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P. O. Box E
Oak Ridge, Tennessee 37831

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ABSTRACT

This report describes a brief, preliminary attempt to (i) model SO_2 concentrations and fluxes to deciduous forest canopies at two research sites operated by the Tennessee Valley Authority, (ii) to assess the utility of the present measurement program and data set for modeling purposes, and (iii) to recommend improvements necessary to facilitate further analyses.

The Camp Branch and Cross Creek watershed sites characteristics and meteorology are described. The wind roses for these sites are presented and discussed in some detail, to facilitate future analysis and experimental planning. A sector-box model with time-dependent mixed-layer depth, first-order chemical conversion of SO_2 to $SO_4^=$, and wet and dry en route removal of both chemical species was used to approximate long-range transport from two large coal-fired power plants. SO_2 concentrations at Cross Creek due to a source < 25 km distant were predicted with some success; individual predictions were accurate within a factor of ten, but with a great deal of scatter. For all other source-receptor combinations, individual concentrations were rather poorly predicted. This suggests that future modeling work should recognize the influence of factors such as complex terrain and smaller but nearby sources that were not incorporated into this first effort. However, predicted SO_2 fluxes based on median concentration values were within about a factor of three of the flux estimates based on observations.

A one-dimensional flux model based on canopy radiation balance and measured vertical gradients (differences) of SO_2 concentration, temperature, and moisture is presented. To approximate local fluxes to the watersheds using this model, the vertical profile data must be determined accurately enough that gradients are not masked by the breadth of the data confidence

intervals. The SO_2 concentration data from a period of ideal conditions were examined; it was found that the standard deviation of the concentration measured at each level exceeded the gradient that would be expected from depositional processes. It was therefore concluded that the existing SO_2 measurement system is not adequate for use with the suggested flux model, and that improvements to the measurement program will be necessary.

On the basis of these preliminary analyses and on-site equipment inspections, a number of specific improvements in the present measurement and recording techniques are recommended. These include improvements in the techniques for measuring level-to-level differences of temperature, humidity, and sulfur dioxide, special tests of the various sensor systems, the addition of net radiation measurements, an additional level of measurement near the canopy zero plane, data quality control via regular statistical testing, and an additional measurement program to study the effect of local terrain on concentrations. Possible improvements to the modeling effort are also outlined in some detail.

1. INTRODUCTION

1.1 Goals and Scope of Work.

The work described in this report was performed by the Atmospheric Turbulence and Diffusion Laboratory (ATDL) under a cooperative research agreement with the Tennessee Valley Authority (TVA), and is part of a program on sulfur deposition being conducted by the TVA and the U.S. Environmental Protection Agency (EPA) for "Evaluation of Ecological and Related Economic Consequences of Changing Energy Production and Use Within the TVA Region". The research utilized data collected between April 1, 1978, and March 31, 1981, at the TVA's densely forested Camp Branch and Cross Creek watershed study sites on the Cumberland Plateau in east-central Tennessee. ATDL has developed two simple models to predict airborne concentrations and mass fluxes of sulfur to those sites, and compared the results to the data. ATDL personnel have also visited each of the sites and inspected the equipment installed and the methods of data collection.

The goals of the work were to (a) conduct a brief preliminary assessment of the utility of the presently available SO_2 and meteorological data sets from the Camp Branch and Cross Creek site, (b) estimate sulfur fluxes to the watersheds using the data and simple models, and (c) provide recommendations for additional, improved, and/or different measurements, and suggestions for future model development. These goals are of strong interest to ATDL (as well as to the TVA and EPA) because of our ongoing research on atmosphere-canopy interactions at the Department of Energy's Walker Branch Watershed near Oak Ridge National Laboratory in east Tennessee. Understanding gained at any of these sites should be of considerable benefit at other sites, and should enhance our ability to predict the transfer of airborne pollutants to forested areas. At the present time, this ability is still quite limited, despite its practical importance.

1.2 Report Format.

Section 2 deals with the characteristics and meteorology of the Camp Branch and Cross Creek sites, as well as the meteorology at two major sulfur sources within 100 km of either site, the Widow's Creek and Kingston steam plants. Typical mixing heights deduced from the closest National Weather Service (NWS) radiosonde site (Nashville, TN) reports are also described. Section 3 describes the rationale and operation of a simple sector-box model used to estimate airborne sulfur concentrations produced by the two power plants over the watersheds. Estimates of sulfur concentrations and fluxes deposited on the watersheds are compared to measurements. Section 4 outlines a one-dimensional model for flux estimates that requires only rather easily measured data, and discusses the data available from Camp Branch and Cross Creek relative to the model requirements. Section 5 summarizes the results, conclusions, and problems arising in the modeling work. Section 6 presents specific recommendations for (a) additional and modified instrumentation and data collection at the watersheds, (b) additional data and changes in reporting to improve source characterization for model use, and (c) further lines of model development.

2. SITE CHARACTERISTICS AND METEOROLOGY

2.1 General Comments.

Kelly (1980) has described the Camp Branch and Cross Creek watersheds in some detail. Their location is indicated in Figure 1. Camp Branch (35° 38' N, 85° 18' W) is a 94 ha catchment ranging in elevation from 518 m to 597 m MSL located near the northern end of the Sequatchie River Valley roughly 40 km SSW of Crossville, TN and 70 km N of Chattanooga, TN. It is a rather remote location not exposed to any nearby anthropogenic sulfur sources. Cross Creek (35° 04' N, 85° 51' W) is a 36 ha catchment with elevations between 495 m and 574 m MSL located roughly 50 km W of Chattanooga, about 10 km from the Tennessee-Alabama border. It is only 22.3 km NNW of a significant sulfur source, the TVA's Widow's Creek power plant in northern Alabama.

Both sites are covered by fairly dense upland oak-mixed-hardwood deciduous forest, with pine-dominated stands in formerly agricultural areas. Kelly's (1980) dry biomass estimates for the dominant cover types are about 163,000 kg/ha and 202,000 kg/ha at Camp Branch and Cross Creek, respectively.

Both Camp Branch and Cross Creek experience a temperate continental climate. The winters are generally moderate, with a few brief cold periods and modest snow accumulation. The summers are mild to hot, generally quite humid, and punctuated by frequent afternoon thunderstorms. Precipitation is fairly evenly distributed over the year, with a weak winter or spring rainfall maximum, and a minimum in autumn. Total precipitation is on the order of 150 cm/year. In this preliminary study, emphasis was placed primarily on the winds observed at each site. Local terrain features are known to have a strong influence on near-surface wind observations, particularly at night when the wind speeds are generally low and the atmosphere is stable. Under such conditions, local drainages of cold air can often be expected. Consequently the observed winds at these sites were broken into a day/night set of monthly averages over the period April 1, 1978 to March 31, 1981; the resulting speed/direction joint frequency distributions are discussed below. Data on the Camp Branch and Cross Creek winds have not been considered in any detail prior to this study. Hence, at the request of TVA personnel, a rather detailed discussion of the data and an extensive set of wind roses are presented, to facilitate future analyses and experimental planning. It should be noted that the three year interval available is too short for an adequate climatological study; remarks concerning seasonal variations are based on a limited sample, and should be regarded with some caution.

2.2 Instrumentation.

A 25 m free-standing tower at each site has been equipped by the TVA to monitor wind speed and direction, air temperature, dew point temperature, and incoming solar radiation at the tower top, roughly 5 m above the tree tops. A particle sampler, a wet-dry precipitation collector, and a sulfur dioxide monitor are also located at this height. Within the canopy, 7 m above ground, dew point and sulfur dioxide are monitored, and airborne particles are collected. At a height of 1 m, air temperature, dew point, and sulfur dioxide concentration are measured; a particle sampler and a second wet-dry precipitation collector are also at this level. A rain gauge is placed near the watershed crest at both sites. Details of the instrument types and response characteristics can be found in Kelly (1979).

Data are collected by a minicomputer-controlled system capable of sampling the instrument outputs at appropriate intervals and then forming hourly averages for recording. Thus, for example, wind speed is sampled every 15 seconds, direction every 5 sec, air temperature and dew point once per minute, and precipitation hourly. A measure of the local turbulence intensity is provided by the standard deviation of the wind direction distribution about the hourly mean value.

2.3 Camp Branch Winds.

Figure 2 shows the annual daytime wind rose for Camp Branch, calculated from three years of on-site data using Schlatter's (1978) technique*. More than 50% of the winds have a westerly component, with flow from the WNW through NNW being the most frequent. However, flow from the S and SE is almost as likely. Winds from the N through ESE are quite infrequent, and will usually be light when they do occur. The winds in general are rather light and typical of the inland portions of the southeastern U.S., with most winds being in the 2 to 4 m/s range, and only a very few cases greater than 6 m/s.

Figure 3 shows the monthly daytime wind roses for Camp Branch. There seems to be a pronounced seasonal effect. During the winter months (taken as October through April), the monthly roses bear a strong resemblance to the annual rose of Figure 2. The most likely wind directions are the NW and SE quadrants, with the NW quadrant being slightly favored. Winds from the NE quadrant are infrequent and very light. Strong winds will most commonly be from the west. No periods of calm (wind speed < 0.2 m/s) are likely during these months. During the summer months (May through September), however, the direction frequency distribution is much more uniform, with winds from any direction except the NE quadrant being (roughly) equally likely. Wind speeds are much lighter during the summer, with speeds above 4 m/s being rare. Calm periods can be observed in June, July, and August.

Figure 4 is the annual nocturnal wind rose for Camp Branch. It is quite different from the daytime rose (Figure 2), in that it has a strong southeasterly bias, while winds between W and SW are almost as unlikely as those from N through NE. As expected, the wind speeds are usually lighter than by day,

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*Wind rose data are presented and discussed in considerable detail because no previous analyses of the Camp Branch and Cross Creek winds are known. The information should be useful in planning future studies at these sites.

with more than 50% of the speeds being lower than 2 m/s.

Figure 5 provides the monthly nighttime wind roses for Camp Branch. There seems to be a somewhat more limited seasonal dependence in these nocturnal data. The winter months of December through March show a bimodal direction distribution; the winds will generally be northwesterly or southeasterly, with the southeasterly sector being favored during the endpoints of the period, December and March. Winds from the NE quadrant are quite unusual. April and May are transition months where westerly winds become less common, and winds from the ENE begin to occur. By June (Figure 5f), the summer rose appears: very few winds from the N through SW, with most nighttime winds coming from southeasterly directions at speeds < 2 m/s. This picture persists through September. During October, a strong SSE direction bias persists, but winds from the northwest begin to occur. By November, these northwesterlies contribute often enough to make the distribution almost uniform, except for the persistent contributions from the S and SSE.

It may be possible to explain these nocturnal wind roses at Camp Branch on the basis of the site topography and vegetation: during the winter months, the canopy will be mostly bare and the westerly synoptic winds can be fairly strong. The local flow may then be influenced by channeling of these winds up Cane Creek Valley; this creek is the main drainage for the area, and runs toward the NNW. At other times of the year, and at times in the winter when the synoptic winds are light, cold air drainage from the southeast quadrant seems likely, since the terrain gradually rises in that direction to form the western edge of the Sequatchie River Valley. Data from other sites in the region would be needed to validate this hypothesis.

Data from Smithville, on the northwest slope of the Cumberland Plateau roughly 30 km NW of Camp Branch, also suggest northwesterly upslope winds by day, and southeasterly drainage winds at night (U.S. Weather Bureau, 1953). In fact, the annual day and night wind roses from Smithville are rather similar to those observed at Camp Branch, except for north to northeasterly winds, which are comparatively rare at Camp Branch.

2.4 Cross Creek Winds.

The annual daytime windrose from Cross Creek is shown in Figure 6. The distribution is quite unlike the one at Camp Branch, with almost 18% of the winds coming from the SW. In fact, the rose is almost trimodal, with significant contributions from the WNW and from the ENE. Winds from the N and NNE are rather unlikely. Somewhat stronger winds can be experienced at this site, with values up to 8 m/s being observed; despite this, a calm (wind < 0.2 m/s) frequency of 1.8% was found. The calms occur almost entirely during the summer months.

Figure 7 shows the monthly daytime wind roses from Cross Creek. Again a seasonal breakdown is possible. During the winter months, December through April, the rose is somewhat similar to the annual distribution of Figure 6, with major contributions from the WNW, SE, and ENE. Winds as strong as 10 m/s generally come from the SW. By May and June the contribution from winds with a westerly component is nearly uniform except for the roughly 20% of winds from the SW. The winds become increasingly light, with 10.2% being calm (< 0.2 m/s) in June. The roses for July and August are similar to each other, with almost no contribution from northerly or southerly winds. About one-third of the time during mid-summer the wind is from the western quadrants, and almost 25% of the time it is from the SW. An ENE contribution persists. The winds remain light, generally < 4 m/s, but there are almost no calms by August. The autumn is a time of transition; during the period September through November, the SW contribution decreases markedly, and winds with westerly components begin to occur. The frequency distributions in October and November are rather uniform except for the southwesterly component. Wind speeds up to 8 m/s are regularly observed by November, although 1.4% of the time the wind is calm.

Figure 8 shows the annual nighttime wind rose for Cross Creek. The distribution appears to be bimodal, with significant contributions from the WSW and from the NE and ENE. Winds as great as 8 m/s are infrequent, and about 2% of the time is calm (< 0.2 m/s).

The monthly nocturnal wind roses for Cross Creek are shown in Figure 9. The only fairly clear-cut seasonal trend is associated with winds from the NW quadrant. Between December and March more than 30% of the winds come from directions between W and N. This contribution drops off steadily through the spring and summer to less than 15% by September, but then abruptly increases again in the autumn. The generally bimodal character of the wind rose is otherwise persistent, with strong contributions from the WSW and NE through ENE. In July and August, the WSE wind seems especially important, while in September, winds from the NE and ENE occur about 40% of the time. There is some suggestion of upvalley (from the SW or WSW) flow by day and downvalley (NE or ENE) drainage by night along Cross Creek Valley in these records. Wind speeds up to 10 m/s are observed during the winter and early spring, but by June winds faster than 4 m/s are rare, with calms occurring roughly 12% of the time in both June and July. In August, the winds remain light, < 4 m/s, and generally < 2 m/s, but calms are rare. By September and October, the wind speeds are again reaching values of 6 to 8 m/s on occasion.

2.5 Winds at the Sources.

In this preliminary study, it was arbitrarily decided to limit the sources considered to major ones located within 100 km of either Camp Branch or Cross Creek, since it was felt that other, more distant, sources would contribute relatively little to the pollutant concentration. The TVA's Widow's Creek steam plant in northern Alabama and the Kingston steam plant in east Tennessee seemed the most likely candidates. The Bull Run steam plant was neglected, since it is more than 100 km from Camp Branch and almost 200 km from Cross Creek. The Watts Bar steam plant was neglected mainly on the grounds of size, although nearby terrain, likely wind directions, and distance to the receptor sites were also factors. Other potential sulfur sources in the area are small by comparison with the Widow's Creek and Kingston plants.

2.5.1 Kingston steam plant.

Wind speed and direction are routinely recorded at the 110 m level of a meteorological tower near the steam plant. Winds from the NE and ENE directions can carry effluent from the plant to either of the two watersheds.

Figure 10 shows the day and night annual wind roses at Kingston; monthly day/night wind roses were also prepared and analyzed, but are not included here for reasons of space. As the annual roses suggest, NE and ENE are not really predominant wind directions. Only during September does the daytime incidence of these directions become as large as 25%; at night in September, it is 22%. At night in February and again in August, the NE and ENE directions appear 22% of the time. At all other times, these directions occur less than 20% of the time. On an annual basis, the frequency is on the order of 15 to 16%. Winds from these directions can reach speeds of 10 m/s or so, but are nearly always weaker, 6 m/s or less.

2.5.2 Widow's Creek steam plant.

There are two meteorological stations near the Widow's Creek steam plant. One is in the river valley, close to the plant; the other is on the plateau (Sand Mountain) across the river from the plant and some 270 m above it (see Figure 11, from Hanna, 1980). The abrupt and nearly two-dimensional change in elevation near this plant is known to have a strong influence on the valley winds in particular, which are generally parallel to the terrain (Hanna, 1980). For this reason, data from both the valley and mountain meteorological stations were considered in this report, since the wind field encountered by a plume depends on its rise. Data at both stations are routinely recorded at the 61 m level. Winds from the SSE can carry effluent to Cross Creek, while winds from the SSW and SW directions will transport material to Camp Branch.

Figure 12 illustrates the day and night annual wind roses at the valley station near the steam plant. The monthly day/night wind roses, though not shown here, are quite similar. At this in-valley location, winds from the SSE are quite rare, never occurring more than 4% of the time. When SSE winds are observed, they are often quite brisk, with speeds up to 10 m/s. Winds from the SSW through SW sector are very common, especially during late spring and summer days, and occur more than 20% of the daytime hours in every month but September (13%). Wind speed during these periods is generally moderate, less than 6 m/s, although stronger winds are certainly possible. At night, the SSW through SW sector is especially important during spring and early summer; its contribution dies off somewhat in late summer and early fall, and then recovers during the winter. The nocturnal annual average contribution from these directions is close to 20%. As might be expected, the nighttime wind speeds are a bit weaker than their daytime counterparts; i.e, nearly always less than 6 m/s for these wind directions.

Figure 13 shows for contrast the day and night annual wind roses from the mountain station above the steam plant. The distribution of wind directions is clearly much more uniform that at the valley station. By day, winds from the SSE can be expected about 10% of the time during late autumn and early winter, but occur only on the order of 5% of the time during the rest of the year. Daytime wind speeds associated with this wind direction can be fairly brisk, 8 to 10 m/s, but are usually somewhat less. At night, the SSE direction occurs 5 to 7% of the time in late winter and spring; the likelihood of this wind direction increases to about 10% for most of the remaining months, with a drop to 7% in September countered by an increase to 12% in November. The nighttime speeds associated with the SSE direction are again rather high at this station, reaching 8 to 10 m/s except in summer, when 6 to 8 m/s maximum values are more likely. Nocturnal winds from this direction are nearly always greater than 2 m/s at this mountain site. On an annual basis, daytime winds from the SSW through SW sector are not uncommon, occurring roughly 13% of the time. There is relatively little variability over the months; winds from this sector are observed between 10 and 18% of the time in all months but September, when only 9% of the winds fall in this range. The maximum likelihood of 18% occurs in December, but 17% is found in June. Daytime winds speeds associated with the SSW through SW sector can be as high as 10 m/s during the winter months, although an upper limit of perhaps 8 m/s is more probable in both winter and spring. By summer, the likely average wind speed maxima are in the 4 to 6 m/s range, gradually rising to 6 or 8 m/s by late autumn. The SSW through SW direction is somewhat more prevalent at night during the spring and summer months, occurring between 15 and 17% of the time from March through August. The minimum probability of nocturnal winds from this sector falls in September (just as by day), with only 7%. Intermediate frequencies of occurrence are observed during autumn and winter. Nighttime winds from the SSW through SW direction are usually less than 8 m/s over most of the year, and less than 6 m/s during the summer.

2.6 Mixing Layer Depth.

No direct measurements of mixing layer depth are available at Camp Branch or Cross Creek or, for that matter, at the two major sources considered, the Widow's Creek and Kingston Steam Plants. This is a fairly serious deficiency from a modeling standpoint, since it is still unclear how mixing layer depth varies with terrain and vegetative cover, making extrapolation from other locations a risky business. Furthermore, even if the region where the mixed layer is of interest is close to, say, a NWS radiosonde station, the computation of mixing layer depth at various times of the day from the 0000 GMT and 1200 GMT ascents is not straightforward. The U.S. Environmental Protection Agency models generally incorporate an interpolation scheme based on Holzworth's (1967, 1972) method of estimating the morning and afternoon mixing depths from the radiosonde data; see, for example, the "Preprocessor" to the CRSTER model (U.S. EPA, 1977). This technique may be adequate by day, but probably is inappropriate at night when the EPA scheme may not be a very good approximation to the physical situation. Benkley and Schulman (1979) have recently criticized the EPA approach. They suggested an alternative model, which estimates both the mechanically-driven mixing depth, as forced by the local wind, and the convective mixing depth, using local surface temperature and the radiosonde data. The larger of these two values is then assumed to be the mixing layer depth. Their method appears to correlate well with a limited data set from the grassy flatlands of central Illinois, particularly during the evening when the EPA procedure showed little predictive skill. How either method performs in rolling forested terrain is unknown.

In this brief preliminary study, it was not feasible to develop a numerical method for mixing depth estimates using the method of Benkley and Schulman. Instead, the readily available EPA technique was applied, using the applicable sections from the CRSTER code (U.S. EPA, 1977). The rural mixing depth (HLH1 in the code) was calculated on an hour-by-hour basis from the radiosondes released at the Nashville, TN airport, the closest reporting station. The data were provided to ATDL by the TVA's Air Resources Program at Muscle Shoals, AL, and covered the years 1977-1979. These data were used to generate hourly estimates of mixing layer depth between April 1, 1978, and December 31, 1979. Data for the period January 1, 1980 through March 31, 1981 were unavailable. To provide crude estimates of the mixing depth during this time, the entire 1977-1979 radiosonde record was used to calculate monthly-averages of the hourly mixing depth. These average values were then used as needed to fill the gaps in the original data set. The estimates for January 1, 1980, through March 31, 1981, must therefore be regarded as highly speculative. The average mixing layer depths were found to have a strong seasonal variation.

3. A SIMPLE TRANSPORT MODEL

3.1 Model Description and Data Requirements.

Models available for estimating atmospheric transport, diffusion and deposition have recently been described by Hosker (1980) and Rao (1981), among others, and range from the simple to the extremely complex. The model selected for use in this preliminary study is based on one developed for the National Research Council by North and Merkhofer (1975). Rao (1975) improved the North and Merkhofer model by including plume rise calculations based on Briggs' (1975) recommendations, and washout computations following the approach of Scriven and Fisher (1975). While simple, Rao's model incorporates a number of phenomena important for medium- to long-range pollutant transport, such as chemical transformation of one species to another, wet and dry deposition en route of both species, and the time-dependence of the depth of the near-surface mixing layer of the atmosphere. Since the sources considered are power plants, plume rise due to buoyancy and/or momentum is calculated and checked against the mixing layer depth to see if dispersion actually occurs in this layer. A mean wind dependent on atmospheric stability is used to transport the pollutant. The procedure is as follows.

Two pollutant species are assumed to be emitted at some arbitrary location at rates Q_1 and Q_2 (kg/hr), respectively. These species are carried off by the mean transport wind U_m (m/s). In view of the travel distances involved, and for simplicity, plume-type diffusion is not considered; instead, the pollutant is assumed to be well-mixed within a "pie"-shaped sector of angle θ (radians) and mixing layer depth H (m). As the pollutants travel downwind within this sector, species 1 is converted to species 2 by a first-order chemical reaction: $C_1 \xrightarrow{k_c} C_2$, where k_c is the reaction rate. For the sulfur dioxide to sulfate reaction, we assume a conversion rate of 1% per hour (e.g., see the review by Eliassen, 1980). Both species can be removed by turbulent dry deposition to the underlying vegetation and ground surface, with characteristic dry deposition velocities of v_{d1} and v_{d2} (m/s), respectively. Both species can be washed out by rainfall as well, at a rate (sec^{-1}) $k_R = f\sqrt{I} \times 10^{-4}$, where f is the fraction ($0 \leqq f \leqq 1$) of the time period of interest during which precipitation occurs, and I is the average rainfall intensity (mm/hr) during that fraction, (see, e.g., Scriven and Fisher, 1975). The overall deposition rate for species j is then $k_j = k_R + v_{dj}/H$.

Let the well-mixed plume sector be divided into a wedge-shaped sector of length x_o (m) adjacent to the source, and a sequence of progressively larger volume segments, each of length Δx (m). It is assumed that the near-source concentrations out to the distance x_o are not significantly affected by the removal or chemical transformation processes. Within this first segment, let C_{jo} be the volumetric concentration of species j. Regardless of x_o,

$$C_{20}/C_{10} = Q_2/Q_1, \qquad (1)$$

the ratio of the source strengths. To calculate C_{10}, note that during an arbitrary time interval Δt, a pollutant mass $M_1 = Q_1 \Delta t$ is emitted. This same amount of material must exit the segment through its end area A_o, given by $A_o = x_o \theta H$, such that $M_1 = C_{10} U_m A_o \Delta t$. Thus the concentration of species 1 in the sector next to the source is given by

$$C_{10} = \frac{Q_1}{U_m x_o H \theta} \qquad (2)$$

For segments further downwind, mass conservation requires that the quantity of species j entering the volume must equal the amount leaving, plus the amount removed en route, plus or minus the amount chemically transformed within the segment. Thus, at any x, over an arbitrary time interval Δt,

$$C_1(x) \cdot x \ \theta \ H \ U_m \Delta t = C_1(x+\Delta x) \cdot (x+\Delta x) \ \theta \ H \ U_m \Delta t + C_1(x) \cdot (k_1 + k_c) \ \Delta t \ V_s(x), \qquad (3)$$

and

$$C_2(x)\cdot x\ \theta\ H\ U_m \Delta t = C_2(x+\Delta x)\cdot(x+\Delta x)\ \theta\ H\ U_m \Delta t + C_2(x)\cdot k_2\ \Delta t\ V_s(x) - \bar{m}\ C_1(x)\cdot k_c\ \Delta t\ V_s(x), \tag{4}$$

where $V_s(x)$ is the segment volume and $\bar{m}$ is the ratio of the molecular weight of species 2 to that of species 1. For the $SO_2 \rightarrow SO_4^=$ reaction, $\bar{m} = 1.499$. From the geometry of a segment,

$$V_s(x) = H\ [(x+\Delta x)^2 - x^2]\ \theta/2 \tag{5}$$

or

$$V_s(x) = H\ x\ \Delta x\ \theta\ (1 + \Delta x/2x) \tag{6}$$

Because $V_s(x)$ only appears in terms involving the removal and transformation rates, which serve mainly as corrections to the atmospheric dispersion, $\Delta x/2x$ was neglected in Equation (6) compared to unity*, so that

$$V_s(x) \cong H\ x\ \Delta x\ \theta. \tag{7}$$

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*First, $\Delta x/2x \gtrsim 0.1$ for $x \gtrsim 2.5$ km; the calculations were performed out to distances $\gtrsim 75$ km. Second, the volume-related term $1 + \Delta x/2x$ is itself multiplied by a factor that is generally quite small except in heavy rain. Consider the combination of Equations (3) and (6); the term of interest is

$$1 - (k_1+k_c)(\Delta x/U_m)(1+\Delta x/2x)$$

The factor $(k_1+k_c)(\Delta x/U_m)$ is essentially the ratio of the characteristic time for flow through a segment $(\Delta x/U_m)$ to the characteristic time for removal and/or chemical transformation. This factor was evaluated for plausible ranges of weather conditions, and was $\lesssim 0.15$ for all cases where $U_m > 2$ m/s, $H \gtrsim 100$ m, and rain intensity $\tilde{I} \lesssim 25$ mm/hr (for rain time factor $\bar{f}=1$). The wind restriction is met 94% to 99% of the time according to the meteorological data for the source-receptor pairs of interest. The mixing layer restriction (less critical, anyway) should be met except under very stable conditions. However, neither of these restrictions are needed in dry weather; the factor will always be small. For $U_m > 2$ m/s and $H \gtrsim 100$ m, the factor $\gtrsim 0.1$ only for moderate to heavy rainfall $(\bar{I} > 10$ mm/hr$)$. Under most conditions, then, the simple approximation to $V_s(x)$ in Equation (7) should be adequate, and is consistent with other modeling accuracies in this preliminary work.

Then Equations (3) and (4) become

$$C_1(x+\Delta x) \cong C_1(x)\left[1 - \frac{k_1+k_c}{U_m}\Delta x\right]\frac{x}{x+\Delta x} \tag{8}$$

and

$$C_2(x+\Delta x) \cong C_2(x)\left[1 - \frac{k_2}{U_m}\Delta x\right]\frac{x}{x+\Delta x} + C_1(x)\left[\frac{\bar{m}k_c}{U_m}\Delta x\right]\frac{x}{x+\Delta x} \tag{9}$$

The behavior of these expressions for C_1 and C_2 relative to the initial segment concentration C_{10} is indicated in Figures 14a through d for a range of parameter values, assuming a 5 m/s wind at 50 m height during unstable atmospheric conditions. Note that C_1/C_{10} is not very sensitive to the parameters used unless rather extreme values are employed.

Equations (7), (8), and (9) were used to derive estimates of the airborne concentrations of sulfur dioxide (C_1) and sulfate particles (C_2) at the Camp Branch and Cross Creek watersheds, marching downwind from each source in distance increments $\Delta x = 0.5$ km. The model calculated the strength for each SO_2-emitting stack at sources near these sites, determined whether or not the plume from that stack remained within the mixed layer, and then calculated the total source strength Q_1 due to all contributing stacks at that source. The sulfate emission rate was assumed in this preliminary study to be 1% by volume of the sulfur dioxide rate, so that $Q_2/Q_1 = 0.01\,\bar{m}$. The distance for pollutant transport substantially unaltered by removal mechanisms was estimated to be $x_o = 0.5$ km, which should be reasonable in all but the heaviest of rainstorms. Mixing depths were evaluated as discussed in Section 2.6, above. The mean transport wind was assumed to occur at a height H/2 above the ground, and a stability-dependent power law was used to estimate its value:

$$U_m = U(z_T)\left[\frac{H}{2z_T}\right]^p \tag{10}$$

where z_T is the tower height for the wind speed observations $U(z_T)$ near the source, and p ranges from 0.1 to 0.3 as atmospheric stability increases. Because p is small, the choice of height for the transport wind is not critical. The sector angle θ through which the plume was mixed was taken in this initial assessment as 15° (North and Merkhofer, 1975), although this could be made to depend on a plume width estimate based on the TVA's measured standard deviation of wind direction σ_θ at each source location. The deposition velocity for sulfur dioxide was taken as 1 cm/sec, a reasonable estimate, at least in daytime, considering the forested terrain of the area (see McMahon and Denison, 1979, and Sehmel, 1980). Recent experiments at a similarly vegetated site suggest, however, that this value may be roughly a factor of two too high as a diurnal average (Hicks, private communication), and this should be borne in mind when considering the results. The effect on concentrations should be small. The deposition velocity of sub-micron sulfate particles is known to be small, and was assumed here to be 0.3 cm/sec (a compromise value; see McMahon and Denison, 1979, and Hidy *et al.*, 1976). Again, recent data over a forested area suggest this value may not be appropriate as a diurnal average; an estimate of 0.5 cm/sec might have been better. Again, the effect on the concentration results should be small. Measured rainfall intensities were used to evaluate k_R, as described above.

3.2 Data Manipulations.

3.2.1 Source data.

As mentioned above, only the TVA's Widow's Creek and Kingston steam plants were treated as sources in this preliminary assessment. The TVA's Data Services Branch in Knoxville, TN provided magnetic tape records of meteorological data from both plants, as well as from the watershed site. The TVA's Air Resources Branch in Muscle Shoals, AL, supplied tapes of the Nashville mixing height data described previously, as well as coal use and emissions data for both steam plants.

Wind direction data from both plants were used to select periods for analysis. Whenever the wind at Widow's Creek was from 206° ± 7.5°, it was assumed that the effluent plumes could affect the Camp Branch site, 92.8 km away; when the Widow's Creek wind direction was 156° ± 7.5°, the plumes were assumed to affect Cross Creek, 22.3 km away. Similarly, winds at Kingston from 67° ± 7.5° carried effluent to Camp Branch, 76.6 km away, while winds from 52.5° ± 7.5° transported it to Cross Creek, 152.1 km distant. Both the "valley" (near-plant) and "mountain" meteorological tower data were used at Widow's Creek, in view of the known strong effect of the local terrain on the near-surface wind field and turbulence at that site (Section 2.5; see also Hanna, 1980).

For each hour determined from the wind direction screening, the pertinent emissions information was calculated for the steam plant in question using coal analysis and consumption data. To find Q_j, the SO_2 source strength for the jth coal-fired boiler unit, the coal sulfur content in % was converted to a fraction and multiplied by the pounds of coal burned during that day, the ratio of the molecular weights of SO_2 to S (1.998), and a S $\rightarrow$ SO_2 conversion efficiency estimate of 0.95. The result was then converted to units of kg/hour and recorded as the average hourly emission from the jth boiler on that day. Often several effluent streams are fed to a single stack; the average source strength for this stack is just the sum of the Q_j's over all the contributing units.

Unit 8 at the Widow's Creek steam plant required separate treatment because it is fitted with a sulfur dioxide scrubbing system. The data recorded by the TVA for this unit depend upon the date. Between April 1, 1978 and May 31, 1979, the SO_2 emission was estimated using the calculation method just outlined, plus the additional assumption that only 20% of the SO_2 evolved was actually emitted -- i.e., the scrubber was 80% efficient. Between June 1, 1979, and December 31, 1979, the TVA supplied (John Blackwell's letter of March 10, 1982, to Bruce Hicks; private communication) tabular data from a stack monitor on the twenty-four hour average SO_2 emission, in pounds per million BTU's of heat. These data were combined with the TVA records of heat content per pound of coal burned and the quantity of coal used, averaged over 24 hours, and scaled to give the average hourly emission rate from Unit 8 in kg/hour. From January 1, 1980, through March 31, 1981, the stack monitor output was available on the coal data tape, facilitating the computation.

The effluent exit velocity from any stack is important in the calculation of plume rise, and depends upon the operating load. The TVA supplied emission velocity estimates for each stack at Widow's Creek and Kingston for 50, 75, and 100% of the manufacturer's nominal maximum heat input to that stack. These velocities were used to deduce a least-squares best-fit expression for plume exit speed as a function of heat input to the stack, and the coal analysis and consumption data were used to calculate the average hourly heat input for each day of interest. The results were recorded for later use along with the average hourly source strengths for each stack. The stack internal diameters and height, and the plume exit temperature (which did not seem to vary significantly with load) were also recorded. Table 1 (John Blackwell's letter; private communication) reproduces the stack-specific data supplied by the TVA. The plume rise computations follow Briggs' (1975) recommendations, and are used mainly to

TABLE 1

STACK AND EMISSION PARAMETERS FOR KINGSTON AND WIDOW'S CREEK STEAM PLANTS*

		Stack Parameters			Generation Per Stack		Heat Input Per Stack	Emissions Parameters	
Steam Plant	Units	No.	Height (m)	Internal Diameter (m)	Percent of Nameplate	Power (MWe)	(MBTU/hr)	Velocity (m/s)	Temperature (°K)
Kingston	1-5	1	304.8	7.92	100	900	8,450	32.7	422
					75	675	6,430	24.8	422
					50	450	4,410	17.0	422
	6-9	1	304.8	7.92	100	823	7,680	29.7	422
					75	617	5,870	22.7	422
					50	412	4,060	15.7	422
Widow's Creek	1-6	1	304.8	8.23	100	853	8,780	33.0	428
					75	640	6,710	26.0	419
					50	426	4,630	20.0	416
	7	1	152.4	6.34	100	575	5,440	31.5	399
					75	431	4,120	23.8	399
					50	288	2,790	16.2	399
	8	1	152.4	7.39	100	550	5,460	26.8	347
					75	413	4,110	22.0	347
					50	275	2,770	17.2	347

* Courtesy of the TVA's Air Resources Program (letter from John Blackwell to Bruce Hicks on March 10, 1982).

see if the plume remains below the mixing height and can therefore contact the ground.

3.2.2 Receptor data.

Most of the data required to operate the simple model described in Section 3.1 were obtained from the meteorological and emissions records of the two steam plants. The mixing layer depth H was deduced from the Nashville, TN airport radiosonde flights, as described above.

Rainfall data from the two watershed sites were used to estimate f, the fraction of the time period of interest during which precipitation (and hence wet removal of pollutants) occurs. In this preliminary study, the simplest possible estimate was used: if it was raining at Camp Branch or at Cross Creek in any given hour, f was taken to be unity for calculations related to that site during that hour. Otherwise, f was set equal to zero. A more sophisticated technique might check for the presence of rainfall at both the source and receptor, and choose f accordingly; if rain occurred at both locations, f would be unity, while if rain occurred only at one location, f would be approximated by one-half, and if no rain was observed, f would be zero. Since rainfall records at the TVA steam plants were not provided, this method could not be applied. The method could be further refined by considering rainfall records from other sites in the neighborhood to fine-tune the amount of wet removal, but the simplicity of the model probably does not warrant such attention to detail, even if the data were available. The measured rainfall intensity was also retrieved from the data, converted to mm/hour, and used in estimating the rainfall-induced pollutant removal rate k_R operating on the pollutant plumes.

The average sulfur dioxide concentrations from Camp Branch and Cross Creek at the 25m height on the watershed towers were selected for comparison to the model predictions, which were converted from units of $\mu g/m^3$ to ppm by volume to be consistent with the TVA's data tapes. The restriction to specific wind directions limited the number of hours in any month for which calculations were attempted --typically 100 hours or less. This small data set was further reduced because missing data often made computations impossible. In many instances, evaluation of the effective plume height indicated that the plume was above the mixing height, and therefore not contributing in the concentration calculations. As a result of these considerations, it was deemed impractical to assess the concentrations and fluxes on a monthly basis as originally planned, and the data were treated as a single group over the whole period of record.

3.3 Predicted and Observed SO_2 Concentrations

3.3.1 Average concentrations using Widow's Creek data.

The model described above is inherently capable of predicting only time-averaged concentrations; generally, the longer the averaging time, the better the results will be. Most models of this type behave similarly. Comparisons of Gaussian and sector dispersion models with data indicate that the most scatter occurs for short time periods--a few hours or less--and improves as the interval is increased to a month or, better yet, a year (Buckner, 1981). Attempts to deal with hourly data, as in this preliminary study, can be anticipated to show a great deal of scatter between predicted and observed values because of random factors unaccounted for in the model. This expectation is confirmed by Figures 15a through 15d, which show the scatter diagrams of predicted vs. observed average sulfur dioxide concentrations at the Cross Creek (CC) and Camp Branch (CB) watershed sites. The predictions of Figures 15a and b are based on hourly meteorological data from the "valley" meteorological tower adjacent to the Widow's Creek steam plant, while those of Figures 15c and d were determined using information from the tower on Sand Mountain, well above the plant (see Figure 11).

Figure 15a suggests that hourly Cross Creek concentrations greater than about 4 parts per billion (ppb) can be predicted with somewhat limited success using meteorological data from the Widow's Creek valley tower. The prediction accuracy seems to be within about a factor of ten, which is fairly typical for modeling work over moderately complex terrain and travel distances greater than 10 or 20 km (see Smith, 1980, for an interesting discussion of factors limiting modeling ability under these conditions). At very low concentrations (1 to 5 ppb), however, the model tends to overpredict by as much as a factor of fifty.

Figure 15b shows relatively little correlation between the predicted and observed concentrations at Camp Branch using Widow's Creek valley data. Concentrations less than 4 ppb tend to be overpredicted by factors up to twenty, while concentrations above 5 ppb are underpredicted to an even greater degree. In view of the considerable distance (about 93 km) and terrain complexity between the Widow's Creek plant and Camp Branch, such behavior is perhaps not too surprising. In particular it may be possible to explain the serious underprediction of the higher concentrations at Camp Branch in terms of contributions from other sources neglected in this preliminary study.

Figure 15c shows that the predicted Cross Creek concentrations using data from the Widow's Creek mountain meteorological tower do not correlate well with the observations, although the predictions are generally within a factor of ten for observations between 5 and 30 ppb, and within a factor of twenty out to 100 ppb. The tendency is to overpredict rather badly at very low concentrations, and underpredict nearly as badly at high concentrations.

Figure 15d indicates that the Camp Branch concentrations are predicted about as poorly using the mountain tower data as they were with the valley tower information, although the concentration magnitudes are within a factor of ten below 8 ppb or so, and within a factor of twenty out to 20 ppb.

Bowne (1981) has recommended a sequence of statistical tests for verification of air pollution models. Fox's (1981) summary of an American Meteorological Society workshop on dispersion model performance evaluations presents a somewhat similar list. Although time and financial constraints precluded the application of a complete set of statistical analyses to the model results, it was decided to at least include a comparison of the modeled and observed cumulative frequency distributions of SO_2 concentrations. Figure 16a shows these distributions for the Cross Creek site as observed and predicted from both the valley and mountain meteorological data from Widow's Creek. The somewhat larger data sample generated using the mountain station winds shows a greater frequency of occurrence for all observed concentrations than the distribution observed using valley wind data; both are approximately log-normal, as would be expected for such data. The predicted distribution based on the valley meteorological data has a roughly log-normal distribution whose slope (related to the standard deviation of the distribution) is similar to that of the observed distributions, although the modeled distribution tends to overpredict the concentration at any given probability by a factor somewhere between 2.5 and 5. As noted in the discussion of Figure 15c, the mountain meteorological data do not provide as good a prediction of Cross Creek concentrations as do the valley data, as evidenced by the disparity in slope (greater standard deviation) of the predicted frequency distribution. Figure 16b shows the distributions for the Camp Branch site; the observed and predicted distributions are clearly quite different. The choice of meteorological measurement site (valley or mountain) is apparently not very significant for this remote location.

3.3.2 Average concentrations using Kingston data.

Figures 17a and b show the scatter diagrams of predicted vs. observed average sulfur dioxide concentrations at the Cross Creek (CC) and Camp Branch (CB) watersheds. There seems to be no significant correlation between the predicted and observed values at either site, although the model does predict concentration magnitudes within a factor of ten between about 2 ppb and 50 ppb at Camp Branch, the site closest (about 77 km) to the Kingston steam plant. The model tends to grossly overpredict concentrations at the more distant (152 km) Cross Creek site. Perhaps the plume is more strongly diluted than the model asserts when the plume passes up and over the Cumberland Plateau.

Figure 18 shows the predicted and observed cumulative frequency distributions of SO_2 concentrations for both watershed sites, using data from the Kingston plant. Obviously the predicted and observed distributions are quite different, as anticipated from Figure 17. The observed distributions are rather similar, and have slopes (standard deviations) roughly equal to those observed at the two sites using either of the Widow's Creek meteorological towers (Figures 16a and b), while the slopes of the predicted distributions are similar to those predicted at Camp Branch only using either set of Widow's Creek stations.

3.3.3. Average flux estimates.

As mentioned earlier, the restrictions imposed by the limitation to specific wind directions, missing data, and plumes estimated to be above the mixed layer drastically reduced the number of hours per month for which predicted and modeled comparisons could be performed. No detailed analysis therefore seemed warranted, and the data were left undifferentiated over the period of record. Detailed flux computations were likewise impossible.

However, rough estimates of the average fluxes of SO_2 to the watershed sites can be attempted using the product of the approximate deposition velocity of 1 cm/sec and an average concentration:

$$\bar{F} \cong v_{d1} \bar{C}_1 \qquad (11)$$

The "average" (actually, the median) concentrations were estimated from the cumulative frequency distributions of Figures 16 and 18 at the 50% point. Table 2 shows the "average" observed and predicted SO_2 concentrations using the various meteorological sites and emission sources, and the corresponding "average" mass fluxes of SO_2 to the two watersheds. The Widow's Creek steam plant is predicted to deliver an SO_2 flux of about 0.12 $\mu g/m^2 sec$ at Camp Branch, during periods when an average flux of about 0.06 $\mu g/m^2 sec$ is estimated from observations; at Cross Creek, the corresponding values are about 0.47 $\mu g/m^2 sec$ and 0.20 $\mu g/m^2 sec$ respectively. The Kingston plant is predicted to deliver an SO_2 flux to Camp Branch of about 0.25 $\mu g/m^2 sec$ at times when an average flux of about 0.08 $\mu g/m^2 sec$ is computed from observations; the Cross Creek values are about 0.10 $\mu g/m^2 sec$ and 0.14 $\mu g/m^2 sec$, respectively.

TABLE 2

ESTIMATED AVERAGE CONCENTRATION AND FLUX OF SO_2

AT CAMP BRANCH AND CROSS CREEK

Receptor Site	Source and Met. Site	Average Concentration (ppm)		Average Flux ($\mu g/m^2 sec$)	
		Observed	Predicted	"Observed"	Predicted
CB	WCV	.0020	.0046	.053	.123
	WCM	.0026	.0042	.069	.112
	K	.0029	.0093	.077	.248
CC	WCV	.0054	.0195	.144	.520
	WCM	.0094	.0160	.251	.426
	K	.0053	.0038	.141	.101

4. A ONE-DIMENSIONAL FLUX MODEL

4.1 Model Description and Data Requirements.

Over uniform flat surfaces with little vegetation, the vertical fluxes of momentum, heat, and moisture are often specified in terms of eddy diffusivities and local vertical gradients:

$$\tau = \rho K_m \frac{\partial u}{\partial z} \quad (12)$$

$$H = -\rho c_p K_h \frac{\partial \theta}{\partial z} \quad (13)$$

$$LE = -\rho L K_w \frac{\partial q}{\partial z} \quad (14)$$

where τ, H, and LE are the momentum, sensible heat, and latent heat fluxes, respectively, c_p is the specific heat of air, L is the latent heat of vaporization, u, θ, and q are the mean wind, potential temperature, and specific humidity, respectively, and the various K's are the corresponding eddy diffusivities. Field studies have shown that atmospheric pollutants are transferred by turbulence much like heat or moisture; that is, the flux to the surface of a contaminant of mass concentration C can be expressed as

$$F_c = -K_c \frac{\partial C}{\partial z} \quad . \qquad (15)$$

In a neutrally-stable atmosphere, the eddy diffusivity for momentum, K_m, is linear with height, so that $K_m = ku_* z$, where k is von Karman's constant ($\cong$ 0.4) and u_* is the friction velocity, defined as $\sqrt{\tau/\rho}$. Equation (12) can then be integrated to give the familiar logarithmic velocity profile. If one assumes the eddy diffusitivies for other transferred properties are the same as K_m and that the fluxes are roughly constant within the layer adjacent to the surface, then Equations (13) through (15) can also be integrated.

In practice, real-world complexities limit the utility of this approach. First of all, the eddy diffusivities are not linear with height in a non-neutrally stable atmosphere, so that the profiles of u, θ, q, and C must include a stability-dependent correction term. Secondly, it has implicitly been assumed that all of the sources and sinks involved in the transfer processes for momentum, heat, water vapor, and pollutant are co-located -- i.e., the displacement height d and roughness length z_0 are the same for all the profiles. It is not clear that this assumption is fulfilled over a forest. Finally, the requirement for a constant flux layer will be violated at all but "perfect" meteorological sites, which gives rise to the customary search for flat, uniform surfaces for conducting experiments. Over a forest, the wake effects of individual treetops probably preclude the application of flux-gradient relations for heights below roughly 10 z_0 above the momentum zero-plane displacement height, even for an otherwise uniform canopy.

The problems associated with interpreting near-canopy gradient data are sufficient that the use of conventional flux-gradient relationships should be avoided. Fortunately, alternatives are available. The use of eddy correlation methods to measure fluxes directly is especially attractive, although only a few instruments are presently available with the requisite speed of response.

Instead, a new method to infer deposition rates from gradient measurements has been developed, and was tested against the TVA's data for Camp Branch and Cross Creek. The method extends measurements of fluxes which can be evaluated directly to other quantities by comparing gradients, and referring results to an easily measured quantity, the net radiation R_N. The procedure is as follows (see Hicks and Wesely, 1978).

The radiation balance for an arbitrary vegetation surface can be written as:

$$H + LE = R_N - G - P - S, \qquad (16)$$

where H and LE are the sensible and latent heat fluxes, G is the rate of heat transfer to the ground, P is the energy flux used in photosynthesis, and S is the energy flux used to warm the biomass (the "storage" term). The Bowen ratio β is defined as the sensible to latent heat ratio,

$$\beta = H/LE. \qquad (17)$$

Therefore

$$H = \frac{\beta}{1+\beta}(R_N - G - P - S), \quad (18)$$

and

$$LE = \frac{1}{1+\beta}(R_N - G - P - S) \quad . \quad (19)$$

Now measure the potential temperature difference $\Delta\theta$ and specific humidity difference Δq across some convenient height interval Δz above a canopy. From the finite-difference form of Equations (13) and (14),

$$\beta \cong \frac{c_p \Delta\theta}{L \Delta q} \quad . \quad (20)$$

A similar ratio can be formed from the expressions for pollutant flux and heat flux, Equations (15) and (13); the result is

$$F_c = \frac{H \Delta C}{\rho c_p \Delta\theta} \quad (21)$$

The dry deposition velocity v_d is defined in terms of the pollutant flux and local concentration, $v_d = F_c/C$. Hence

$$v_d = \frac{\Delta C}{C} \frac{H}{\rho c_p \Delta\theta} \quad . \quad (22)$$

Substitute Equations (18) and (20) to get

$$v_d = \frac{\Delta C}{C} \frac{R_N - G - P - S}{\rho L \Delta q + \rho c_p \Delta\theta} \quad . \quad (23)$$

Notice that this expression allows the evaluation of v_d (and hence the local pollutant flux F_c) without any direct measurement of a turbulent flux. Instead, it relies on the (relatively) easily measured differences in temperature, specific humidity, and concentration, and on the components of the local energy balance, some of which are often negligible in specific instances.

The assumptions leading to Equation (23), while important, are not believed to be prohibiting. For example, to apply the relationships for gradients and differences of the meteorological variables, it is necessary that the corresponding sources and sinks be coincident. While this requirement will generally be satisfied over surfaces such as pasture, water, or tarmac, the validity of the assumption should be tested over complex surfaces such as forest. A suitable test might compare results derived using differences obtained over different height intervals. In any case, some caution is advisable.

4.2 Data Manipulations.

4.2.1 Approximation of the radiation balance.

Application of Equation (23) to the Camp Branch and Cross Creek sites requires data on net radiation and other energy balance components that were unfortunately not directly measured. Approximations were therefore necessary. The most important term, the net radiation R_N, was estimated from temperature data and insolation (short-wave solar radiation) measurements as follows.

The incoming long-wave sky radiation contribution was estimated from the relation of Paltridge and Platt (1976, based on Swinbank's 1963 work):

$$R_{L\ down} \cong (5.31 \times 10^{-13})\ T^6 \qquad (24)$$

where T is the local (Kelvin) air temperature and $R_{L\ down}$ has units of W/m^2.

The outgoing long-wave radiation was calculated from the usual Stefan-Boltzmann relation and an assumed canopy emissivity of 0.96 (probably accurate to about 3%):

$$R_{L\ up} \cong 0.96\ \sigma\ T_s^4 \qquad (25)$$

where the Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ (W/m^2K^4) and T_s is the absolute temperature of the canopy surface. It was assumed, since foliage temperature was not directly measured, that the foliage was about 2 degrees (K) warmer than the in-canopy air temperature by day, and 2 degrees cooler at night.

The net radiation was then estimated to be

$$R_N \cong (1 - 0.15)\ R + R_{L\ down} - R_{L\ up} \qquad (26)$$

where R is the measured insolation, and the factor 0.15 is an estimate of the deciduous canopy albedo (e.g., Rauner, 1976).

4.2.2 Use of the TVA data.

Before Equations (23) and (26) can be applied to a data set to estimate v_d, one must also be able to estimate the remaining components of the energy balance, G, P, and S. Perhaps more importantly, the gradients (or differences) of C, q, and θ must be reasonably well behaved, and measured with considerable accuracy. It was decided to test this latter requirement first. It is not immediately obvious how commercially-available pollutant concentration monitors can best be used in this sort of application. The TVA data obtained at Cross Creek and at Camp Branch provide an excellent opportunity to test the quality of gradient information that can be obtained by routine monitoring methods.

The large amount of data generated at the two TVA field sites makes a comprehensive analysis rather difficult. Therefore, a data subset was selected from periods corresponding to the best understood conditions, with maximum likelihood that the sensors were responding adequately. The following criteria were imposed.

(1) Only afternoon data (1200-1500, LST) were used, so as to eliminate periods of rapidly changing meteorological conditions, and to focus on unstable stratification, when the transfer relations are best understood. An additional advantage of this afternoon period is that the energy flux balance components G, P, and S are likely to be negligible compared to R_N (e.g., Hicks, Hyson, and Moore, 1975), and the model then requires only well-behaved gradients (or differences) of C, q, and θ.

(2) Only occasions with complete sets of relevant data were considered.

(3) Sulfur dioxide average data were selected for this preliminary study, rather than peak values, since the micrometeorological relations given above are intended to address average values only.

(4) To eliminate circumstances in which instrument sensitivity problems could have arisen, occasions when concentrations less than 0.003 ppm were reported were disregarded.

(5) After all these criteria were imposed, there was still too much information available for ready analysis and assimilation of the results. Consequently, two months of information were arbitrarily selected (January and July,

1979) to represent leafless and leafed canopy conditions, respectively.

Initial statistical tests showed no significant differences between the Cross Creek and Camp Branch gradients, or even between summer and winter conditions. (Note that these are the results of the statistical tests. Of course the physics, chemistry, and biology of the situations are quite dissimilar.) In consequence, for purposes of statistical analyses of the gradient information, the four subsets of data were combined.

4.3 Results of Data Analysis.

Statistical treatments based on the reported concentrations alone can be highly misleading, because they may reflect mostly the consequences of very large run-to-run variability in concentration measurements, rather than real level-to-level gradients. To minimize the statistical noise introduced by time-variant air pollution conditions, the concentrations were normalized for each hour according to the average value of the concentrations recorded at the three measurement levels (27, 7, and 1 m above the forest floor). The resulting normalized values for the averages, standard deviations, and standard errors are shown in Table 3.

The table shows no evidence of a statistically significant gradient; however, it appears fairly certain that the averages reported are truly representative of different sets of data. The main thing to be noted in the table is that the standard deviation at every level is more than the magnitude of the gradient that would be expected to be present due to depositional processes. In other words, it is not possible with the existing measurement system to look at sulfur dioxide deposition on a run-by-run basis. The standard errors show that even after sampling 270 hours of data during the best possible conditions,

TABLE 3

NORMALIZED AVERAGE SO_2 CONCENTRATIONS, STANDARD DEVIATIONS, AND STANDARD ERRORS FOR TOWER DATA AT BOTH WATERSHEDS

Height (m)	Average Normalized Concentration	Standard Deviation	Standard Error
27	0.947	0.130	0.025
7	1.026	0.053	0.010
1	0.982	0.125	0.019

the resulting averages were still determined too inaccurately to detect deposition-related gradients, by a factor of about ten. Thus, it would seem that the present TVA monitoring system would need to be operated for about 2700 hours in order to derive a single evaluation of deposition velocity using Equation (23).

It is equally clear that the averages tabulated above do not indicate a uniform gradient through the canopy. In fact, they suggest a source within the canopy, with fluxes both upwards and downwards from some source at 7 m height. The differences between the averages are indeed statistically significant, and they are similar (in magnitude) to the differences expected on the basis of depositional phenomena alone. The hypothesis that a source exists within the canopy is distinctly unpalatable, and alternative explanations should be sought. The most obvious possibility lies in the instrumentation and sampling systems. Even though the sampling system employs a single detector which cycles through sampling streams drawn from each of the heights of measurement, it is still necessary to verify that zero gradient is measured when the inlet ports are at the same height. Sampling line effects and the presence of water vapor gradients may also be contributing factors. Other recommendations are given in Section 6, below.

5. SUMMARY AND CONCLUSIONS

5.1 Predicted and Observed SO_2 Concentrations.

The simple sector-box model described in Section 3 was applied to data collected between April 1, 1978, and March 31, 1981 to estimate pollutant concentrations over two watersheds. Moderately good correlation between predicted and observed average SO_2 concentrations was found only for the Cross Creek (CC) site using data from the "valley" meteorological tower adjacent to the Widow's Creek steam plant. The model is able to estimate the CC concentrations to within about a factor of ten accuracy, a rather typical figure for regional transport modeling in complex terrain. The model tends to seriously underestimate SO_2 concentrations at Camp Branch (CB) when using Widow's Creek data, suggesting that other sources may be contributing to this site. SO_2 concentrations predicted using Kingston steam plant data are also generally within a factor of ten of the observed values at CB, although there is little correlation with the observations. CC concentrations are grossly overpredicted using Kingston data; perhaps the Kingston plume is diluted more than the model assumes when the effluent passes up and over the Cumberland Plateau. It should be noted that no attempt has been made in this limited study to "tune" the model parameters to optimize agreement with observations; some work along these lines would considerably improve the predictions.

5.2 Flux Estimates

The limited number of hours each month for which computations linking a particular source and receptor could be performed precluded a month-by-month study of pollutant fluxes using the simple sector-box model. By lumping the data together, and using the resulting concentration cumulative frequency distributions with a reasonable value for the dry deposition velocity, rough estimates of the average SO_2 mass flux to the watersheds were made. The value predicted at CB using Widow's Creek data is roughly twice the value deduced from concentration observations; at CC, the corresponding overprediction is a factor of about 2.4. Similarly, the SO_2 flux to CB predicted using Kingston data is roughly three times the "observed" value, but at CC, the corresponding average flux is underestimated by roughly 30%.

A simple one-dimensional model to estimate pollutant fluxes (or deposition velocities) using net radiation data and measured gradients of temperature, humidity, and concentration was developed for application to the CB and CC sites. However, a statistical analysis of data from carefully selected optimum periods suggested that run-to-run variability and possible biases in the monitoring equipment prevent an adequately accurate determination of the concentration gradient, even during these idealized conditions. It was therefore impossible to apply the model to the watershed data sets without a far more exhaustive analysis of the data than was possible in this limited study.

6. RECOMMENDATIONS

6.1 Improvements in Watershed Instrumentation and Data Collection

Most of the suggestions for improving the watershed monitoring program are based on the needs of the one-dimensional flux model developed in Section 4; a few have been mentioned earlier in a memo to Dr. J. M. Kelly of the TVA following a visit by ATDL staff to the watershed sites in July, 1981, and are repeated here for convenience.

The most important need is for direct and accurate measurements of level-to-level differences (i.e., the gradients) of temperature, humidity, and sulfur dioxide. Because of the generally well-mixed flow over a forested area, gradients of these quantities can be expected to be small; consequently, their approximation by subtracting individual measurements of the quantities at various levels is insufficiently precise. The use of a single sensor translating device, cycling between levels, is encouraged since instrument-to-instrument calibration errors are eliminated. Automatic level-interchanging or self-checking systems can also be used for gradient measurements (e.g., Black and McNaughton, 1971; McCaughey, 1981; Rosenberg and Brown, 1974). For humidity measurements, the "plumbing" should be heat-traced to eliminate condensation, and should be constructed from water-impervious materials (e.g., polyethylene tubing is good; Teflon and Tygon tubing are unacceptable).

Next, a series of tests of the sensing systems should be conducted, in which all the sensors of a particular quantity are placed in close proximity at some convenient level and the resulting measurements are compared. No differences (gradients) should be detectable during this test. This test should be repeated regularly during the monitoring period to verify that equipment drifts are not generating spurious difference measurements.

Effects of signal cables and/or sampling line losses should be determined experimentally by changing line lengths after a period of intensive study. The influence of high humidity within the forest canopy should be tested, perhaps by injecting small quantities of water vapor into the SO_2 sampling lines while conducting the comparison tests.

Direct measurements of above-canopy net radiation should be added. Measurements or estimates of the heat flux to the ground, the heat flux used to warm the canopy biomass, and the energy flux used in photosynthesis may also be helpful or even essential to the modeling effort, depending on the season and time of day.

Data are presently collected above the treetops (25 m) and at two levels (7 m and 1 m) within the canopy. It is recommended that a fourth level of measurement be installed at or above the height of the canopy's aerodynamic zero plane displacement, estimated to be about 15 m. Sampling and interpretation problems associated with in-canopy measurements could be avoided if the new level was actually placed somewhat above the treetops at, say, 22 m. However it would probably then be difficult to detect vertical gradients over the resulting 3 m distance. Perhaps an increase in tower height of 7 to 10 m would be an optimum solution. If data logging practicalities limit the number of measurements, the sampling program at 1 m should be abandoned. The above-canopy difference measurements of temperature, humidity, and concentration (wind might usefully be added) should then be made between the uppermost two levels.

Statistical analyses of the collected data should be performed on a regular basis as a means of quality control, and to determine the sampling duration necessary to detect deposition-related gradients.

The watershed sites are sufficiently irregular that topographically-induced flows (drainage, channeling) may affect local transport, diffusion, deposition, and the resulting sulfur concentrations. Low-threshold wind measurement equipment located within the canopy will be needed to explore the possibility of cold-air drainages serving as a transport or even a temporary storage mechanism for pollutants. Day/night analyses of the data will be necessary. The sector-box transport model developed in Section 3 cannot cope with terrain-induced effects; if these are detected, a more elaborate transport model will be required.

The sector-box model encountered only a few problems with the existing watershed measurement system. The most significant difficulty is the typically quite low concentration of SO_2 observed at the sites, and the resulting limited resolution available from the existing instruments. It is difficult to compare (probably noisy) single-digit observations with the predicted values in a meaningful way. An improvement in SO_2 sampler resolution would be highly desirable, but may not be possible with the present state of the art.

It would be useful for model comparisons if monthly average sulfur concentrations and fluxes were generated from the sampler data during the data processing and recording.

Finally, it would be helpful to users if the watershed data tapes were edited and subjected to quality control tests. Dubious values or gaps in the record should be flagged. Two gaps were noted in the Camp Branch record, which does not begin on April 1, 1978 but instead on April 11, and has a gap on July 1 and 2, 1979. The Cross Creek record appears to be gap-free between 0100, April 1, 1978, and 2400, March 31, 1981.

6.2 Improvements in Source Emissions and Meteorological Data

Some shortcomings in the emissions and meteorological data sets from the Widow's Creek and Kingston steam plants became apparent while using the sector-box model of Section 3. It would be useful if the emissions data were edited to eliminate misfiled ("shuffled") records, and if the coal consumption and properties data could be combined to generate direct estimated values of SO_2 and sulfate emissions.

The recovery rate for meteorological data at the steam plants probably needs some improvement. Figures 19a through f show the number of hours per month in which the wind direction was appropriate for transport of effluent from a steam plant to a watershed (solid lines), as well as the percentage of those hours in which missing data precluded model calculations (dotted lines), and the percentage of the hours in which the power plant plume was estimated to lie above the mixed layer so that zero concentration of SO_2 was projected for the watershed. There is some indication that missing data (generally air temperatures) are especially likely in January and February of each year, which suggests an equipment failure related to cold weather. No attempt was made here to confirm this. Generally speaking, missing data precluded computations using the sector-box model somewhere between 25% and 40% of the time when the winds predicted transport to the Camp Branch and Cross Creek sites. Periods when the wind came from other directions were not checked for completeness of the data records.

Rainfall data from the steam plants were not provided; consequently the time fraction during which wet removal took place, as well as its effective rate, had to be estimated solely from watershed data. In view of the large intervening distances, this restriction must lead to significant errors, particularly in the summer when isolated convective storms of limited extent abound. Hourly rainfall records should be added to the source meteorological data.

Although not strictly necessary for the sector-box model, which requires only a single user-specified deposition velocity for sulfate particles, a particle size distribution for the plant effluent would permit a better assessment of enroute plume depletion.

6.3 Modeling Improvements

For regional transport over complex terrain, a puff or segmented plume-trajectory model is probably the best choice (e.g., Bass, 1980; Miller, Cotter, and Hanna, 1981; Smith, 1980). However, limited wind field data may preclude its use for the region surrounding the CB and CC sites.

The simple sector-box model of Section 3 is capable of improvement, and has the advantage of requiring only readily available meteorological information. For example, a more site-specific estimate of plume dilution can be obtained by adjusting the sector spread angle θ on the basis of observed standard deviations of wind direction (σ_θ) near particular sources. Calculations should also probably be limited to cases where the necessary wind direction persists for several hours, to allow for the sometimes long travel times likely over the distances involved. Heck and Ellis (1981) have addressed the adequacy of the sector-box model, and stressed the importance of reasonable values for parameters such as θ and H.

The emission rates used in the model are actually daily averages, and do not reflect the hour-by-hour variability of power plant loads. Consequently it might be reasonable to further restrict model application and comparisons with observed concentrations to a much more limited time resolution. The model results might well be improved by considering other possible sulfur sources in the area (e.g., Watts Bar and Bull Run steam plants, the Bowaters paper mill, and others), and by adjusting ("tuning") important model parameters such as x_o, Δx, v_{d1} and v_{d2}, and the chemical transformation rate k_c.

The wet removal parameterization might be adjusted to depend on the nature of the likely rainfall event -- thunderstorms in summer, say, and large-scale slow-moving storms in winter.

A major problem in applying the sector-box model is the need for reliable estimates of the mixing layer depth H. If the estimated H is too large, one of two scenarios is possible: the model will calculate nonzero concentrations even for plumes which actually are above the mixed layer and hence not contributing to the watershed pollutant burden, or else the model will underpredict concentrations for those cases where the plume really is within the mixed layer. Either of these possibilities may occur at night with the nocturnal mixing layer depths estimated using the CRSTER (U.S.EPA, 1977) preprocessor described above. On the other hand, if the estimate of H is too small, there are two other cases: the model may exclude the plume from the mixed layer and erroneously predict a zero concentration, or else the model may overpredict the concentration during periods when both the modeled and real plumes are within the mixed layer. These possibilities may be significant for afternoon concentration estimates, especially those for July and August, 1980, which were forced to rely on what seemed to be rather low estimates of H from the CRSTER method. A considerable improvement in modeling reliability is likely (e.g., see Tennekes, 1979) if a better technique for estimating H is employed. The method of Benkley and Schulman (1979) seems preferable to the CRSTER technique, but verification of the procedure using aircraft, sonde, or acoustic radar data from intensive measurement periods would provide a good deal more user confidence.

ACKNOWLEDGEMENTS

This work was performed under Interagency Agreements among the National Oceanic and Atmospheric Administration, the U.S. Department of Energy, the U. S. Environmental Protection Agency, and the Tennessee Valley Authority. The authors are grateful to the TVA's project officer, Dr. J. M. Kelly, for his patience and cooperation, and to numerous TVA personnel, including J. P. Blackwell, T. Crawford, H. Jones, W. M. McMaster, C. D. Nicholson, and A. Reid, for their help in obtaining and analyzing meteorological and emissions data from the power plants and the watersheds. Programming assistance was received from H. F. Snodgrass (formerly with Oak Ridge Associated Universities) and B. Kirk (formerly of Oak Ridge National Laboratory), and especially from L. Satterfield (ORAU), who is also responsible for most of the figures. Able and patient typing assistance was provided by M. Rogers and E. Yates, both of ORAU.

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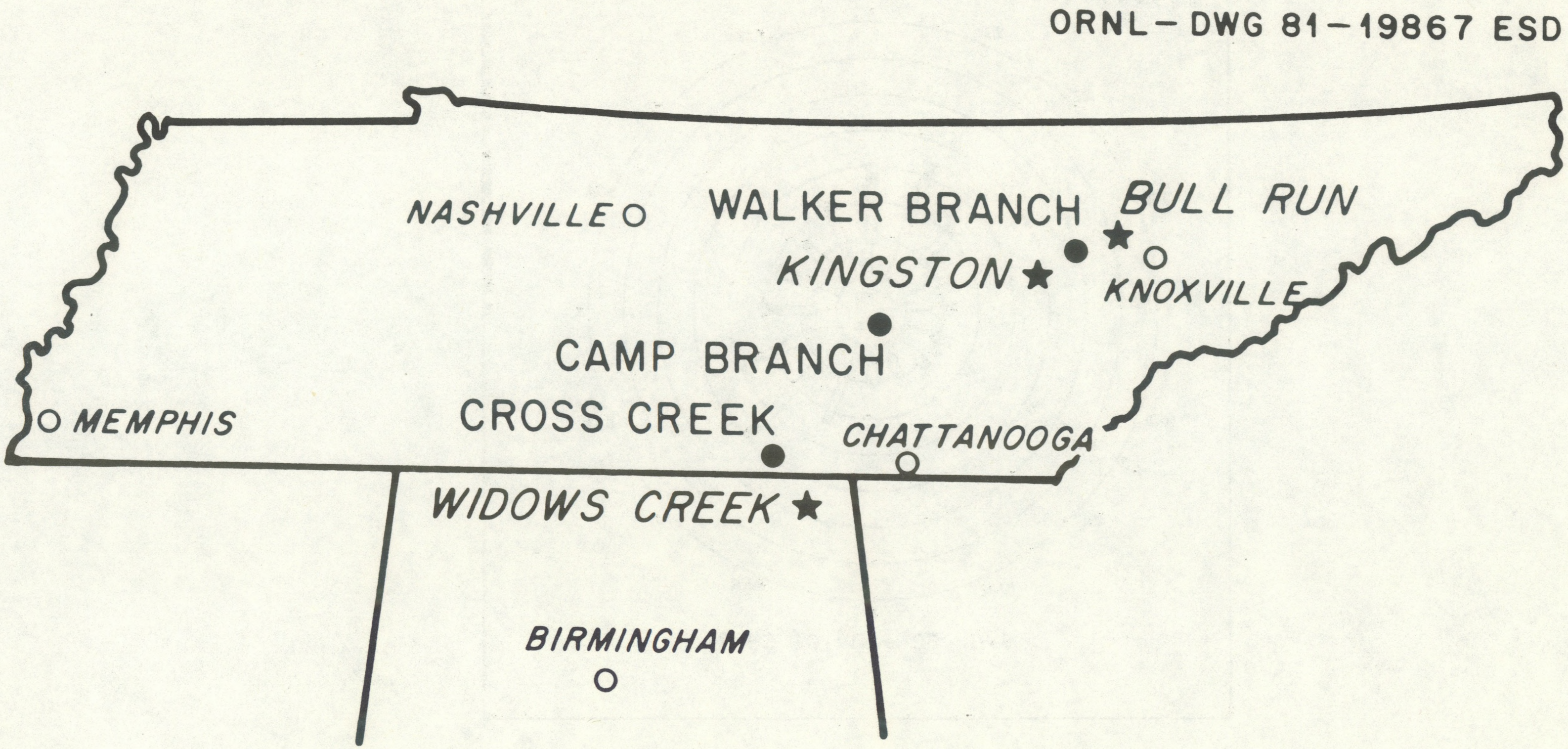


FIGURE 1. LOCATION OF CAMP BRANCH AND CROSS CREEK WATERSHED SITES RELATIVE TO OTHER TENNESSEE LANDMARKS.

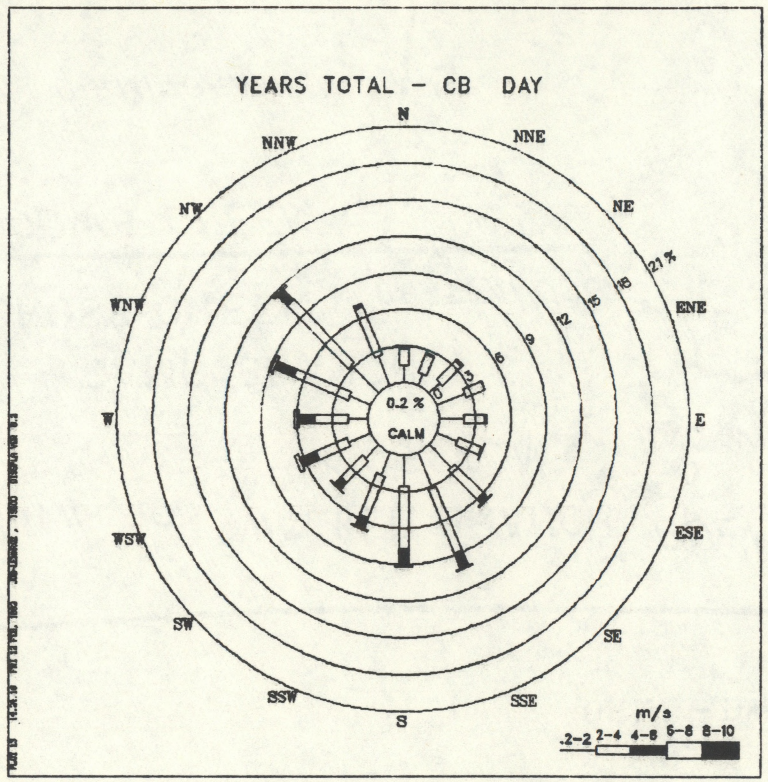


FIGURE 2. ANNUAL DAYTIME WIND ROSE FOR CAMP BRANCH.

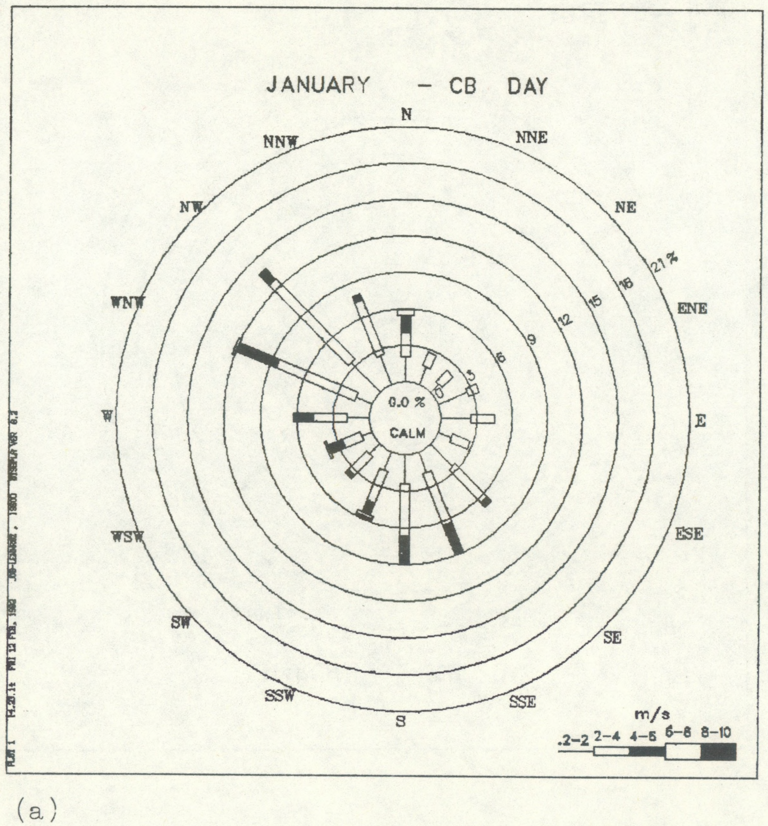
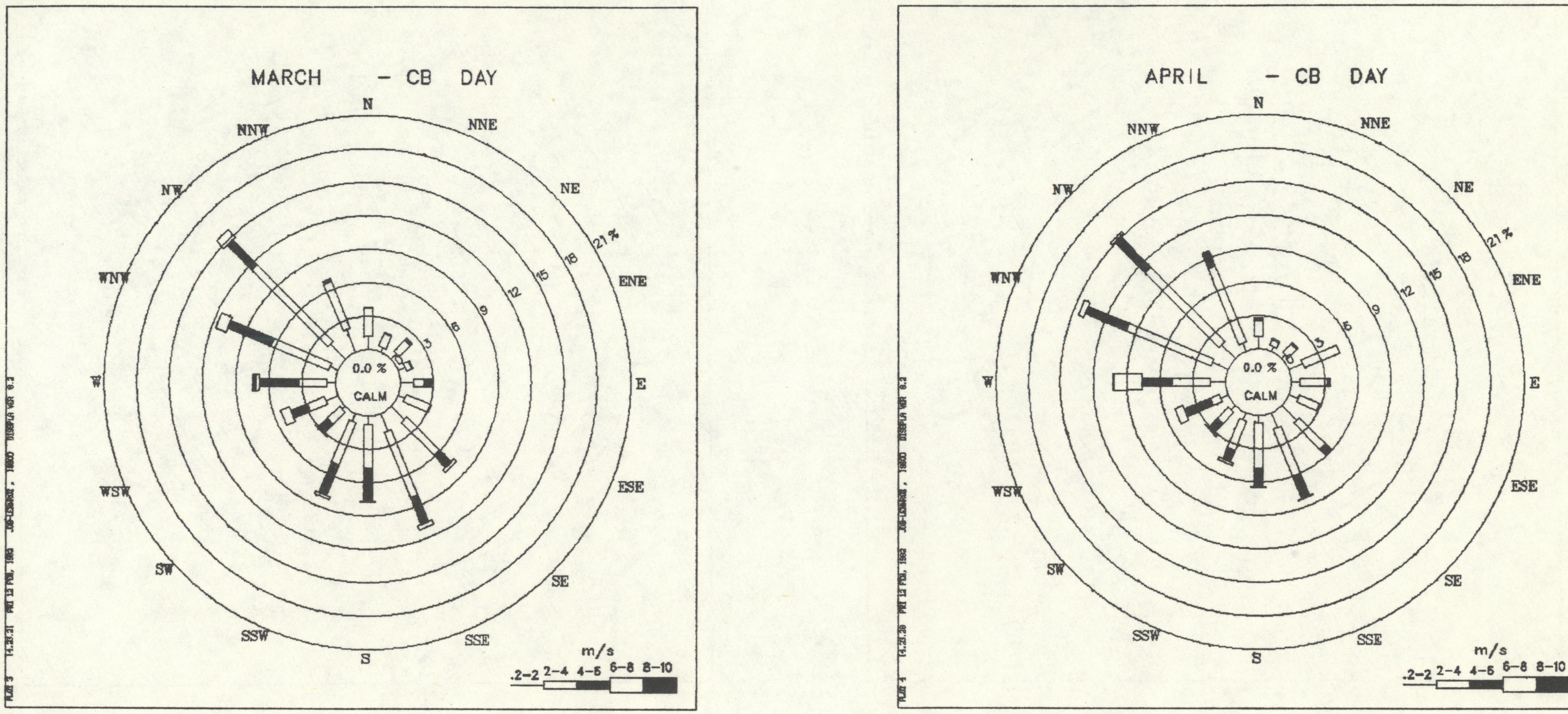


FIGURE 3. MONTHLY DAYTIME WIND ROSES FOR CAMP BRANCH.



(c) (d)

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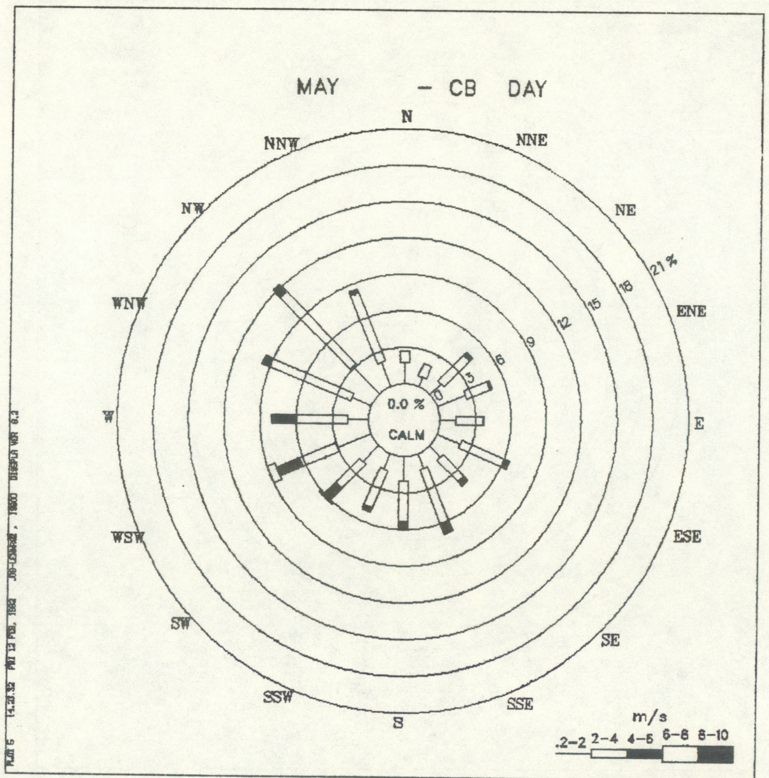

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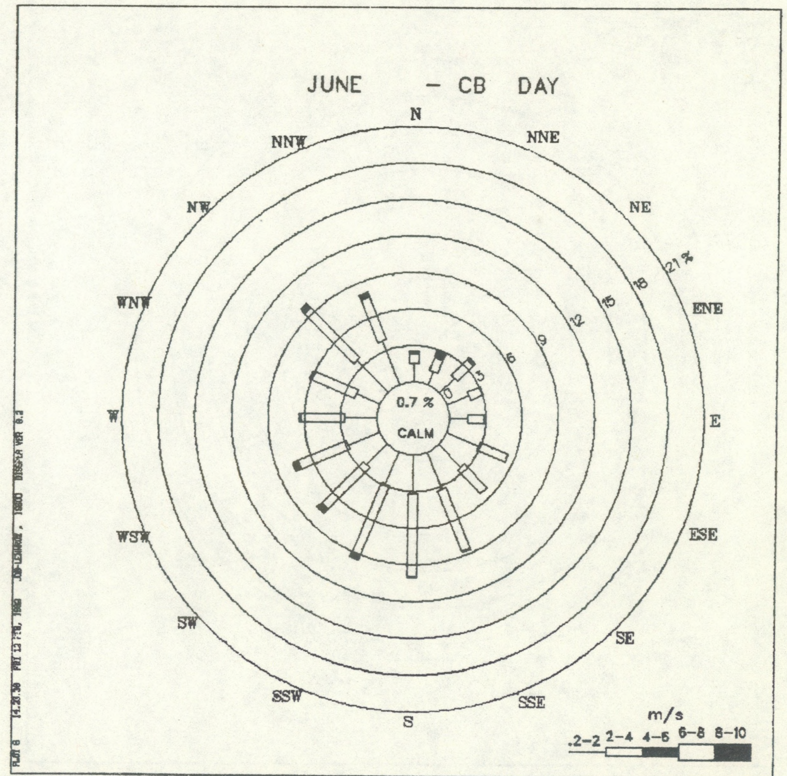

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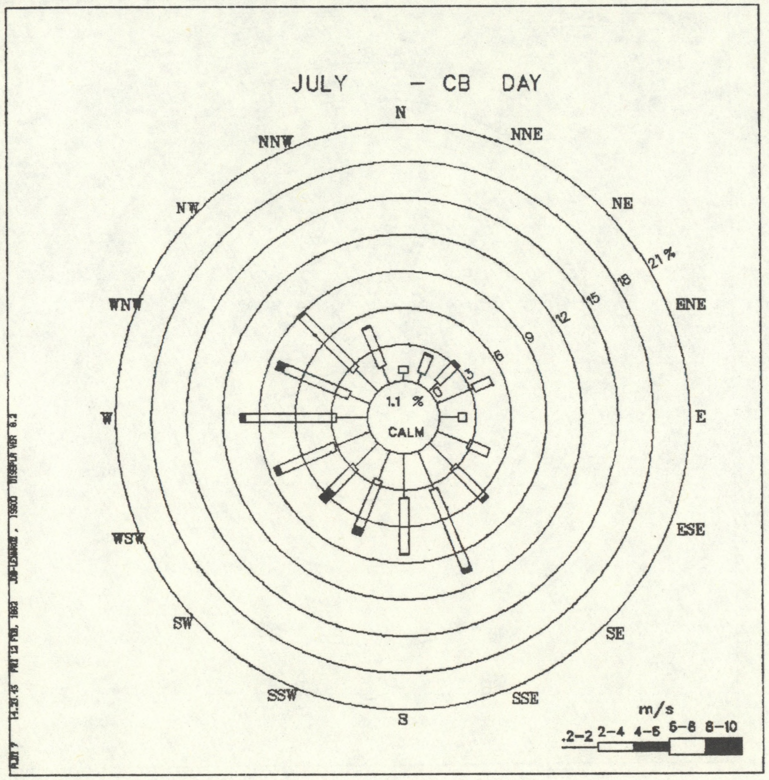

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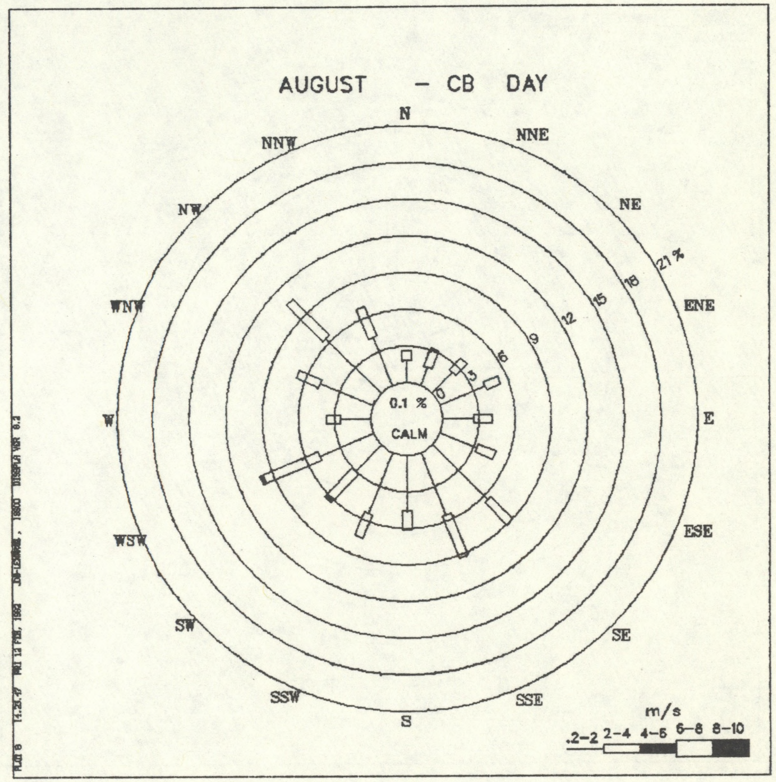

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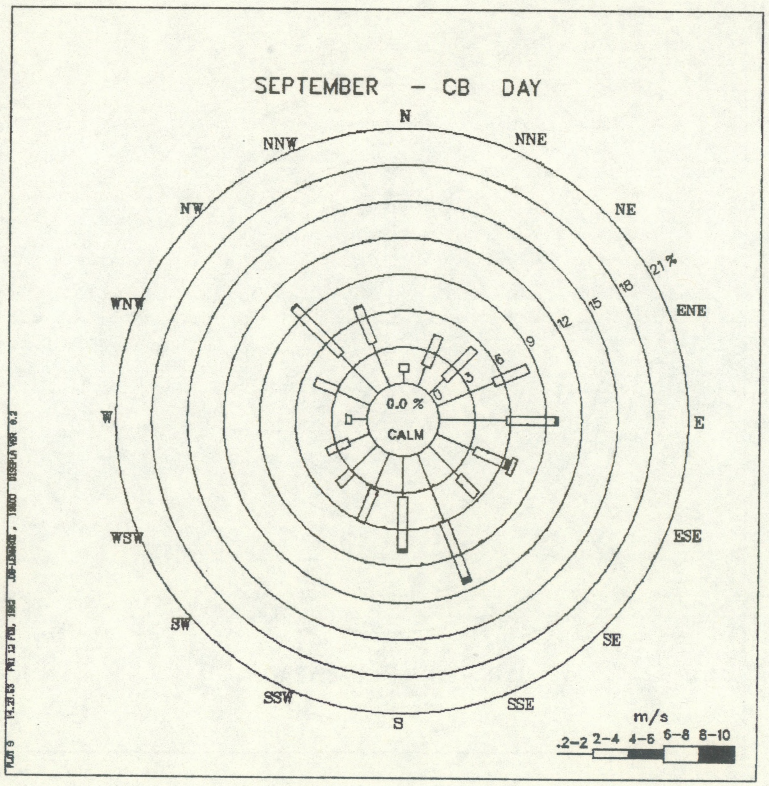

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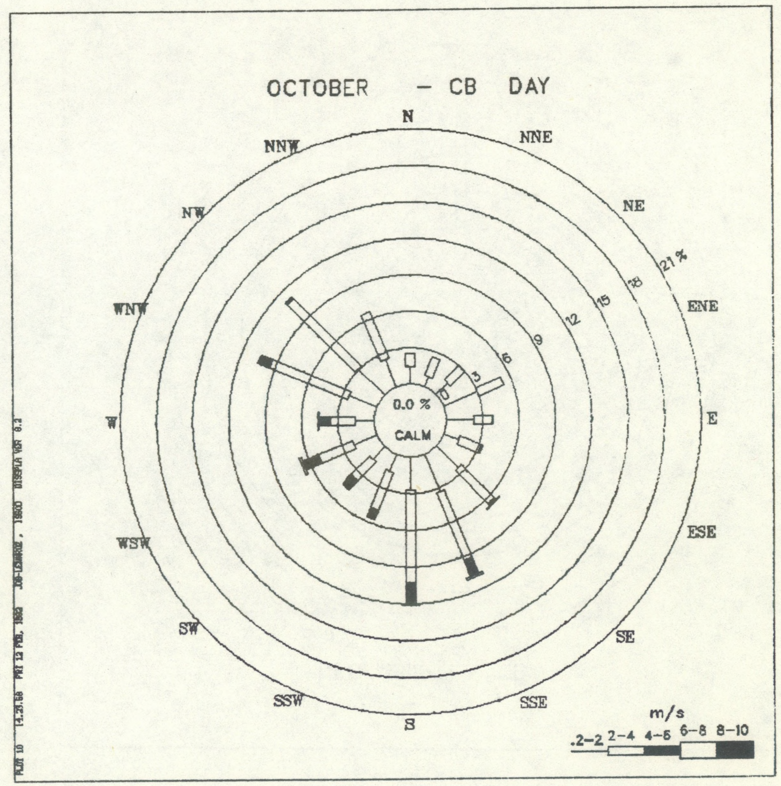

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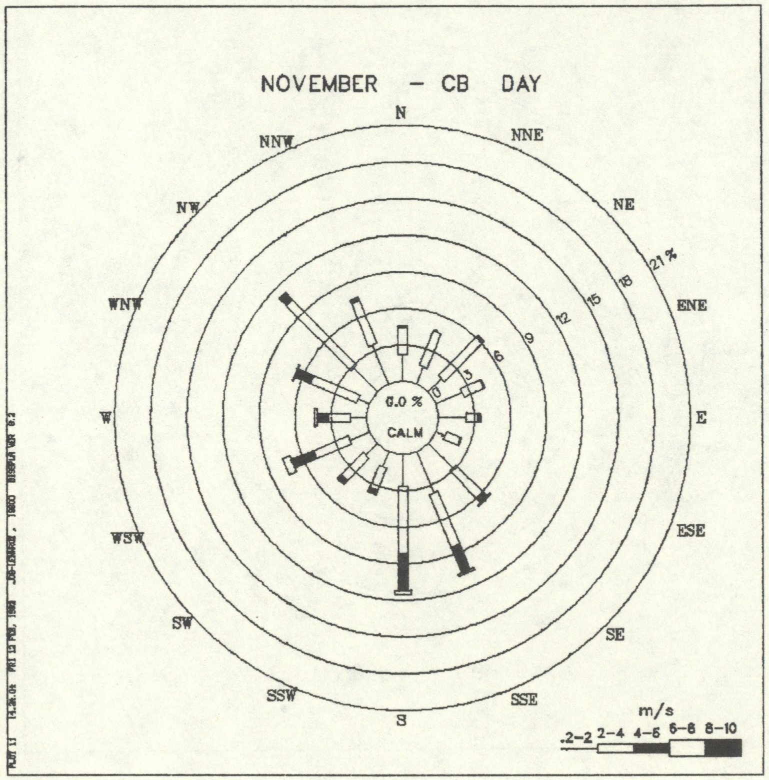

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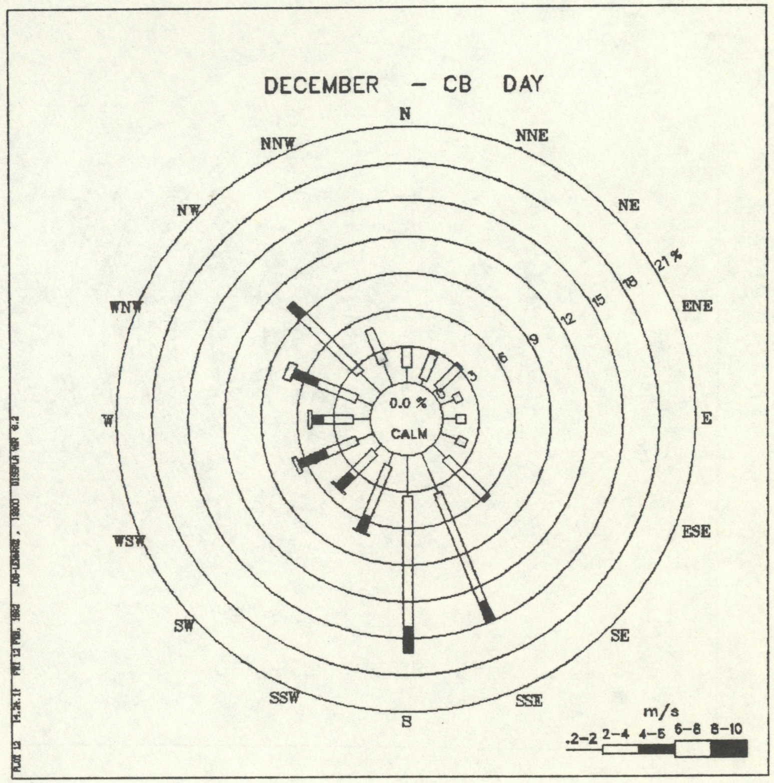

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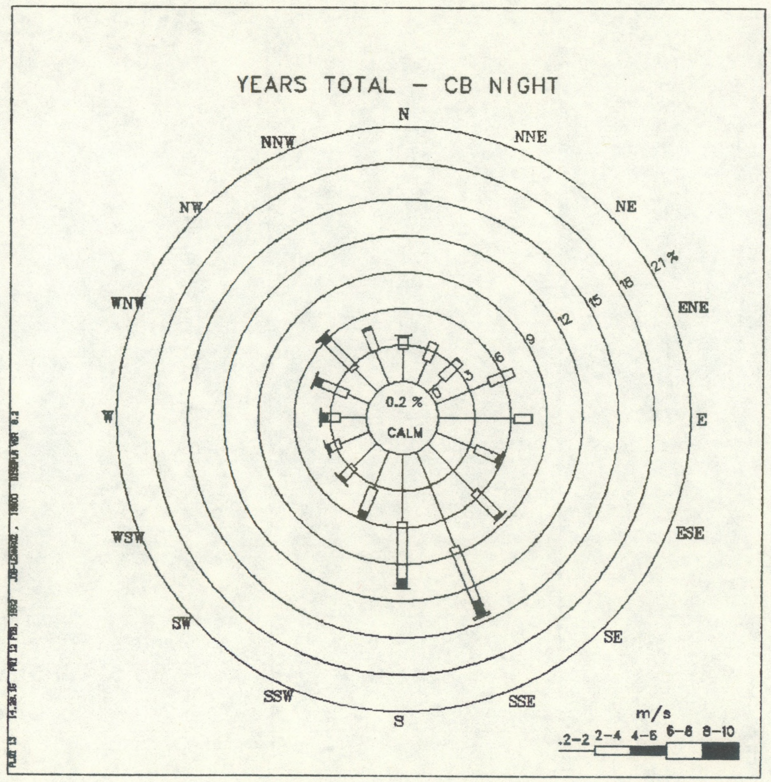
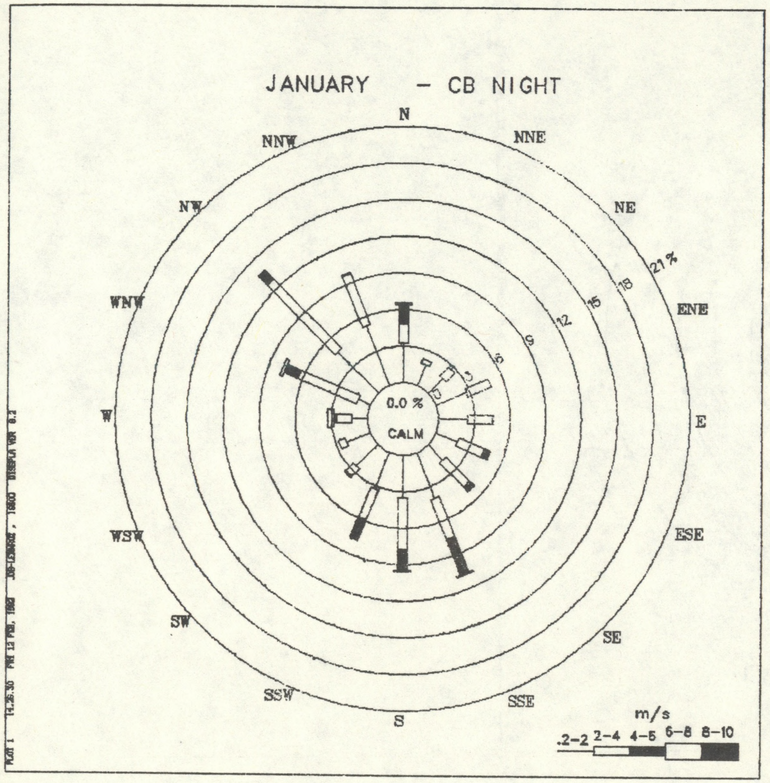


FIGURE 4. ANNUAL NOCTURNAL WIND ROSE FOR CAMP BRANCH.



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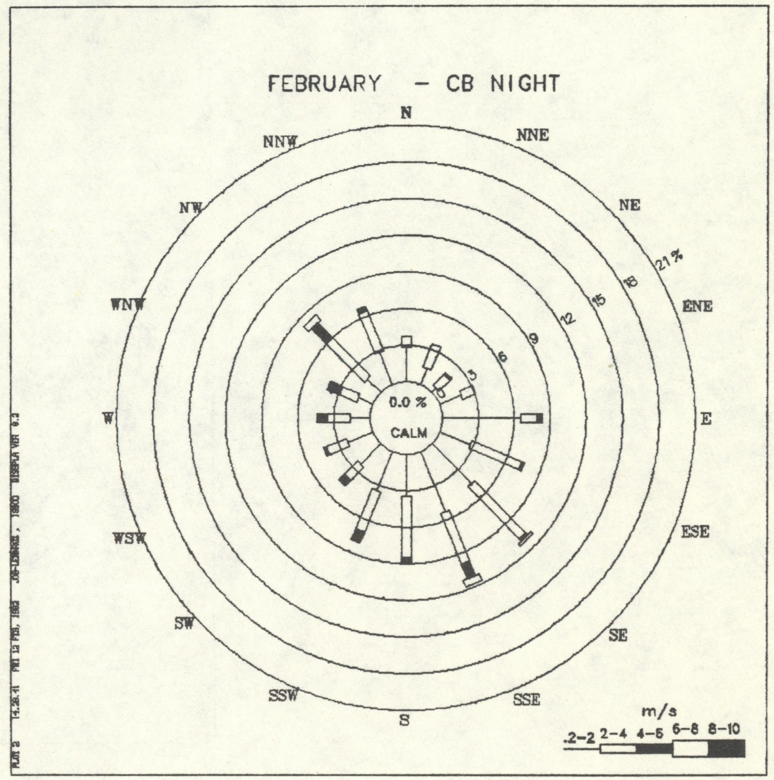

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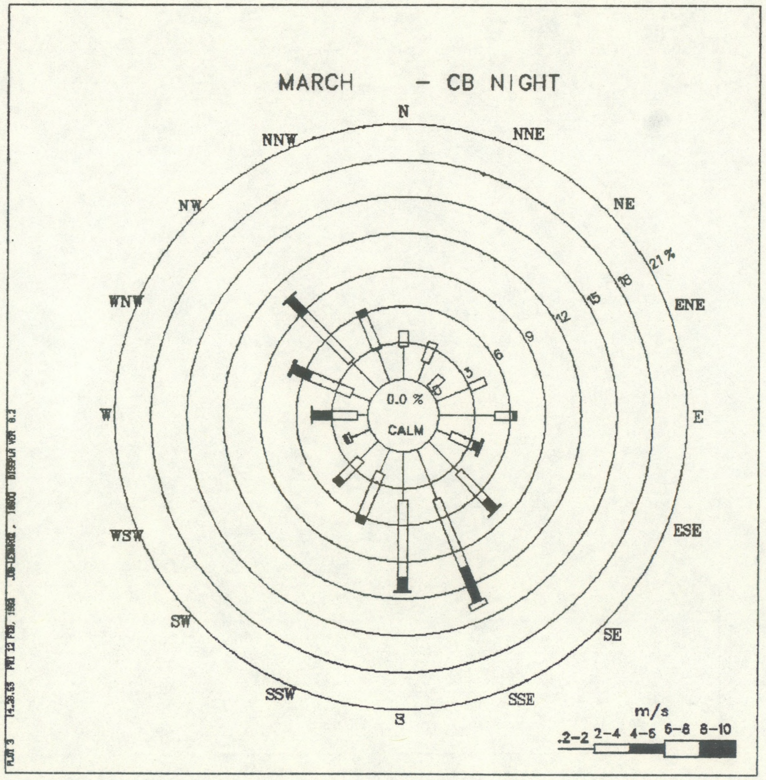
FIGURE 5. MONTHLY NOCTURNAL WIND ROSES FOR CAMP BRANCH.



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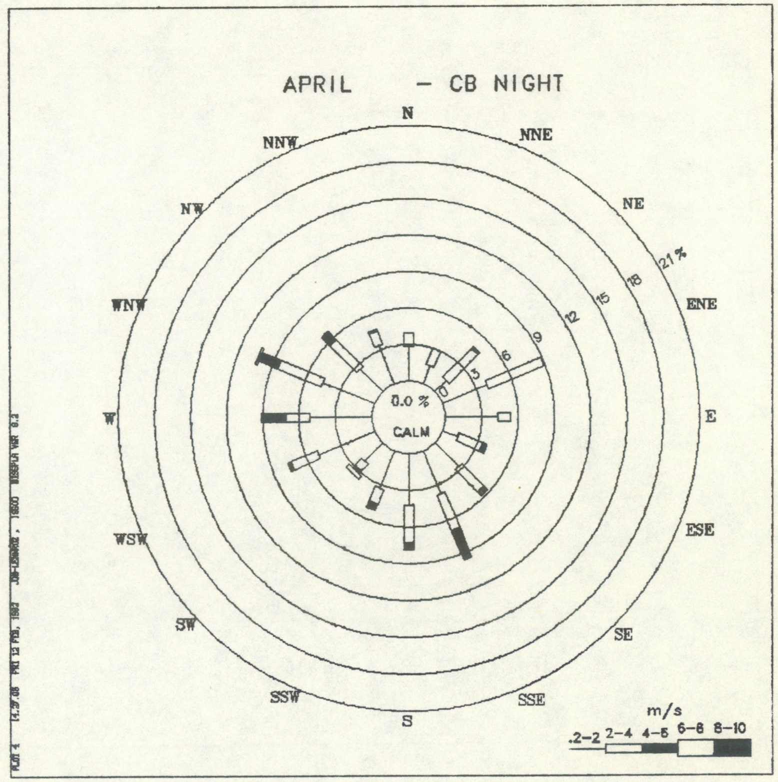

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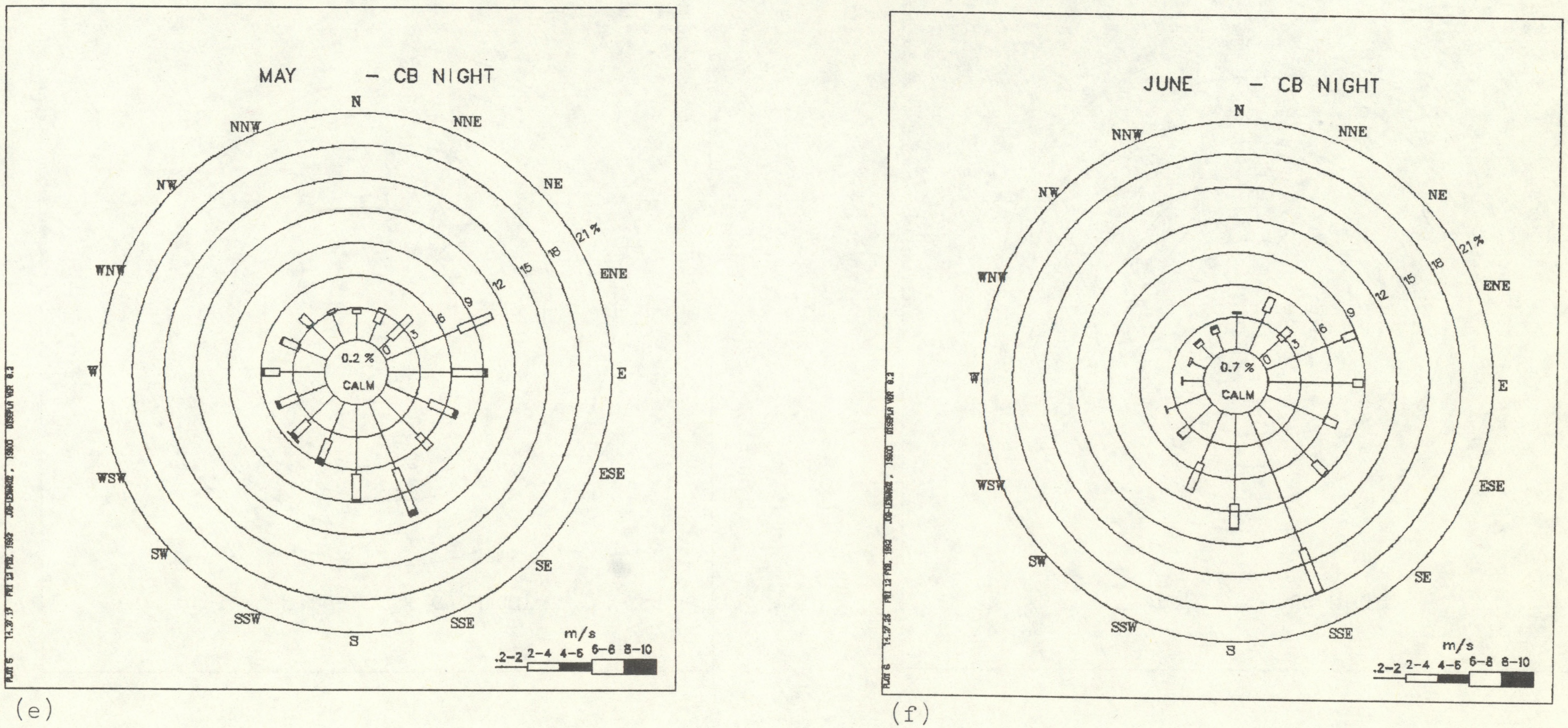

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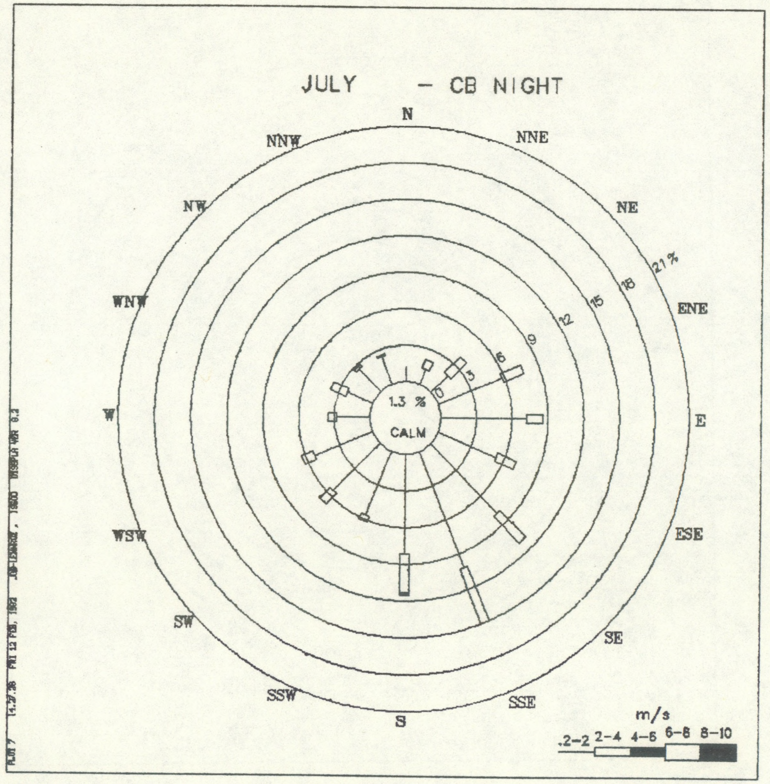

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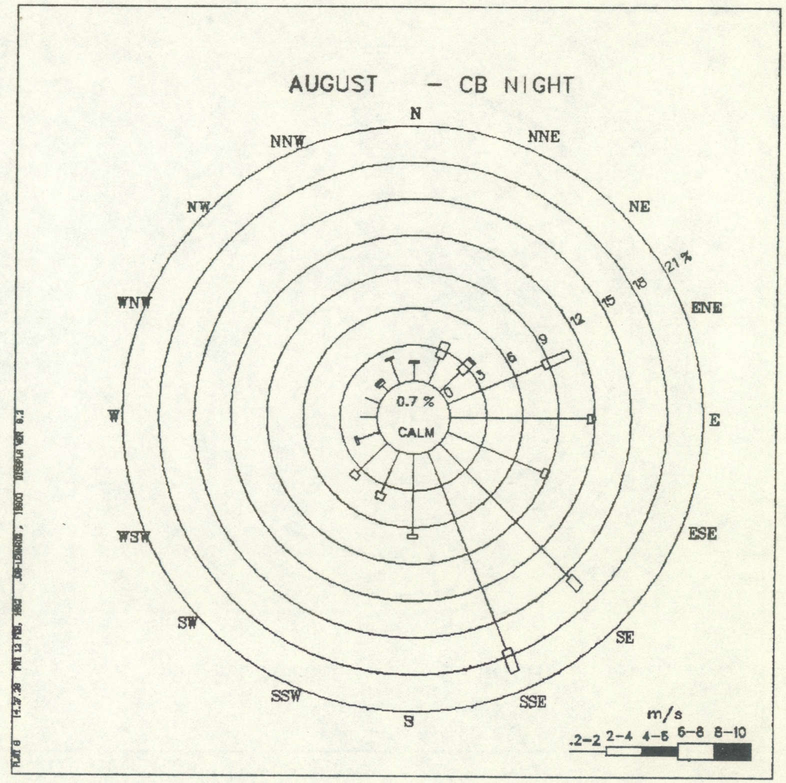

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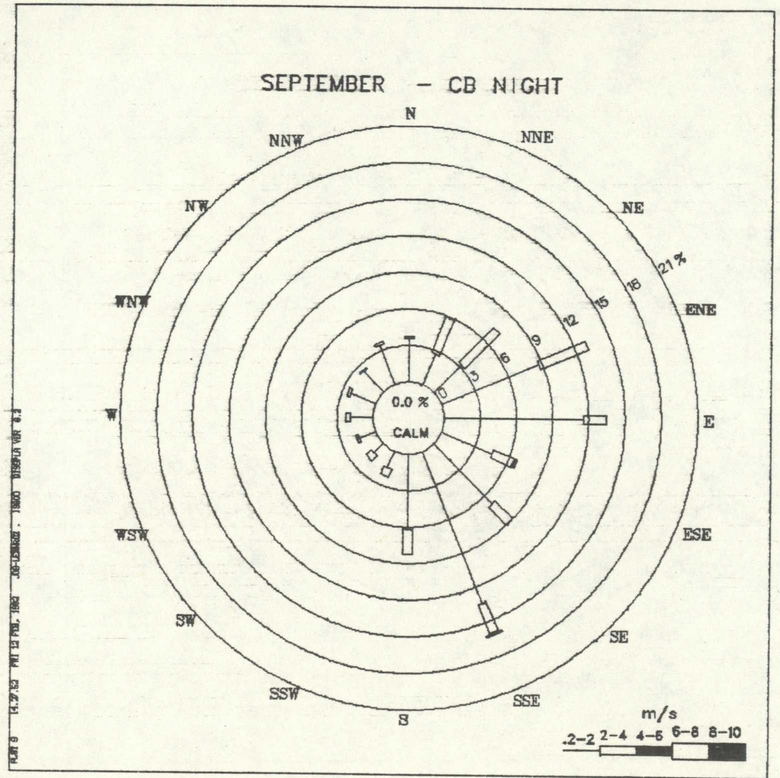

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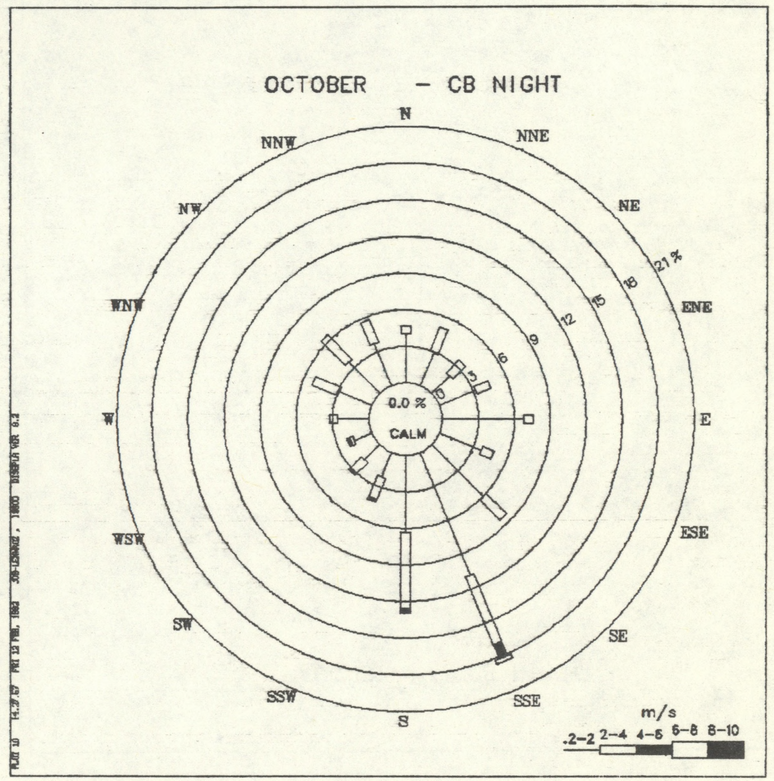

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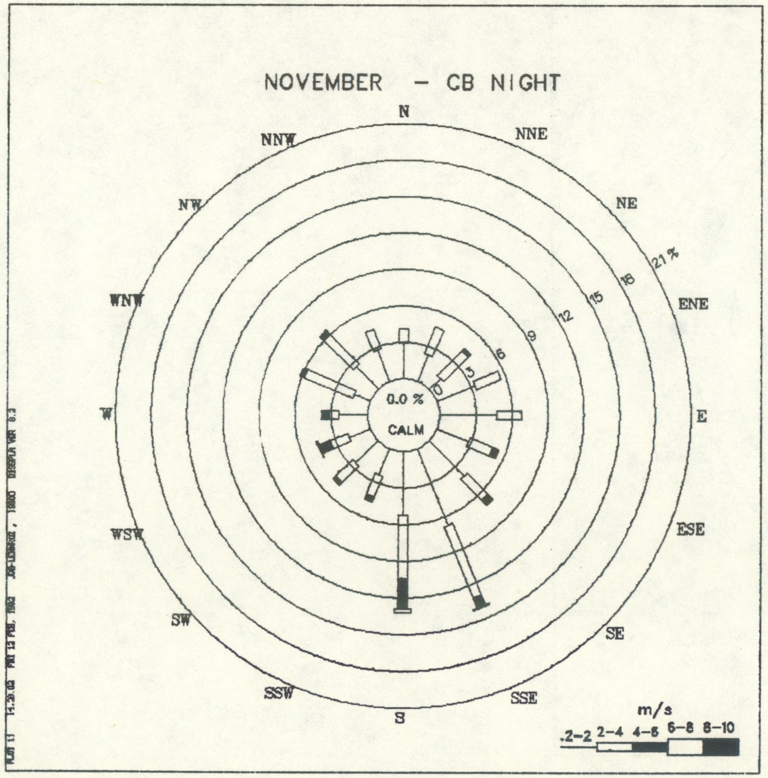

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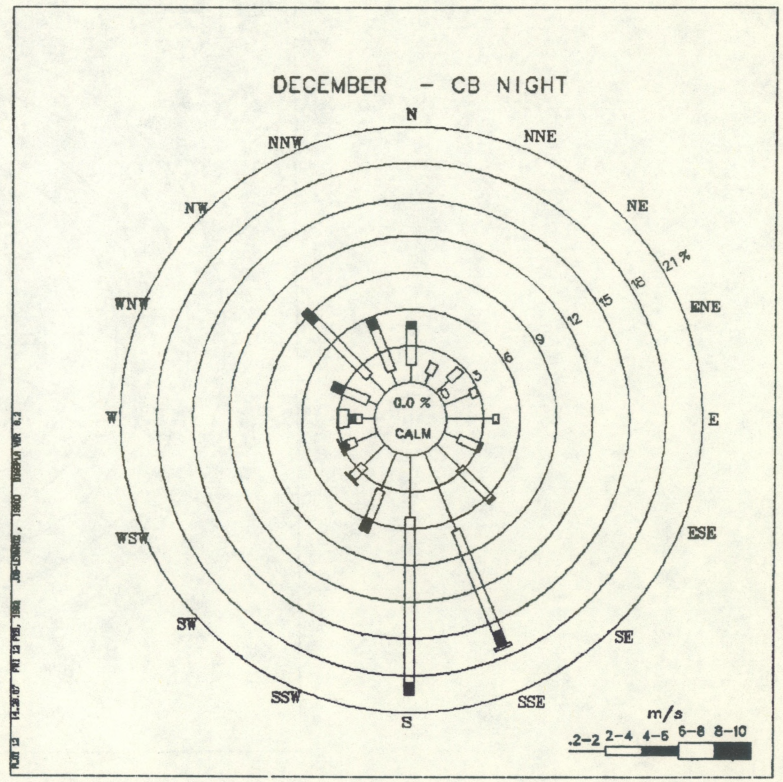

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FIGURE 5. (continued)

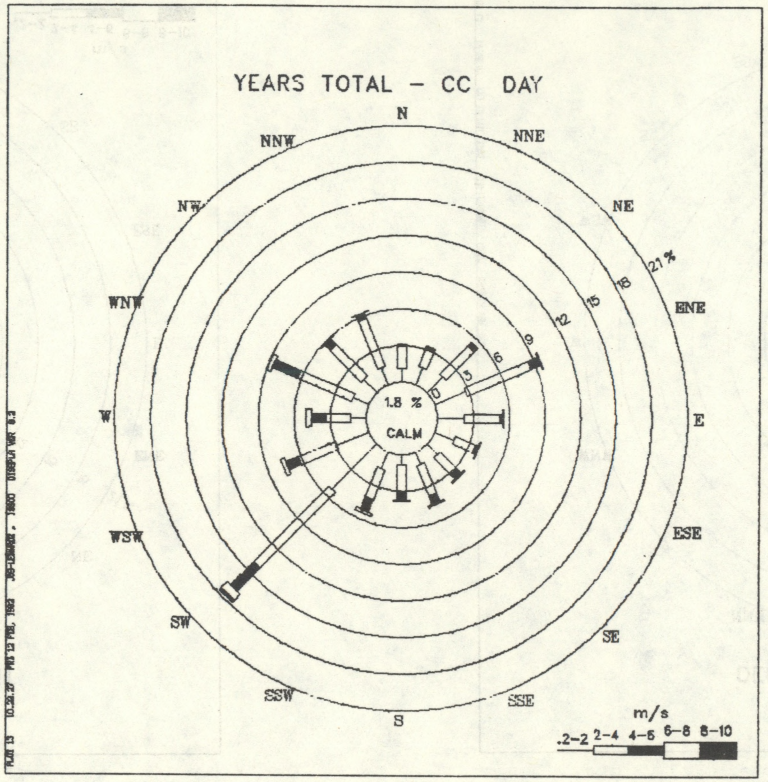
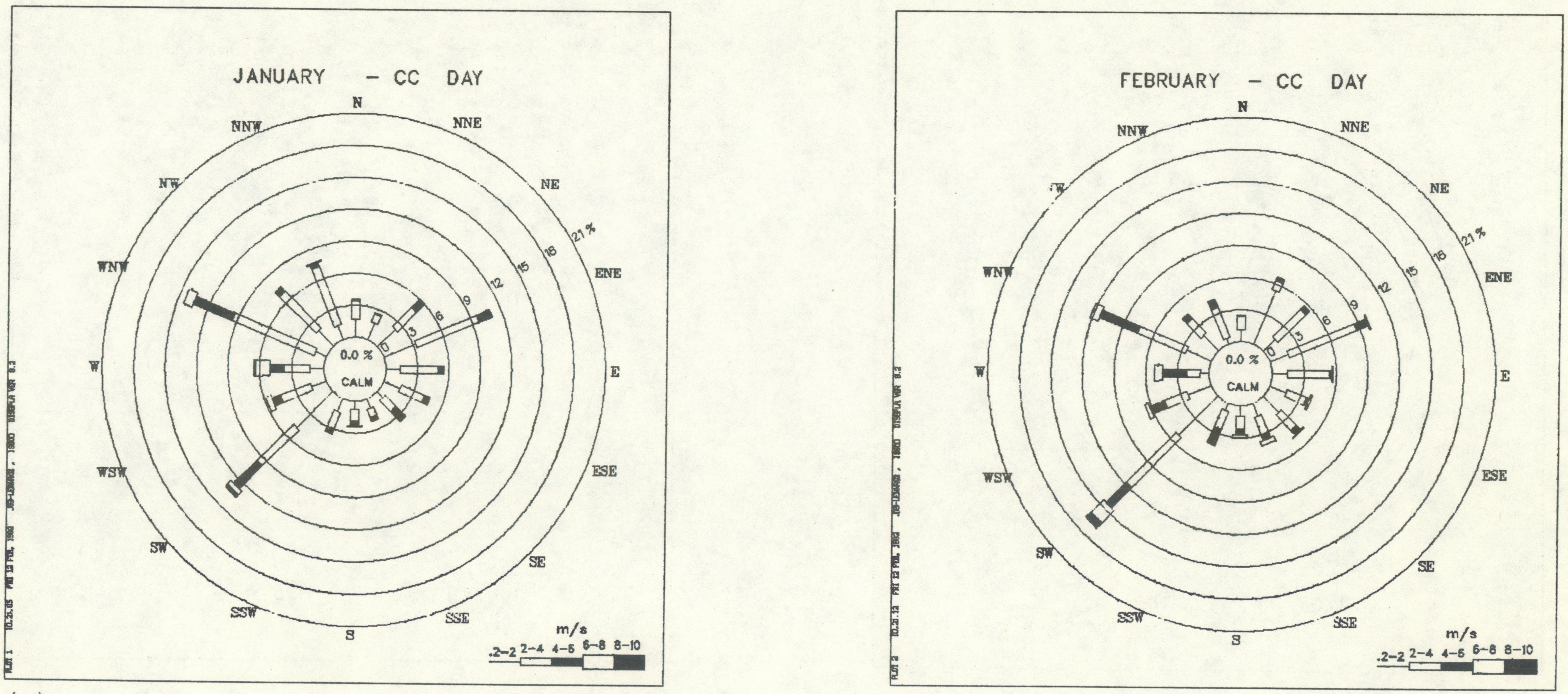
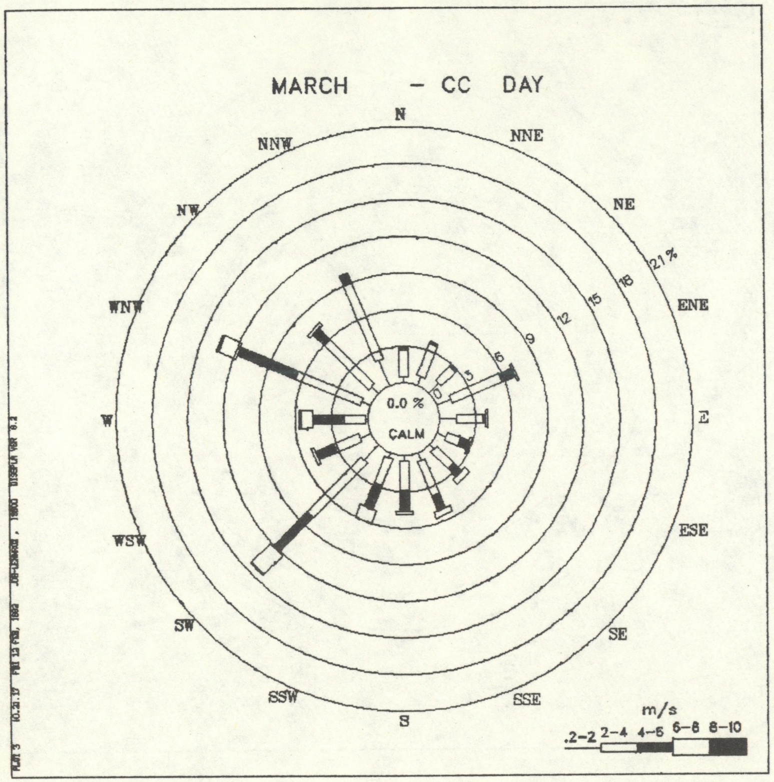


FIGURE 6. ANNUAL DAYTIME WIND ROSE FOR CROSS CREEK.



(a) (b)

FIGURE 7. MONTHLY DAYTIME WIND ROSES FOR CROSS CREEK.



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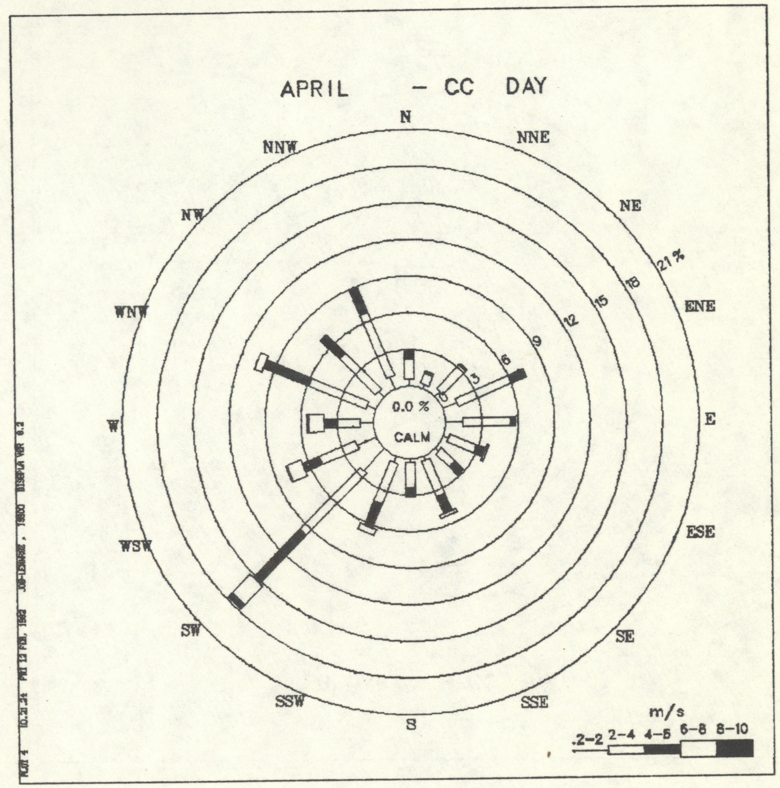

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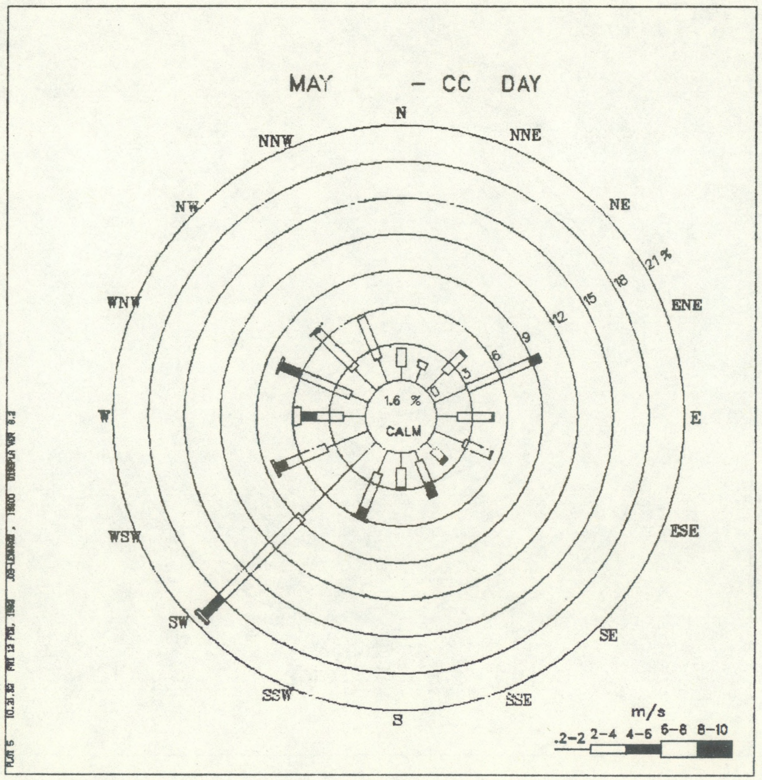
FIGURE 7. (continued)



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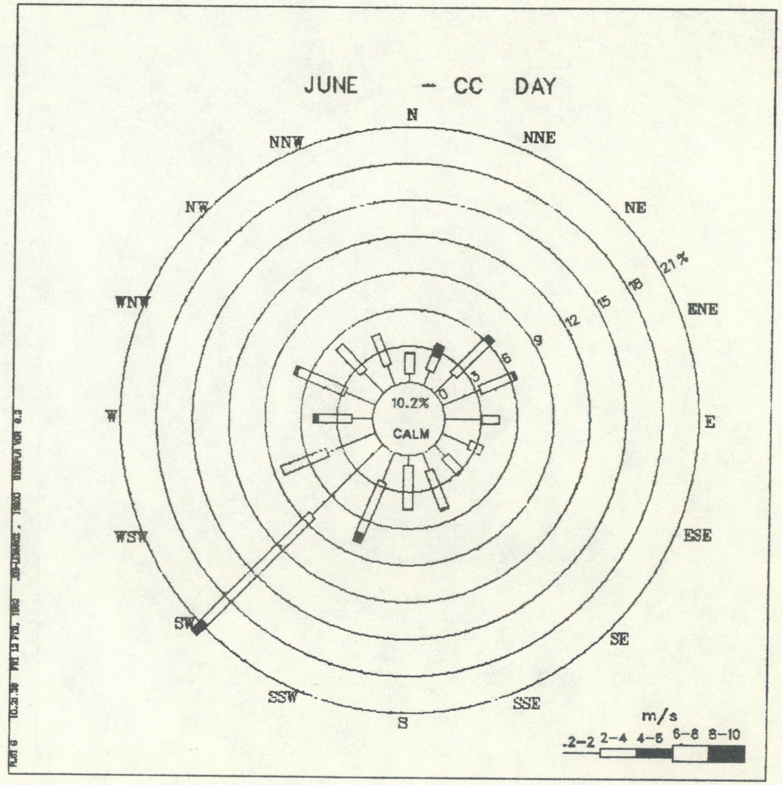
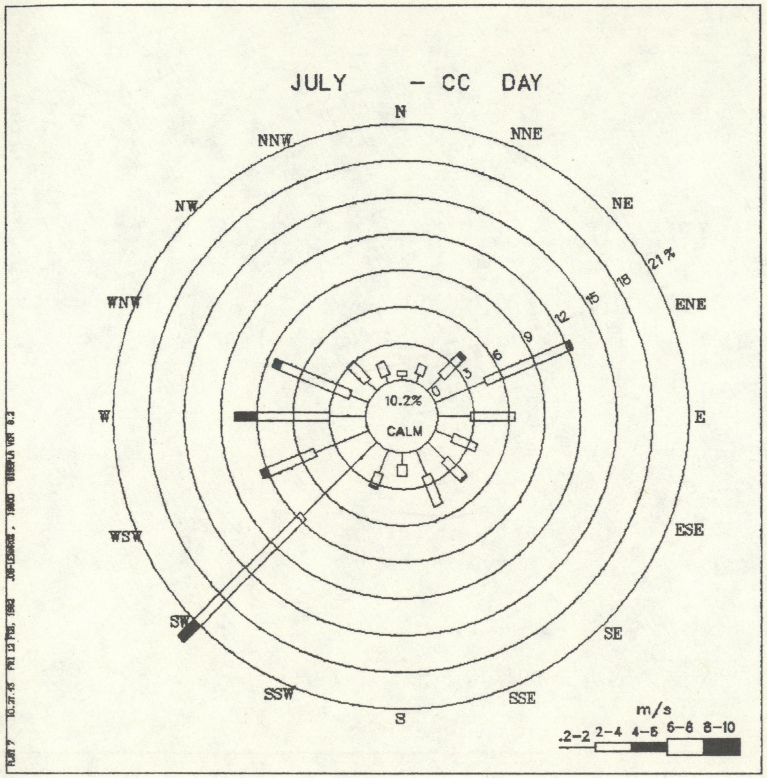
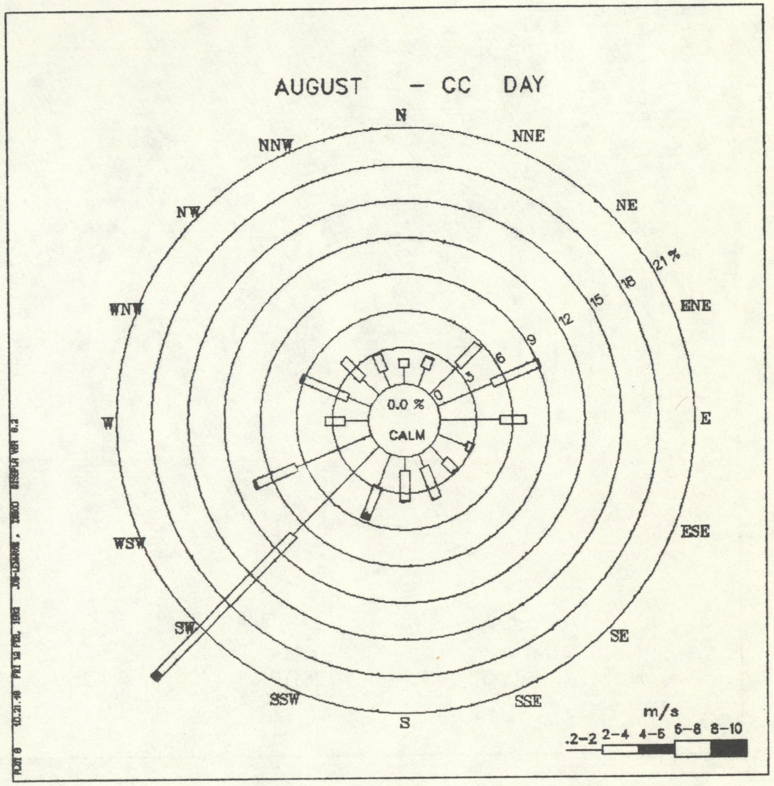


(f)

FIGURE 7. (continued)

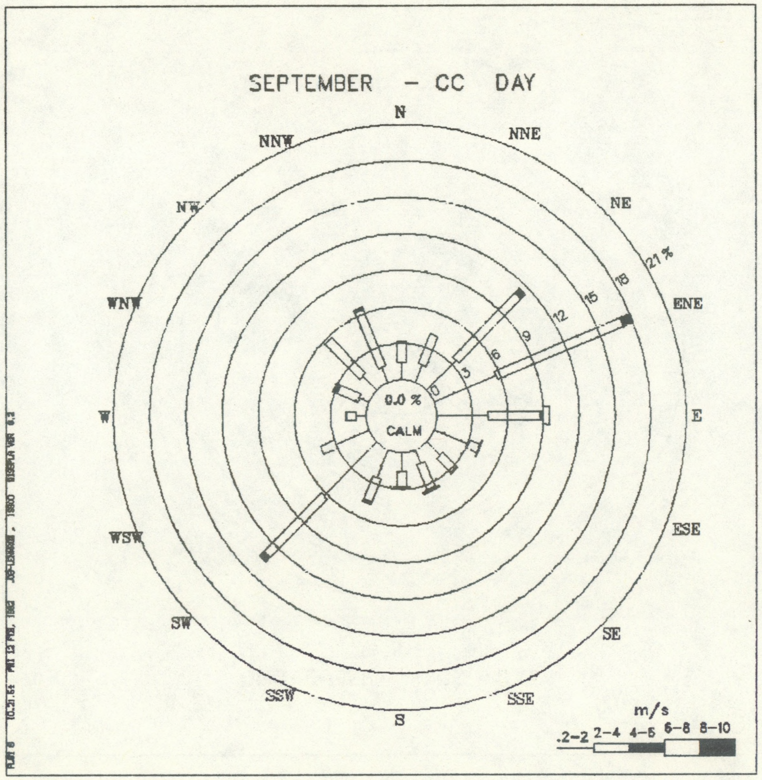


(g)

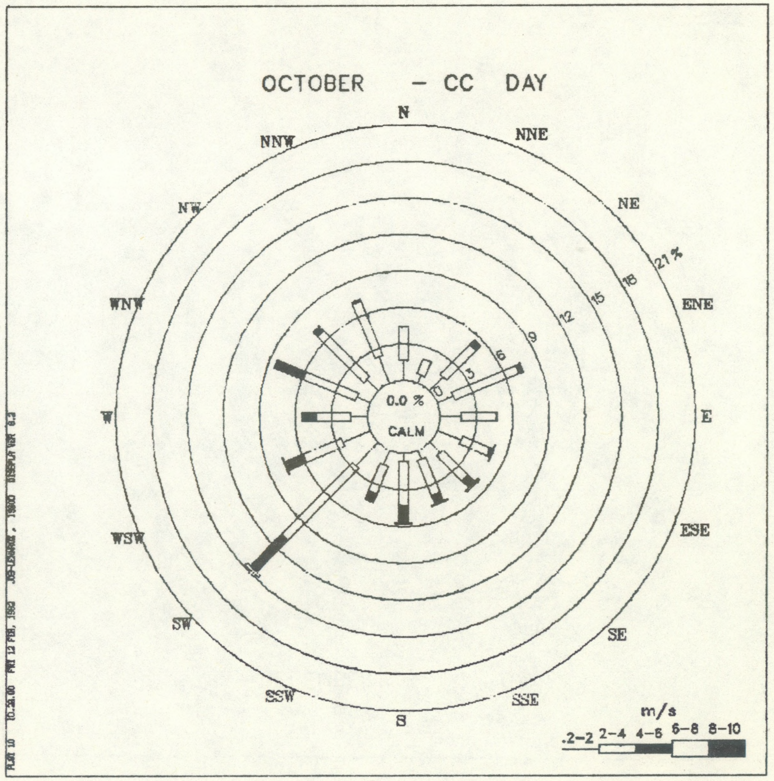


(h)

FIGURE 7. (continued)

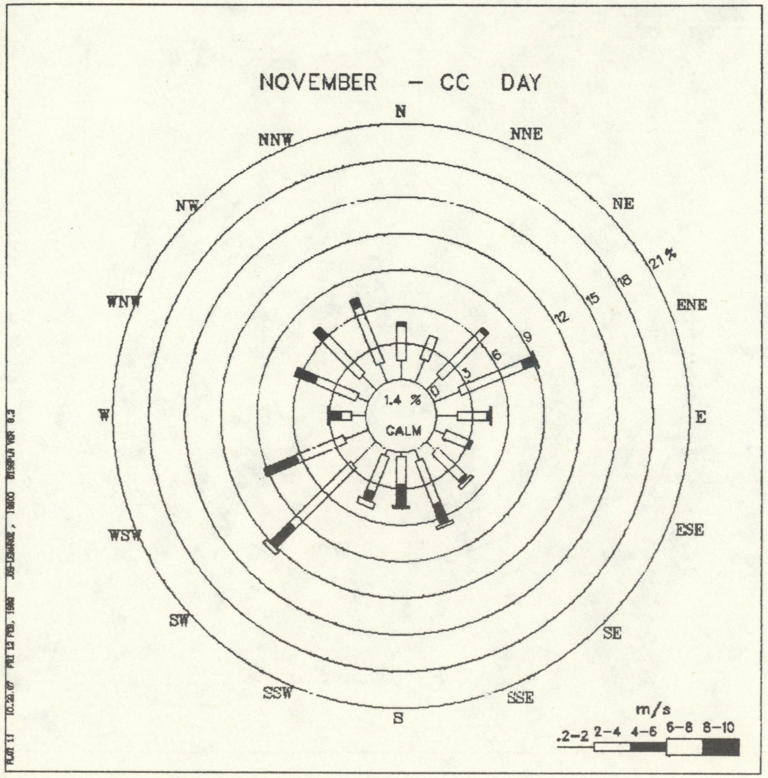


(i)

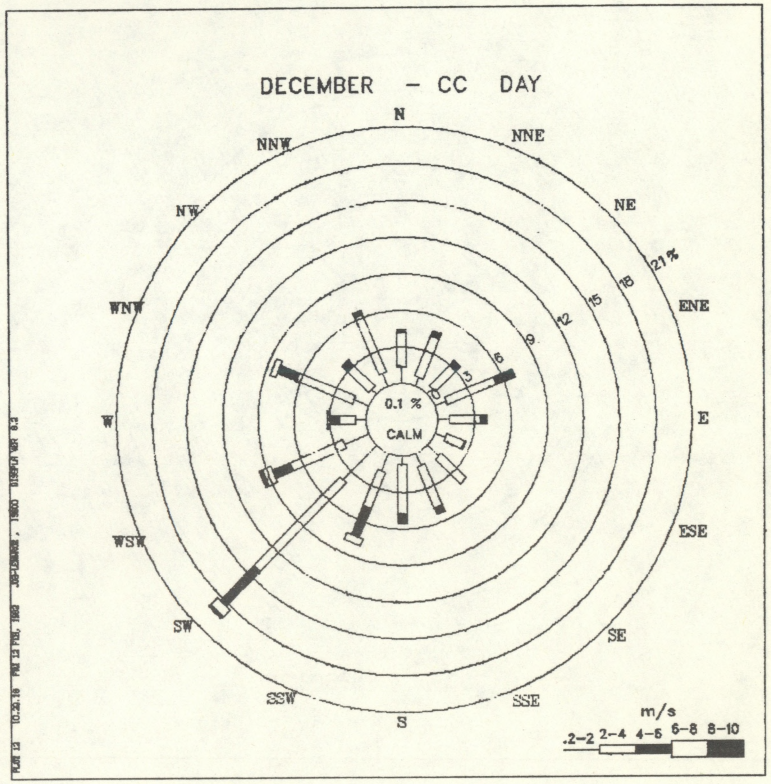


(j)

FIGURE 7. (continued)



(k)



(l)

FIGURE 7. (continued)

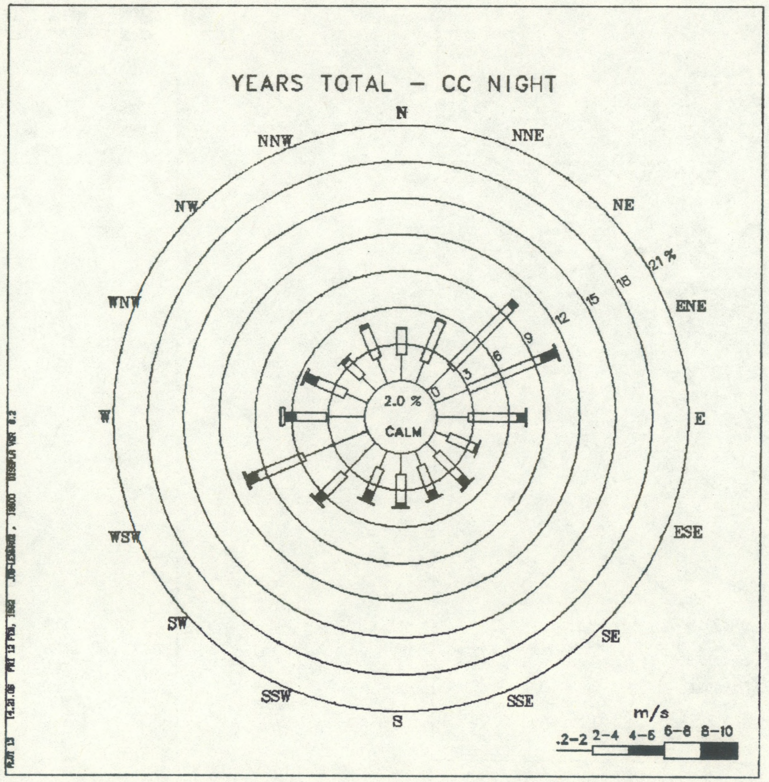
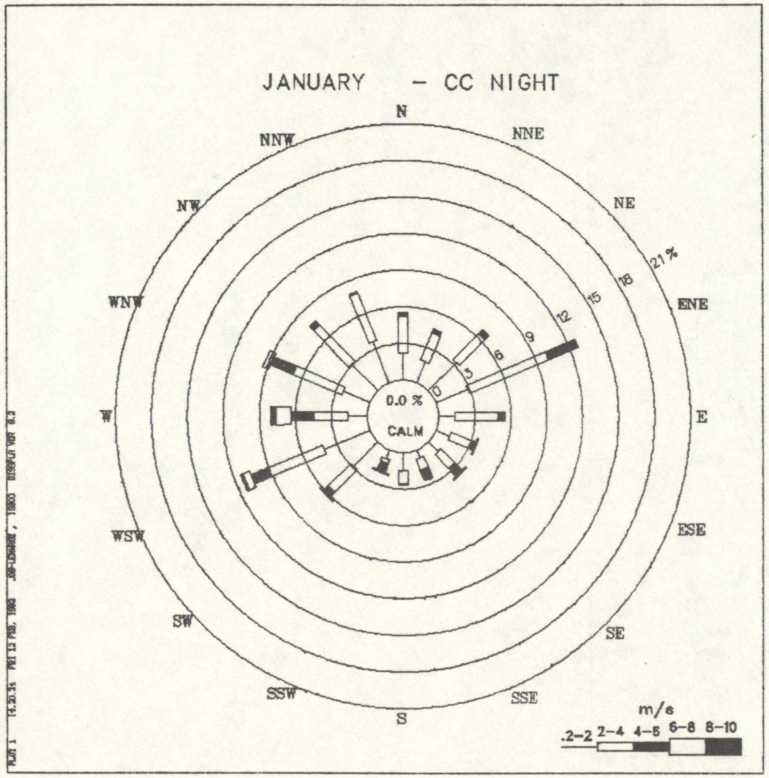
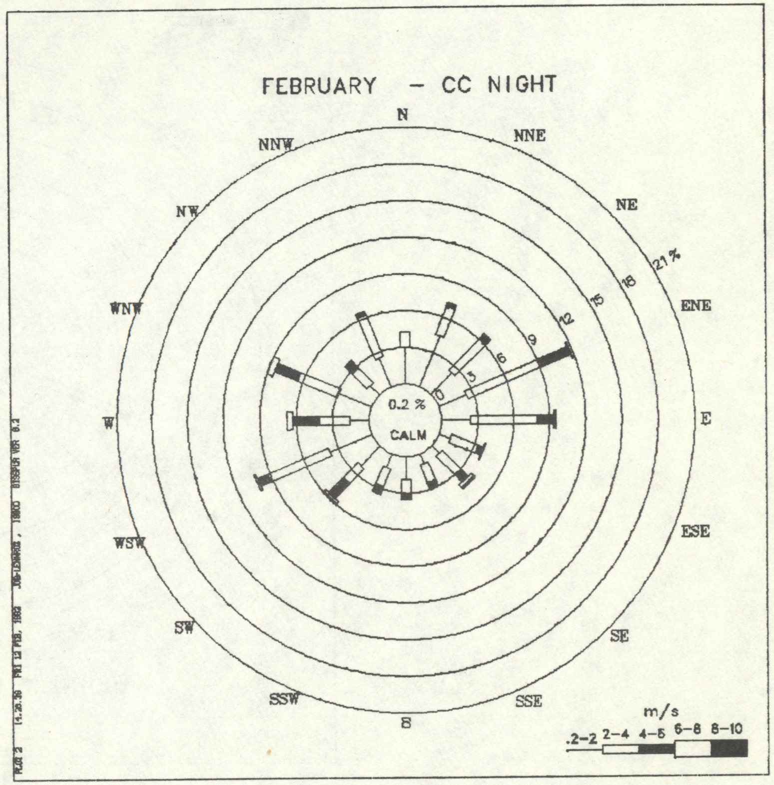


FIGURE 8. ANNUAL NOCTURNAL WIND ROSE FOR CROSS CREEK.

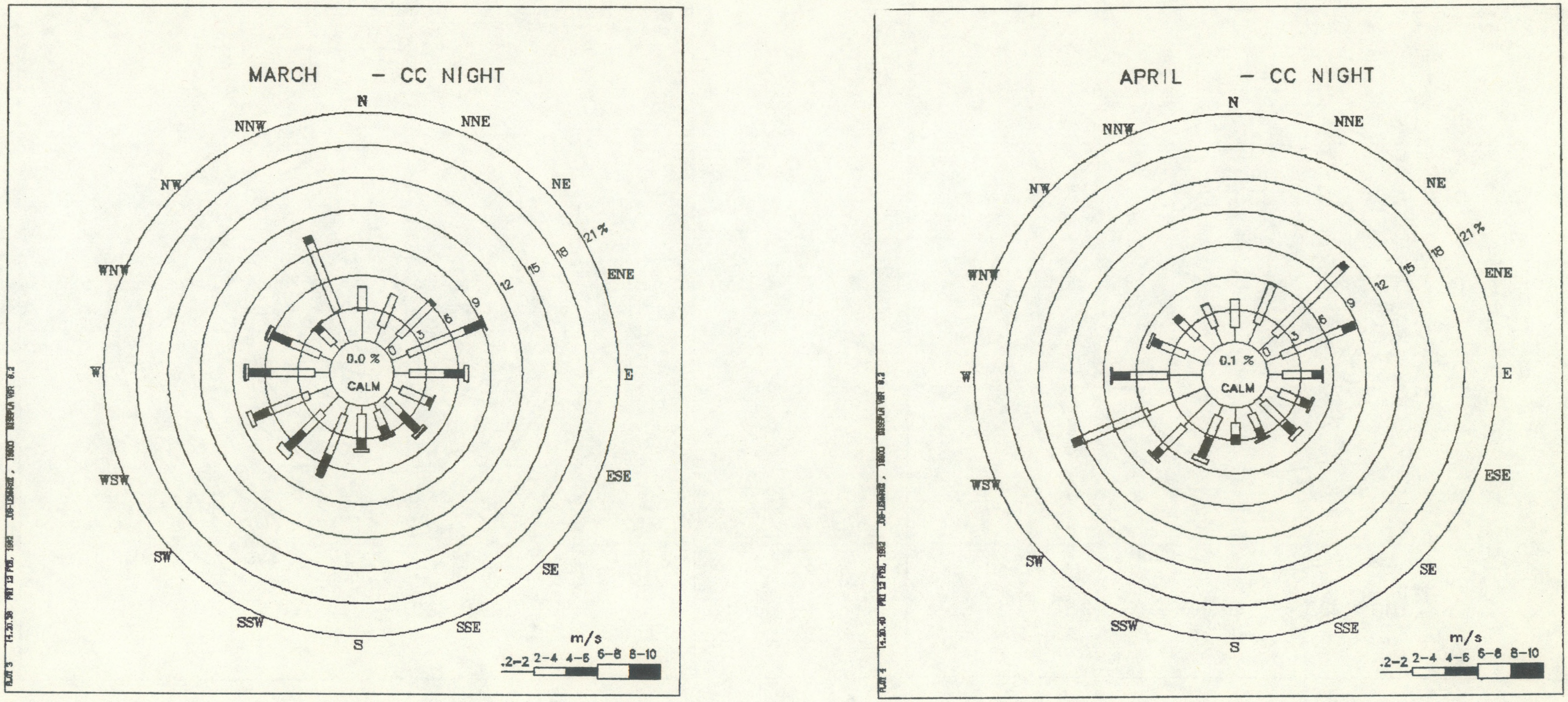


(a)



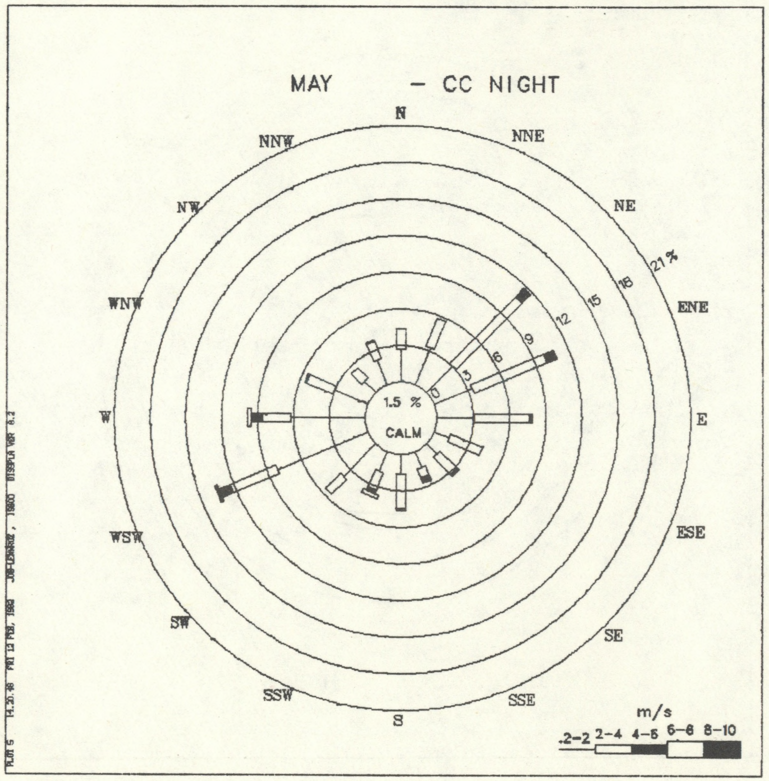
(b)

FIGURE 9. MONTHLY NOCTURNAL WIND ROSES FOR CROSS CREEK.

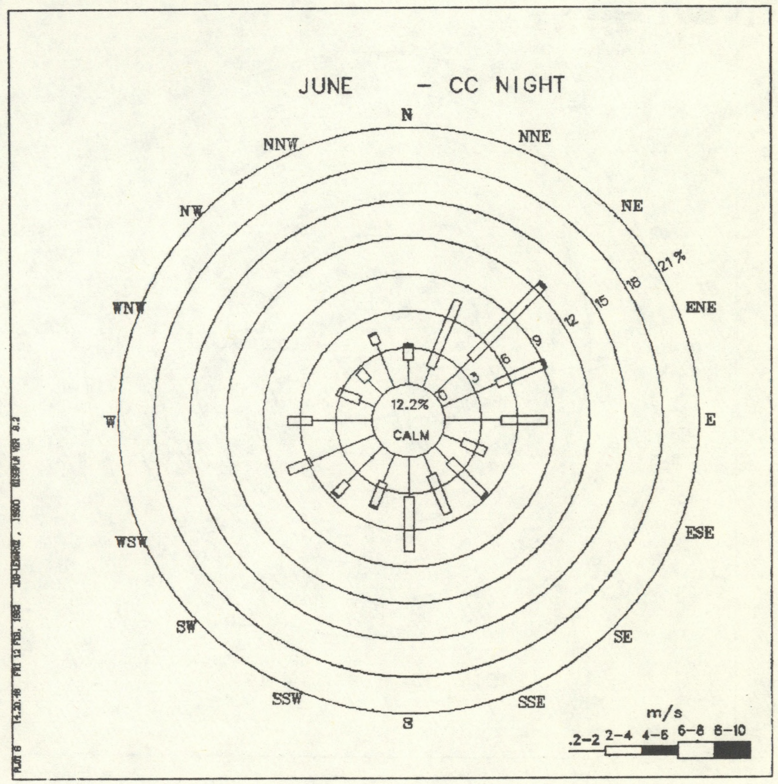


(c) (d)

FIGURE 9. (continued)

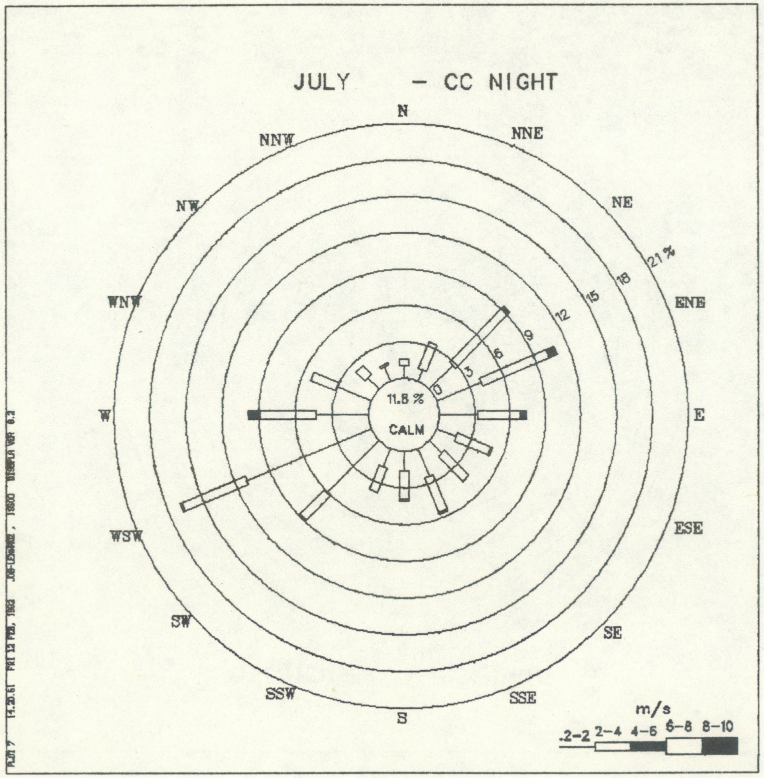


(e)

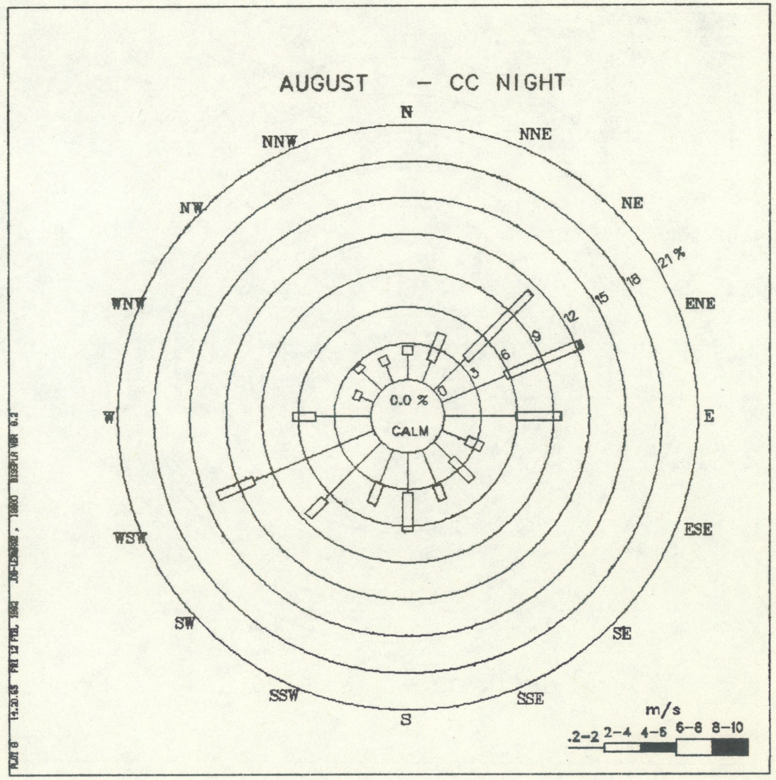


(f)

FIGURE 9. (continued)

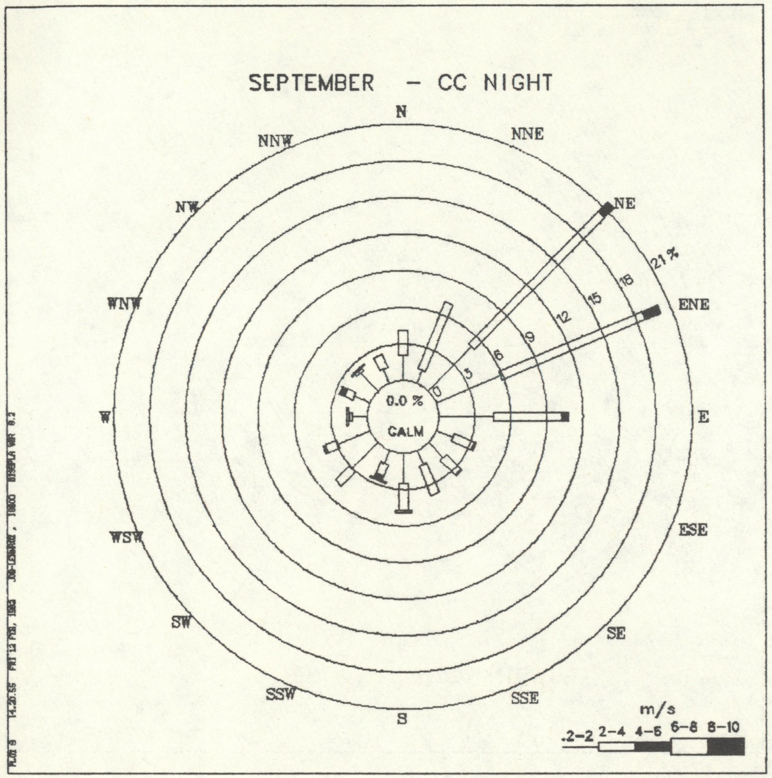


(g)

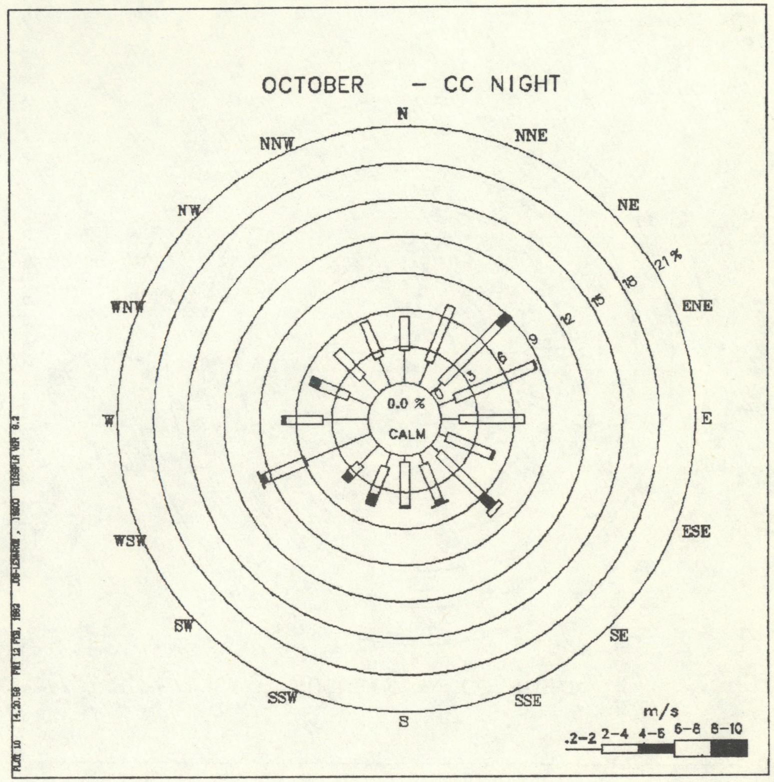


(h)

FIGURE 9. (continued)

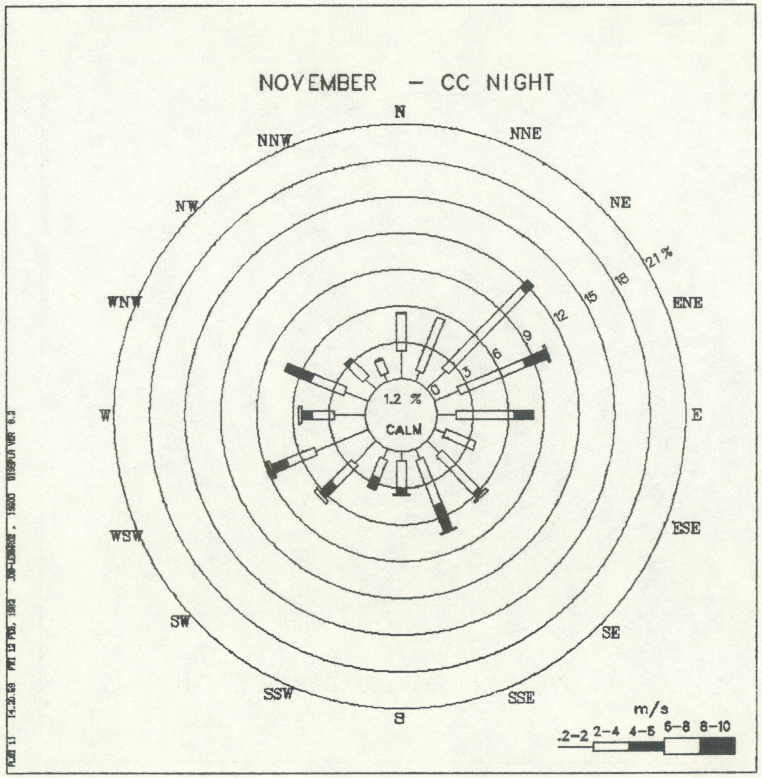


(i)

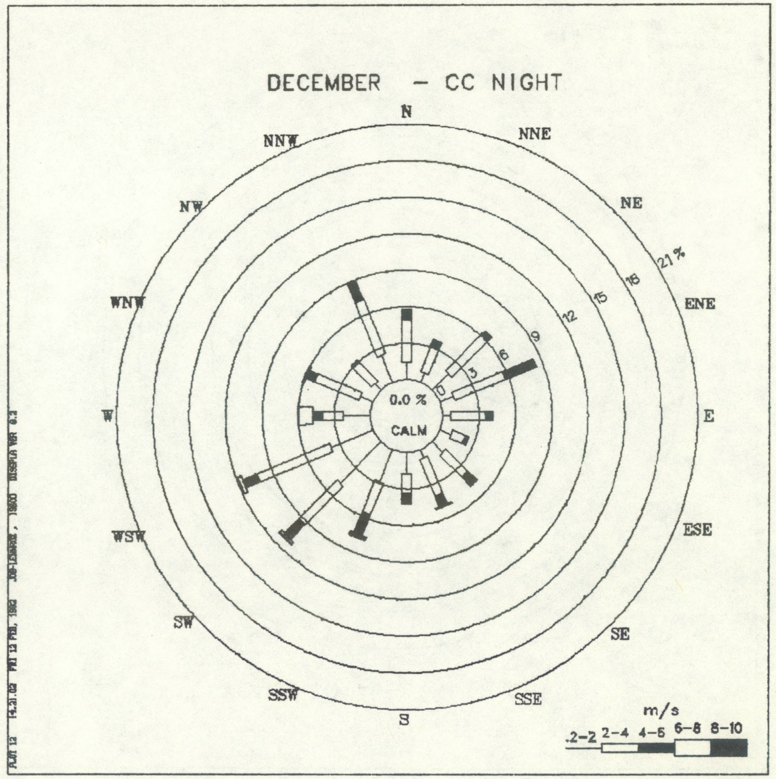


(j)

FIGURE 9. (continued)



(k)



(l)

FIGURE 9. (continued)

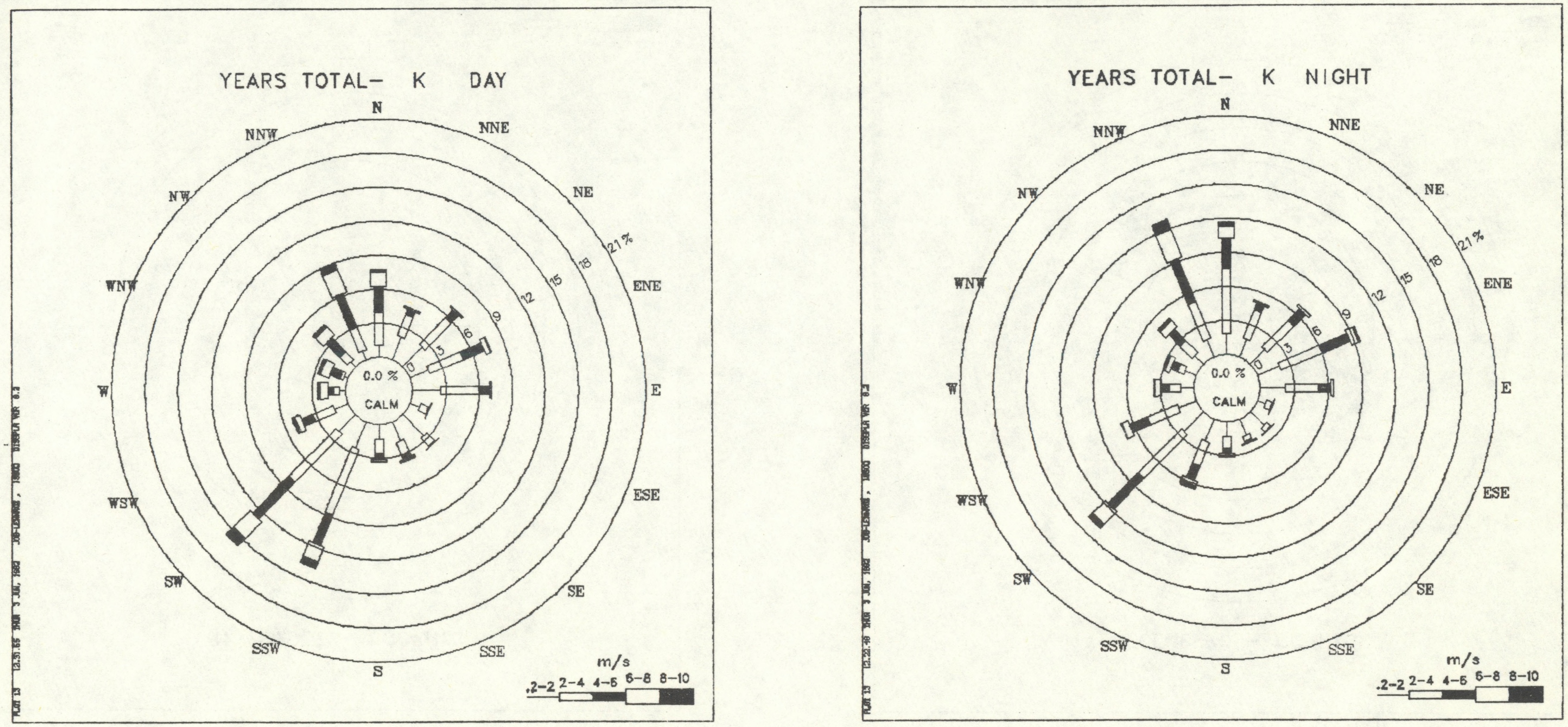


FIGURE 10. ANNUAL DAY AND NIGHT WIND ROSES FOR KINGSTON STEAM PLANT METEOROLOGICAL TOWER (110 m).

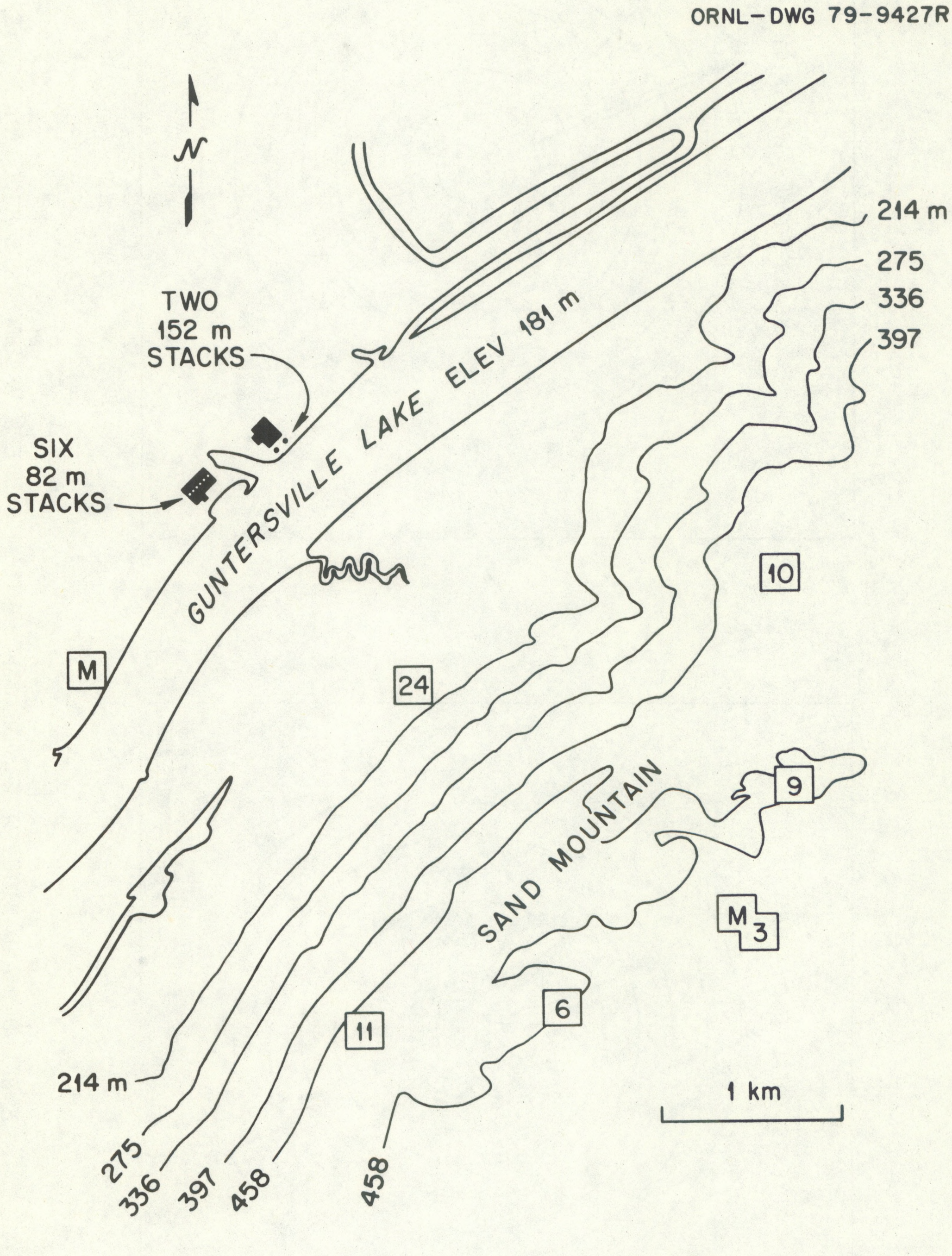


FIGURE 11. MAP OF AREA WITHIN 4 km OF WIDOW'S CREEK STEAM PLANT. THE TWO METEOROLOGICAL STATIONS (M) AND SIX OF THE SO_2 STATIONS ARE SHOWN. ELEVATIONS ARE GIVEN IN METERS.

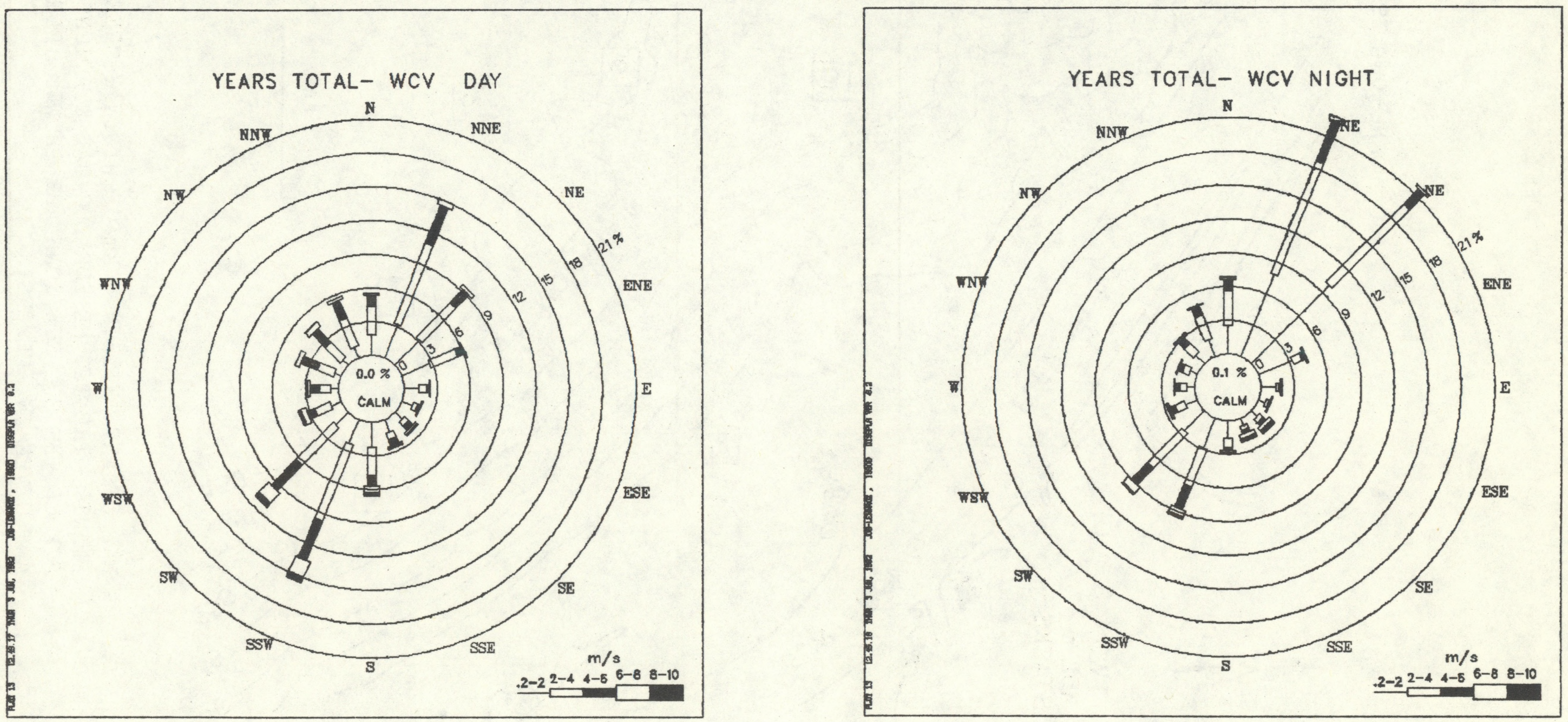
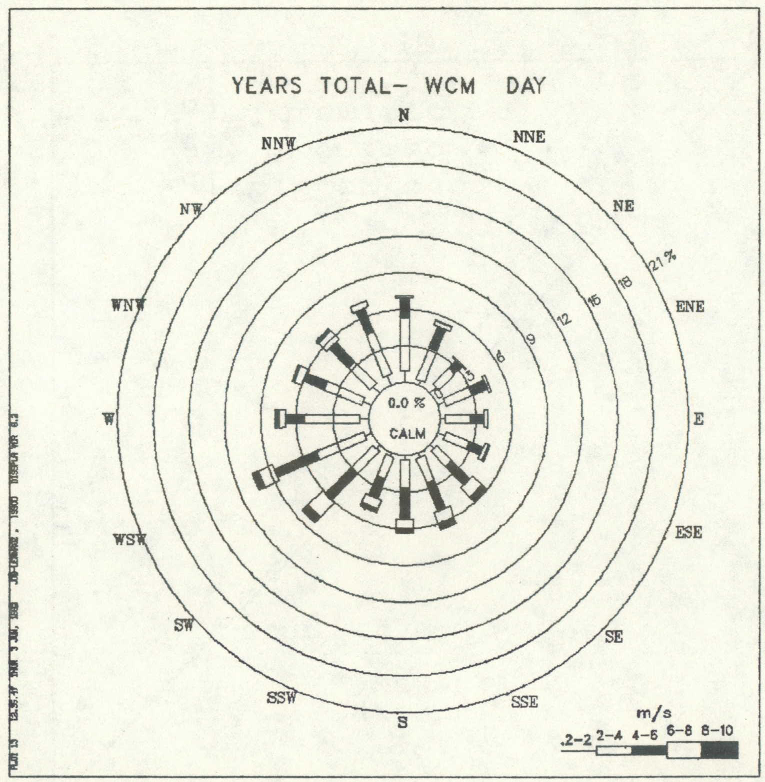


FIGURE 12. ANNUAL DAY AND NIGHT WIND ROSES FOR WIDOW'S CREEK VALLEY METEOROLOGICAL TOWER (61 m).



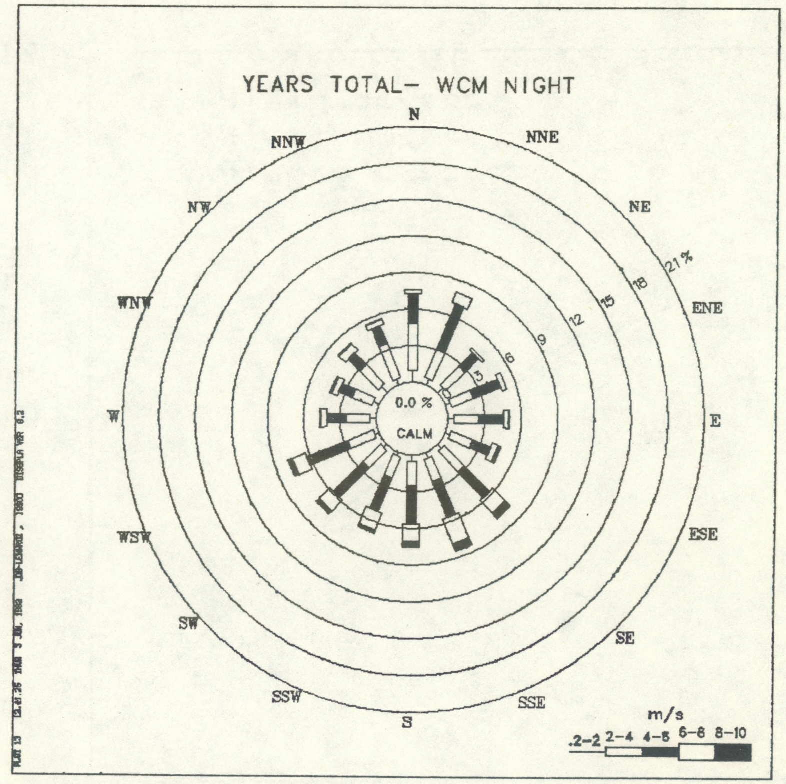


FIGURE 13. ANNUAL DAY AND NIGHT WIND ROSES FOR WIDOW'S CREEK MOUNTAIN METEOROLOGICAL TOWER (61 m).

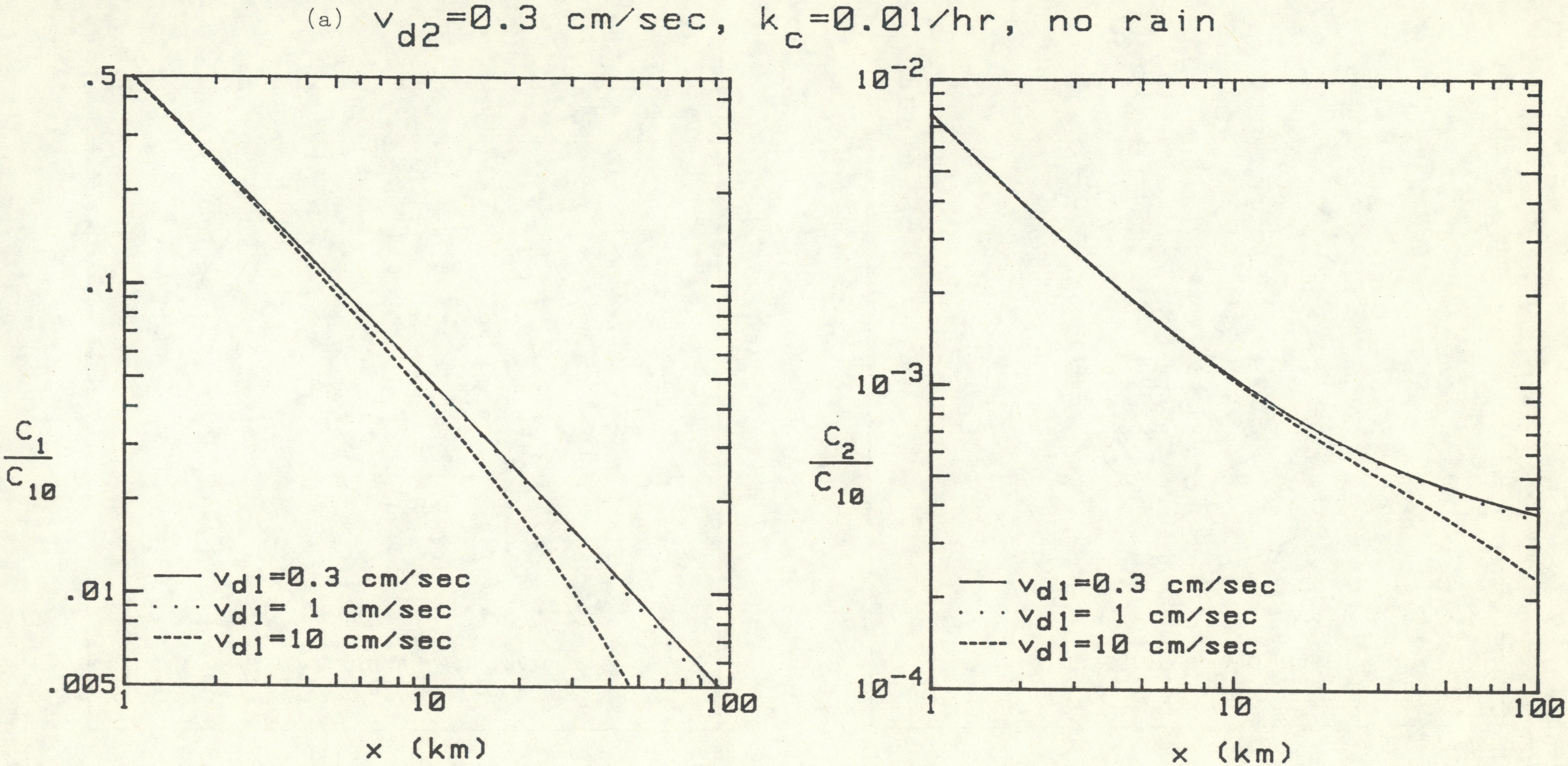


FIGURE 14. SENSITIVITY OF MODEL FOR C_1/C_{10} AND C_2/C_{10} TO VARIATIONS IN DEPOSITION VELOCITY, CHEMICAL REACTION RATE, AND RAINFALL.

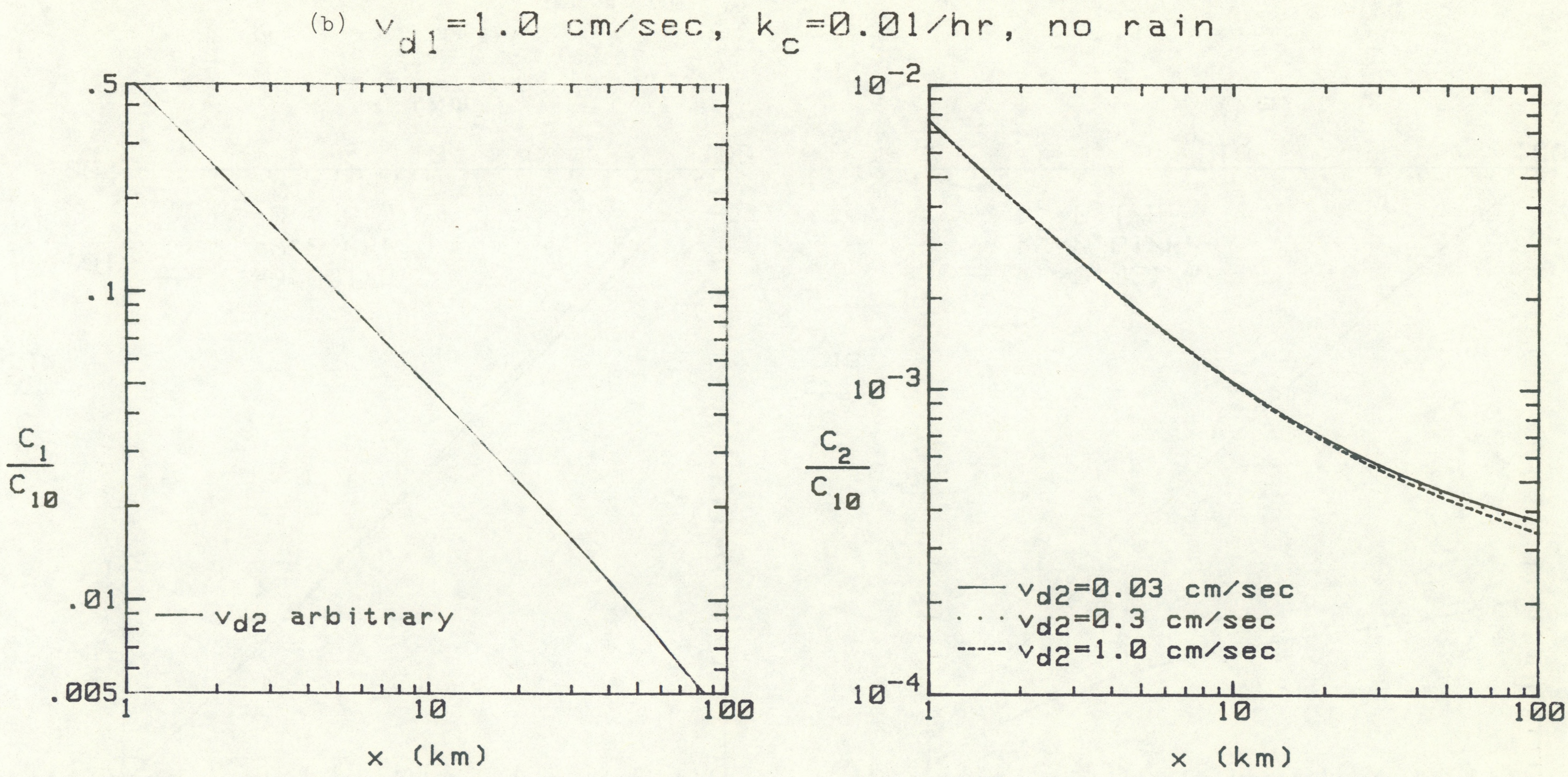


FIGURE 14. (continued)

(c) $v_{d1} = 1.0$ cm/sec, $v_{d2} = 0.3$ cm/sec, no rain

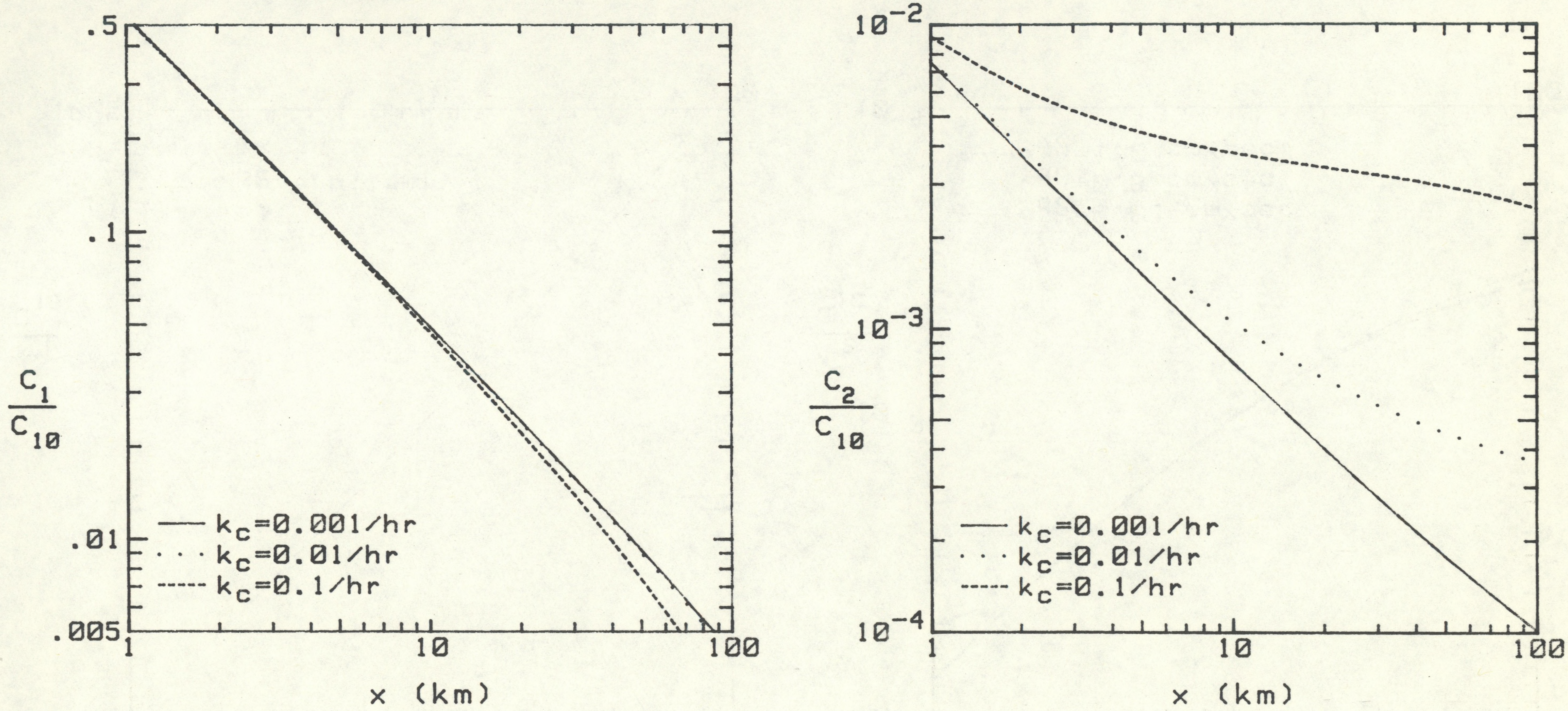


FIGURE 14. (continued)

(d) $v_{d1}=1.0$ cm/sec, $v_{d2}=0.3$ cm/sec, $k_c=0.01$/hr

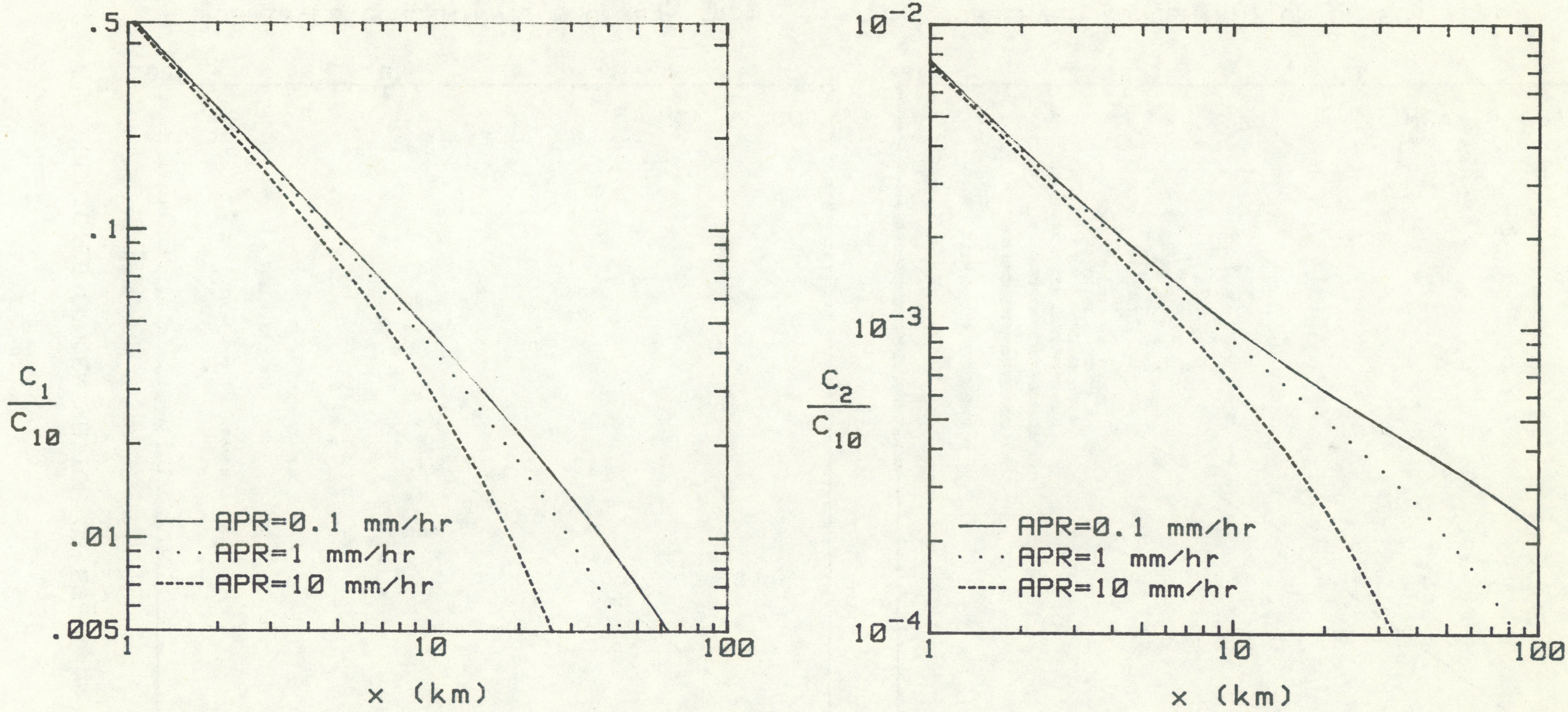


FIGURE 14. (continued)

WIDOW'S CREEK VALLEY METEOROLOGICAL STATION RESULTS

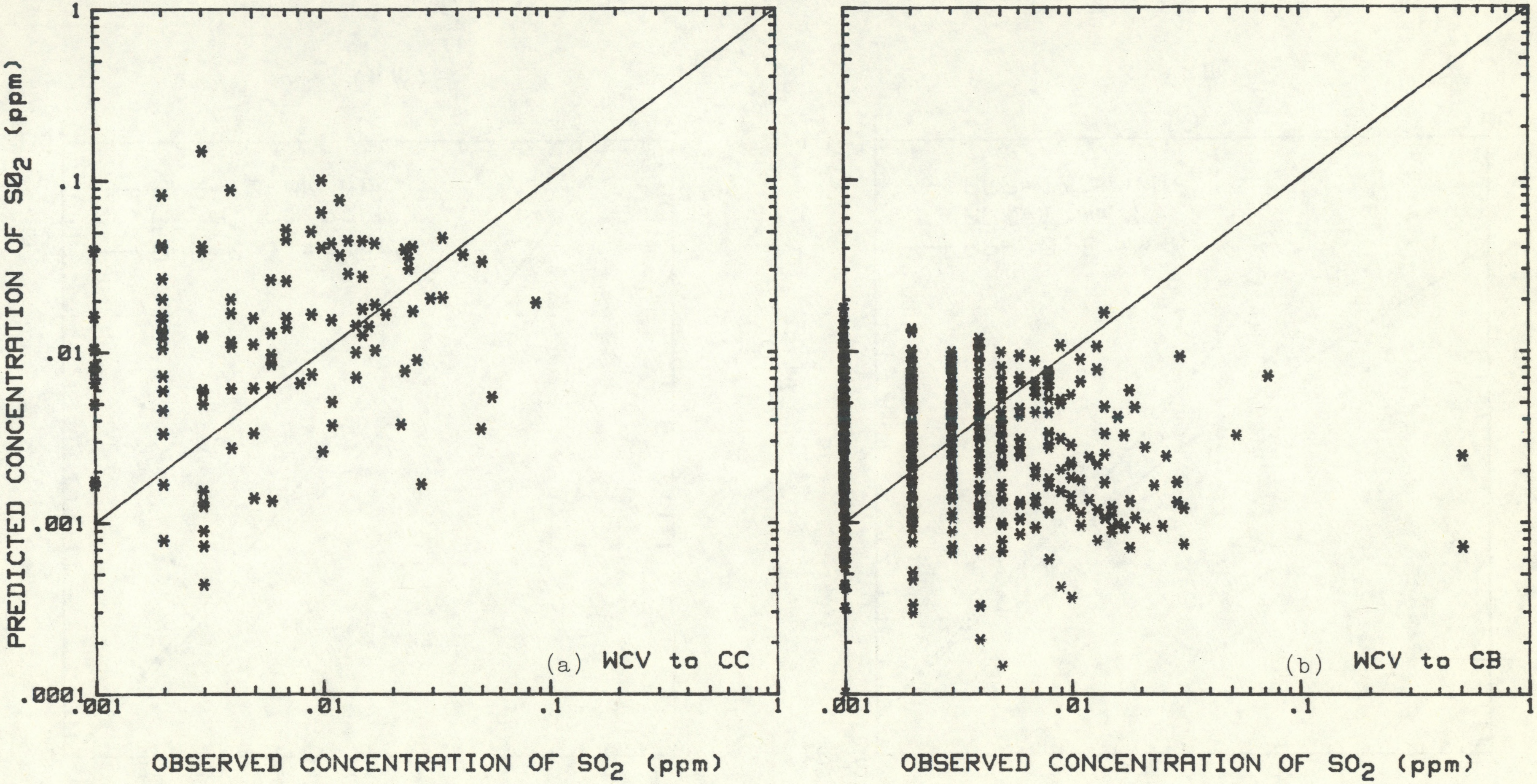


FIGURE 15. COMPARISON OF PREDICTED AND OBSERVED VALUES OF AVERAGE SO_2 CONCENTRATIONS ABOVE THE CROSS CREEK (CC) AND CAMP BRANCH (CB) WATERSHED SITES CALCULATED USING EMISSIONS AND METEOROLOGICAL DATA FROM THE WIDOW'S CREEK (WC) AND KINGSTON (K) STEAM PLANTS.

WIDOW'S CREEK MOUNTAIN METEOROLOGICAL STATION RESULTS

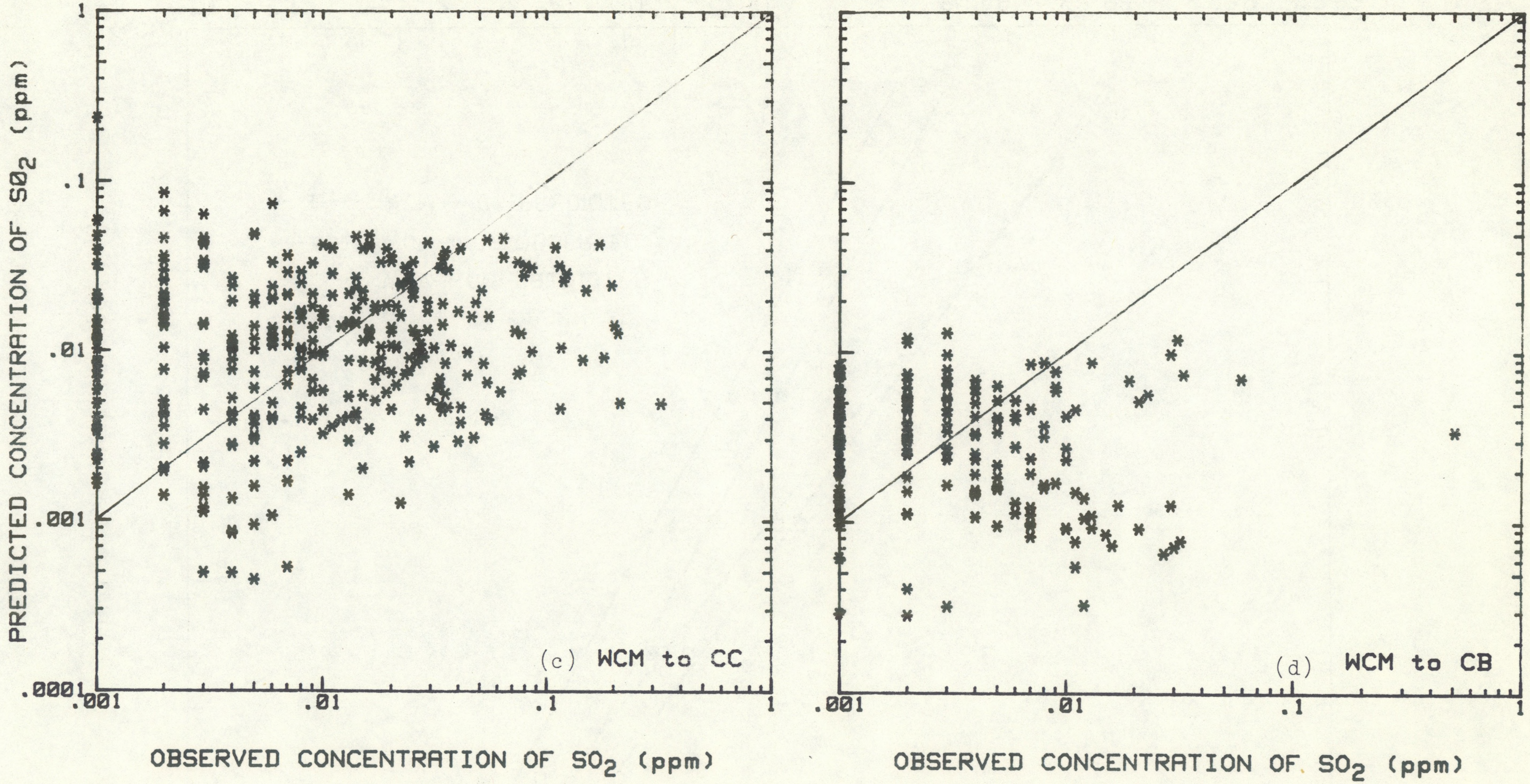


FIGURE 15. (continued)

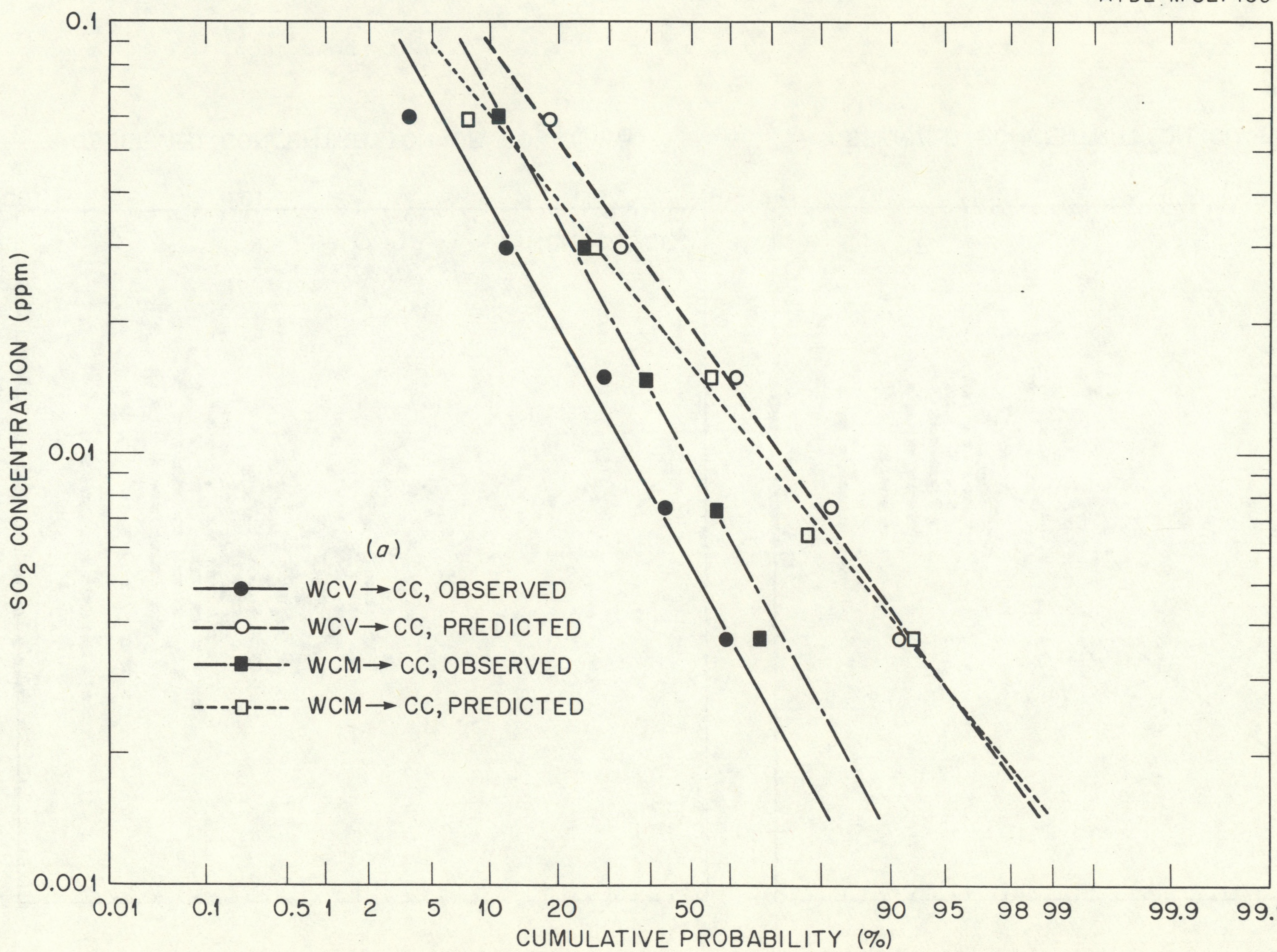


FIGURE 16. CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED AND PREDICTED SO_2 CONCENTRATIONS AT THE CROSS CREEK WATERSHED SITE USING DATA FROM THE WIDOW'S CREEK VALLEY (WCV) AND MOUNTAIN (WCM) METEOROLOGICAL TOWERS.

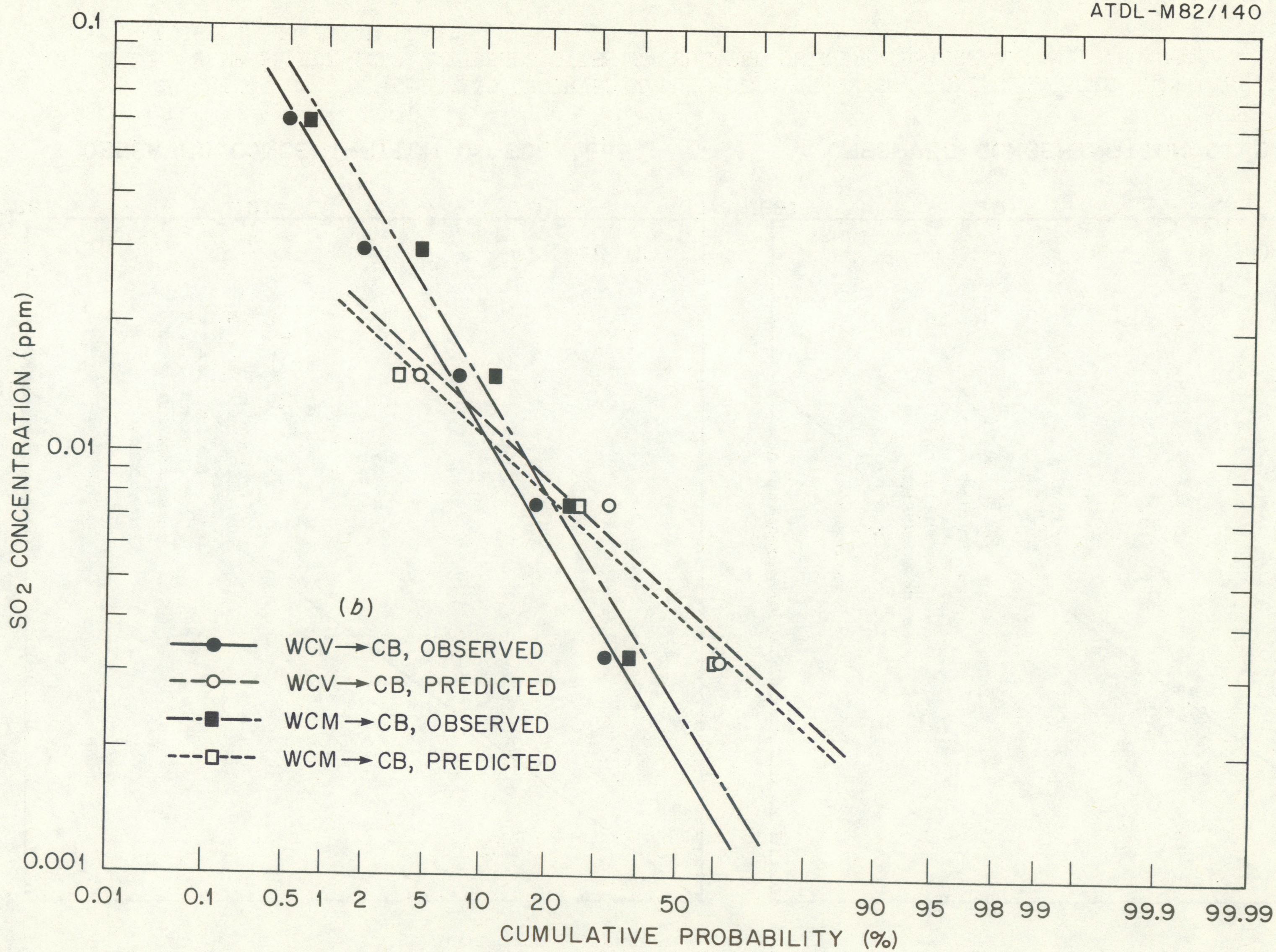


FIGURE 16. (continued)

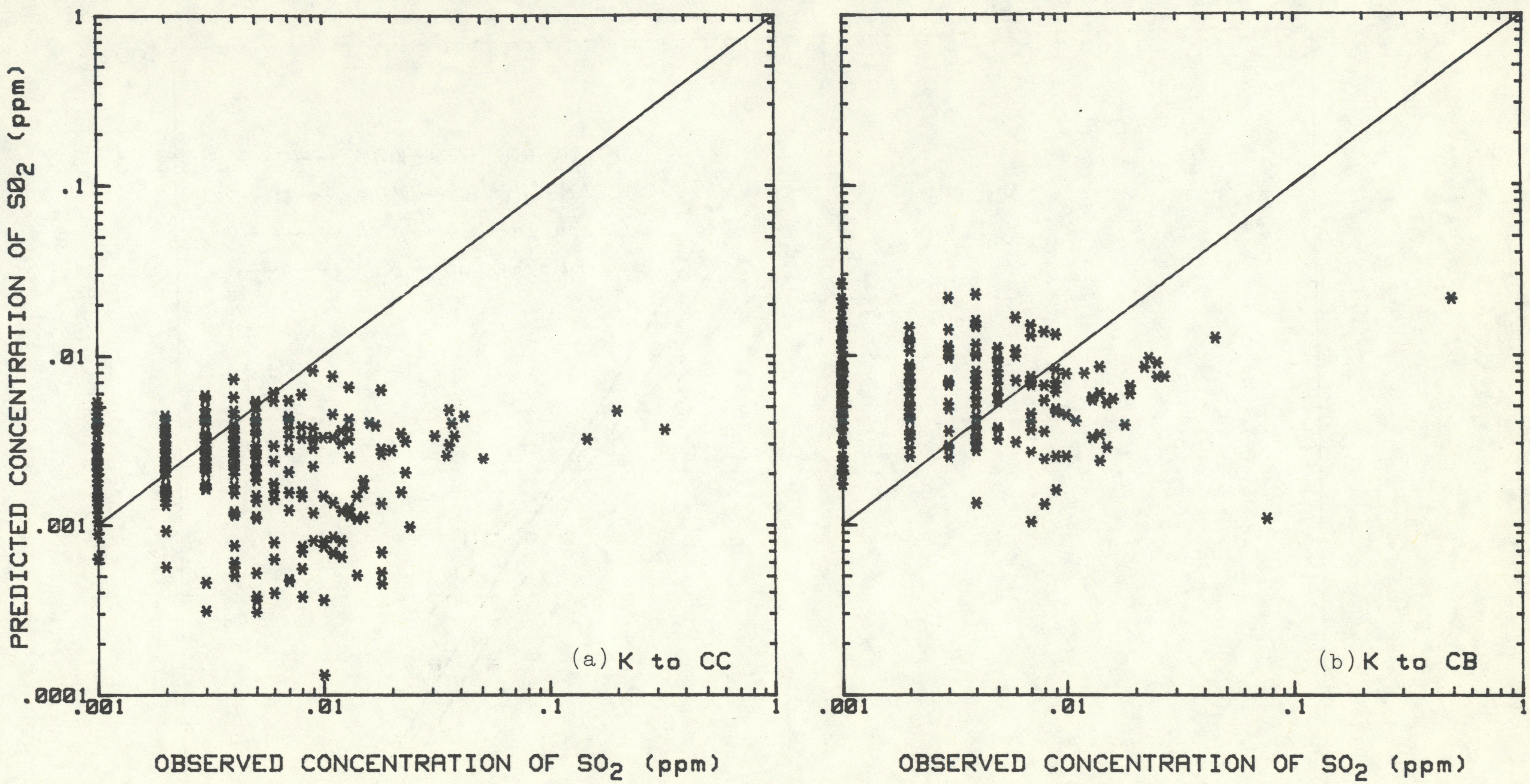


FIGURE 17. COMPARISON OF PREDICTED AND OBSERVED VALUES OF AVERAGE SO_2 CONCENTRATIONS ABOVE THE CROSS CREEK (CC) AND CAMP BRANCH (CB) WATERSHED SITES CALCULATED USING EMISSIONS AND METEOROLOGICAL DATA FROM THE KINGSTON (K) STEAM PLANT

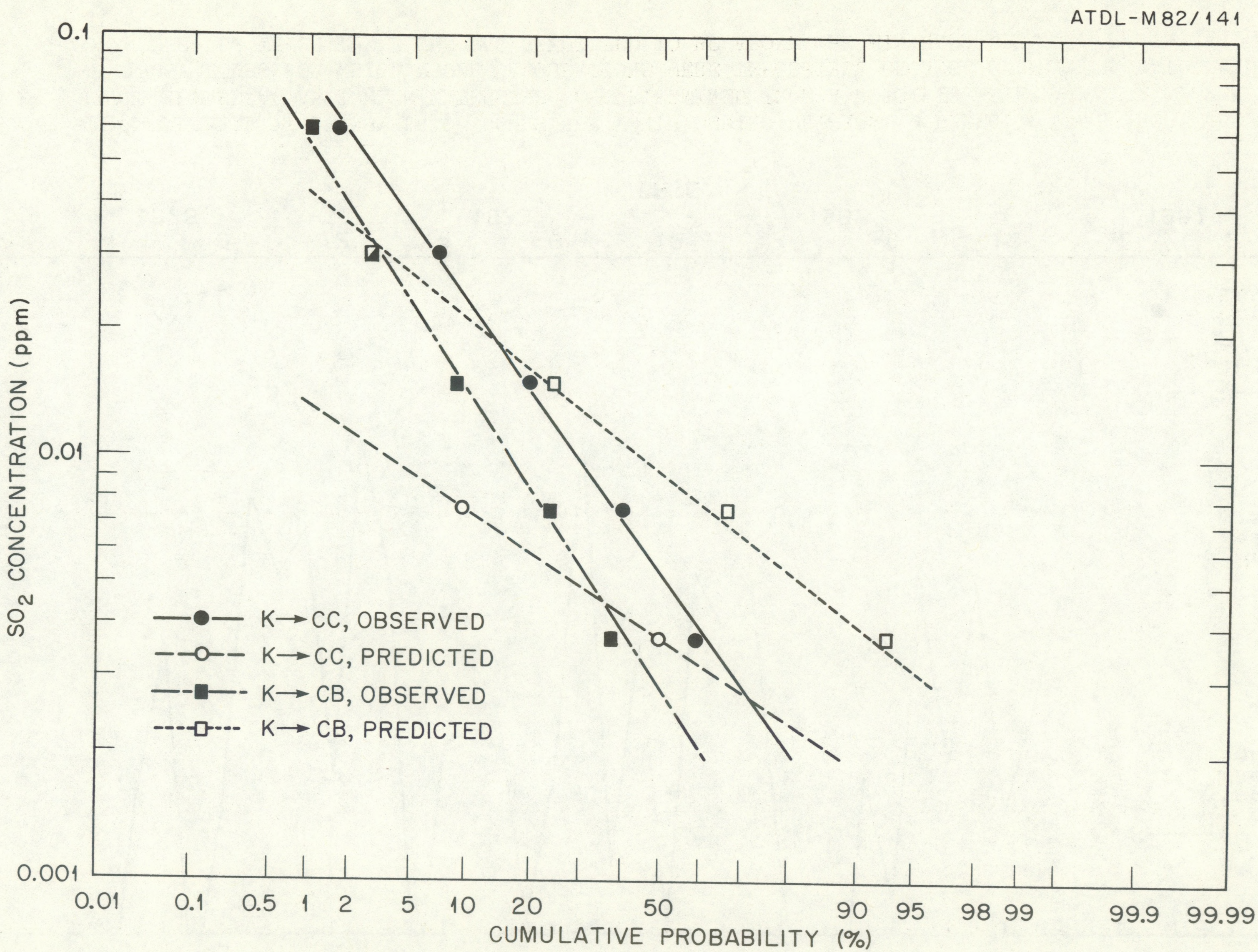


FIGURE 18. CUMULATIVE FREQUENCY DISTRIBUTIONS OF OBSERVED AND PREDICTED SO_2 CONCENTRATIONS AT THE CROSS CREEK (CC) AND CAMP BRANCH (CB) WATERSHED SITES USING KINGSTON STEAM PLANT DATA.

(a) WCV to CB

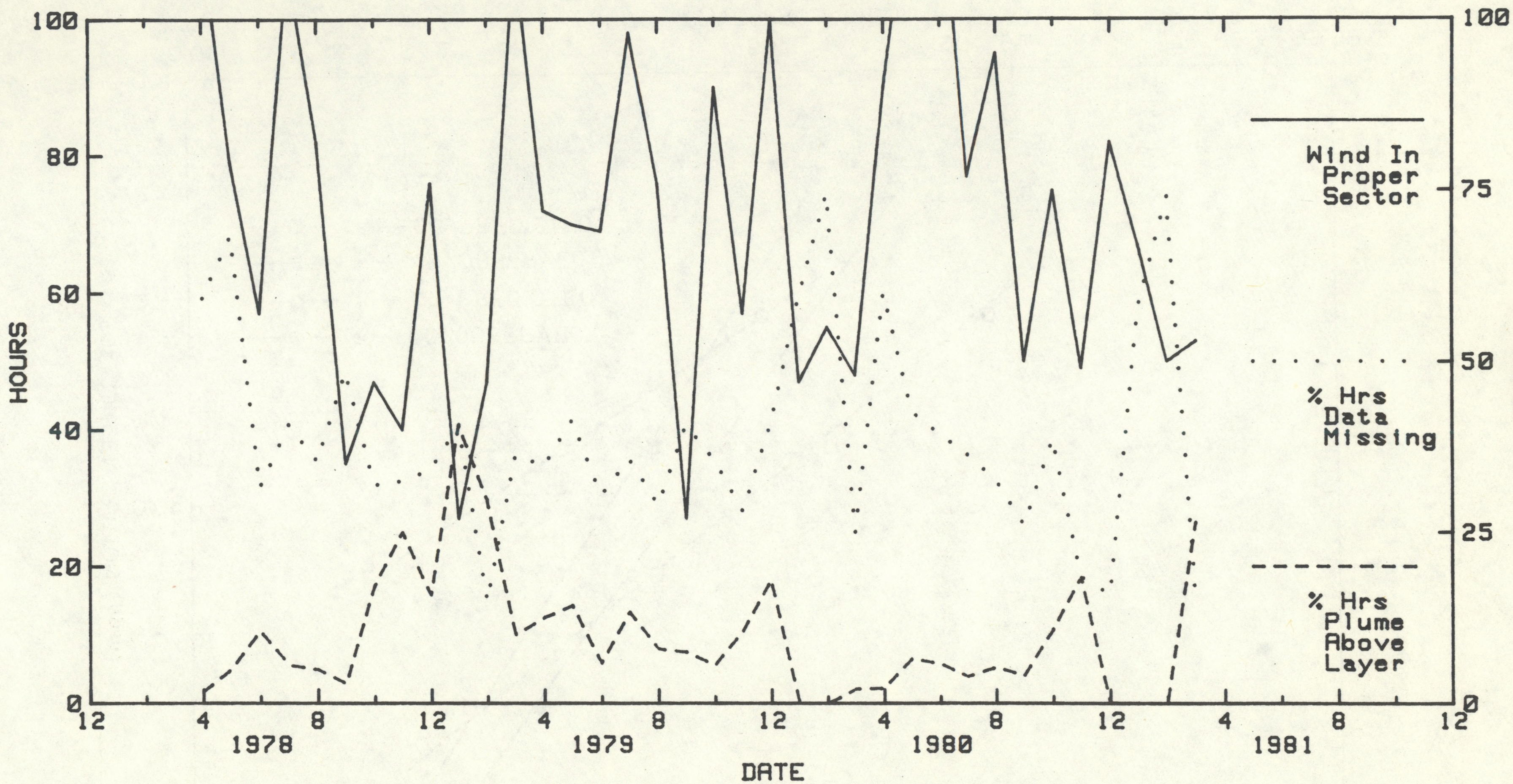


FIGURE 19. TIME-VARIABILITY OF NUMBER OF HOURS PER MONTH DURING WHICH WIND DIRECTION WAS FROM A PARTICULAR POWER PLANT TOWARD A PARTICULAR WATERSHED AS DETERMINED FROM A SPECIFIC METEOROLOGICAL TOWER, THE PERCENTAGE OF THOSE HOURS FOR WHICH MODEL CALCULATIONS WERE IMPOSSIBLE BECAUSE OF MISSING DATA, AND THE PERCENTAGE OF HOURS FOR WHICH THE PLUME WAS PREDICTED TO BE ABOVE THE MIXING LAYER.

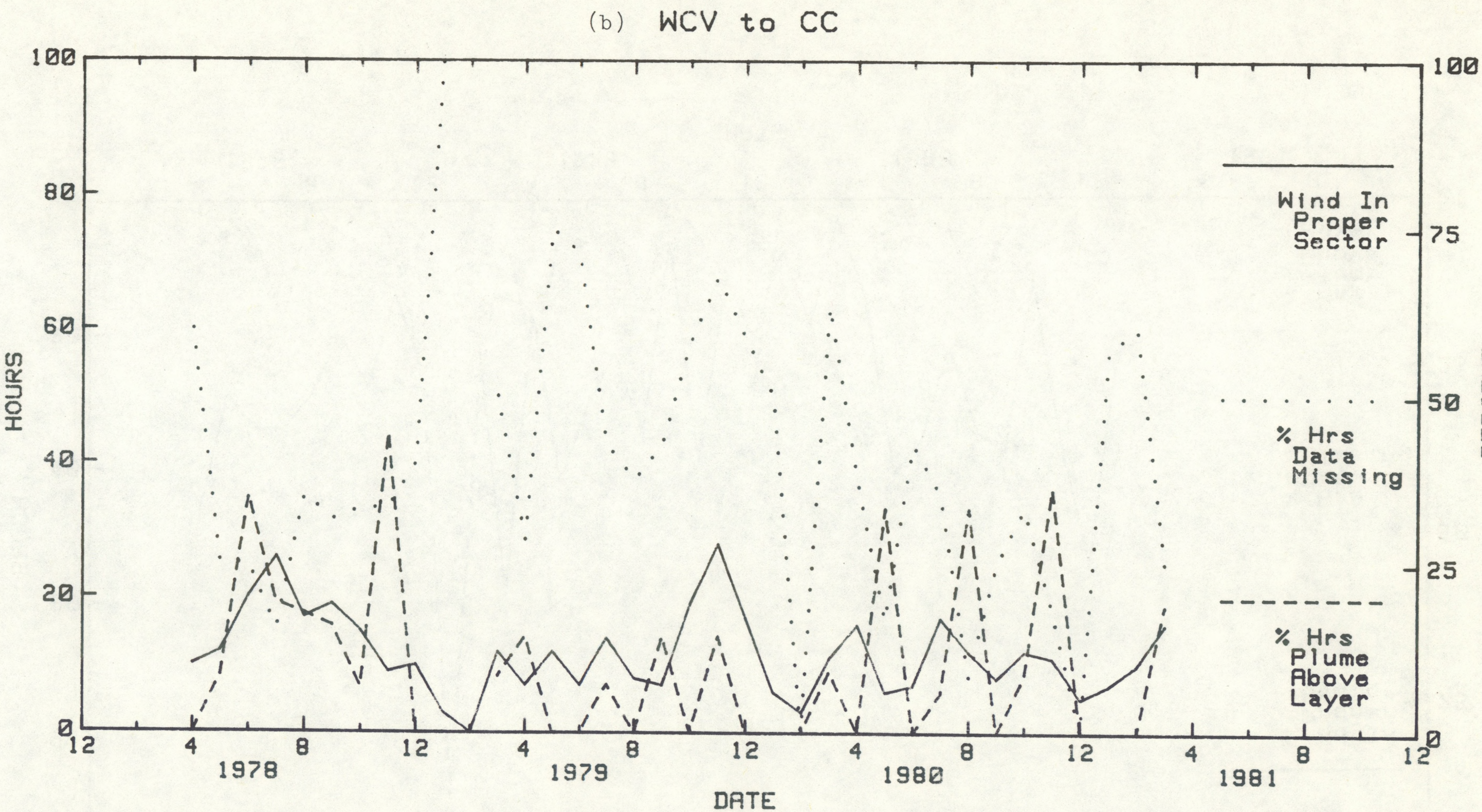


FIGURE 19. (continued)

(c) WCM to CB

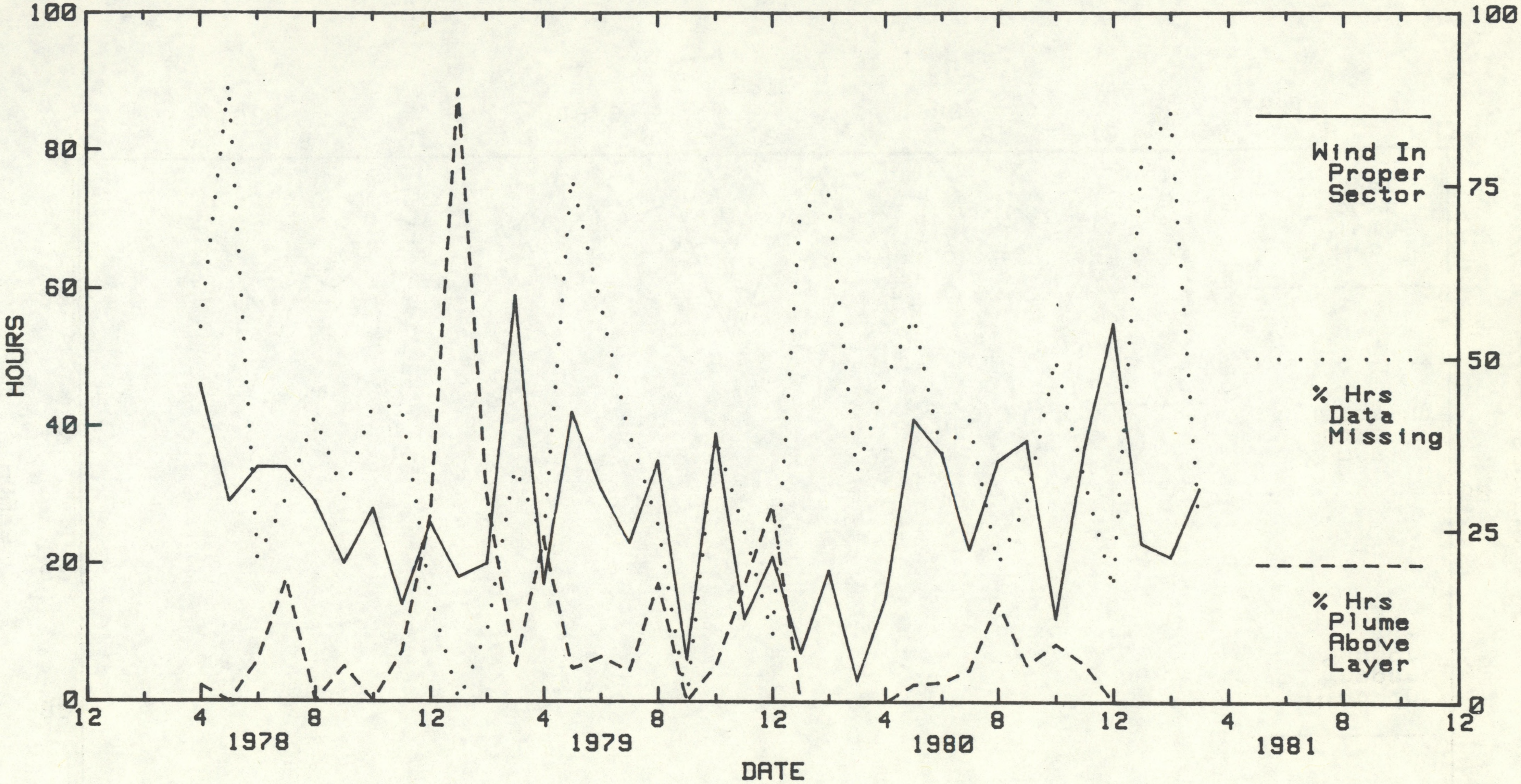


FIGURE 19. (continued)

(d) WCM to CC

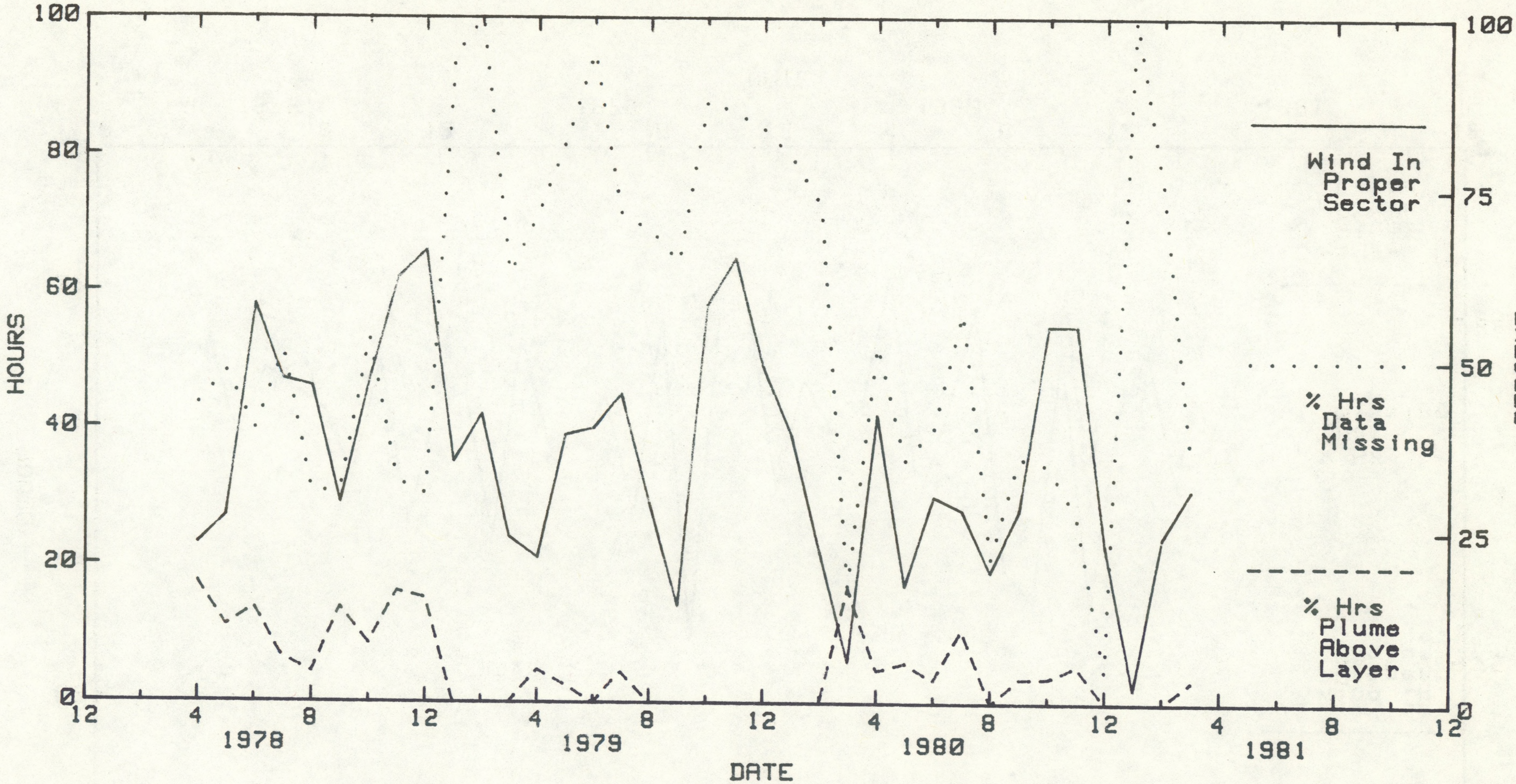


FIGURE 19. (continued)

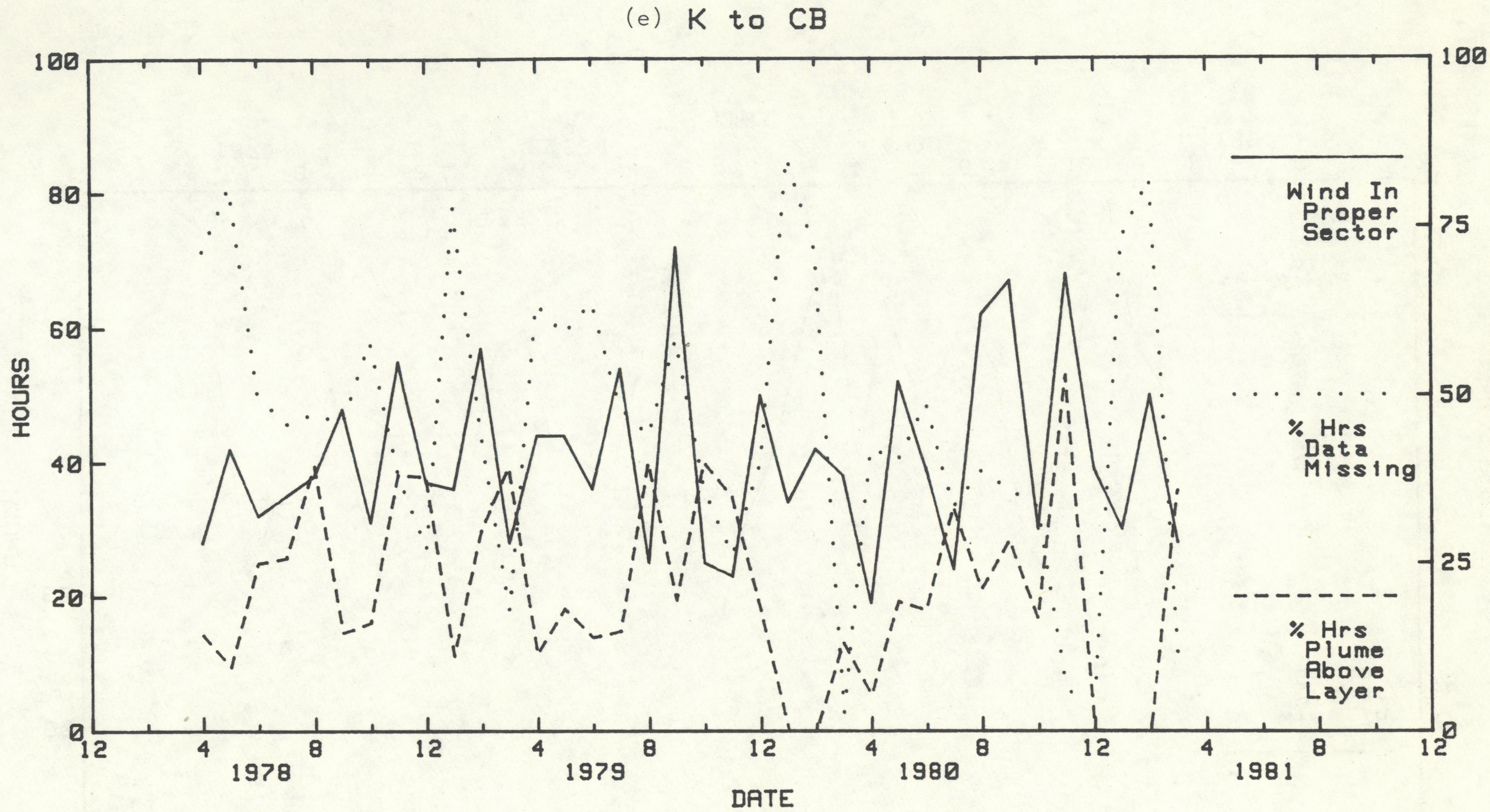


FIGURE 19. (continued)

(f) K to CC

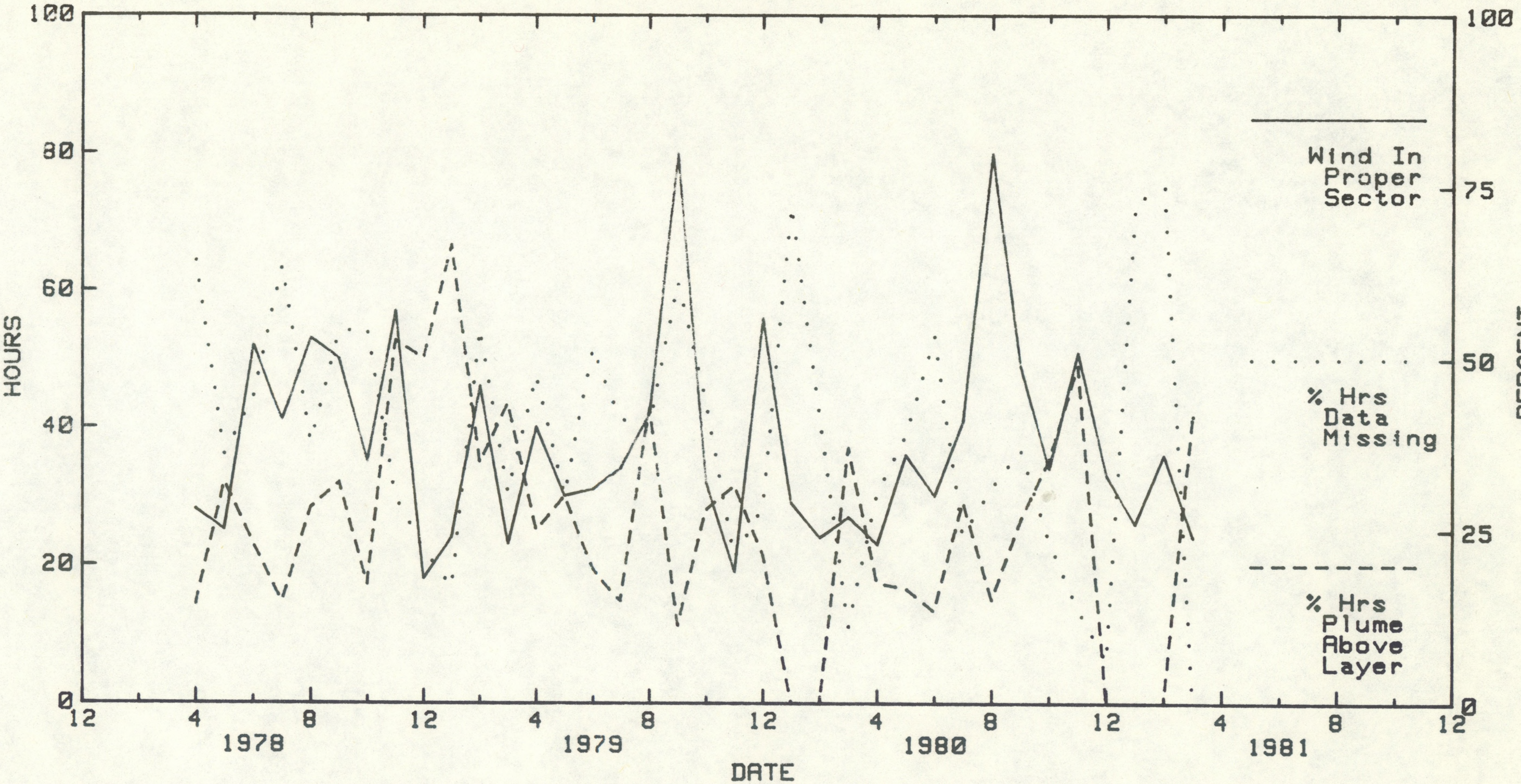


FIGURE 19. (continued)