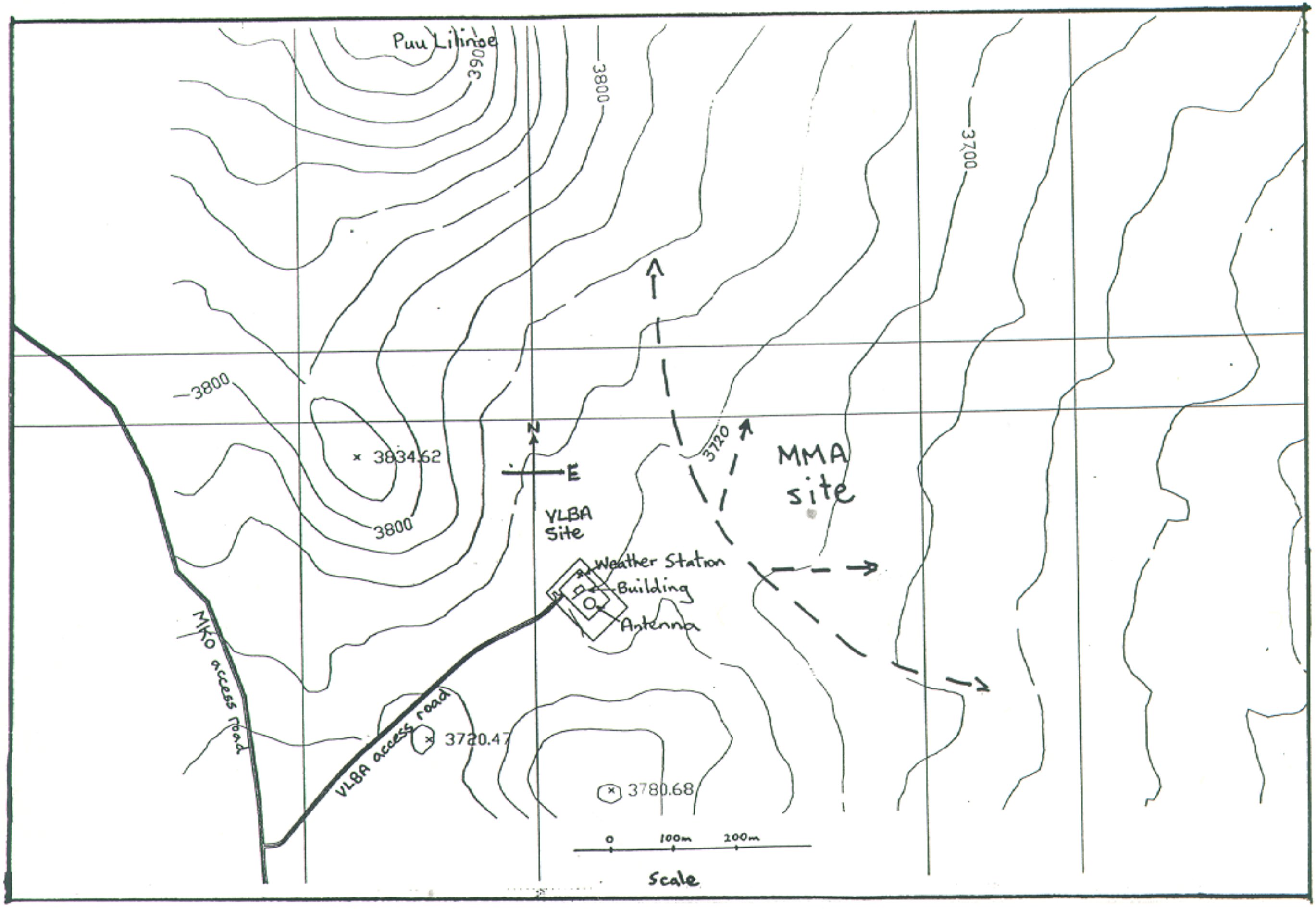

Figure 1. Local terrain around the VLBA site.

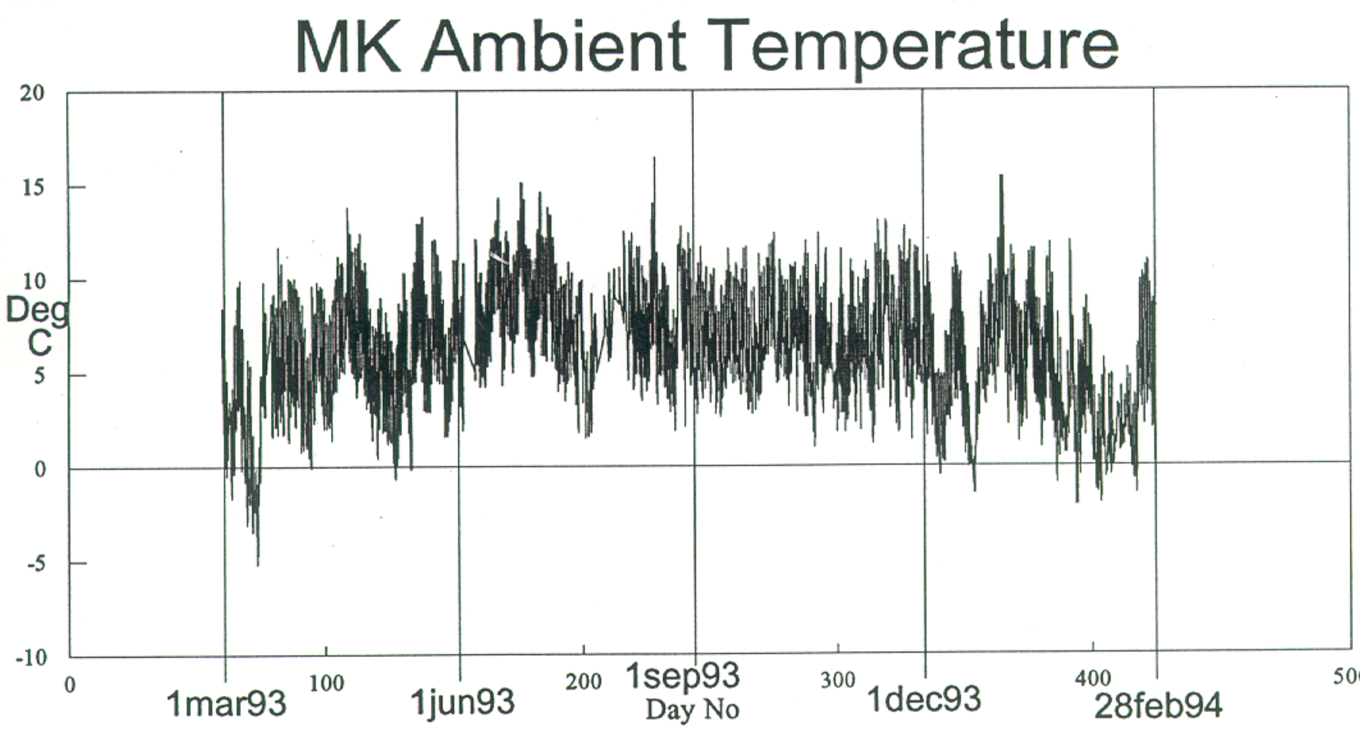

Figure 2. One hour median ambient temperature plotted as a function of time.

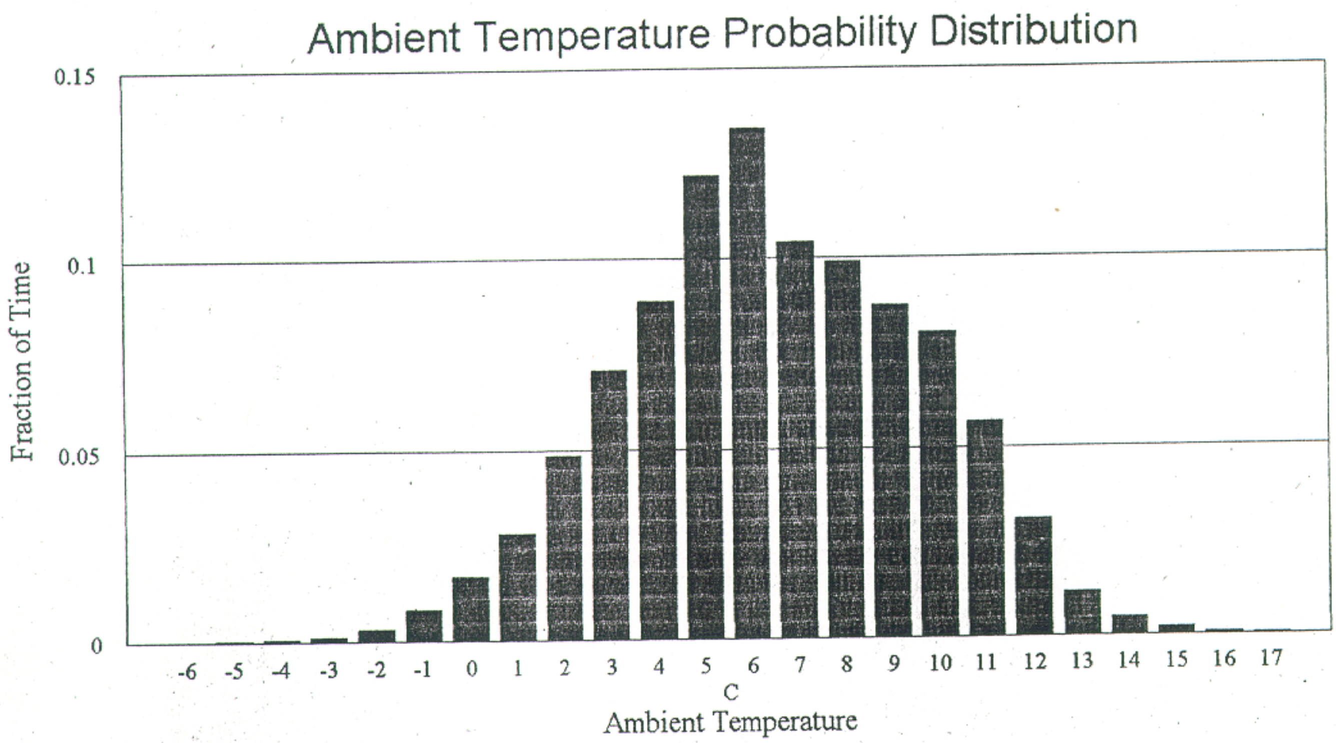

Figure 3. Ambient temperature probability distribution. The bar for temperature T shows the fraction of the 8130 measurements lying in the range T to T+1.

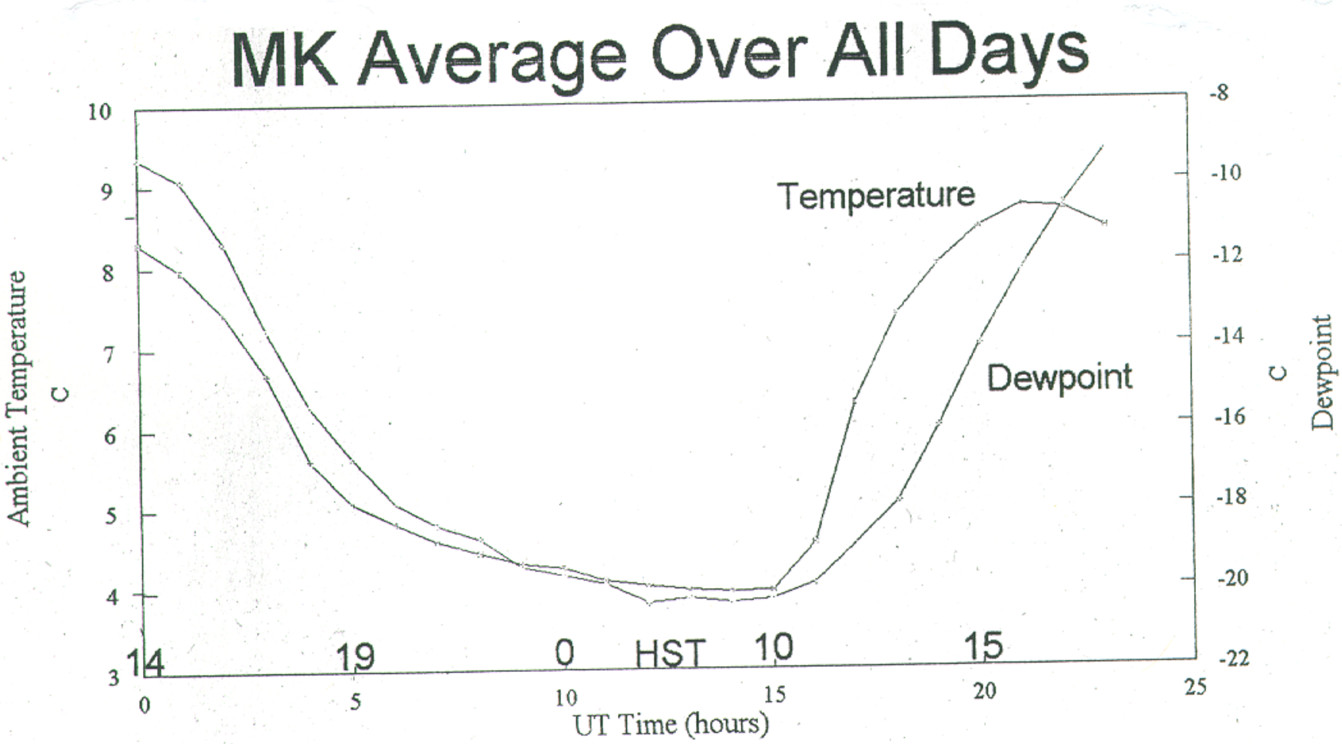

Figure 4. Ambient temperature and dewpoint for each hour of the day, averaged over all 339 days.

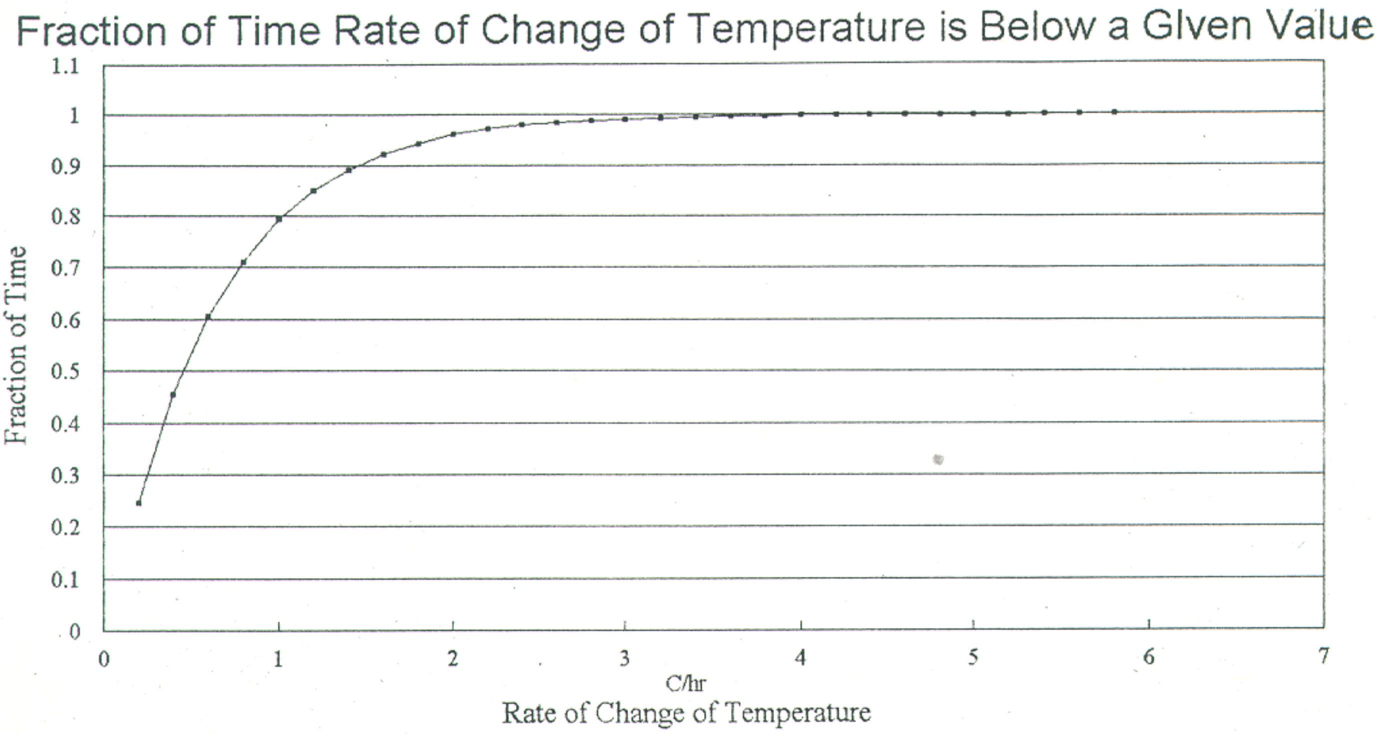

Figure 5. Cumulative probability distribution of rate of change of temperature computed for a time scale of 1 hour. Rate of change of temperature at time t_n is computed as $(T_n-T_{n-1})/(t_n-t_{n-1})$, where T_n is the temperature measured at time t_n. The curve shows the distribution of 8129 rates computed for n = 2 to 8130.

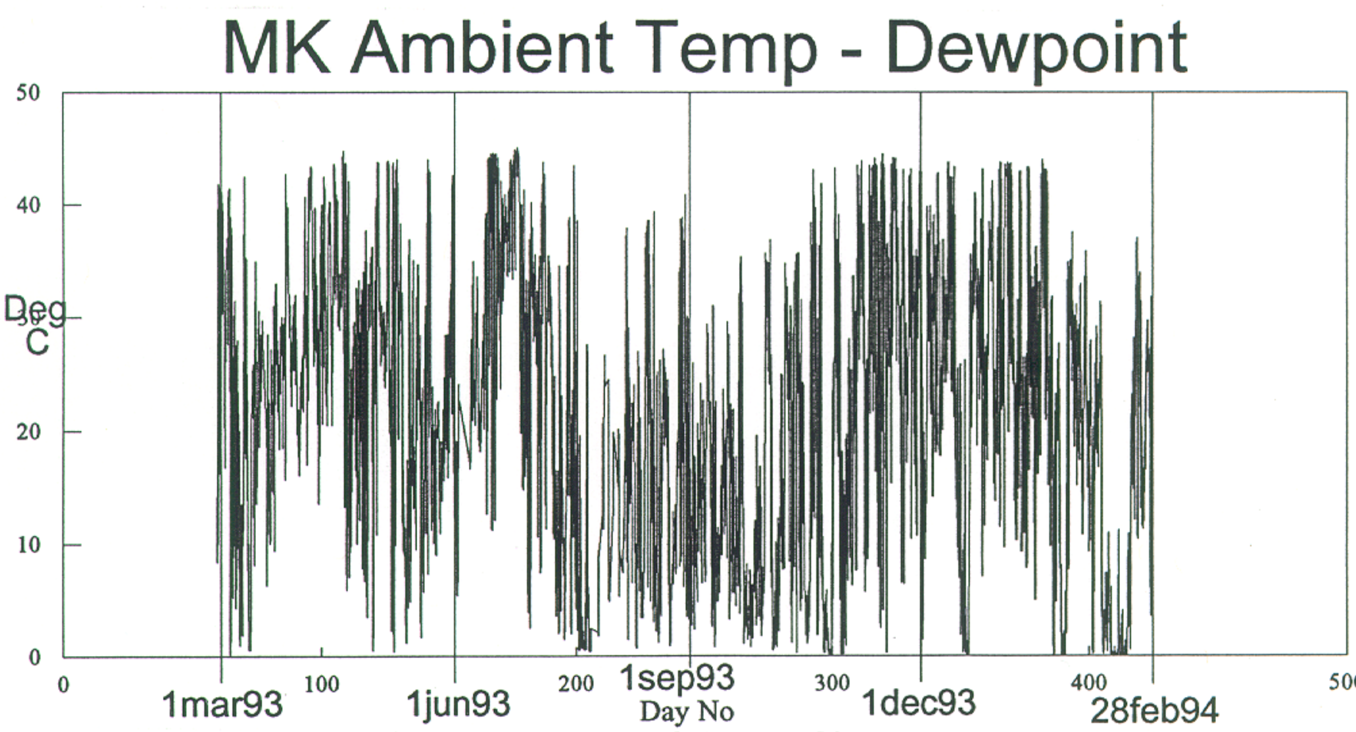

Figure 6. The difference (one hour median ambient temperature - one hour median dewpoint) plotted as a function of time.

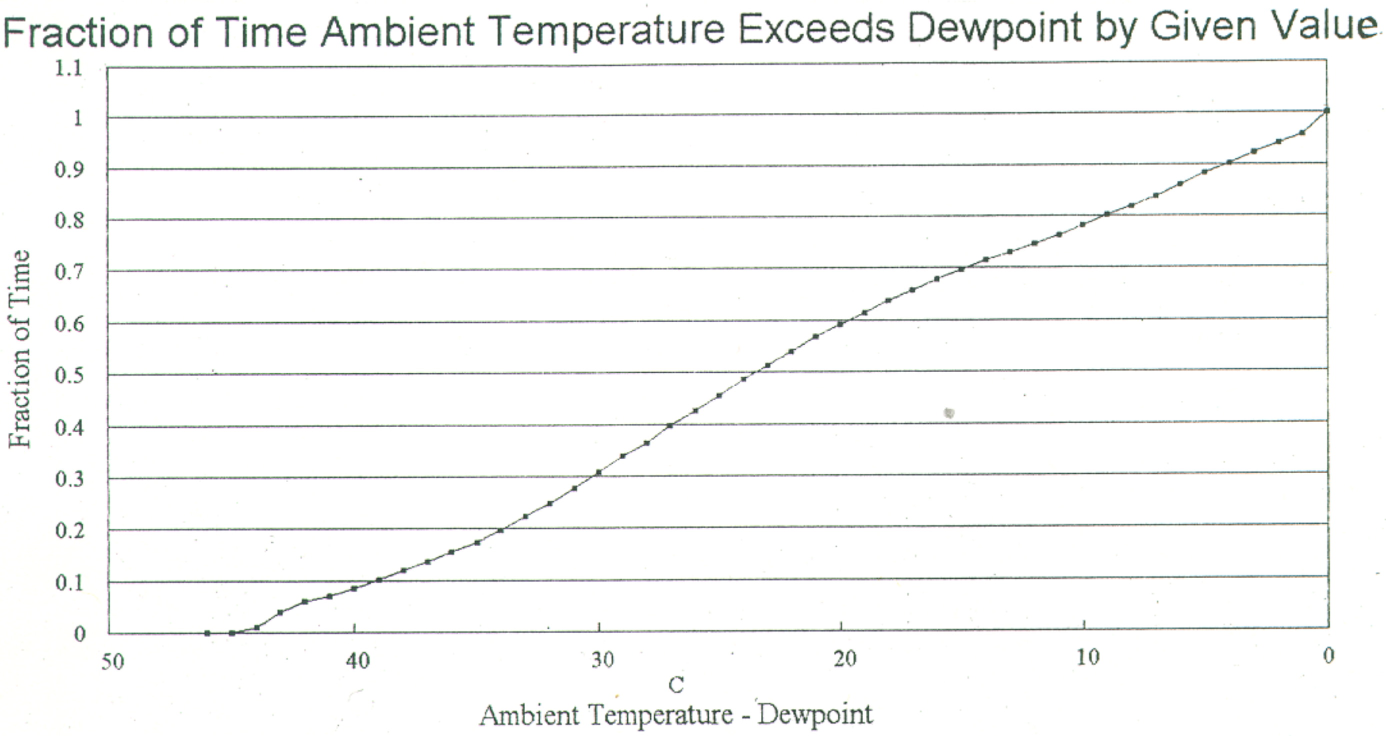

Figure 7. Cumulative probability distribution for the difference ambient temperature - dewpoint.

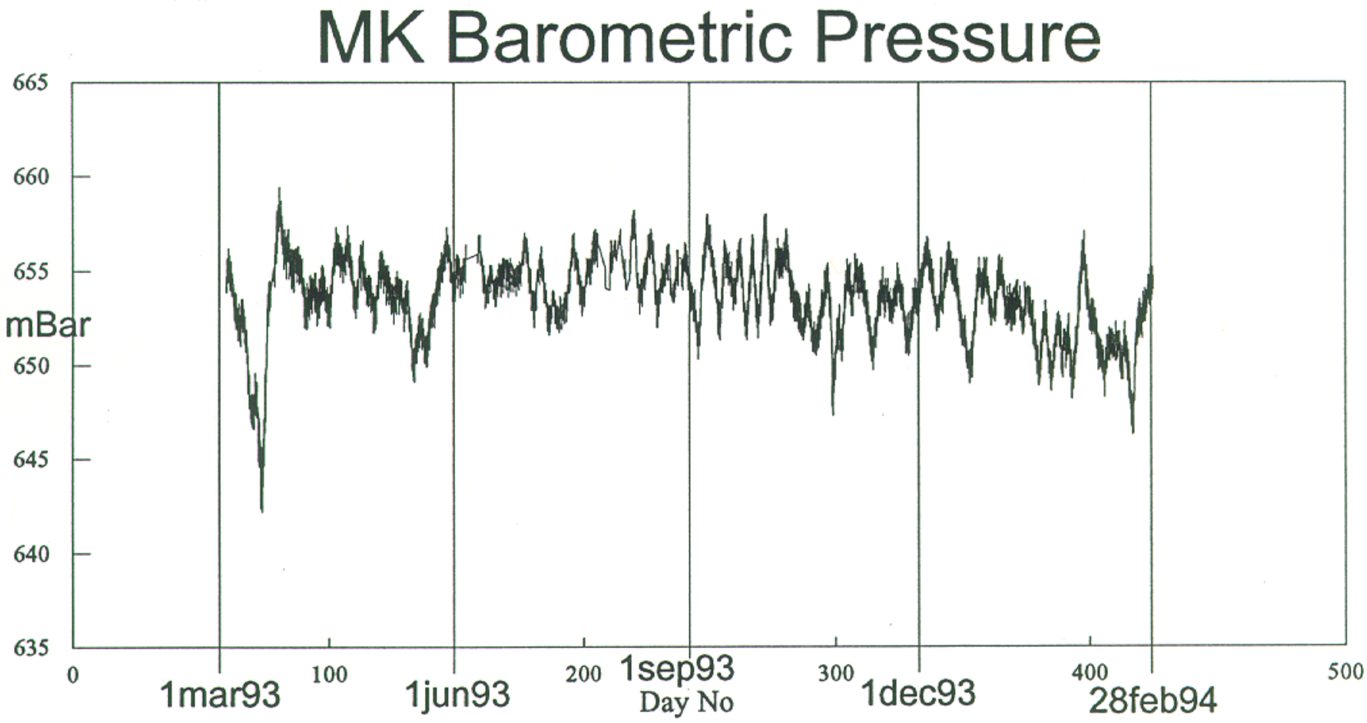

Figure 8. Barometric pressure plotted as a function of time.

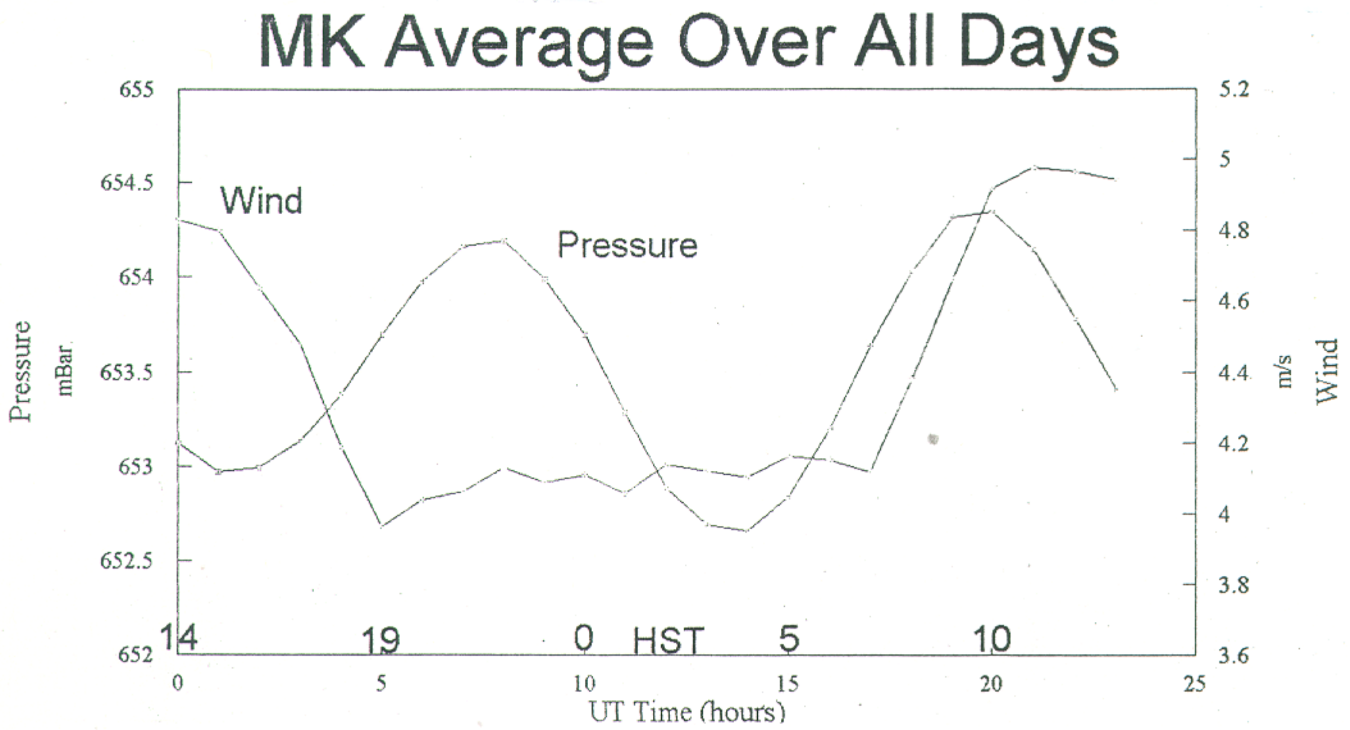

Figure 9. Average diurnal variation of pressure and wind speed.

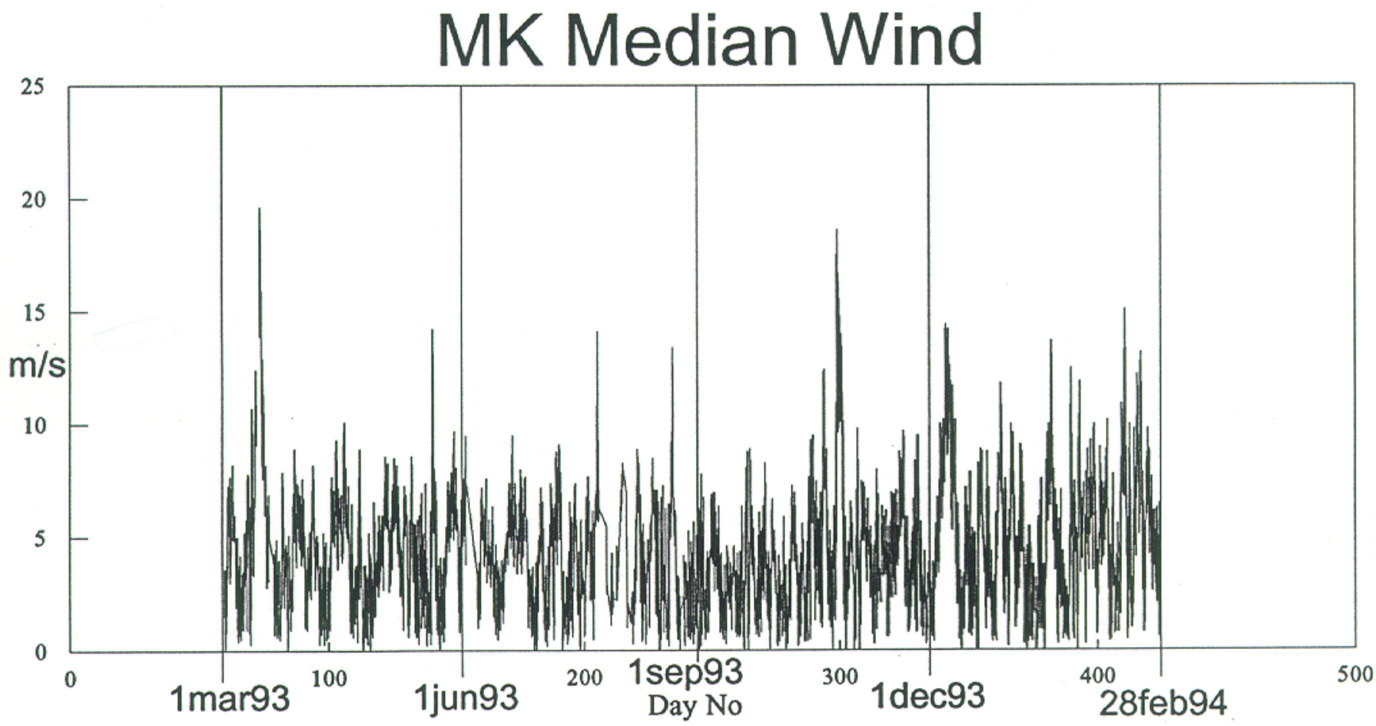

Figure 10. Hourly median wind speed plotted as a function of time.

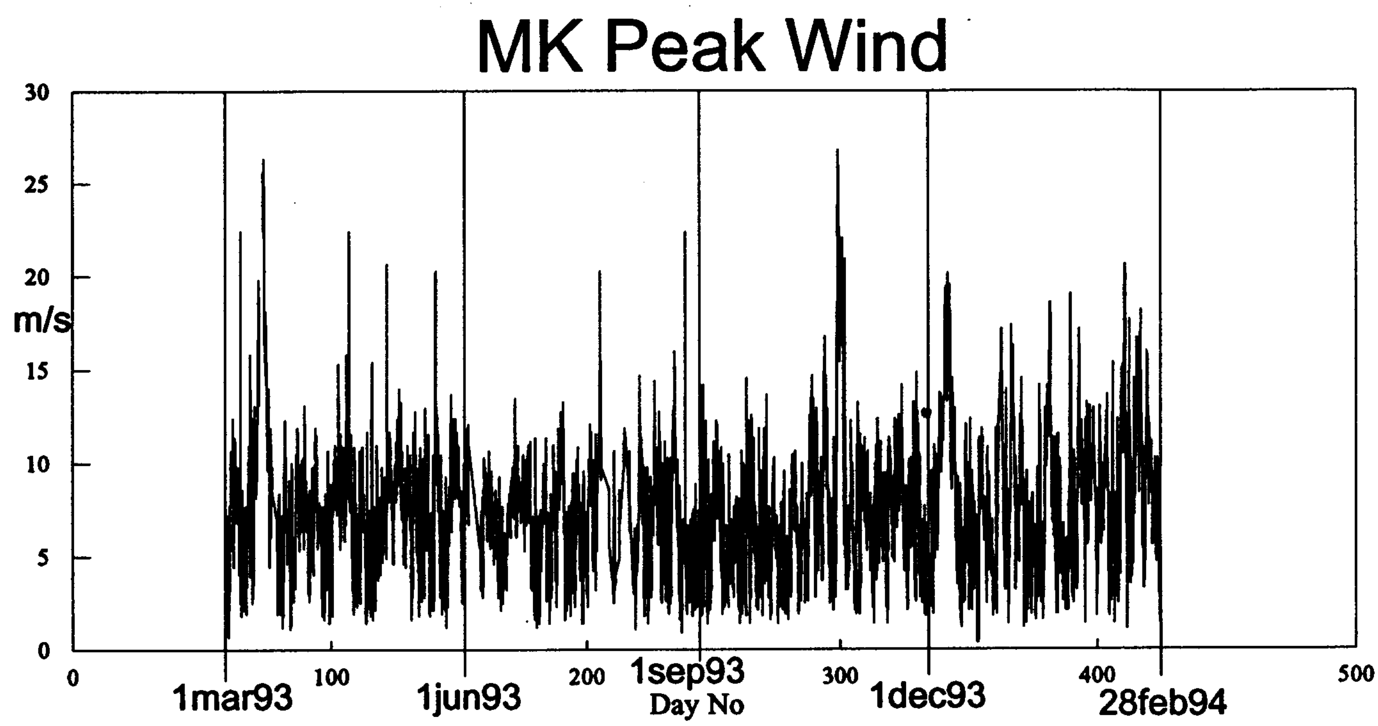

Figure 11. Hourly peak wind speed plotted as a function of time.

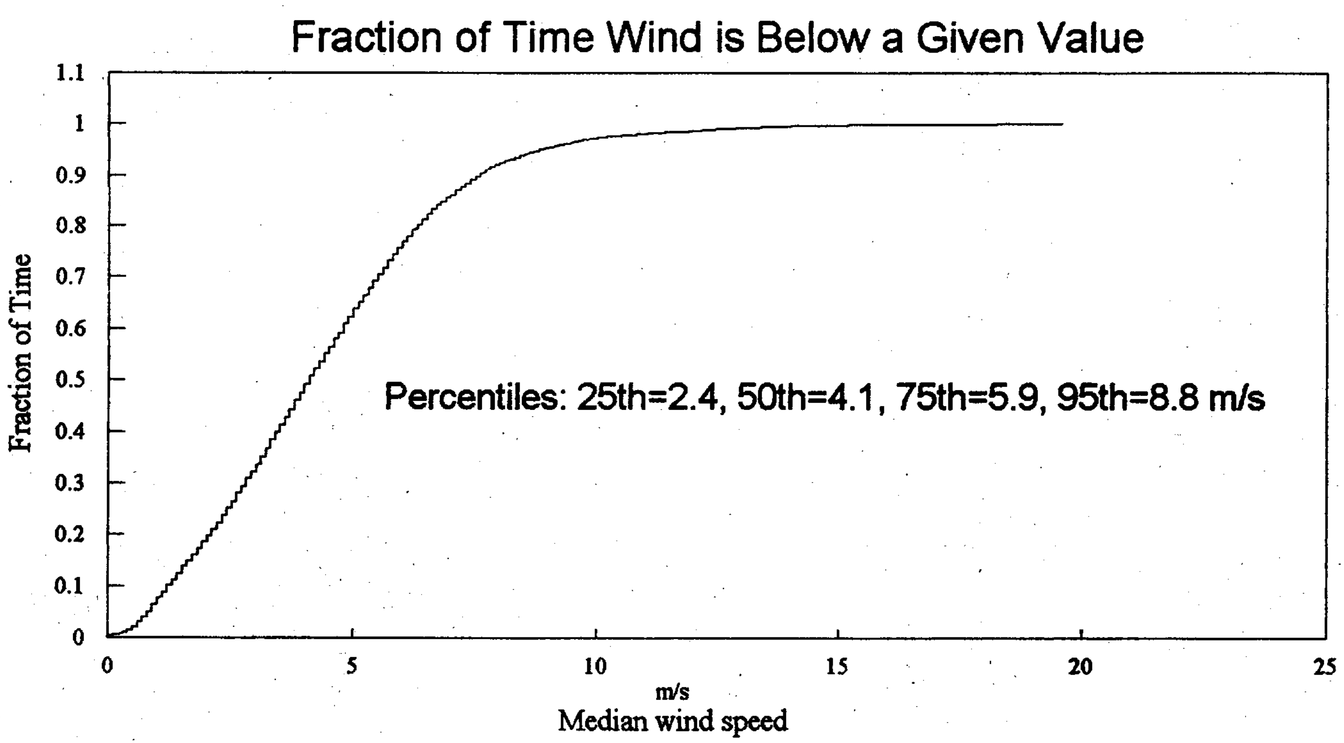

Figure 12. Cumulative probability distribution for hourly median wind speed.

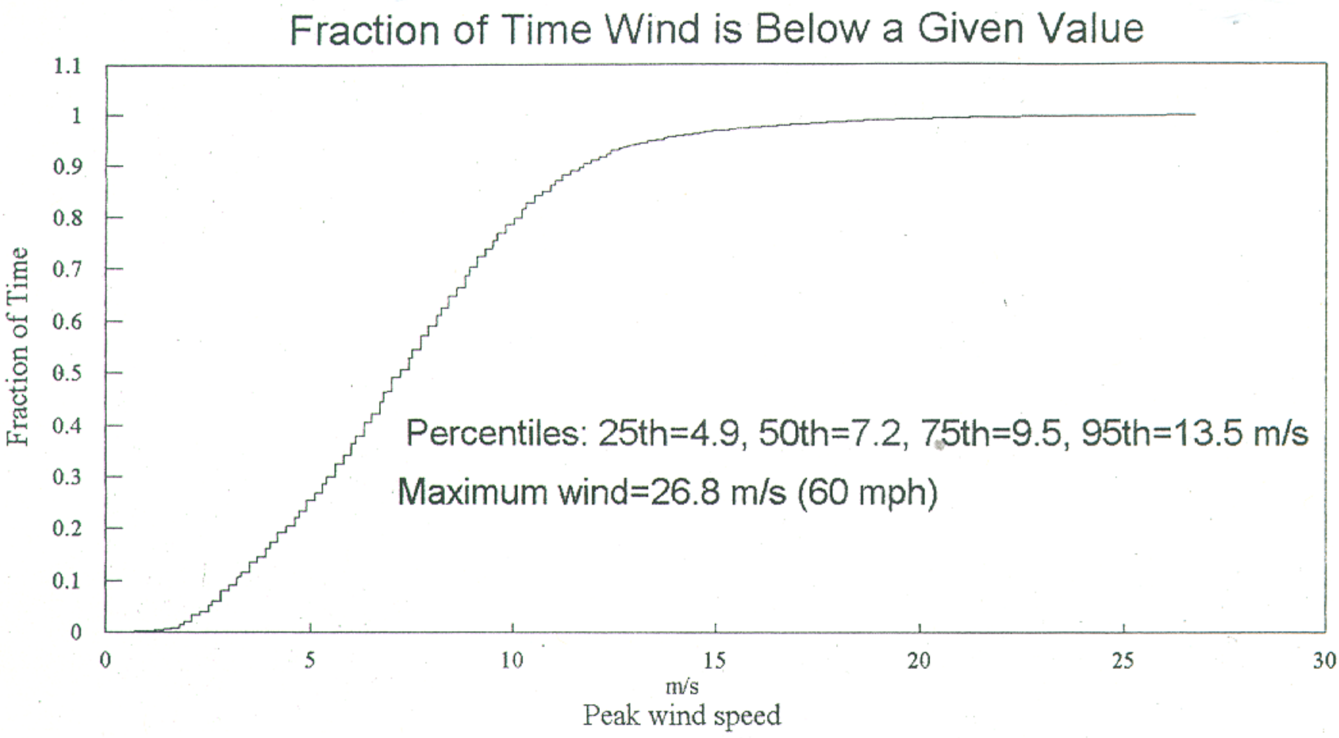

Figure 13. Cumulative probability distribution for hourly peak wind speed.

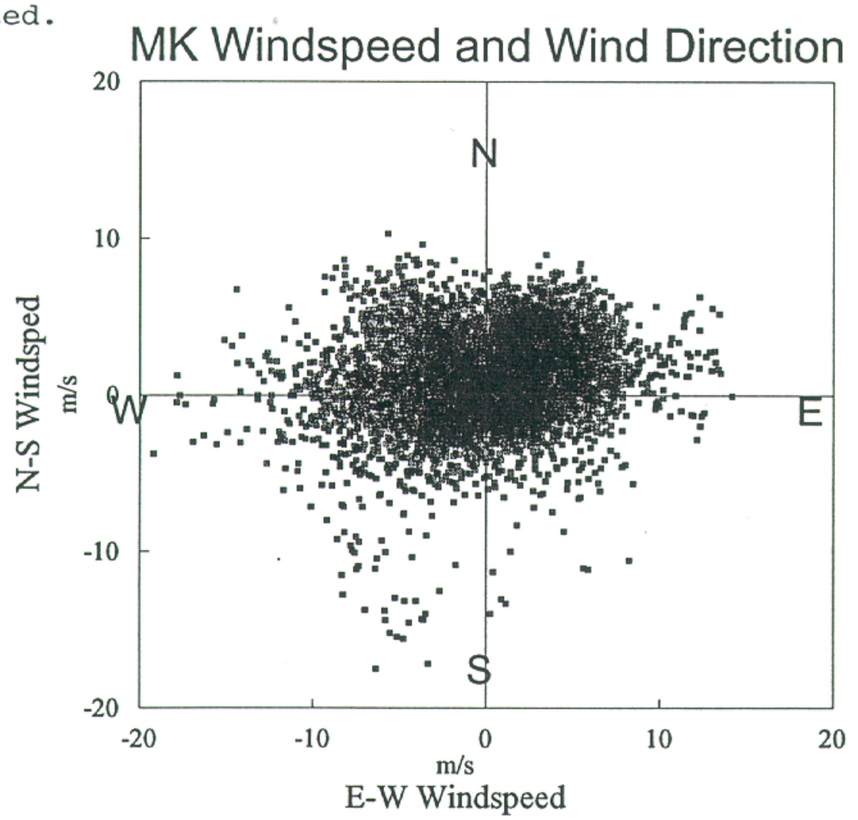

Figure 14. Hourly median wind speed measurements resolved into E-W and N-S components.

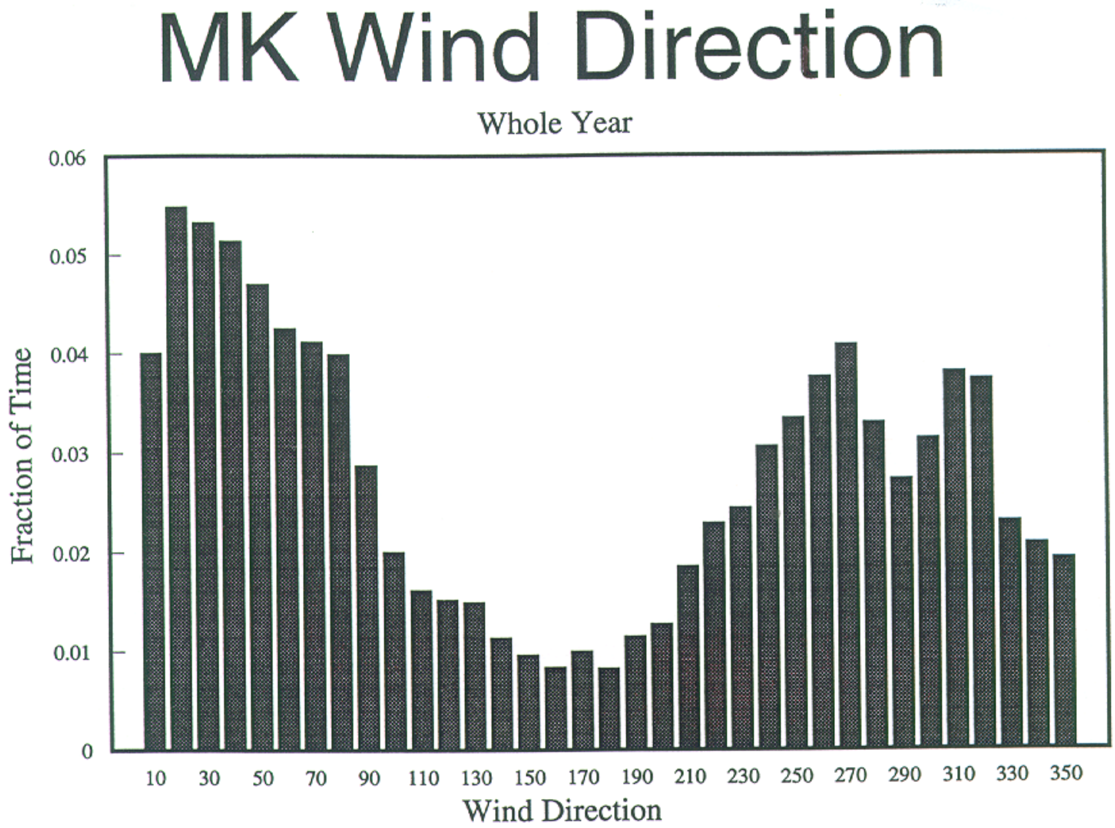

Figure 15. Wind direction probability distribution, whole year, all hours.

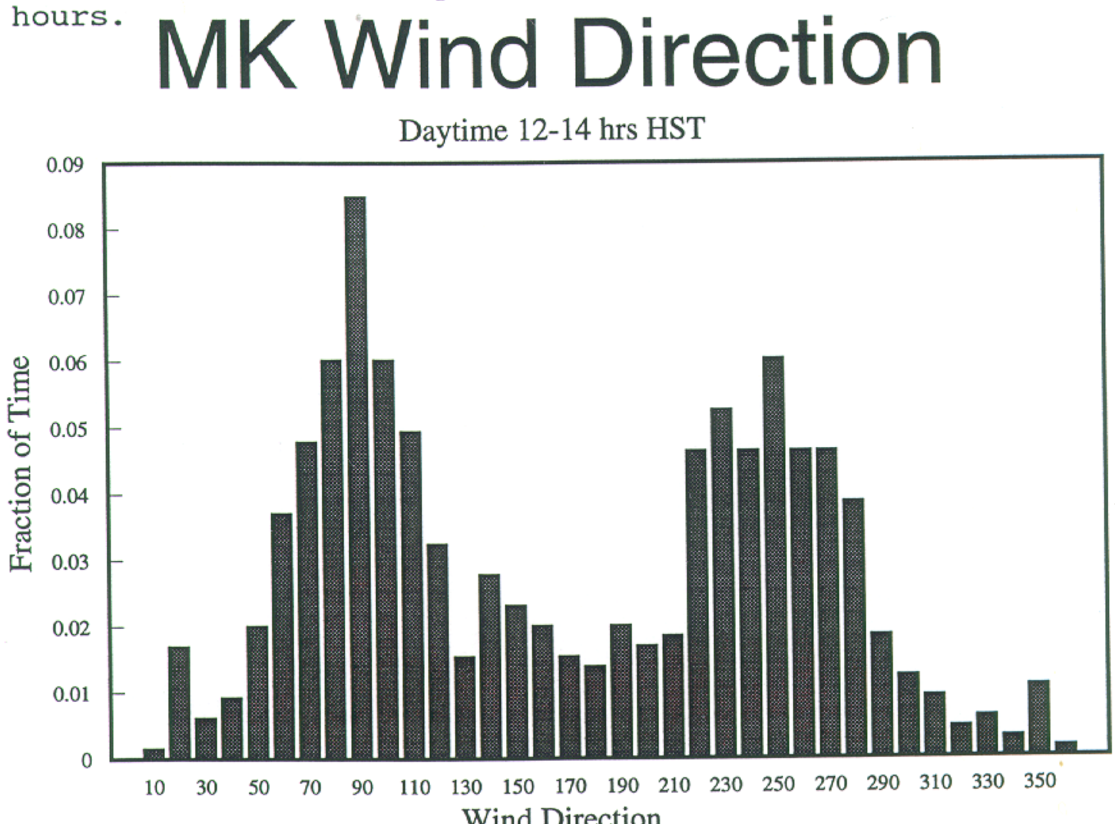

Figure 16. Wind direction probability distribution, whole year, daytime hours, 12-14 hrs HST.

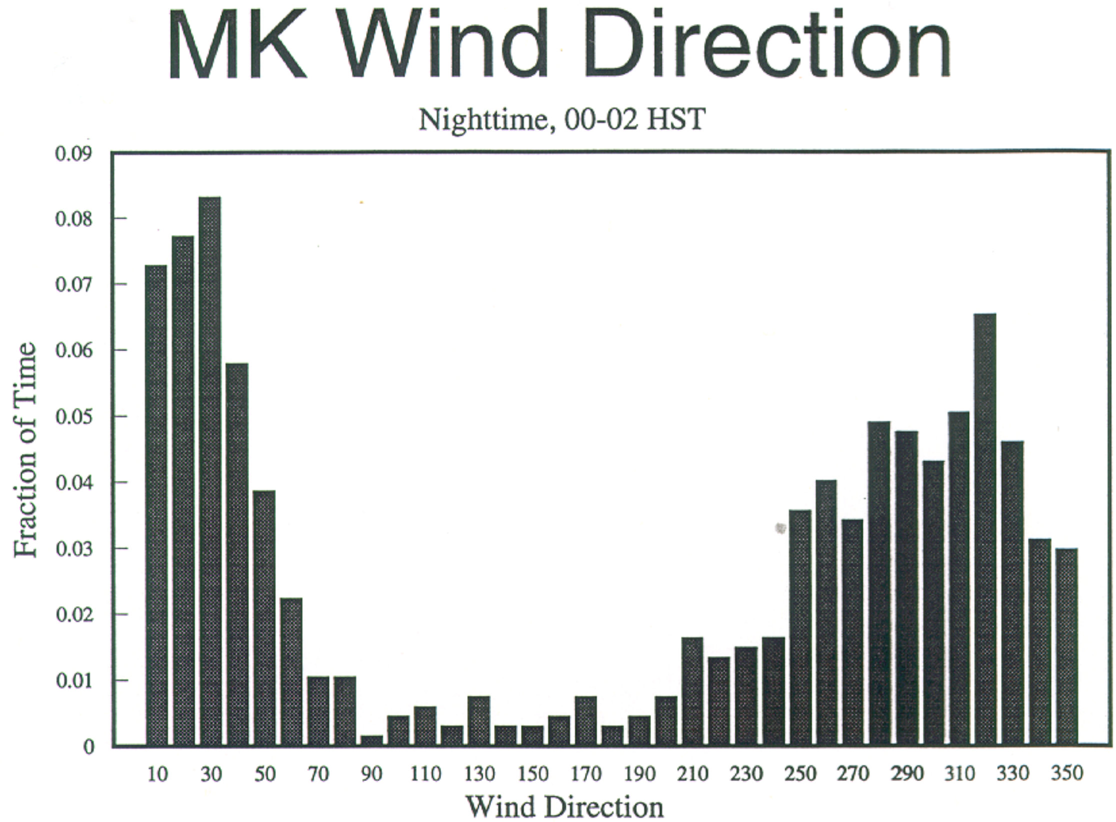

Figure 17. Wind direction probability distribution, whole year, nighttime hours, 00-02 hrs HST.

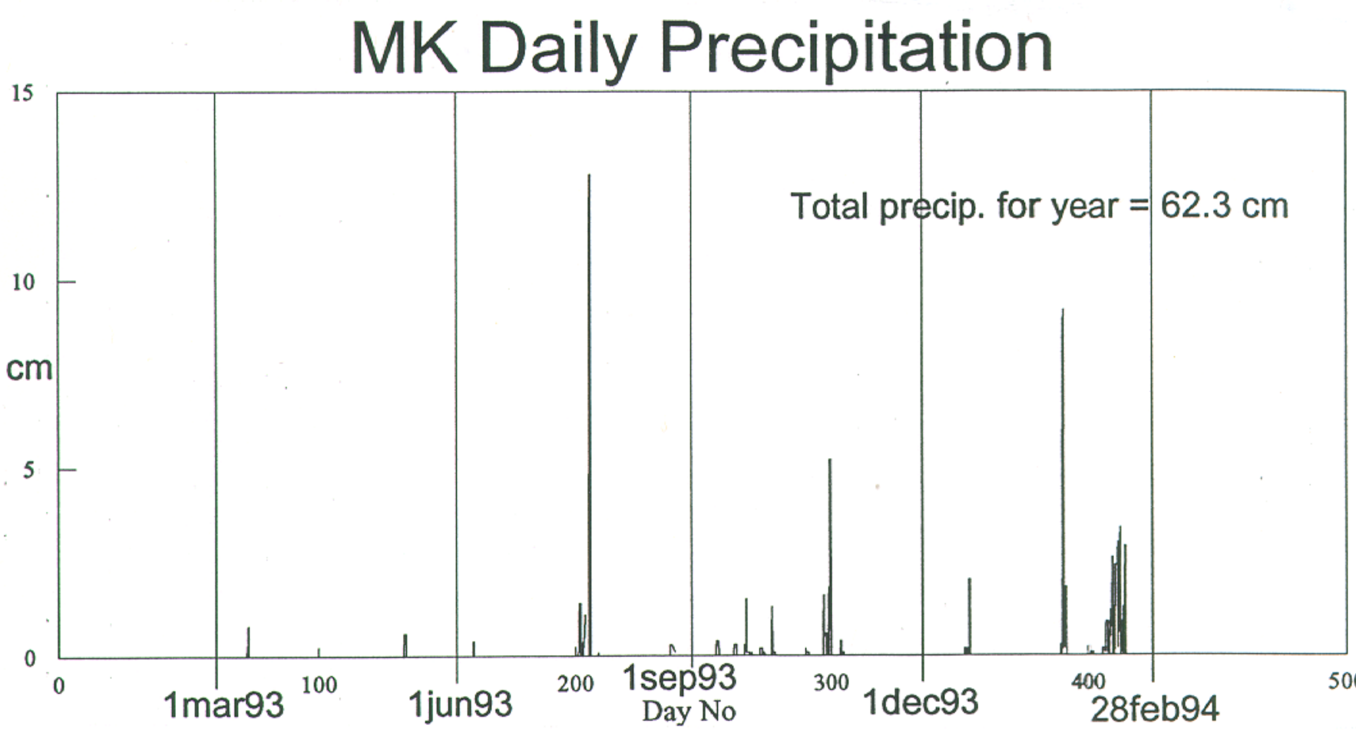

Figure 18. Daily Precipitation.

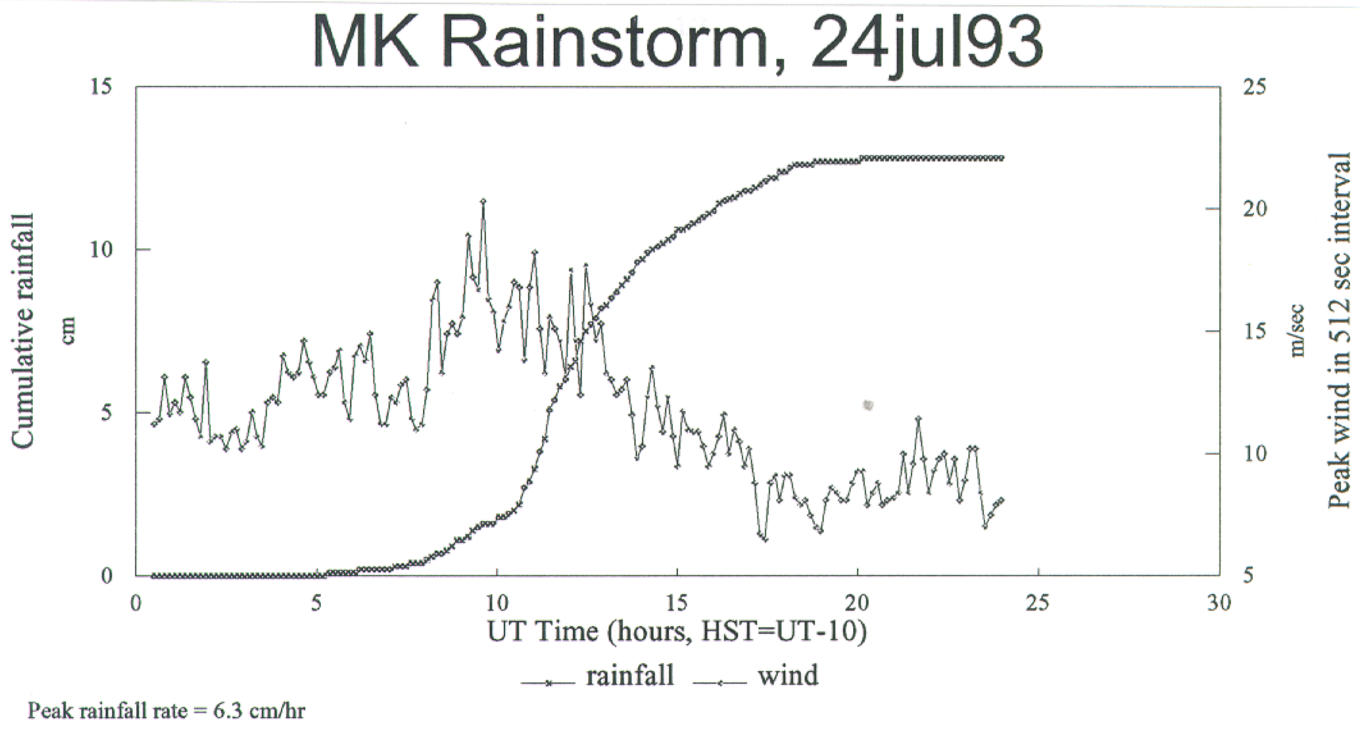

Figure 19. Cumulative rainfall and wind during the heavy rainstorm of 24 July, 1994.

Figure 20. Ice damage to the dichroic plate during the winter storm of 14mar93.

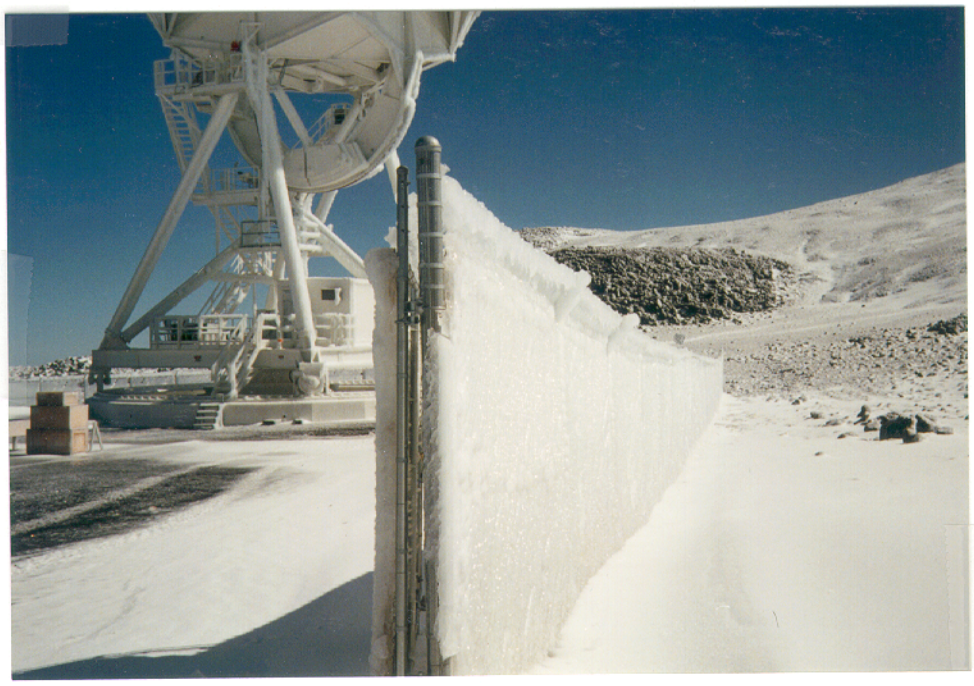

Figure 21. Ice buildup on chain link fence on SW side of site, 6 Jan 93.

Figure 22. Ice buildup on antenna pedestal structure, 6 Jan 93.

Figure 23. Ice buildup on antenna quadruped, 6 Jan 93.

Figure 24. 12 cm of ice buildup in the reflector backup structure, 6 Jan 93.