PRELIMINARY INVESTIGATION OF LIGHT SCATTERING AND VISIBILITY IN TWO EASTERN NATIONAL PARKS

by

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Table of Contents

List of Tables

List of Figures

Figure		Page

Introduction

In recent years public awareness has increased concerning the possible and probable consequences that accompany the emission of man-made pollutants into the atmosphere. More and more effort is being made to preserve the quality of our air resources, as can be seen in the growing interest in air pollution research and increased legislative action.

Of prime concern recently has been the deterioration of visibility in the so-called "pristine" areas. These generally remote regions, consisting mainly of wilderness areas and national parks, have been designated as mandatory class I Prevention of Significant Deterioration (PSD) areas in the 1977 Clean Air Act Amendments (1). In these Amendments, "Congress . . . declares as a national goal the prevention of any future, and the remedying of any existing impairment of visibility in mandatory class I Federal areas which impairment results from manmade air pollution."

A general decrease in visibility as measured at airports in the U. S. has been evident over the past two decades (2, 3, 4). The worst seasonal decline has occurred in the summer months. In fact, in the mid-1950's the summertime exhibited the best visibility of all the seasons. Now it is by far the worst season for observed visibility.

The implications of visibility degradation in pristine areas such as national parks are significant and far reaching. The inability to observe the natural beauty of an area results in a decrease in the aesthetic value of the area. Economic losses may be felt due to reduced tourism resulting from the decrease in aesthetic value mentioned previously. For example, more than 3 million tourists a year and often as many as 20,000 per day visit and drive along the Skyline Drive in the Shenandoah National Park in Virginia. Aviation may be hindered in low visibility areas also in that low visibility due to haze, fog, and smoke may contribute to hazardous visual flight conditions.

Long term effects of the presence of aerosols which scatter light and cause visibility reduction may include global climate modifications such as decreased average temperatures due to shading by the haze layer. The haze layer may also be linked with other problems such as adverse health effects, acid rain, and vegetation damage (2, 5).

Visibility degradation, for the most part, is caused by the scattering of light by atmospheric aerosols. These aerosols are generally the result of complex secondary reactions involving anthropogenic pollutant emissions and natural pollutants existing in the atmosphere. Meteorological conditions play a major role in the formation, transport, and dispersion of light scattering aerosols.

The geographic areas studied in this investigation include two mandatory Federal class I PSD areas (1). These areas include the Great Smoky Mountain National Park in Tennessee and North Carolina, and the Shenandoah National Park in Virginia.

The objective of this study is to test a hypothesis which states that visibility and light scattering levels in and around the areas mentioned above vary both horizontally and vertically. Results obtained in this investigation may be further utilized by legislators and National Park Service officials in decision and policy-making processes regarding the preservation of air resources in these regions.

To achieve this objective an airborne platform equipped to monitor ambient levels of atmospheric parameters was utilized. The use of an airborne monitoring platform has a major advantage over using ground monitoring stations in that analysis of parameters may take place in a wide, three-dimensional range of locations.

The parameters measured for this study included altitude above mean sea level, ambient temperature and dew point temperature for determining relative humidity, and the atmospheric light scattering coefficient, which is related to visibility at low relative humidities. Other parameters were simultaneously measured with those previously mentioned including ozone and sulfur dioxide concentrations.

Literature Review

Malm (6) broadly defines visibility as "the degree of clearness of the atmosphere." However no reference to distance is implied in this definition. Williamson (7) indicates that a more proper term would be "visual range", which he defines as the greatest distance at which an observer can distinguish a contrast between an object and its background. He further defines "prevailing visibility" as the greatest visual range which is attained or surpassed around at least half of the horizon, but not necessarily in continuous sectors.

According to Seinfeld (8) two physical phenomena are responsible for visibility degradation, namely absorption, which is responsible for the coloration of objects, and scattering of light. However many feel that light scattering is primarily responsible for visibility degradation (7, 9, 10). Light scattering reduces contrast, thus essentially reducing visibility (8, 9). Both scattering and absorption depend on the size of any particles or gas molecules present in the atmosphere, and on the electronic properties of the gas molecules present (11).

Light may be absorbed by both particles and gases, however the role of absorption in the deterioration of visibility is generally thought to be negligible (7, 9, 10). If the concentration of light absorbing materials in the atmosphere is high, absorption may contribute to visibility degradation (7, 12, 13). According to Ahlquist and Charlson (10), even if the visual range is affected by light absorption, information on aerosols present in the sample will still be made known by measuring the light scattering of these aerosols, since all particles scatter light to some degree.

The amount of light scattered by gaseous atmospheric constituents is a known, predictable quantity (14, 15, 16). In 1899 Lord Rayleigh, as reported by Middleton (9), observed the sky to be bluest when the air was the most pure. He hypothesized that the blue color was due to the scattering of sunlight by individual molecules of permanent atmospheric gases. Williamson (7) asserts that this is not exactly correct, but that light is scattered by groups of molecules in areas of the atmosphere where the concentration of molecules is momentarily higher than the average. The increase in density on a very small scale causes the incident light to be scattered. This phenomenon is known as Rayleigh scattering (7, 9). The quantities associated with Rayleigh scattering will be discussed later in more detail.

In a polluted atmosphere where deterioration of visibility is a major problem, Rayleigh scattering is generally much less than scattering by aerosols (12, 14). Therefore it is usually assumed that a reduction in visibility is due to an increase in light scattering by atmospheric aerosols (9, 12, 17, 18, 19, 20).

The size of a particle has a tremendous effect on its light scattering properties. Particles with a diameter less than approximately 0.1 micron scatter light equally well in the forward or backward directions (7, 8). Rayleigh and others (9, 21, 22) have found light scattering by very small particles to be inversely proportional to the fourth power of the wavelength of the incident light. Very large particles whose diameters are greater than several microns scatter light three ways, namely by reflection, diffraction, or refraction (7, 8). However, light scattered by these particles is not significantly altered from its original forward direction. Large particles, assuming no light is absorbed, are responsible for a white haze appearing near the direction of the sun (7).

The particles most responsible for scattering light are those whose diameters are comparable to the wavelength of the incident light (7, 8, 23). These particles are contained in what Leaderer, et. al. (5), call the "accumulation mode". It has been found that the human eye is most sensitive to solar radiation of wavelength 550 nanometers (nm), which is included in the visible radiation spectrum (6, 9, 21). Charlson, et al. (21), report that the amount of light scattered by these particles is proportional to the wavelength of the incident light raised to the inverse first to second power. Ahlquist and Charlson (22) state that scattering is proportional to the wavelength raised to the inverse 1.3 power for these aerosols. Light is scattered from these particles in directions different from that of the incident light (7). Therefore particles in the range greater than 0.1 micron and less than 1.0 micron in diameter are the most effective light scatterers (7, 8, 14, 17). Hence these particles are primarily responsible for visibility degradation due to light scattering.

According to Steffens (24) most deterioration of visibility occurs in the air nearest to the observer such that if the visual range were measured to be 100 yards, 50 percent of the visibility reduction would occur in the 18 yards of haze nearest to the observer. Only 10 percent of the obscuration would be produced in the 40 yards closest to the object.

Middleton (9) and Williamson (7) report that in 1924, Koschmieder devised a theory on contrast reduction, represented by the following equation:

$$C_R = C_o e^{-\sigma_o R} \qquad (1)$$

where,

C_o = the inherent contrast, or contrast at the viewed object

C_R = the apparent contrast, or contrast at a distance R from the object

σ_o = the attenuation or extinction coefficient

Visual range would be the maximum value of R for which the contrast C_R may be observed. The term "contrast threshold" is now introduced and may be represented by the ratio of C_R to C_o. It may be defined more precisely as the contrast presented to an observer which results in a 50 percent probability of a specific object being observed. Koschmieder is reported to have found the value of the contrast threshold to be 0.02. This results in the following equation:

$$\frac{C_R}{C_o} = 0.02 = e^{-\sigma_o R} \tag{2}$$

Taking the natural logarithm of the equation yields:

$$-\ln 0.02 = \sigma_o R \tag{3}$$

and

$$R = \frac{-\ln 0.02}{\sigma_o} = \frac{3.912}{\sigma_o} \tag{4}$$

Since the maximum value of R would be evident at the contrast threshold, equation 4 may now be written as (7):

$$L_v = \frac{3.912}{\sigma_o} \qquad (5)$$

where,

L_v = Visual range

L_v and σ_o must be in comparable units for Equation 5 to apply (23). The attenuation or extinction coefficient, σ_o, may be represented by (7, 9, 18):

$$\sigma_o = b_{scat} + b_{abs} \qquad (6)$$

where,

b_{scat} = light scattering coefficient due to atmospheric aerosols and gases

b_{abs} = light absorption coefficient due to atmospheric aerosols and gases

In previous discussion it was determined that the atmospheric light absorption is considered to be negligible. Taking this into account, Equation 6 becomes:

$$L_v = \frac{3.912}{b_{scat}} \qquad (7)$$

Since the contrast threshold is based on human eye detection, a wavelength of 550 nm is assumed for the incident light scattered according to Equation 7 (21, 25). In addition, some basic assumptions were utilized in deriving Equation 7 such as (6):

1. A homogeneous atmosphere exists
2. The earth is flat
3. The object is viewed horizontally
4. The object is black, such that $C_o = -1$
5. Radiance from the sky is the same at the object and at the observation point

It is obvious that the afforementioned assumptions are at best idealistic and that, in fact, none of these assumptions may ever hold true. Only in a homogeneous atmosphere may visual range be determined from a single measurement of b_{scat} (12, 14). Because of this the term "meteorological range" is more properly assigned to a distance determined by a single point measurement of b_{scat} (14, 21). The visual range and the meteorological range will be the same if the scattering coefficient is spatially uniform (12). Charlson, et al. (14), suggest that use of an average value of b_{scat} over a certain distance would correctly determine the visual range.

The atmospheric scattering coefficient b_{scat}, can be broken down into two components: the scattering coefficient due to atmospheric aerosols and the Rayleigh scattering coefficient (8, 9).

The Rayleigh scattering coefficient is known and predictable, as was previously mentioned. At sea level the value for Rayleigh scattering is 0.23×10^{-4} meters^{-1} (m^{-1}), assuming standard temperature (273° K) and pressure (1 atm) and an incident light wavelength of 500 nm (16, 21). This value increases linearly with increasing altitude (21). Charlson, et al. (14), and Ahlquist, et al. (15) predict a value of 0.28×10^{-4} m^{-1} at sea level, however this assumes an incident wavelength of approximately 460 nm.

Since the value of Rayleigh scattering is known, the light scattering by aerosols alone can be determined simply by subtracting the Rayleigh scattering coefficient from the total scattering coefficient (8, 9).

It is generally known that atmospheric haziness is due to the presence of a concentration of aerosols which is sufficient to cause obscuration. Previous discussion has shown this obscuration to be caused principally by light scattering by these aerosols. As the concentration of atmospheric particles increases the light scattering coefficient increases and visual range decreases (26, 27).

Sulfate particulates tend to be those which are most responsible for the deterioration of visibility (2, 5, 27, 28). This is because they are the dominant type of particle in the accumulation mode (2). Although they may constitute as little as 15 percent of the total aerosol mass, they may be responsible for as much as 50 percent of the total visibility degradation (2, 5). Nitrates may also contribute significantly to visibility reduction (26, 29). Sulfate and nitrate aerosols are most probably due to secondary reactions of gases such as SO_2, NO_2 and reactive hydrocarbons with other atmospheric constituents (4, 5, 26). For example, Leaderer, et al. (5) claim that SO_2 may be converted to sulfate several ways, namely by direct and indirect photooxidation, by air oxidation in liquid droplets, and by catalyzed oxidation in liquid droplets or on dry surfaces.

Evidence that visibility degradation is related to sulfur emissions through their transformation to sulfates has been documented (3, 26). According to Husar, et al. (3), during the period from 1951 to 1974, the light scattering coefficient, b_{scat} showed a strong correlation with levels of coal combustion, hence with sulfur emissions, in the eastern United States. During a copper smelter workers strike in 1967 and 1968, sulfate emissions decreased drastically while visibility significantly improved (26).

A constant distribution of aerosols throughout the atmosphere is generally assumed (7, 9, 12, 30). This may not always be a correct assumption, however several studies have shown the existence of a fairly uniform particle size distribution (12, 30).

Particles in the accumulation mode may be removed from the atmosphere by rainout (26). However Charlson, et. al. (14), believe this may not be the case. They claim that the haze aerosols may be too small to be inertially collected by the raindrops. They maintain that the cleaning effect often evident following a rainstorm may be attributed to the frontal movement of a cleaner air mass, not to washout by raindrops.

Several relationships have been established between visual range, b_{scat}, and aerosol concentrations. Several authors have found a relationship between visual range and mass as follows (19, 23, 31):

$$L_v \times M = 1.2 \text{ g/m}^2 \qquad (8)$$

where

L_v = visual range (m)

M = aerosol mass concentration (g/m^3)

This corresponds to a mass to b_{scat} ratio equal to 0.31 g/m^2. However the most widely accepted relationship is (7, 12, 16, 18, 21, 30):

$$L_v \times M = 1.8 \text{ g/m}^2 \qquad (9)$$

This corresponds to a mass to b_{scat} ratio equal to 0.45 g/m^2 (12, 15). White and Roberts, as reported by Cass (27) devised two relationships as follows:

$$b_{scat} = 0.032 \pm 0.009 \qquad (10)$$

and

$$b_{scat} = 0.022\ (\text{TSP-Sulfates-Nitrates}) + 0.062\ \text{Sulfates} + (0.022 + 0.050\ RH^2)\text{Nitrates} \pm 1.0 \qquad (11)$$

where

b_{scat} = light scattering coefficient, $(10^4 m)^{-1}$

RH = relative humidity, (%/100)

TSP = total suspended particulates ($\mu g/m^3$)

Sulfates and Nitrates = ($\mu g/m^3$), taken as 1.3 $SO_4^=$ and 1.3 NO_3^- concentrations in order to account for the mass of associated cations

(TSP-Sulfates-Nitrates) = ($\mu g/m^3$), non-sulfate and non-nitrate particulates

Ettinger and Royer (32) formulated a relationship as follows:

$$L_v = \frac{24.}{0.2 + (0.01^{+.01}_{-.003})M} \qquad (12)$$

where

L_v = visual range (miles)

M = aerosol concentration ($\mu g/m^3$)

According to Lyons (28), Husar devised the following relationship for atmospheric extinction and sulfate concentrations:

$$b_{ext} = 3.24 + 0.11\ SO_4^{=} \qquad (13)$$

where

b_{ext} = atmospheric extinction coefficient $(10^4 m)^{-1}$

$SO_4^{=}$ = atmospheric sulfate concentration $(\mu g/m^3)$

It is generally agreed that relative humidity has a significant effect on the light scattering properties of atmospheric aerosols (7, 12, 15, 18, 29, 30, 31). Relative humidity, as defined by Williamson (7), is the ratio of the ambient concentration of water vapor to the concentration at saturation. Relative humidity is usually expressed as a percentage. Most authors believe that relative humidities greater than 70 percent will have the greatest effect on particle light scattering (12, 15, 30, 31). Others feel that relative humidities greater than 60 or 65 percent will significantly alter light scattering (7, 18, 29). Covert, et. al. (29) maintain that reduced visibilities may be the result of low aerosol concentrations if the relative humidity approaches 100 percent. They also found that the light scattering increased by a factor of 1.6-1.9 at a relative humidity of 80 percent (29).

The dependence of light scattering on relative humidity is due to the hygroscopic nature of certain atmospheric aerosols at elevated relative humidities (7, 12, 30, 31). Water vapor in near saturated air tends to condense on the individual particles, thus increasing their size and changing their light scattering properties (7, 31).

Williamson (7) indicates that, due to the hygroscopic effect at high relative humidities, the relationship shown in Equation 7 is inaccurate for relative humidities greater than 65 percent. Several authors (16, 19) recommend heating a sample of air to negate relative humidity effects. The relative humidity is decreased and the water droplets attached to the particles are revaporized.

Several types of instrumental methods are available for measuring visual range or other related parameters. The first type represents those which measure atmospheric extinction. These instruments are generally called telephometers (9). Middleton (9) describes this instrument as one which measures light coming from a distance, while others define telephotometers as instruments which measure the contrast between a black target and the horizon sky (26, 33). The contrast measured may then be used to calculate atmospheric extinction (26). Malm (6) and Cwalinski et al. (33) have found that visual range determined by telephotometer readings correlated best with actual observed visibilities. Therefore, the telephotometer is the best choice for visibility measurements. A significant drawback of the telephotometer is that it can only be used in daylight under cloudless conditions in the background sky (33, 34). Telephotometers may be utilized without regard to geographic location (33). However Malm (6) states that continuous monitors of this type may be used for ground-based applications only, since it is difficult to measure, in a mobile situation, the many atmospheric parameters on which visual range determination depends.

A second type of instrument is one which measures visual range by utilizing an "artificial haze" (9). These instruments basically induce a haze, which is applied to the field of view until an object at a known distance cannot be seen anymore. Information on visual range is derived according to the amount of haze which is necessary to obscure the view. Instruments of this type are limited to daytime use only.

Another type of instrument, the transmissometer, measures light extinction over a folded horizontal path (33). These instruments, however, show the worst correlation with observed visibilities and are considered to be the least favorable devices for measuring visual range.

The fourth method of instrumentation measures light scattering by aerosols in a standard volume of air (9, 10, 14, 16). The instrument is called an "integrating nephelometer" (9, 10, 16). It was devised originally in 1949 by Beuttel and Brewer as an aid in wartime determination of visual range (9, 10). This instrument used the human eye as the sensor device, thus limiting its degree of sensitivity.

Ahlquist and Charlson (10) report that in 1963, Crosby and Koerber improved the sensitivity of the instrument by utilizing a multiplier phototube (photomultiplier tube) as the sensing device. The model most used today was designed in 1967 by Ahlquist and Charlson (10) and provided an updated circuitry for maximizing stability and minimizing power consumption and size. The design of the sample cell was also improved.

The integrating nephelometer measures light scattering at a point in the atmosphere (33, 34). Meteorological range, as measured by the integrating nephelometer, has been shown to have a high correlation with observed measurements of visual range (21). However, the integrating nephelometer does not correlate with observed visual range quite as well as the telephotometer (33, 34). Advantages to using the integrating nephelometer for determining b_{scat} and visual range are (15, 16, 33, 35):

1. Automatic operation
2. Low Maintenance
3. May be operated in fixed or

mobile locations

4. May be used at night
5. In-operation calibration
6. High sensitivity

Charlson, et al. (14), outline various uses for the integrating nephelometer such as:

1. Measurement of visibility reduction due to air pollution
2. Investigations of the inhomogeneity of the atmosphere with respect to b_{scat}.
3. Investigations of the time variation of the mass of suspended particulate matter per volume of air
4. Invesitgations of the nature of both natural and man-made aerosols as they may affect L_v
5. In the laboratory for use in aerosol experiments

Mobile use of the integrating nephelometer has been shown to correlate well with stationary use of the instrument (33). The integrating nephelometer has been adequately utilized in airborne measurement of light scattering (15, 36, 37, 38, 39).

High sensitivity is necessary in the integrating nephelometer so that scattering due to aerosols may be distinguished from Rayleigh scattering (10, 14, 21). The instrument examines a uniformly defined air sample in determining b_{scat} (14). Zero and span readings are verified during calibration through the application of the known scattering coefficients of gases such as particle free air, carbon dioxide, helium or Freon-12 (CCl_2F_2) (10, 15, 16, 21).

Charlson et. al. (21), have determined that the effective wavelength of the light scattered within the integrating nephelometer is 500 nm. This differs from the 550 nm wavelength assumed by Koschmieder in the formulation of Equation 7. A relationship between scattering coefficients at these two wavelengths exists such that (21):

$$b_{550} \simeq 0.84\ b_{500}$$

where,

b_{500} = light scattering coefficient at a wavelength of 500 nm

b_{550} = light scattering coefficient at a wavelength of 550 nm

Recalling Equation 7:

$$L_v = \frac{3.9}{b_{scat}} \qquad (7)$$

where,

L_v = visual range

b_{scat} = light scattering coefficient measured at the maximum human eye sensitivity, wavelength = 550 nm

By substitution:

$$L_v = \frac{3.9}{0.84\ b_{500}} \qquad (15)$$

and

$$L_v = \frac{4.7}{b_{500}} \qquad (16)$$

The product of visual range and mass is given by (21):

$$L_v \times \text{MASS} = 1.8\ \text{g/m}^2 \qquad (17)$$

where

L_v = visual range (meters)

MASS = aerosol mass concentration (g/m^3)

By combining Equation 16 and 17, the following relationship is formulated (16, 21):

$$\text{MASS} = 3.8 \times 10^5\ b_{500}$$

where,

MASS = aerosol mass concentration
($\mu g/m^3$)

b_{500} = light scattering coefficient
(m^{-1})

The above formulas are useful in determing relationships between measured values of b_{scat}, visual range, and aerosol mass concentrations.

Measurements made by the integrating nephelometer are made under the assumption that a uniform distribution of particle sizes exists (40).

Experimental Methods

The instrumentation used in this investigation is mounted in a twin-engine light aircraft described in earlier studies by Stephens et al. (36) and Lubkert (41). Of special interest to this study are a Meterology Research, Inc. (MRI), integrating nephelometer, a Rosemount platinum resistance thermometer, an EG & G hygrometer, and a Giannini pressure transducer. Data from these instruments were gathered by a Hewlett-Packard data logging system consisting of a portable desktop programmable calculator, an electronic scanner, an analog-to-digital converting voltmeter, and a quartz crystal real-time clock. A peripheral plotter, which is controlled by the calculator, was utilized in analyzing the many data. Ozone (O_3) and sulfur dioxide (SO_2) concentration levels, as measured by a Dasibi ozone analyzer and a Meloy sulfur analyzer are also reported in this study. Internal calibration checks were performed on each instrument prior to each flight.

Power is supplied to the system by a 1000 watt Abacus frequency inverter. Twenty eight VDC supplied by onboard rectified alternators is converted to 110 VAC, 60 cycle power which is utilized by the various instruments. Sample air is introduced to the instruments by way of a teflon-lined inlet hose and a stainless steel manifold.

The areas studied in this investigation include the Great Smoky Mountains and the Shenandoah National Parks. The Great

Smoky Mountains National Park, shown in Figure 1, consists of over half a million acres of beautiful mountainous terrain (42). It is located on the eastern Tennessee-western North Carolina border, some 20 miles southeast of Knoxville, Tennessee, and 25 miles west of Asheville, North Carolina. The area directly south of the park in North Carolina is heavily forested, rugged terrain. To the north of the park lies the valley in which Knoxville is located.

The park itself consists of mountainous terrain, most of which is heavily forested. It is divided by the ridge of the Appalachian Mountains and features such peaks as Clingmans Dome and Mt. LeConte, which extend to over 6500 feet in elevation.

The Smokys are a popular recreational area, and are visited annually by many campers, hikers, fishers, and other tourists. In addition, the town of Gatlinburg, Tennessee, hosts over one million tourists annually.

Air quality in the park may be affected by the close proximity of several industrial sites in Tennessee, such as Knoxville and Alcoa. Several Tennessee Valley Authority (TVA) fossil fuel power stations are located in the nearby valley and may contribute to existing pollutant levels.

The Shenandoah National Park, illustrated in Figure 2, is located in northwest-central Virginia in the Blue Ridge Mountains

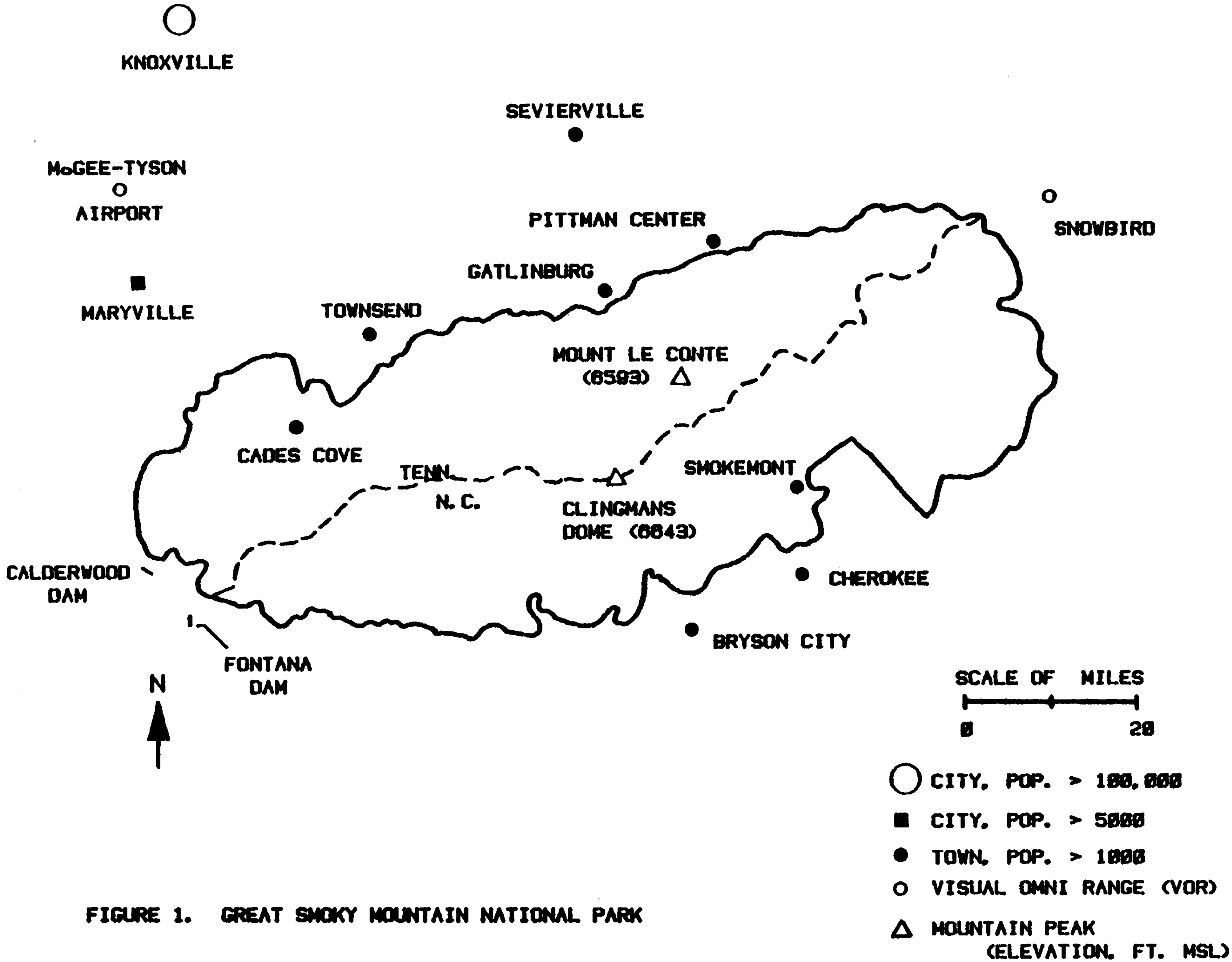


FIGURE 1. GREAT SMOKY MOUNTAIN NATIONAL PARK

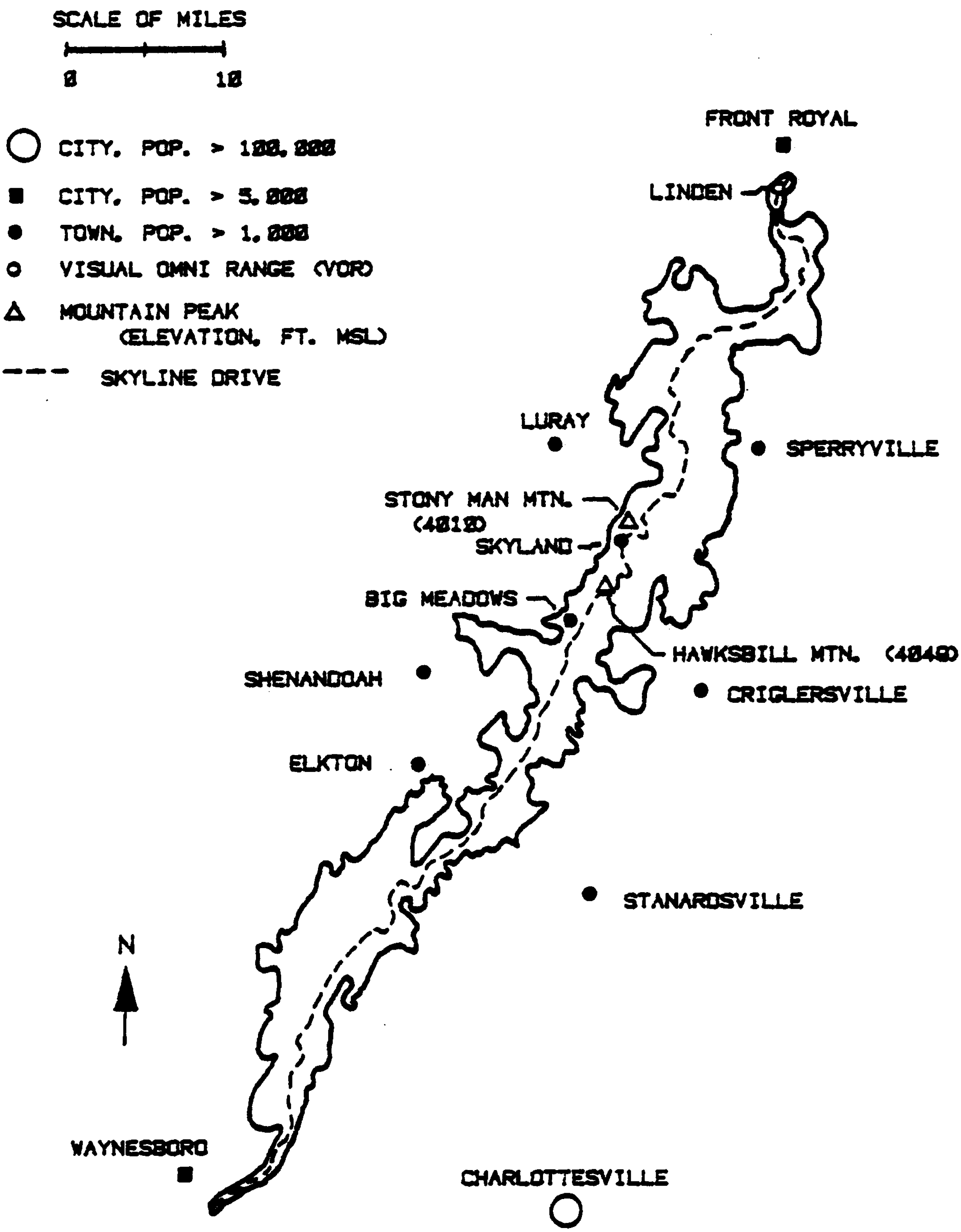


FIGURE 2. SHENANDOAH NATIONAL PARK

and covers nearly 200,000 acres (42). It lies between Waynesboro and Front Royal, Virginia, approximately 30 miles east of the Virginia-West Virginia border and approximately 75 miles southwest of Washington, D. C. The area surrounding the park is essentially flatland, except for the Massanutten Mountain area, which is 15 miles west of the park. Some peaks in the park reach elevations of over 4000 feet. A major attraction of the park is scenic Skyline Drive, which winds along the peaks of the Blue Ridge.

Like the Smokys, the Shenandoah National Park is a popular outdoor recreational area. The resort at Skyland is also a popular place for vacationers.

Air pollution levels in the park may be affected by anthropogenic emissions from the Washington-Baltimore corridor to the northeast or by coal mining operations to the west in West Virginia.

Flights for the purpose of data collection were conducted under the influence of a high pressure air mass. Flights in the Great Smokys were made when possible under the generally well mixed conditions of late afternoon and in early mornings under the influence of the radiation inversion. Sampling flights in the Shenandoah were generally restricted to afternoons.

The sampling flight patterns consisted of vertical spirals conducted at designated locations and horizontal flights at constant altitudes. Spirals generally ranged from elevations of up to 8000 feet down to 1500 feet. These would vary occasionally according to flying conditions. Locations for the vertical spirals were selected on the basis of having a low mean sea level (MSL) ground elevation. In the Great Smoky Mountains areas such as Cades Cove on the north side of the park and Lake Fontana or Cherokee on the south side of the park were often designated for vertical spirals. In the Shenandoah, Luray or Elkton on the northwest side of the Blue Ridge, and Criglersville or Sperryville on the southwest side were often selected for spiral flights.

Horizontal flights were conducted at various altitudes in and around each park. Oftentimes the instruments were operated for warmup purposes and for sampling en route to and from the two national parks and the normal home base of the aircraft, Blacksburg, Virginia.

Results and Discussion

Data collected during sampling flights which were conducted on six days from April to June, 1979, are reported in this study. Each sampling mission typically consisted of vertical spirals and horizontal flights in one of the two national parks previously mentioned. A nominal true air speed of 150 miles per hour was maintained during horizontal flights. During vertical spirals sufficient time was allowed at each altitude to overcome lag time, response time, and amplifier time constant effects inherent to each monitoring instrument before samples of air were analyzed.

In this study data representing seven separate parameters are presented for analysis. These parameters include the time of day, altitude, ambient temperature, dew point temperature, light scattering coefficient (b_{scat}), O_3 concentration, and SO_2 concentration. In addition, the visual range calculated from the corresponding value of b_{scat} is presented.

Ozone concentrations are reported both as a volumetric fraction in parts per billion (PPB) and as a mass fraction in micrograms per cubic meter ($\mu g/m^3$). Altitude is presented in units of feet elevation above mean sea level (MSL). Both ambient temperature and dew point temperature are reported in degrees Fahrenheit (^oF). Units of visual range are in miles while b_{scat} levels are presented in units of inverse meters (m^{-1}). Sulfur dioxide concentrations are reported in PPB.

For the purpose of graphical representation visual range is preferred to b_{scat}, since the significance of this parameter is more easily recognizable. Ozone concentrations will be reported graphically in PPB for this study.

April 20, 1979 - Flight to Shenandoah National Park

Weather conditions on this date showed low pressure air masses existing over eastern and western Canada at the 500 millibar (mbar) level with higher pressures dominating over the state of Virginia. Winds were from the southeast at 13-17 knots at the 500 mbar level.

Vertical spiral data collected during this flight were reported previously by Lubkert (41). A graphical synopsis of the total flight is given in Figure 3. The data plotted in Figure 3 are indicative of distributions seen in typical sampling flights. Each single file represented on the horizontal axis consists of approximately 45 seconds elapsed time. The plot of altitude versus file number shows a typical pattern of horizontal flights, represented by "plateaus" at indicated elevations, and vertical spirals, represented by the "stair stepping" from one altitude to another. This stepping effect is a result of short term level flights at different elevations to allow for synchronization of variable instrumental time lags.

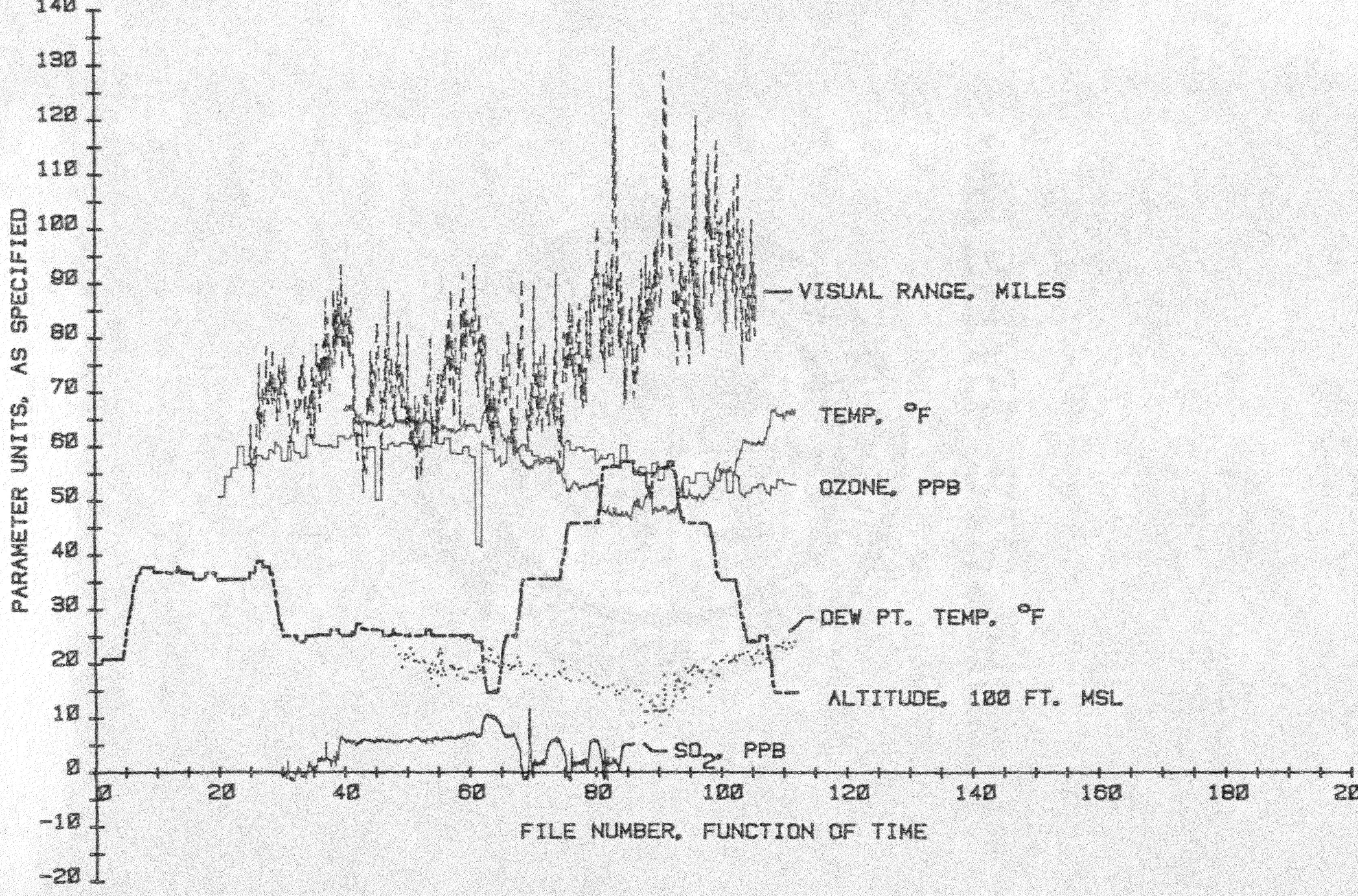


FIGURE 3. CONTINUOUS MULTIPARAMETER RECORD OF FLIGHT TO SHENANDOAH NATIONAL PARK ON APRIL 20, 1979

A constant level flight was performed adjacent to the park from Waynesboro to Shenandoah as is shown in Figure 4. Data at various points along the flight path are presented in Table 1, with visibility data plotted versus time in Figure 4b. Temperature data remain at a fairly constant level during this flight pattern. Correspondingly, the dew point temperature is low for this section of the flight. A low relative humidity is therefore evident, reducing the possibility of hygroscopic effects on aerosols, which may increase light scattering. Consistent with this are the light scattering data which indicate fairly low levels of b_{scat}, thus also indicating generally high values of visual range, L_v. Ozone concentration levels are constant, yet fairly high at approximately 60 PPB. Sulfur dioxide concentration levels are approximately 5 PPB.

Two vertical spirals were performed on this date. The first of thes flights took place west of Skyland from approximately 1500 to 5700 feet MSL. Averaged values for different parameters at various altitudes are presented in Table 2. These data are plotted versus altitude in Figure 5. The data indicate a near adiabatic temperature profile, with temperatures ranging from 47 to 62 ^{o}F. Dew point temperature remains very low, indicating a low relative humidity. Relative humidity, an indication of the degree of atmospheric saturation, may be determined by dividing

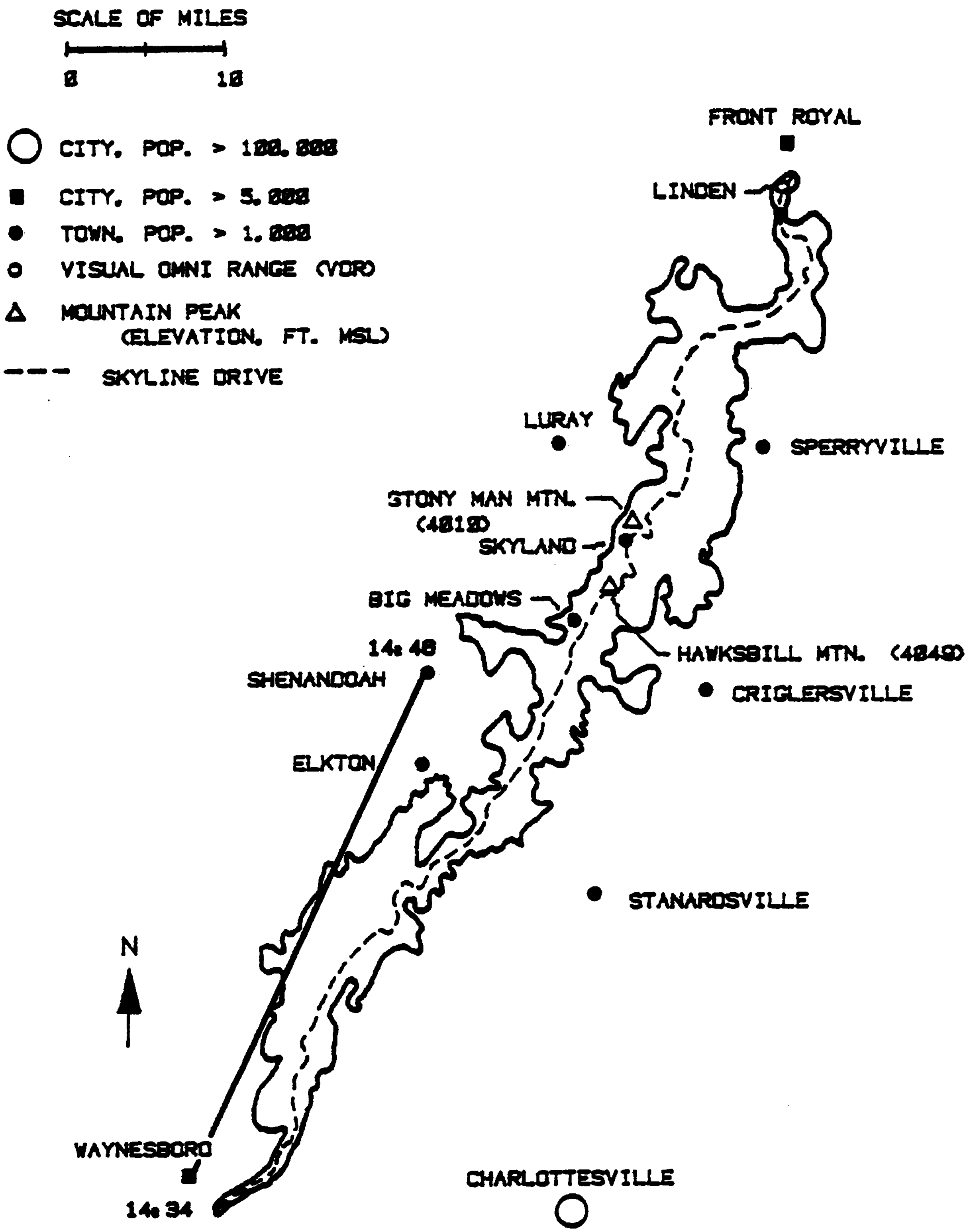


FIGURE 4. FLIGHT ALONG SOUTHWEST SIDE OF SHENANDOAH NATIONAL PARK ON APRIL 20, 1979

Table 1

Horizontal flight from Waynesboro to Shenandoah in the Shenandoah National Park on April 20, 1979 (see Figure 4)

Time (EST)	Altitude (ft. MSL)	Temp. (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 (μg/m^3)	SO_2 (PPB)
14:34	2511	64	NDA[1]	--	0.44	67	59	106.2	5
14:40	2522	64	20	17	0.48	61	60	106.7	5
14:46	2511	63	18	16	0.39	74	58	104.5	6

[1] no data available

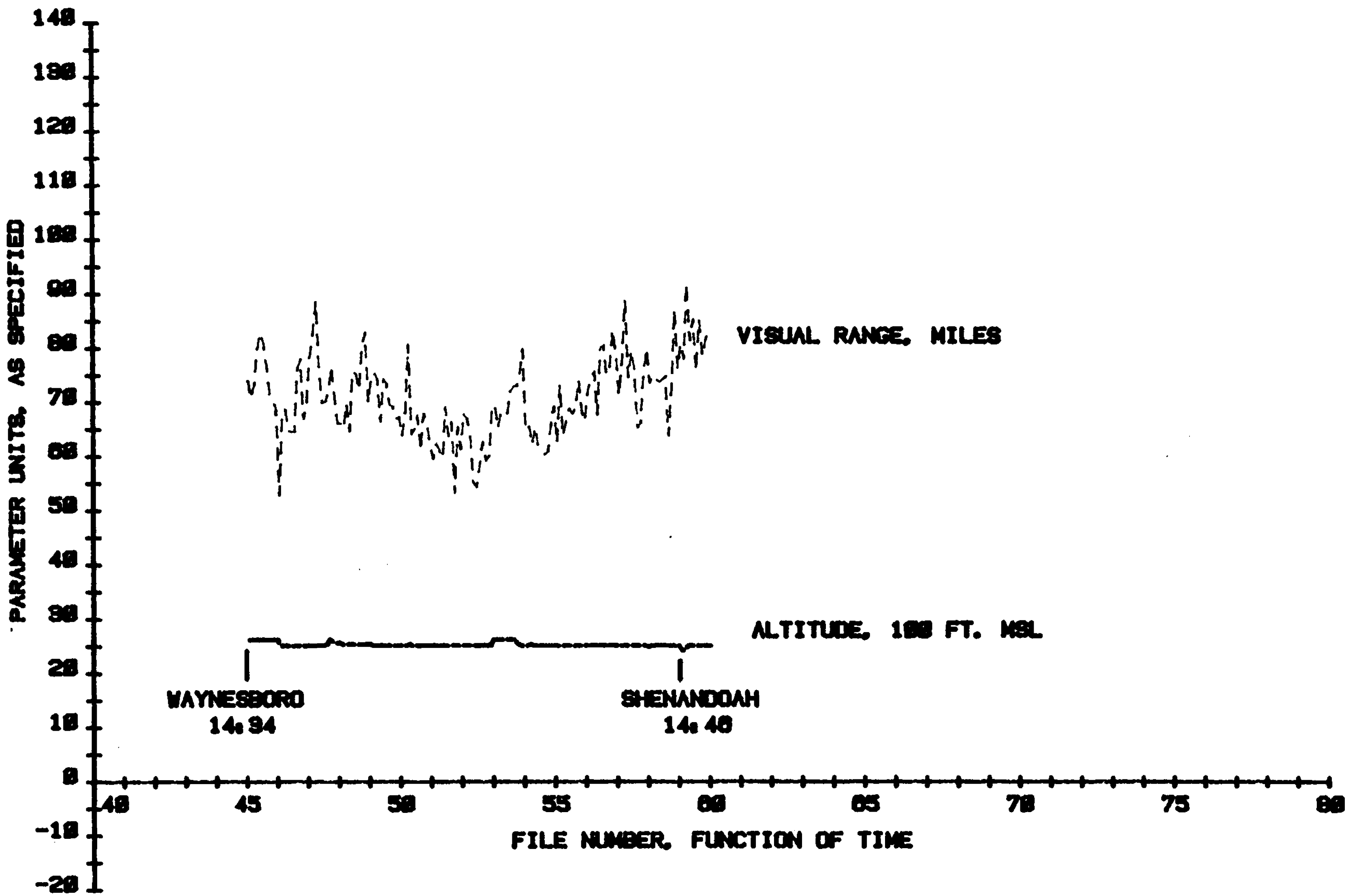


FIGURE 4b. CONTINUOUS RECORD OF FLIGHT ALONG SOUTHWEST SIDE OF SHENANDOAH NATIONAL PARK ON APRIL 20, 1979

Table 2

Spiral adjacent to Skyland in the Shenandoah National Park

on April 20, 1979 (see Figure 5)

Time (EST)	Altitude (ft. MSL)	Temp. (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
14:51	1473	67	21	16	0.44	66	59	110.2	NDA[1]
14:54	2511	61	19	18	0.41	71	61	108.4	7
15:01	3553	57	18	20	0.41	71	57	98.3	5
3:07	4578	53	17	22	0.35	83	59	98.1	4
3:12	5711	47	16	26	0.37	80	60	95.4	3

[1]no data available

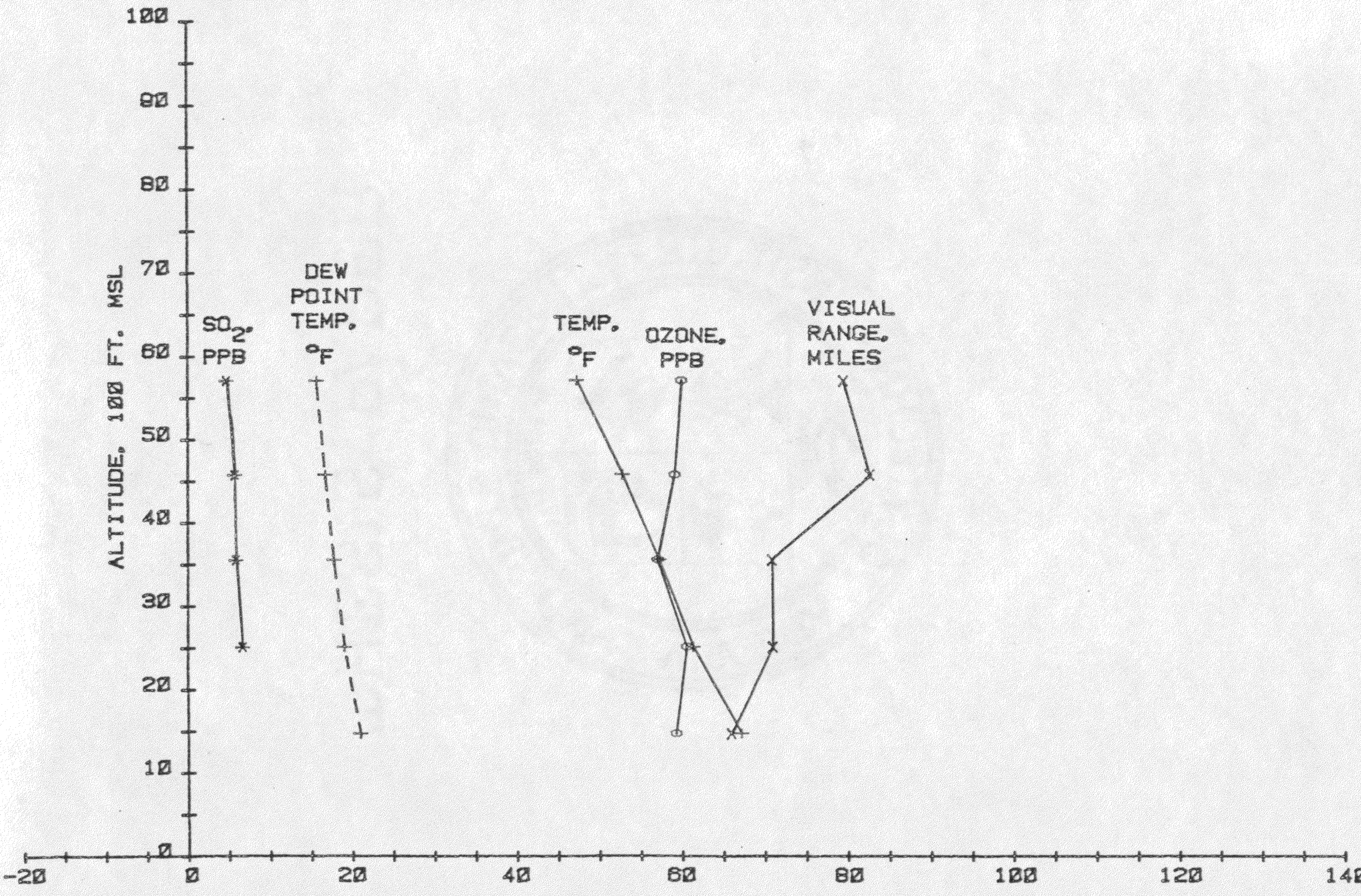


FIGURE 5. SPIRAL ADJACENT TO SKYLAND IN SHENANDOAH NATIONAL PARK ON APRIL 20, 1979

the water vapor pressure at the dew point temperature by the vapor pressure at ambient temperature, and is generally expressed as a percentage. The relative humidity must be greater than 70 percent for hygroscopic effects to take place.

Light scattering varied noticeably from low elevations to high elevations. Recalling a previous equation,

$$L_v = \frac{4.7}{b_{scat}} \qquad (16)$$

visual range may be calculated from measurements of b_{scat}. The visual range is approximately 70 miles at altitudes up to 3500 feet MSL. Above 4500 feet the visual range is over 80 miles. This would indicate the presence of a haze layer, the top of which is located at around 4000 feet MSL corresponding to the top of the mixing layer. Although this haze layer is easily identifiable from the data, the visual range existing within this layer would indicate the presence of fairly low levels of aerosol concentrations.

Ozone concentrations were rather high, yet fairly uniform at 60 PPB throughout the profile. Sulfur dioxide concentrations were low at around 5 PPB.

The second spiral took place on the southeast side of the park at Criglersville. The data for this spiral are indicated in Table 3. These data are shown graphically versus altitude in Figure 6. The temperature data indicate a near adiabatic lapse

Table 3

Spiral at Criglersville in the Shenandoah National Park

on April 20, 1979 (see Figure 6)

Time (EST)	Altitude (ft. MSL)	Temp. ($^\circ$F)	Dew Pt. Temp. ($^\circ$F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
15:19	5662	48	11	19	0.27	110	56	89.5	NDA[1]
15:25	4571	51	17	23	0.34	87	55	91.1	NDA
15:29	3533	55	21	24	0.31	95	51	88.6	NDA
15:34	2507	60	21	20	0.37	79	53	94.7	NDA
15:40	1471	66	24	19	0.42	69	54	100.0	NDA

[1] no data available

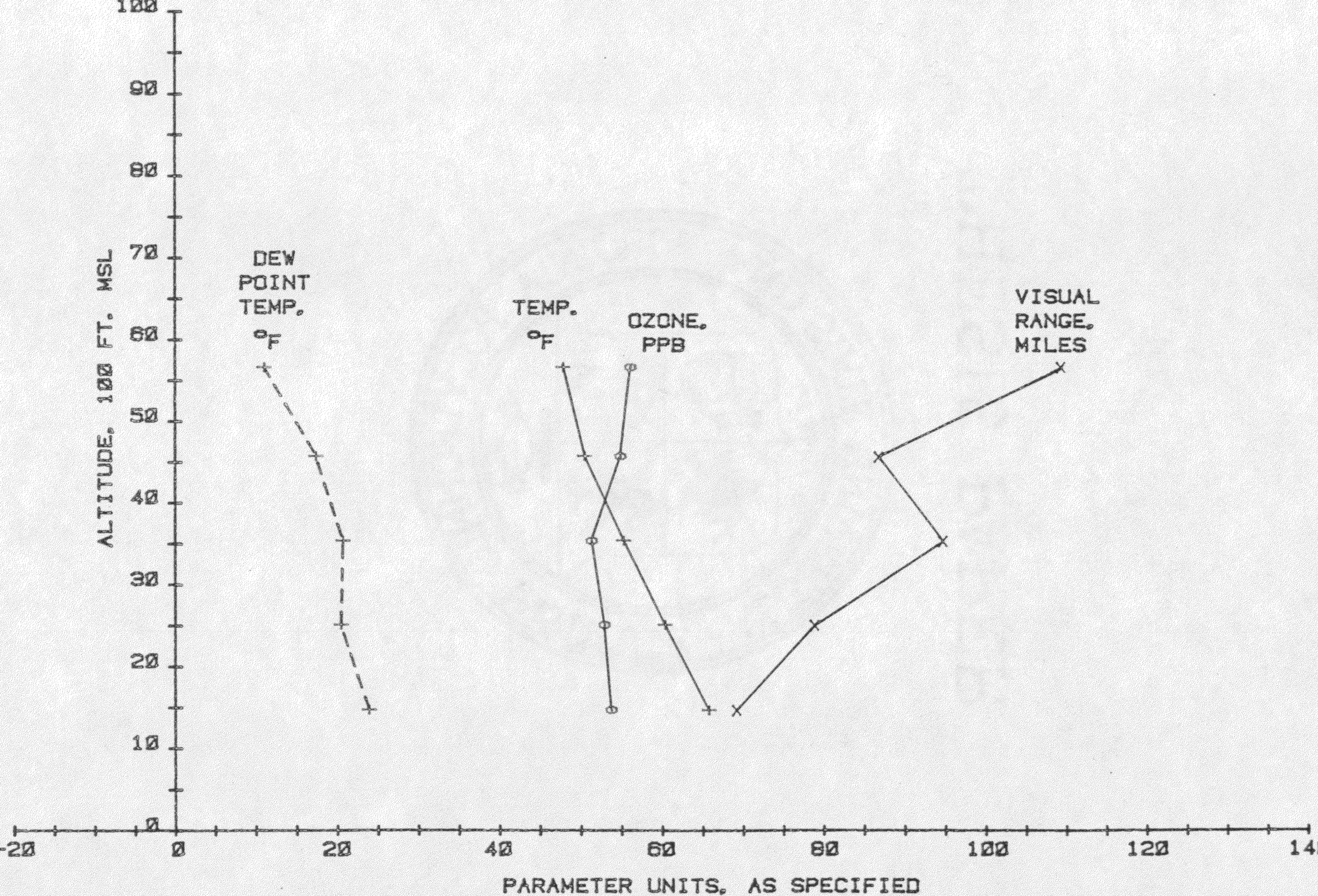


FIGURE 6. SPIRAL OVER CRIGLERSVILLE IN SHENANDOAH NATIONAL PARK ON APRIL 20, 1979

rate up until around 4500 feet MSL. Above 4500 feet the lapse rate tends to be slightly sub-adiabatic. The dew point temperatures again are very low, thus the relative humidity remains low. Visual range is fairly high at low elevations while increasing sharply to an even higher level at higher elevations. The decrease in visual range at 3500 to 4500 feet may be due to a slight trapping effect of the slightly sub-adiabatic lapse rate. Ozone concentrations are uniform at approximately 55 PPB.

A comparison of the two spirals indicates higher visual ranges and lower O_3 concentrations on the southeast side of the park, as is graphically illustrated in Figure 6b. This may be due to a disruptive effect on air mass movement from the southeast caused by the mountain range which divides the park. Meteorological conditions on either side of the park may vary due to this effect so as to allow significant differences in pollutant concentrations from one side of the park to the other.

May 7 and 8, 1979 - Flight to Great Smoky Mountain National Park

A low pressure air mass located southwest of the Great Smokys over the Gulf of Mexico and a high pressure system centered over the Atlantic Ocean off the coast of South Carolina dominated weather conditions on May 7, 1979. Winds at the 500 mbar level were from the east at around 20 knots.

A level pattern was flown at 5700 feet MSL between the pass

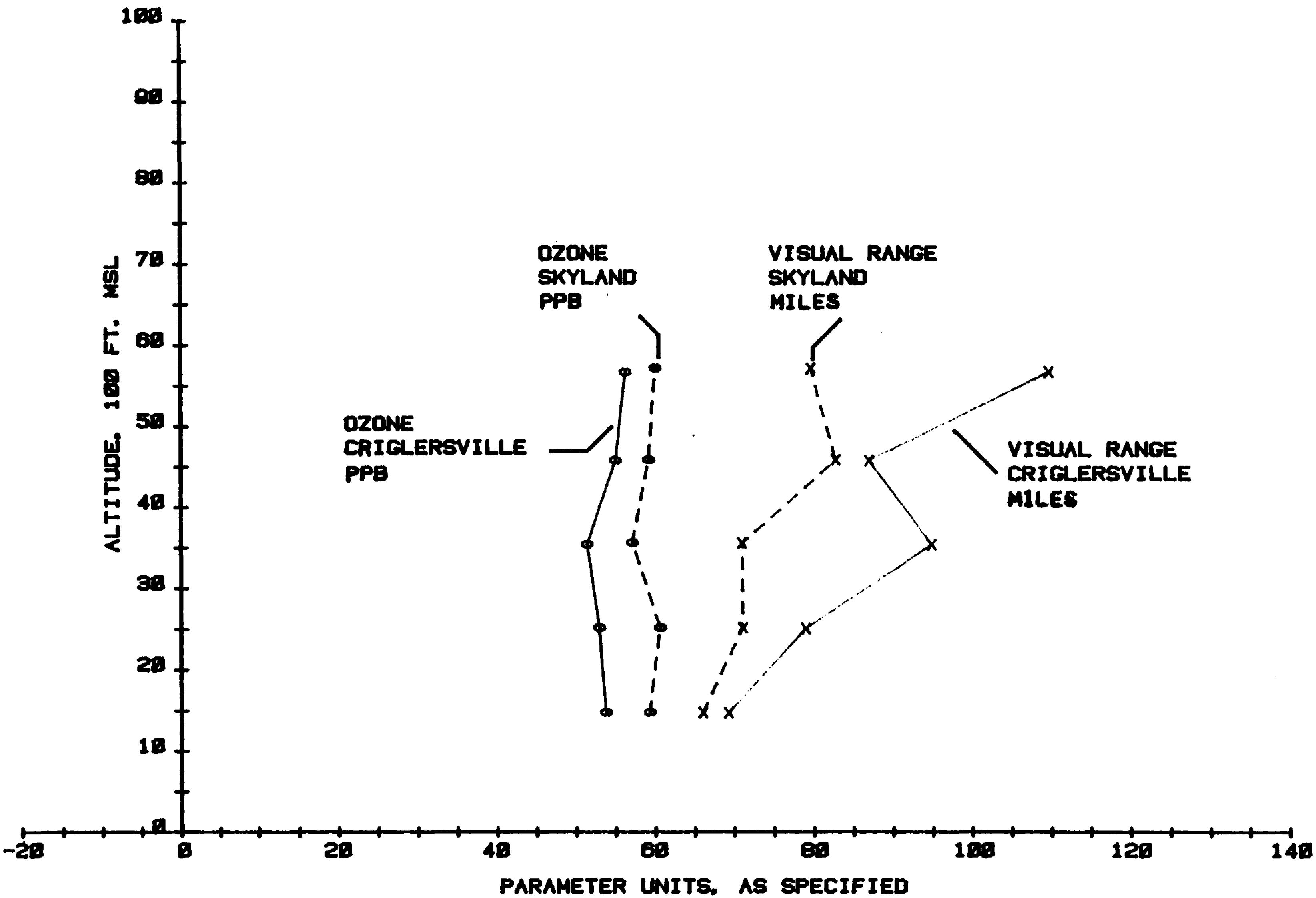


FIGURE 8b. COMPARISON OF VISUAL RANGE AND OZONE AT SKYLAND AND CRIGLERSVILLE IN SHENANDOAH NATIONAL PARK ON APRIL 20, 1979

from Cherokee to Gatlinburg, just north of the mountain ridge, to Cades Cove, as shown in Figure 7. Data from this horizontal flight are presented in Table 4 while visibility data are plotted versus time in Figure 7b.

The data indicate fairly constant temperatures and dew point temperatures for this flight. The temperature was approximately 67 ^{o}F while the dew point temperature averaged 43 ^{o}F, corresponding to a relative humidity of approximately 35 to 45 percent. The visual range decreased from approximately 60 miles at the beginning of the flight to around 55 miles just east of Cades Cove, and then increased back up to around 60 miles at Cades Cove. By using Equation 17 an aerosol concentration range of 18.6 to 20.3 $\mu g/m^3$ is calculated for this flight. Ozone concentrations remained fairly constant at approximately 45 PPB.

Two spirals were flown on this date. The first of these spirals, flown at Cades Cove, was performed from 2500 feet to 6500 feet MSL. Data from the Cades Cove spiral are presented in Table 5 and are shown graphically in Figure 8. The data indicate a near adiabatic temperature lapse rate and low dew point temperatures, which indicate relative humidities well below 70 percent. A visual range of roughly 55 miles is maintained at lower altitudes while L_v is greater than 60 miles at elevations greater than 5500 feet MSL. Ozone concentrations steadily increase from around 35

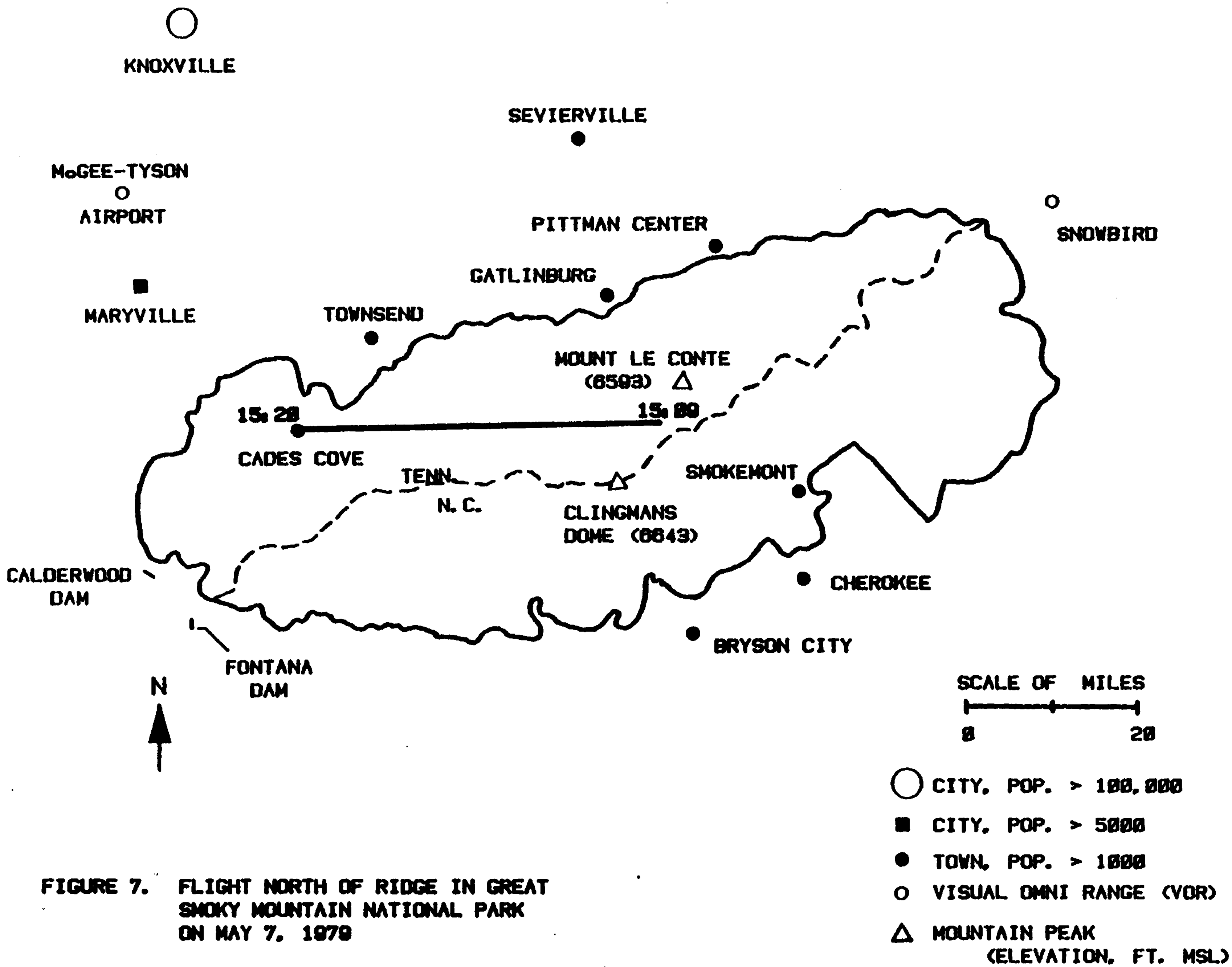


FIGURE 7. FLIGHT NORTH OF RIDGE IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON MAY 7, 1979

Table 4

Horizontal flight from the Cherokee/Gatlinburg pass to Cades Cove in the Great Smoky Mountain National Park on May 7, 1979 (see Figure 7)

Time (EDT)	Altitude (ft. MSL)	Temp. (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
15:09	5684	66	43	43	0.50	59	48	75.9	NDA[1]
15:14	5800	66	45	46	0.55	53	44	69.5	NDA
15:17	5776	67	44	43	0.54	54	40	63.3	NDA
15:20	5800	66	43	43	0.51	58	45	70.6	NDA

[1] no data available

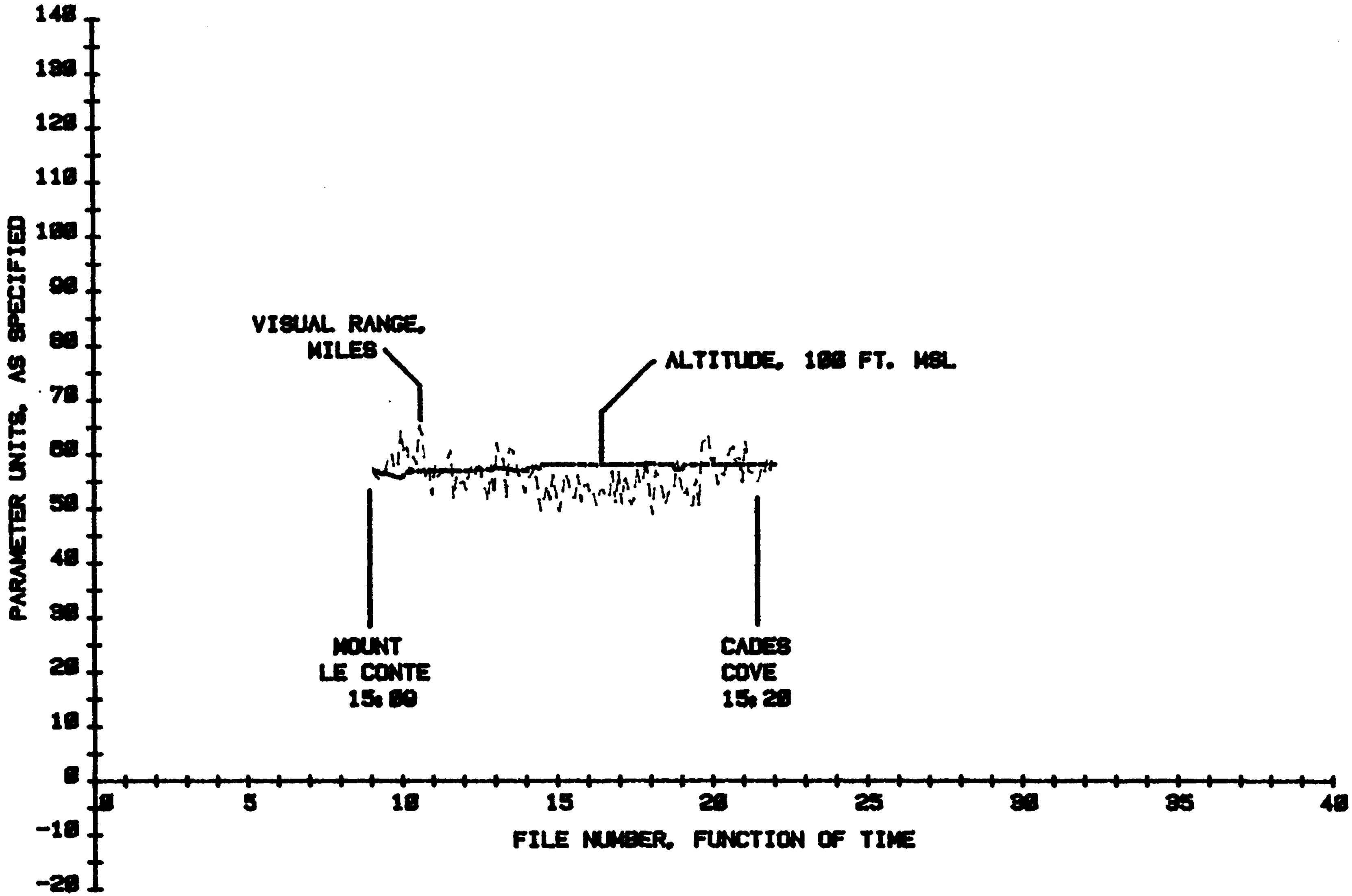


FIGURE 7b. CONTINUOUS RECORD OF FLIGHT NORTH OF RIDGE IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON MAY 7, 1979

Table 5

Spiral at Cades Cove in the Great Smoky Mountain National Park

on May 7, 1979 (see Figure 8)

Time (EDT)	Altitude (ft. MSL)	Temp. (^{o}F)	Dew Pt. Temp. (^{o}F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
16:06	6376	65	41	41	0.45	65	37	56.7	NDA[1]
16:12	5336	69	44	40	0.48	60	47	75.0	NDA
16:16	4311	74	44	34	0.54	54	41	68.5	NDA
16:20	3182	79	45	29	0.55	53	38	66.0	NDA
16:23	2696	82	47	29	0.51	57	37	65.3	NDA

[1] no data available

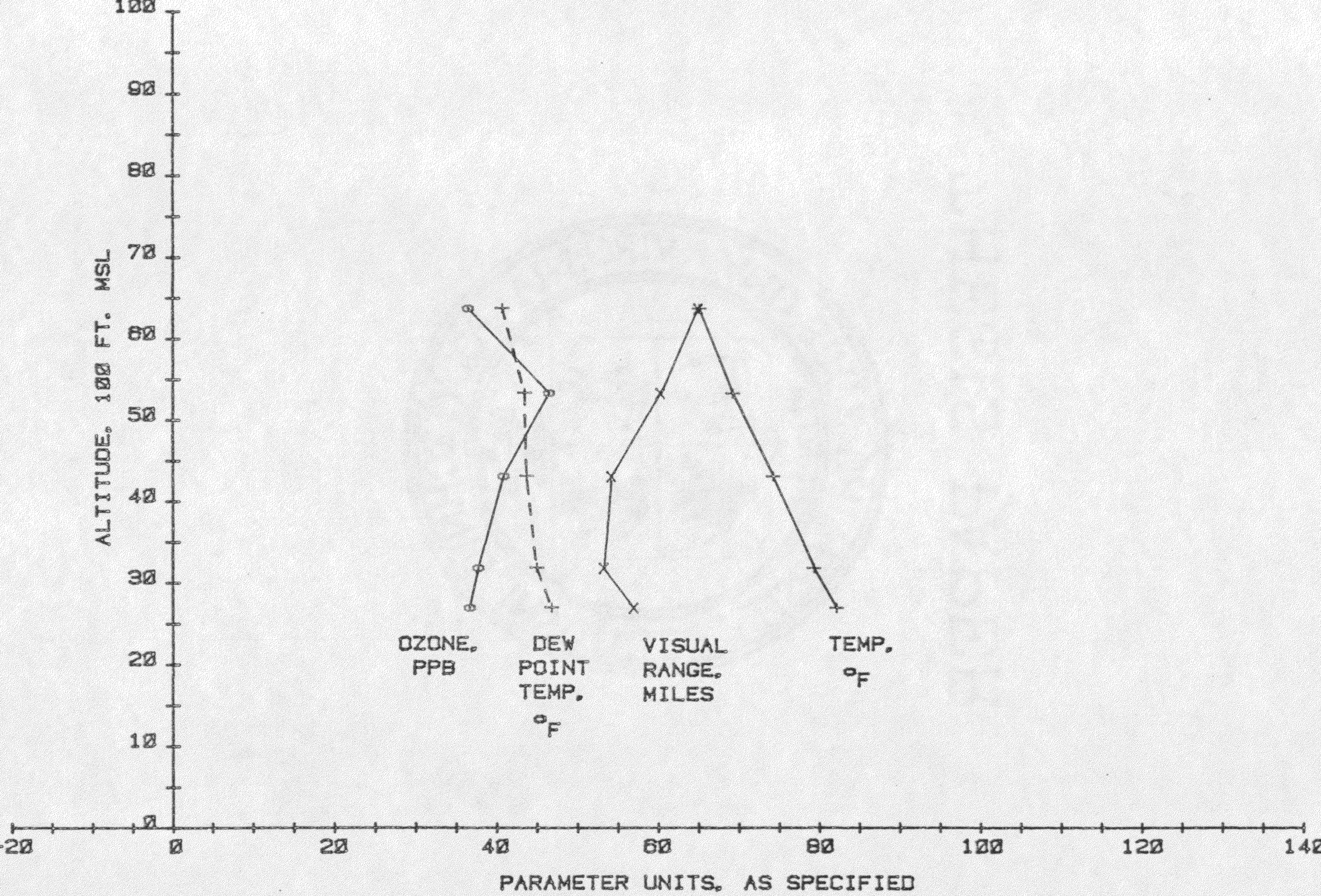


FIGURE 8. SPIRAL OVER CADES COVE IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON MAY 7, 1979

to 50 PPB between the elevations of 2500 to 5500 feet, and then decrease sharply to 35 PPB at 6400 feet.

A spiral in the Smokemont and Cherokee area was performed following the Cades Cove spiral. Figure 9 shows a plot versus altitude of the various data collected, which are presented in Table 6. As was evident at Cades Cove, the ambient temperature profile shows a near adiabatic lapse rate in this spiral. The dew point temperatures are slightly higher than at Cades Cove, however the relative humidity is still less than 70 percent. The visual range shows the same tendencies, with values ranging from approximately 45 miles at low altitudes to over 60 miles at the highest altitude. The O_3 concentration is distributed uniformly at roughly 35 PPB.

Comparing the two spirals, as seen in Figure 9b, indicates that higher levels of visual range existed in the north side of the park than in the south side, except at over 6000 feet where the levels were nearly the same. Although the relative humidity was slightly higher on the south side, it was not high enough to affect the scattering properties of aerosols significantly. While aerosol concentrations were obviously higher on the south side of the park, O_3 concentrations were 5 to 10 PPB lower, except at the highest altitude where the O_3 concentrations were approximately the same.

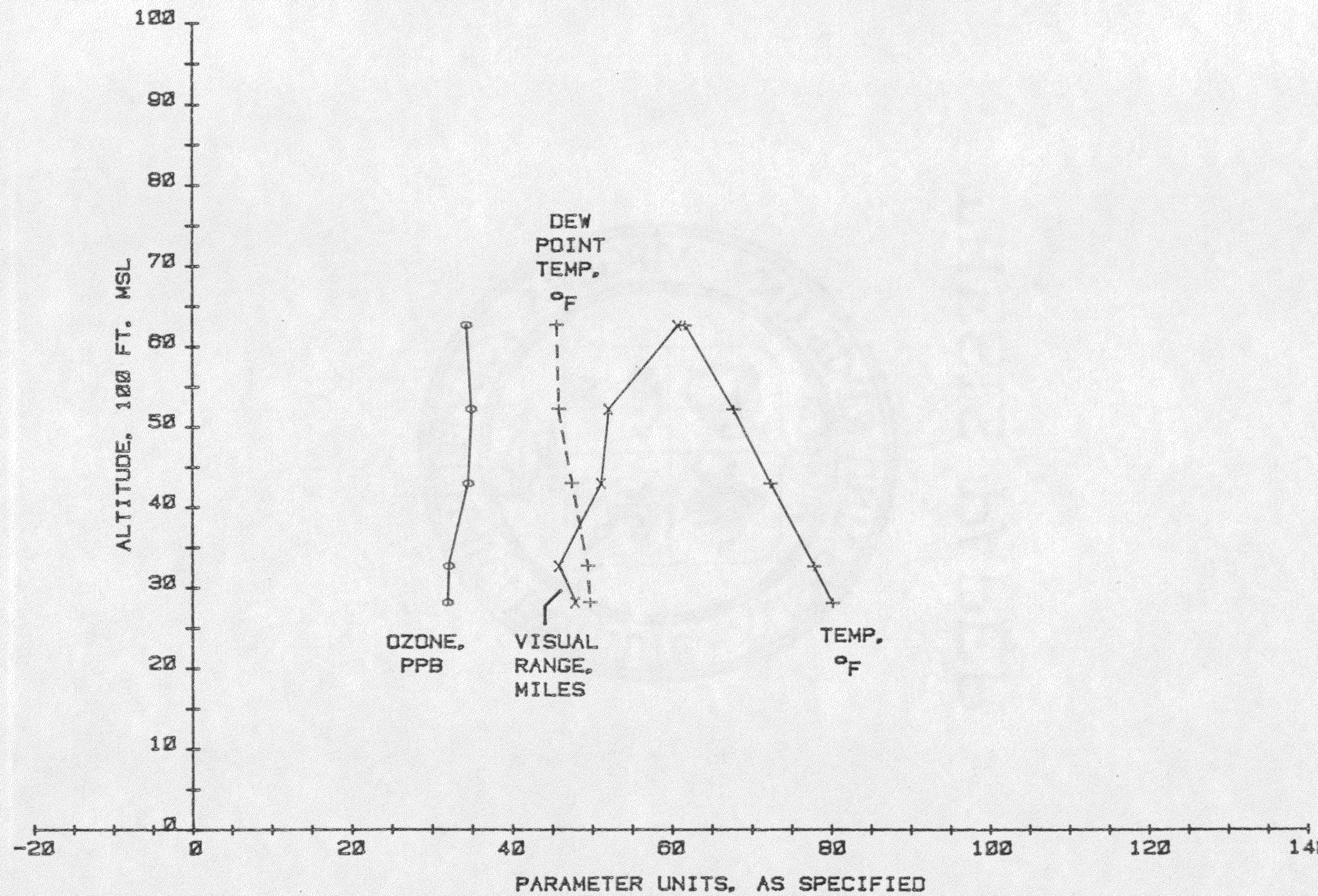


FIGURE 9. SPIRAL AT SMOKEMONT/CHEROKEE IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON MAY 7, 1979

Table 6

Spiral at Smokemont/Cherokee in the Great Smoky Mountain National Park

on May 7, 1979 (see Figure 9)

Time (EDT)	Altitude (ft. MSL)	Temp. (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
16:39	6267	62	46	56	0.48	61	34	53.5	NDA[1]
16:42	5222	68	46	44	0.56	52	35	56.6	NDA
16:45	4296	73	48	41	0.57	51	35	57.9	NDA
16:47	3267	78	50	37	0.64	46	32	55.9	NDA
16:49	2813	80	50	34	0.61	48	32	56.6	NDA

[1] no data available

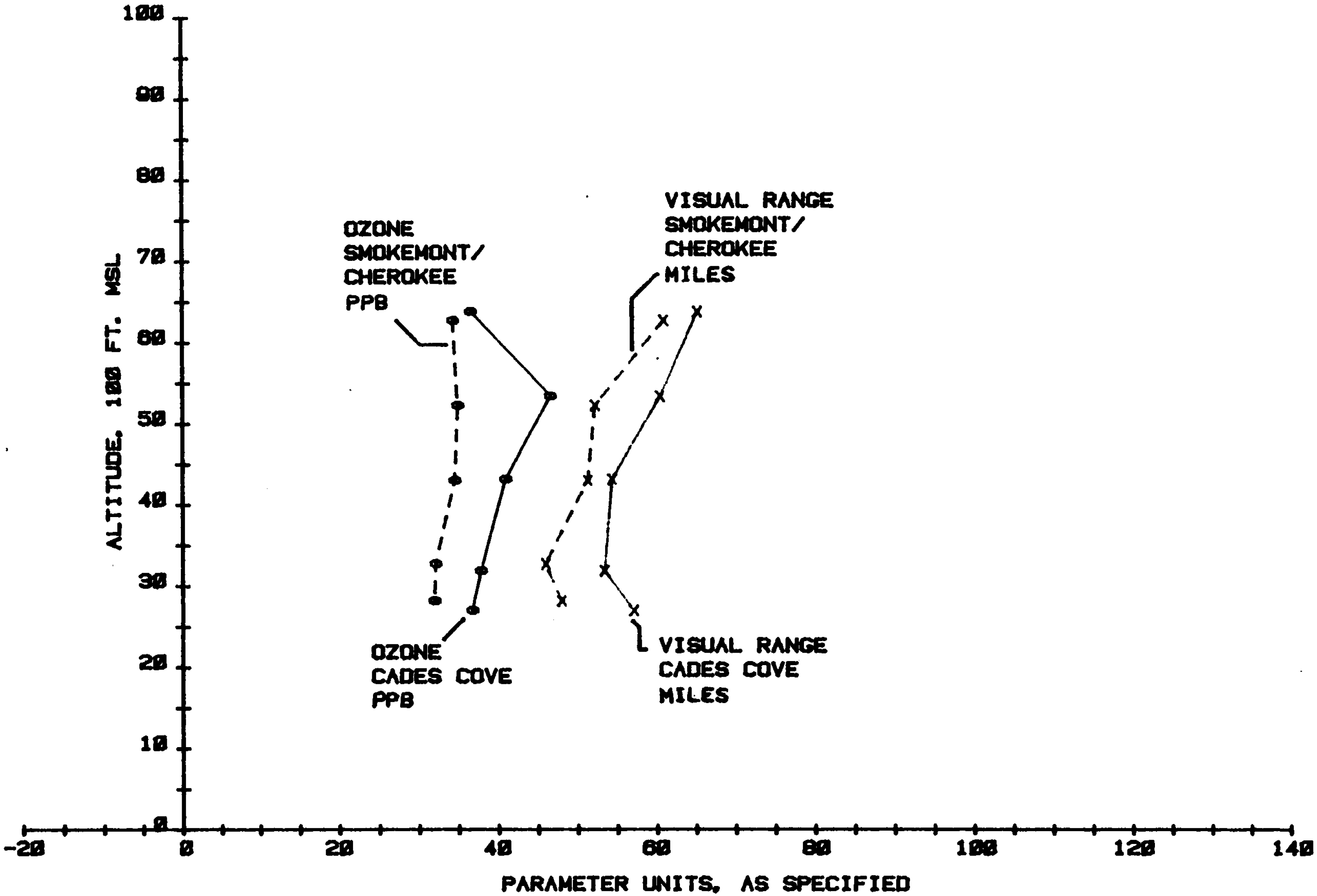


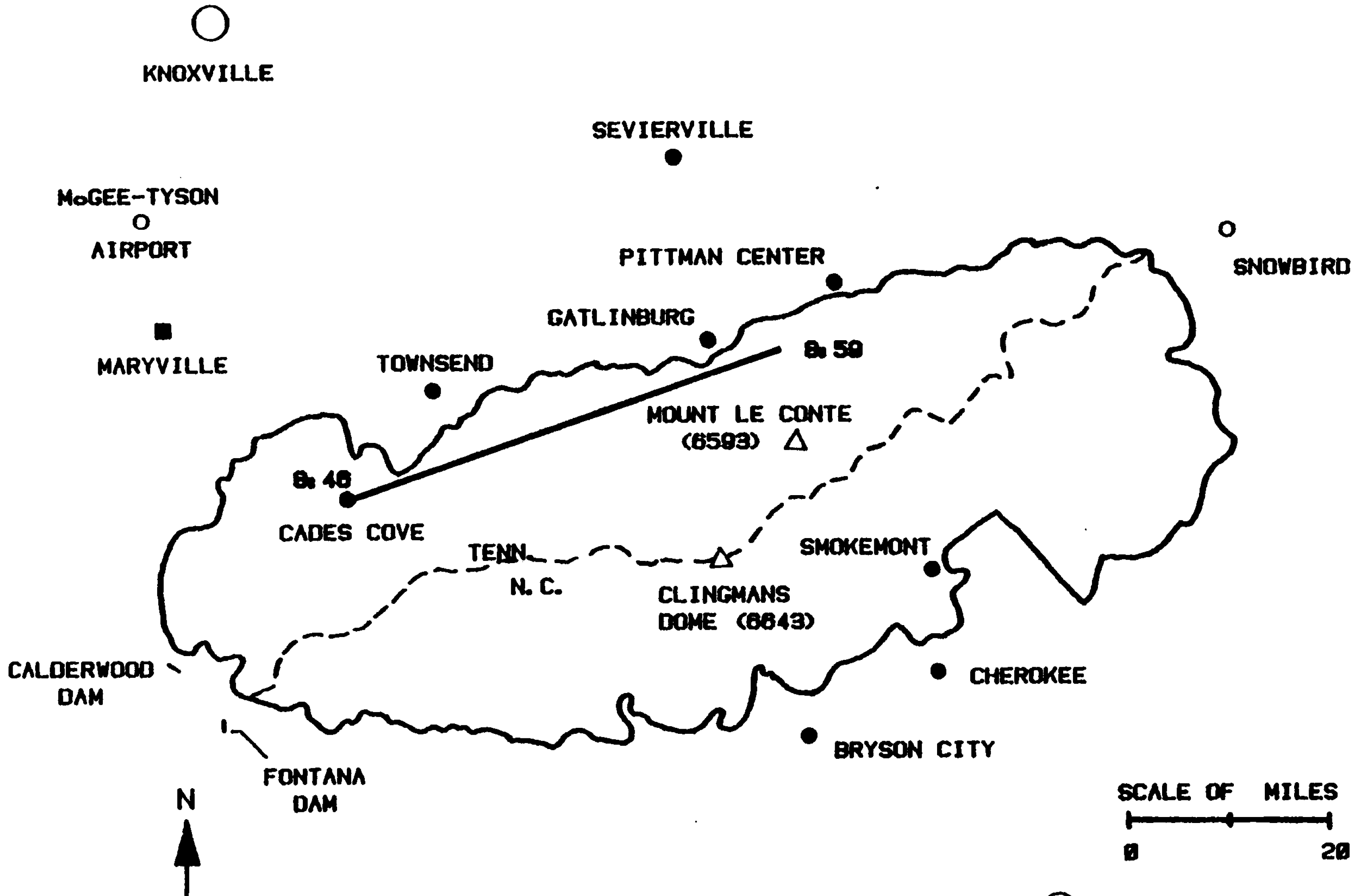
FIGURE 9b. COMPARISON OF VISUAL RANGE AND OZONE AT CADES COVE AND SMOKEMONT/ CHEROKEE IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON MAY 7, 1979

This may be accounted for by better mixing at elevations greater than that of the mountain peaks, which at some locations exceed 6000 feet MSL. These mountains tend to act as a barrier, preventing uniform mixing of pollutants.

By May 8, 1979, the low pressure system over the Gulf of Mexico had moved inland to Alabama and Georgia, tending to dominate the weather in and around the Great Smoky Mountains. Precipitation fell to the east in North Carolina and a cloud layer began to move in as the morning progressed. Wind speeds were approximately 10 knots from the northwest at the 500 mbar level.

Continuous temperature data were not available on this date due to a malfunction in the temperature measuring device. However a voice recording of temperatures indicated on the aircraft instrument panel was made at various points throughout the flight. These data are presented according to their availability and applicability.

Data from a horizontal profile flight ranging from Cades Cove to Pittman Center at around 4300 feet MSL as shown in Figure 10, are presented in Table 7 and Figure 10b. These data indicate uniform levels of visual range and ozone concentrations. The visual ranges are relatively high while the O_3 concentrations are low, indicating low levels of pollutants present along the path of this flight. Evaluations of relative humidity are not presented due to



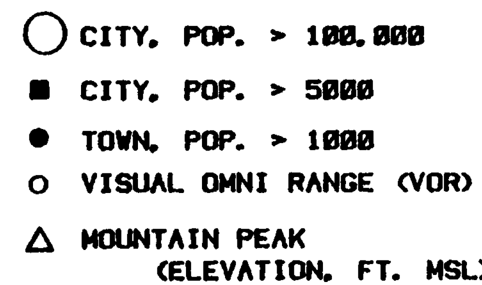


FIGURE 10. FLIGHT FROM CADES COVE TO UPLANDS RESEARCH CENTER IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON MAY 8, 1979

Table 7

Horizontal flight from Cades Cove to Uplands Research Center in the Great Smoky Mountain National Park on May 8, 1979 (see Figure 10)

Time (EDT)	Altitude (ft. MSL)	Temp.[1] (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
8:46	4318	NDA[2]	51	--	0.51	58	33	54.5	NDA
8:53	4222	68	50	52	0.47	62	33	55.5	NDA
8:55	4258	NDA	49	--	0.51	57	31	51.7	NDA
8:59	4311	NDA	50	--	0.50	59	28	47.2	NDA

[1] taken from aircraft instrument panel, when available

[2] no data available

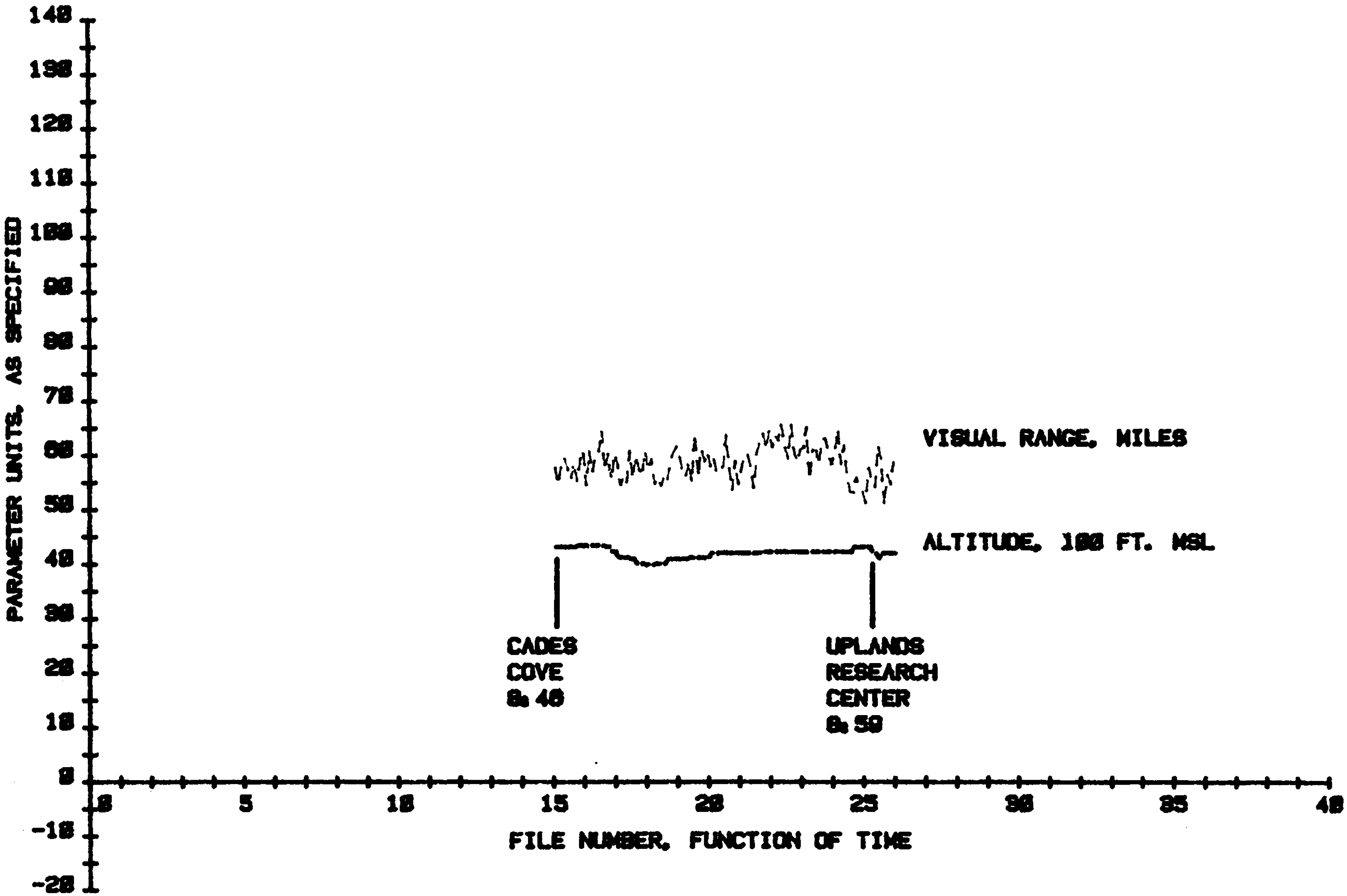


FIGURE 10b. CONTINUOUS RECORD OF FLIGHT FROM CADES COVE TO UPLANDS RESEARCH CENTER IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON MAY 8, 1979

a lack of sufficient temperature data for the total horizontal flight. However temperature was voice recorded over Elkmont, indicating a level of 68 °F. Using this value in conjunction with the 50 °F dew point temperature indicated by the hygrometer results in a relative humidity of 52 percent.

The first of two vertical spirals was flown on the north side of the park at Sevierville, Tennessee. Data collected during this spiral are reported in Table 8 and are plotted versus altitude in Figure 11. The presence of an inversion between 1000 and 2000 feet MSL is indicated by the temperature data. Dew point temperature levels indicate that the relative humidity at the lowest altitude was 70 percent. However, the inlet heater to the nephelometer was operating for this flight, thus negating any hygroscopic effects on the aerosol particles. The relative humidity at all other altitudes was less than 70 percent.

Visual ranges between 30 miles and 81 miles exist in the profile. A slightly uniform visual range of approximately 50 miles exists between 4000 and 5000 feet. Rather rapid and constant visibility alterations take place above and below these altitudes. Ozone concentrations increase only slightly throughout the spiral, with the concentration averaging around 30 to 35 PPB. The concentration at 1300 feet is approximately 25 PPB while higher elevation concentrations may be over 35 PPB. It is important at this time to note the advantage of an airborne monitoring platform as op-

Table 8

Spiral at Sevierville by the Great Smoky Mountain National Park

on May 8, 1979 (see Figure 11)

Time (EDT)	Altitude (ft. MSL)	Temp.[1] (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
7:22	7244	57	42	57	0.36	81	32	48.6	NDA[2]
7:30	6289	59	48	66	0.47	62	38	58.3	NDA
7:34	5267	NDA	50	--	0.62	47	35	56.2	NDA
7:39	4244	64	52	65	0.57	51	33	54.9	NDA
7:44	3200	70	53	54	0.69	42	37	63.7	NDA
7:48	2120	72	56	56	0.86	34	32	58.5	NDA
7:51	1273	67	57	70	0.99	30	24	45.1	NDA

[1]taken from aircraft instrument panel, when available

[2]no data available

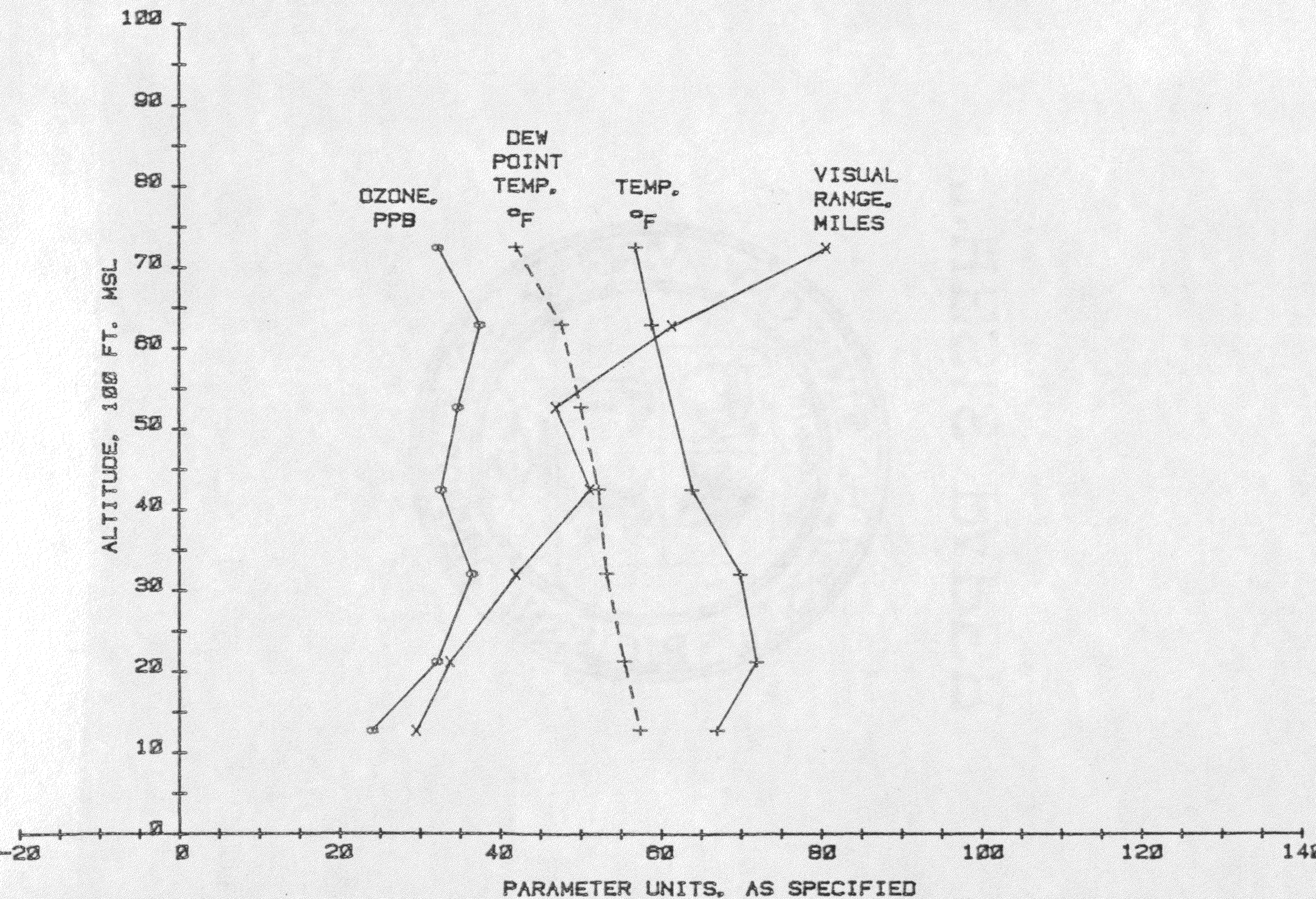


FIGURE 11. SPIRAL OVER SEVIERVILLE, TENNESSEE, NEAR GREAT SMOKY MOUNTAIN NATIONAL PARK ON MAY 8, 1979

posed to a ground monitoring station in that the ground monitoring station would detect the low level O_3 concentration near the ground while obviously failing to identify the higher elevation concentrations. This becomes significant in monitoring ambient air in mountainous areas, since wildlife and vegetation residing in the higher mountainous regions would utilize air at these elevations containing the larger doses of pollutants. The airborne platform can readily detect concentrations at high altitudes.

A second spiral for May 8 was flown on the south side of the park at Lake Fontana. Data are reported for this flight in Table 9 and are graphically illustrated in Figure 12. Temperature and dew point data indicate relative humidities near and, in one case, over 70 percent. The nephelometer inlet heater was not operating for this spiral, so hygroscopic effects on aerosols may have increased light scattering, thus decreasing visibility. A temperature inversion is also indicated between 1500 and 2500 feet MSL.

The visual range data show a fairly constant increase with increasing altitude. A distinct haze layer is not indicated by the data. The visual range is around 35 miles at 2000 feet and it gradually increases to a level of almost 70 miles at altitudes greater than 6000 feet MSL. Since the nephelometer inlet heater was not on during this spiral the lower visual ranges existing at low elevations may have been partially due to high relative hu-

Table 9

Spiral at Lake Fontana in the Great Smoky Mountain National Park on May 8, 1979 (see Figure 12)

Time (EDT)	Altitude (ft. MSL)	Temp.[1] (^oF)	Dew Pt. Temp. (^oF)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
8:04	7200	NDA[2]	42	--	0.44	66	44	66.7	NDA
8:10	5280	56	46	69	0.43	67	37	57.9	NDA
8:14	5244	62	50	64	0.47	62	34	54.9	NDA
8:19	4222	68	55	63	0.54	54	29	49.4	NDA
8:22	3178	NDA	56	--	0.64	46	31	53.3	NDA
8:24	2300	68	59	72	0.74	40	20	36.6	NDA
8:27	1931	70	59	68	0.83	35	20	35.9	NDA

[1]taken from aircraft instrument panel, when available

[2]no data available

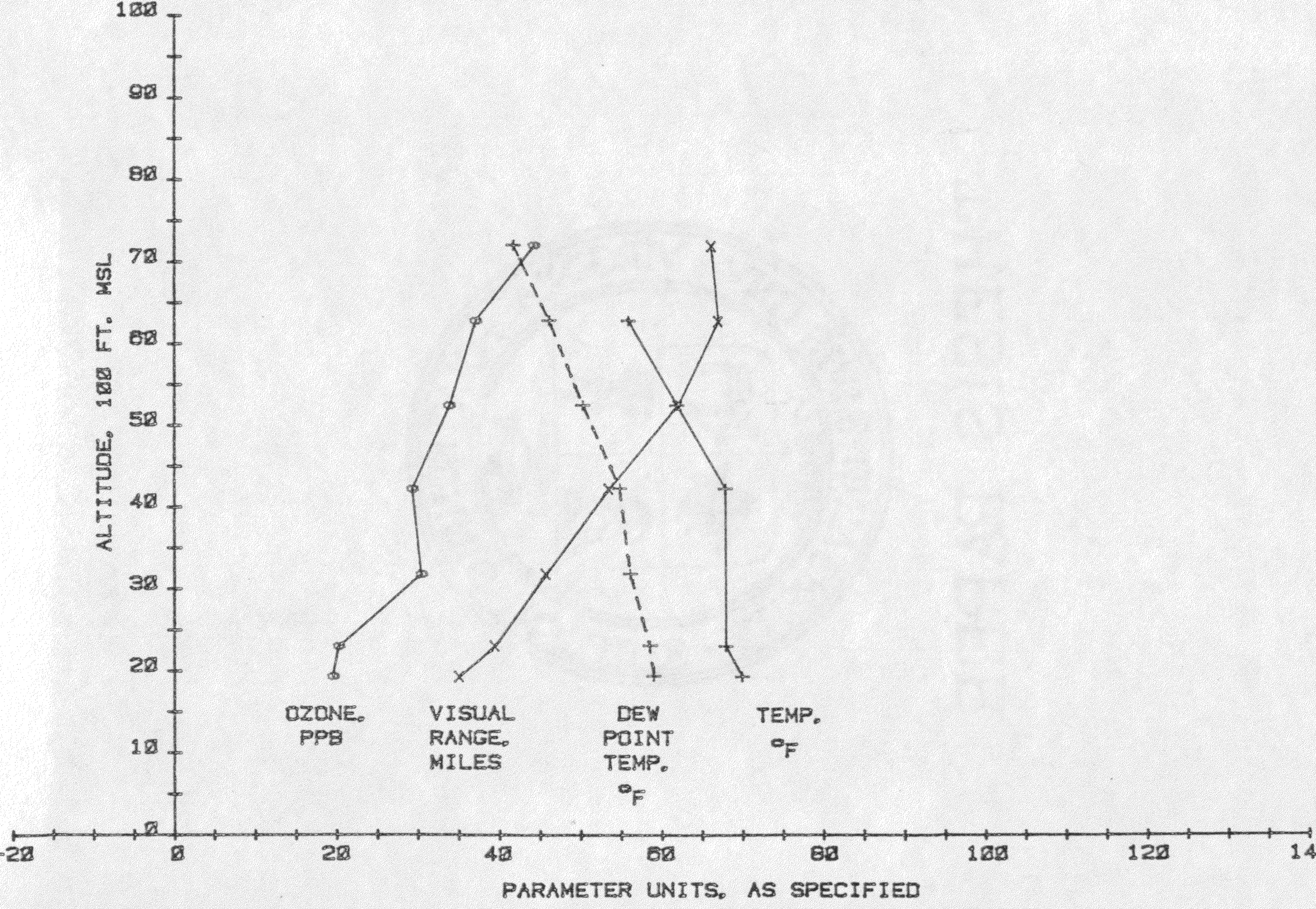


FIGURE 12. SPIRAL OVER LAKE FONTANA IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON MAY 8, 1979

midity.

Ozone concentrations also show an increase from around 20 PPB at low altitudes to 45 PPB at the higher altitudes. Again the importance of monitoring at these higher elevations is made obvious.

A comparison of the two vertical spirals indicates a slightly higher visual range at the south side of the park than at the north side. The O_3 concentrations, especially at elevations below those of the mountain peaks, tend to be lower on the south side of the park. The higher concentrations of pollutants on the north side of the park may be the result of transport of pollutants, by way of the northwest wind, from Knoxville or other industrial sites located to the north of the park. The natural barrier effect of the mountain ranges prohibits the passage of these pollutants into the south side of the park.

A further comparison of this day's data with data collected on the preceeding afternoon indicates slightly lower values of visual range on the morning flight than on the preceeding afternoon flight at the north side of the park. This indicates an increase in aerosol concentrations in this period. Ozone concentrations decreased overnight, which is an indication of scavenging which typically takes place during the night. On the south side of the park visual range was slightly higher at the higher elevations in the morning than on the previous afternoon. This is contrary to what occured on the north side. The difference may be due to meteorological phenomena which, due to the presence of the mountainous barrier, are different on the two sides of the park. Ozone concentrations are approximately equal for the afternoon and next morning cases on the south side, indicating possible inward transport of the pollutant. Ozone transported into the park replenishes what may have been removed by way of scavenging.

June 13-15, 1979 - Flight to Great Smoky Mountain National Park

Weather conditions for this period were dominated by a high pressure region over the Gulf of Mexico and southern U. S. At 7:00 AM EDT on June 13, the winds were from the east at 8 to 12 knots. By 7:00 AM the next morning the wind had shifted to north-northwesterly at approximately 10 knots. Therefore, winds on the afternoon of June 13 may have been more northerly than easterly. At 7:00 AM on June 15 the winds were from the northwest at 15 to 20 knots. Therefore winds were generally from a northerly direction for this series of flights. On June 13 the skies were clear and a haze layer was observed below 10,000 feet MSL.

A horizontal flight was flown at around 6500 feet MSL on June 13 from the northeast park boundary, along the south side of the ridge to Lake Fontana, around the west end of the park to Cades Cove, and then on to Elkmont. This path is plotted on the map in Figure 13. Data for designated points along the flight path are

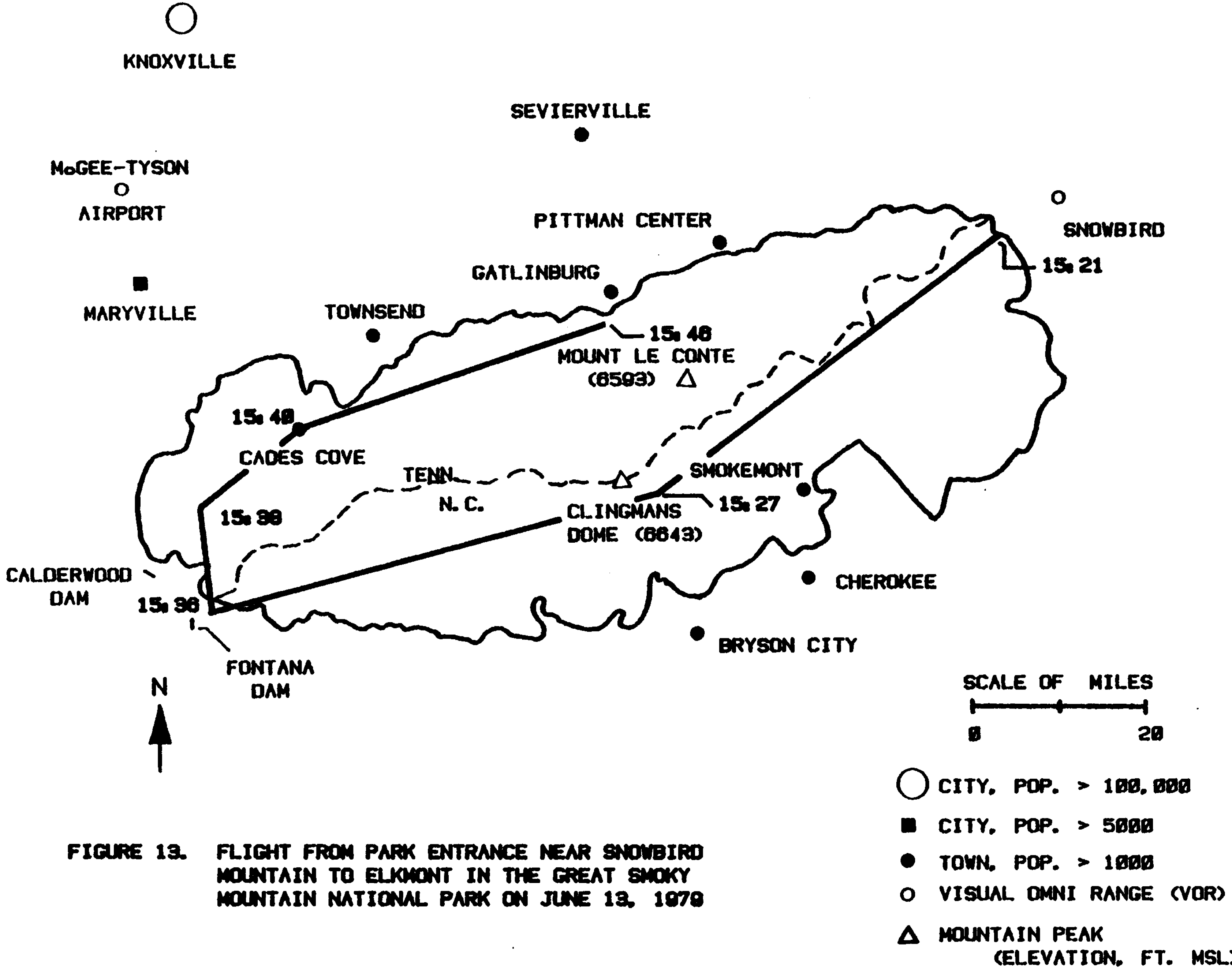


FIGURE 13. FLIGHT FROM PARK ENTRANCE NEAR SNOWBIRD MOUNTAIN TO ELKMONT IN THE GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 13, 1979

presented in Table 10 and in Figure 13b.

Temperature data indicate fairly constant temperatures of between 55 and 58° F for the duration of the flight. Dew point temperatures were between 37 and 45° F for the flight, indicating relative humidities less than 70 percent for this constant altitude profile.

The visual range was between 45 and 50 miles on the southeast side of the park. However, it decreased to around 43 miles on the west side of the park, indicating a higher aerosol concentration in this area. Ozone concentrations also increased, by approximately 5 PPB, on the west side of the park. However, the concentration never exceeded 50 PPB. Sulfur dioxide concentrations increased from around 2 PPB on the east side to around 5 or 6 PPB on the west side.

It becomes obvious from the horizontal profile data that air quality on the east end of the park is higher than on the west end. This is probably due to pollutants being transported into the west end via the northerly winds which occurred in the afternoon. The close proximity to the park of Knoxville, Oak Ridge, Alcoa, and several TVA coal fired power plants may explain the higher concentrations in this region.

One vertical spiral was flown in the park on June 13. This spiral took place on the north side at Cades Cove. Data for this spiral are reported in Table 11 and are plotted versus altitude

Table 10

Horizontal flight from Park Entrance near Snowbird Mountain to Elkmont in the Great Smoky Mountain National Park on June 13, 1979 (see Figure 13)

Time (EDT)	Altitude (ft. MSL)	Temp. (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
15:21	6600	55	41	59	0.62	47	46	70.0	NDA[1]
15:22	6600	55	40	56	0.62	47	45	69.8	NDA
15:24	6542	58	37	45	0.59	50	45	69.6	NDA
15:27	6476	57	40	52	0.59	49	44	68.4	2
15:29	6600	57	41	55	0.61	48	44	68.1	2
15:36	6480	57	43	59	0.78	37	49	76.3	6
15:38	6480	57	43	59	0.68	43	50	76.4	6
15:40	6538	57	41	55	0.67	44	50	76.9	6
15:42	6600	56	45	66	0.71	41	47	72.1	6
15:46	6513	57	42	57	0.61	48	50	77.3	5

[1] no data available

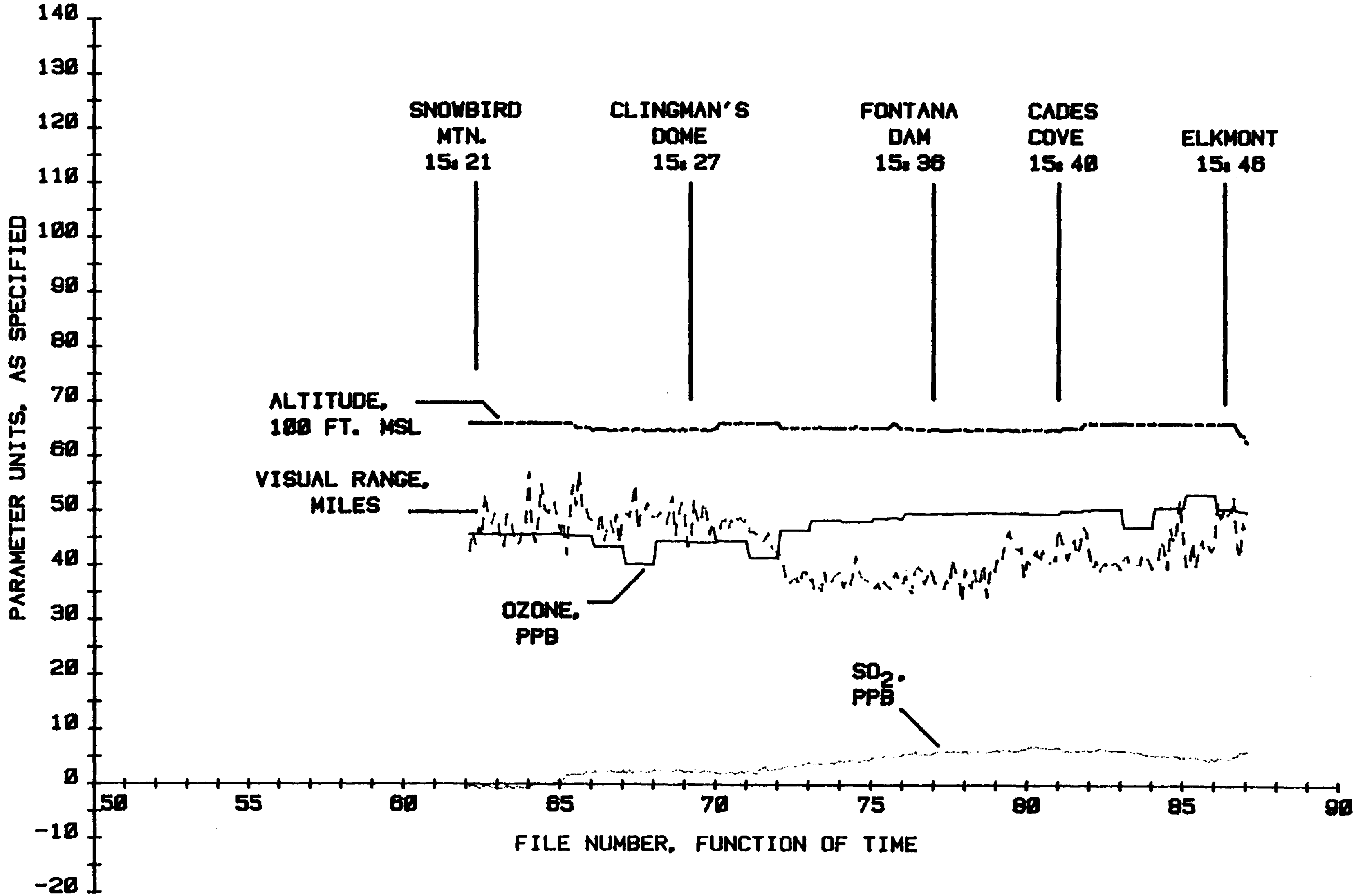


FIGURE 13b. CONTINUOUS RECORD OF FLIGHT FROM PARK ENTRANCE NEAR SNOWBIRD MOUNTAIN TO ELKMONT IN THE GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 13, 1979

Table 11

Spiral at Cades Cove in the Great Smoky Mountain National Park

on June 13, 1979 (see Figure 14)

Time (EDT)	Altitude (ft. MSL)	Temp. (^oF)	Dew Pt. Temp. (^oF)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
16:40	9778	39	27	60	0.24	124	39	53.4	NDA[1]
16:42	8924	46	28	48	0.26	111	39	54.5	NDA
16:44	7960	50	28	41	0.30	98	42	61.9	NDA
16:46	7036	53	40	61	0.66	44	49	74.0	NDA
16:48	6024	58	45	61	0.75	39	54	84.8	NDA
16:50	5107	63	47	55	0.76	38	51	82.9	NDA
16:52	4067	69	48	46	0.77	38	51	86.3	NDA
16:54	3044	74	49	41	0.89	33	54	94.7	NDA
16:56	2000	80	50	34	0.82	35	53	96.5	NDA

[1] no data available

in Figure 14. This spiral was flown from 2000 feet MSL to almost 10,000 feet MSL.

Data indicate a nearly adiabatic temperature lapse rate. The dew point temperatures varied, however the highest relative humidity was 62 percent measured at 6000 feet MSL. A distinct haze layer was identified from the data below approximately 7500 feet MSL. Below this altitude the visual range was less than 45 miles while the visual range was greater than 95 miles at altitudes above 7500 feet. This correlated well with the observed estimation of the height of the haze layer. Ozone concentrations were approximately 55 PPB up to 6000 feet MSL, gradually decreasing to 40 PPB at higher elevations.

As was previously mentioned winds were from the north-northwest at approximately 10 knots on June 14, 1979 at 7:00 AM EDT. The sky was generally clear.

No horizontal flights were flown on this date, however, five vertical spirals were flown. Two of the spirals were flown in the morning and three were flown in the afternoon.

The first of the morning spirals was performed on the south side of the park at Lake Fontana. Data from this spiral are listed in Table 12 and are plotted versus altitude in Figure 15.

A temperature inversion is evident at around 3000 feet MSL according to the data. At some elevations the dew point temper-

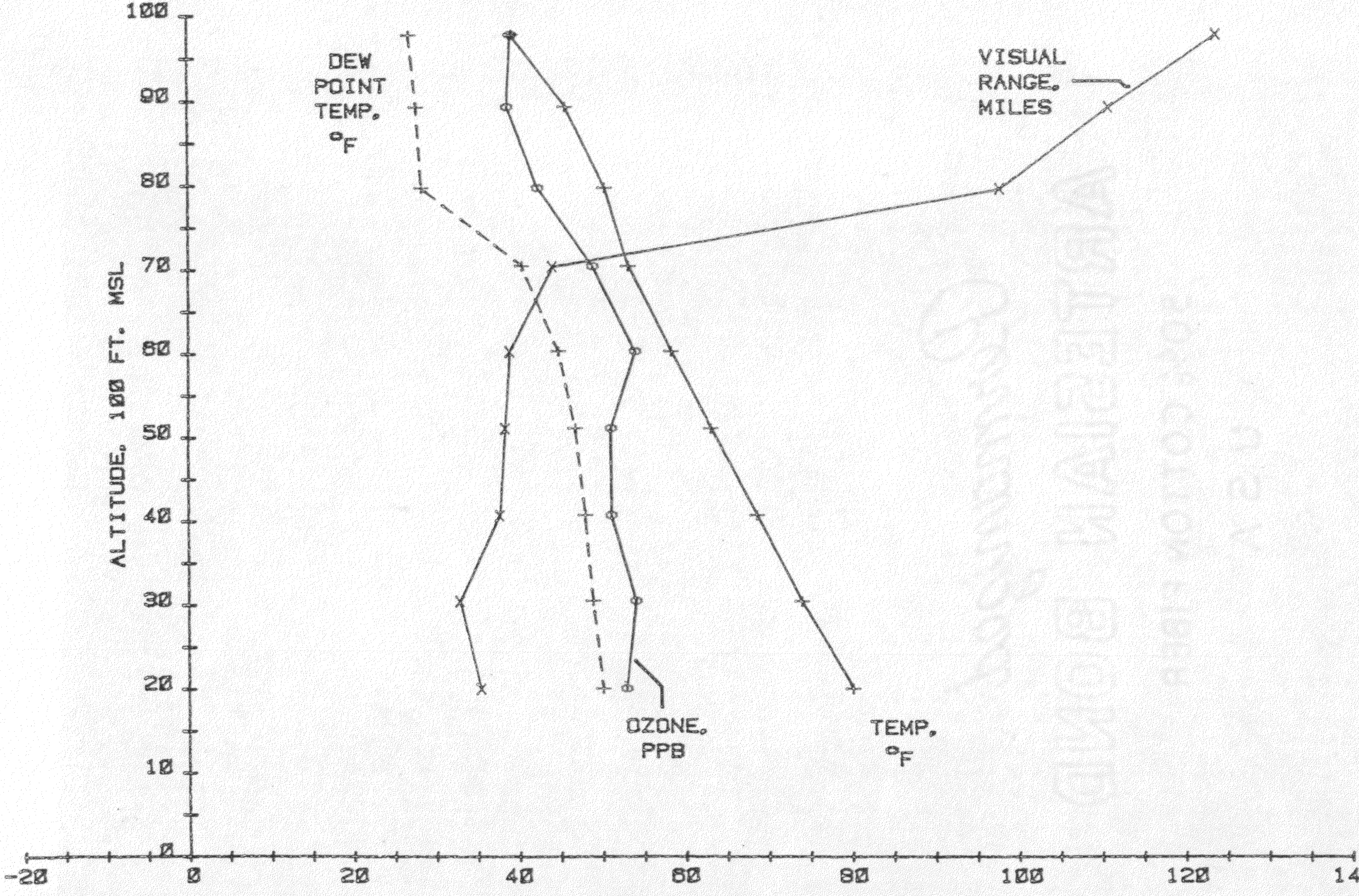


FIGURE 14. SPIRAL OVER CADES COVE IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 13, 1979

Table 12

Spiral at Lake Fontana in the Great Smoky Mountain National Park

on June 14, 1979 (see Figure 15)

Time (EDT)	Altitude (ft. MSL)	Temp. (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} $(10^{-4}m^{-1})$	L_v (miles)	O_3 (PPB)	O_3 $(\mu g/m^3)$	SO_2 (PPB)
6:47	10353	36	27	67	0.84	35	60	80.2	NDA[1]
6:59	9400	39	31	72	1.06	28	57	78.8	1
7:04	8489	43	32	65	0.81	36	61	87.2	0
7:09	7498	47	33	58	1.00	29	62	92.8	2
7:13	6651	49	40	71	1.13	26	66	101.6	2
7:18	5622	54	42	63	1.16	25	65	104.2	1
7:23	4600	58	44	59	1.27	23	63	104.1	0
7:28	3580	62	45	53	1.23	24	70	121.0	1
7:34	2533	59	49	69	1.31	22	45	79.8	0
7:40	1940	60	53	77	1.17	25	29	53.7	0

[1] no data available

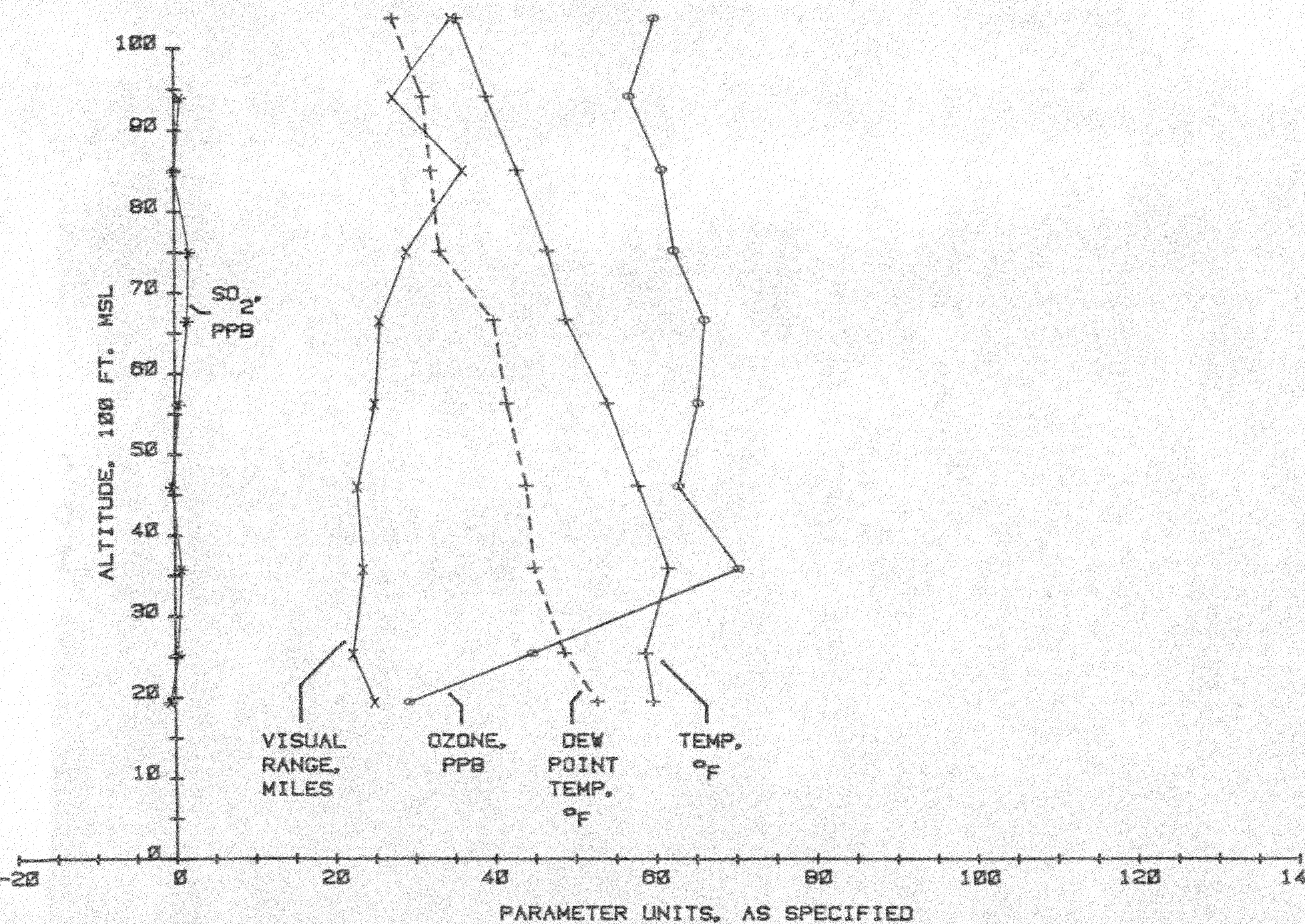


FIGURE 15. SPIRAL OVER LAKE FONTANA IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 14, 1979

ature was fairly high, indicating relative humidities as high as 77 percent. However the inlet heater to the integrating nephelometer was operating for this flight, thus likely reducing the hygroscopic particle effects on light scattering.

Visual range was constant and low at approximately twenty-five miles up to around 6500 feet MSL. Above this altitude the visual range increased to approximately 45 miles. Again the presence of the mountain range "barrier" may prevent adequate dispersion of aerosols below 6500 feet, resulting in higher concentrations and lower visual ranges than at higher altitudes.

Ozone concentrations are low below the inversion and high above the inversion. Once again, ground based monitors would fail to read the higher concentrations "seen" at the higher elevations by the mountain peaks. Sulfur dioxide concentrations were less than 2 PPB for the entire spiral.

A vertical spiral took place on the north side of the park at Cades Cove following the Lake Fontana spiral. Table 13 gives a list of data collected during this flight. The data are plotted versus altitude in Figure 16.

The temperature profile shows that the inversion present on the south side no longer exists on the north side. Dew point temperatures are rather low and the relative humidity never exceeds 70 percent.

Table 13

Spiral at Cades Cove in the Great Smoky Mountain National Park

on June 14, 1979 (see Figure 16)

Time (EDT)	Altitude (ft. MSL)	Temp. (^{o}F)	Dew Pt. Temp. (^{o}F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
7:53	2491	70	46	42	1.12	26	66	118.4	NDA[1]
7:59	3513	68	42	38	1.07	27	67	115.8	NDA
8:03	4649	63	41	44	1.05	28	65	106.9	NDA
8:07	5678	59	38	45	0.95	31	61	96.4	NDA
8:10	6644	55	39	54	0.98	30	61	94.2	NDA
8:14	7444	50	39	65	0.88	33	54	79.6	NDA

[1] no data available

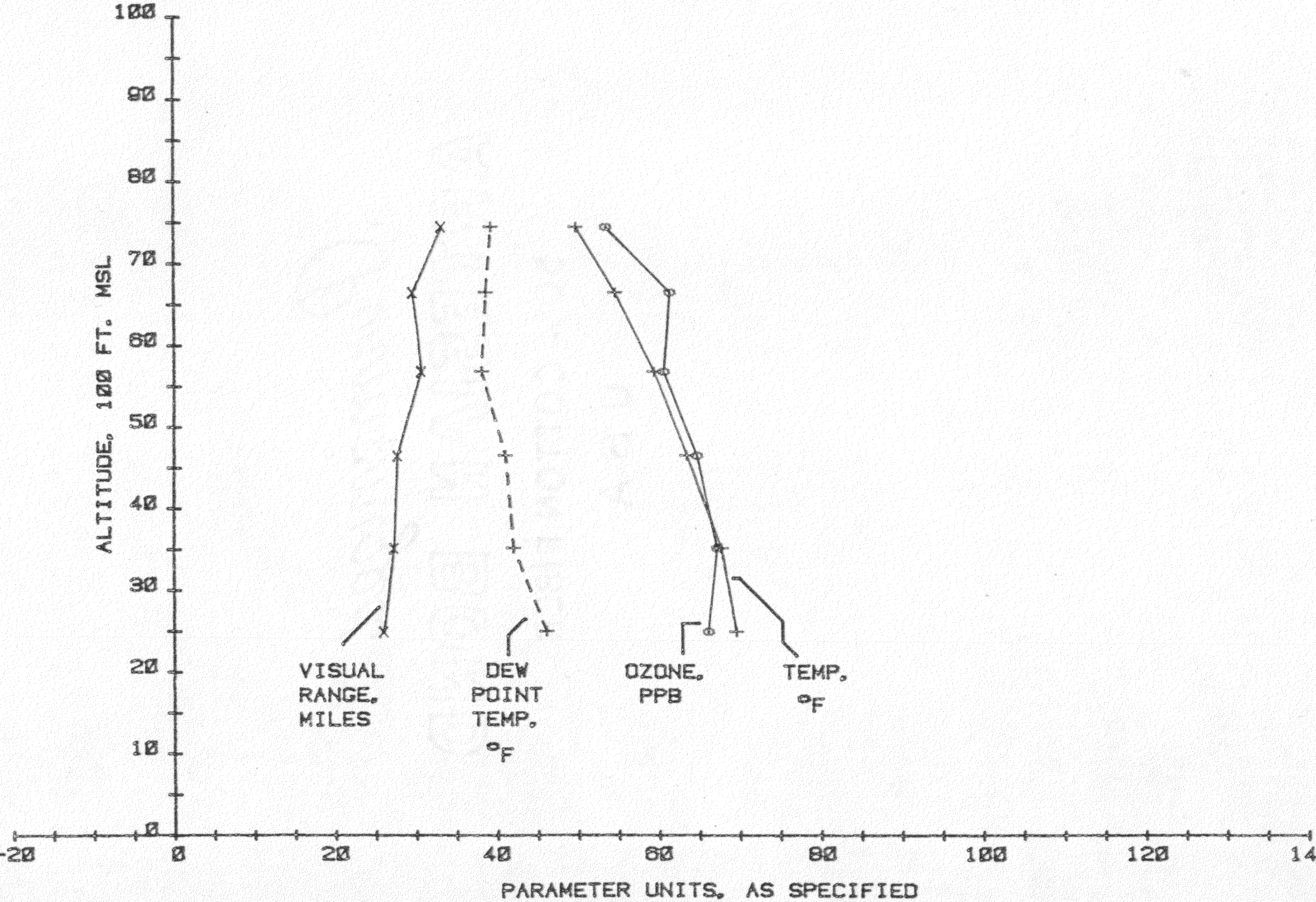


FIGURE 16. SPIRAL OVER CADES COVE IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 14, 1979

The visual range is rather uniformly distributed at approximately 35 miles throughout the spiral. Ozone concentrations are fairly high at around 65 PPB at an elevation of 2500 feet MSL. However, the concentration steadily decreases as the altitude increases.

In comparing the north side spiral with the south side spiral, as shown in Figure 16b, one may note that there is a higher visual range and lower ozone concentration, except under the inversion, on the north side of the park than on the south side. This may indicate better dispersion on the north side as a result of the northerly winds evident on this date.

A comparison of the north side spiral with that taken on the previous afternoon, as is illustrated in Figure 16c, indicates that a lower visual range, thus a higher aerosol concentration, and a higher O_3 concentration are evident in the morning. One may conclude from these data that an air mass containing higher concentrations of pollutants was transported into the park overnight, since these pollutants are generally not produced during the night time.

The first and third of three spirals on the afternoon of June 14 took place on the north side of the park. Data for these sections of the flight are presented in Tables 14 and 15 respectively and are plotted in Figures 17 and 18.

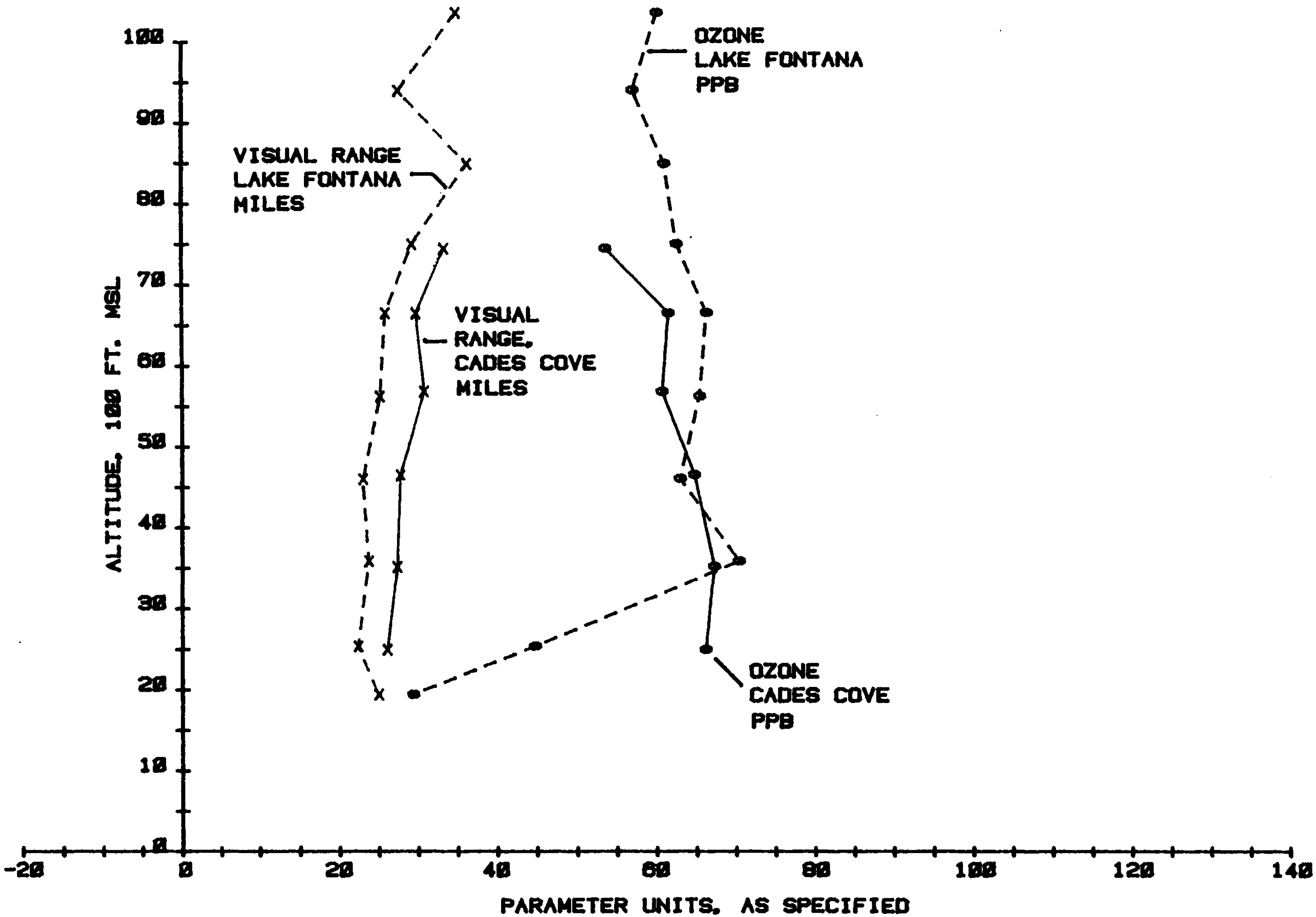


FIGURE 16b. COMPARISON OF VISUAL RANGE AND OZONE AT CADES COVE AND LAKE FONTANA IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 14, 1979

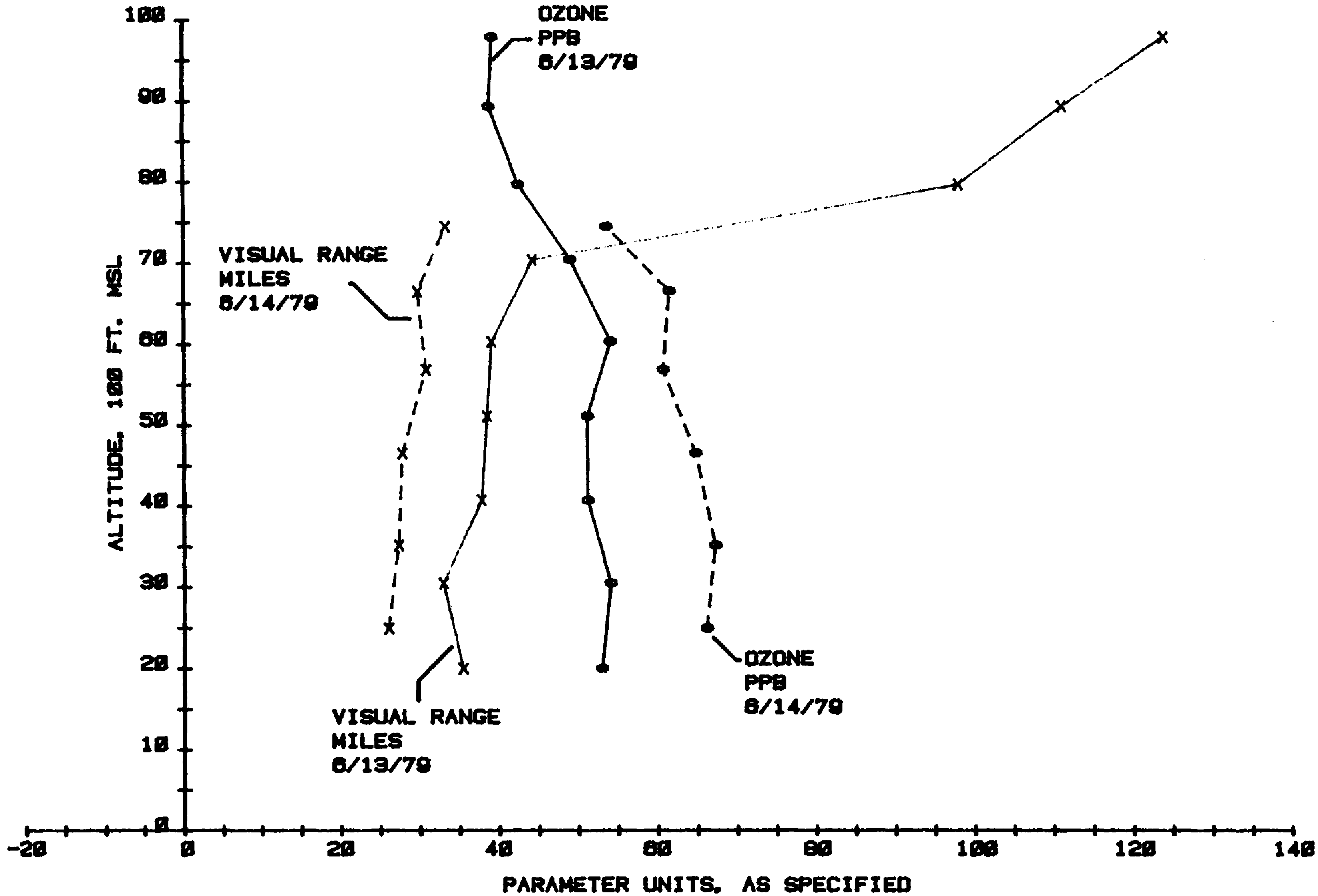


FIGURE 16a. COMPARISON OF VISUAL RANGE AND OZONE AT CADES COVE IN GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 13 AND 14, 1979

Table 14

Spiral on north side of Great Smoky Mountain National Park

on June 14, 1979 (see Figure 17)

Time (EDT)	Altitude (ft. MSL)	Temp. (^{o}F)	Dew Pt. Temp. (^{o}F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
14:13	4400	65	51	60	1.28	23	58	96.0	NDA[1]
14:16	3378	70	52	52	1.33	22	49	84.0	NDA
14:19	2244	75	53	46	1.40	21	75	135.9	NDA
14:22	1196	81	53	37	1.54	19	72	135.9	NDA

[1] no data available

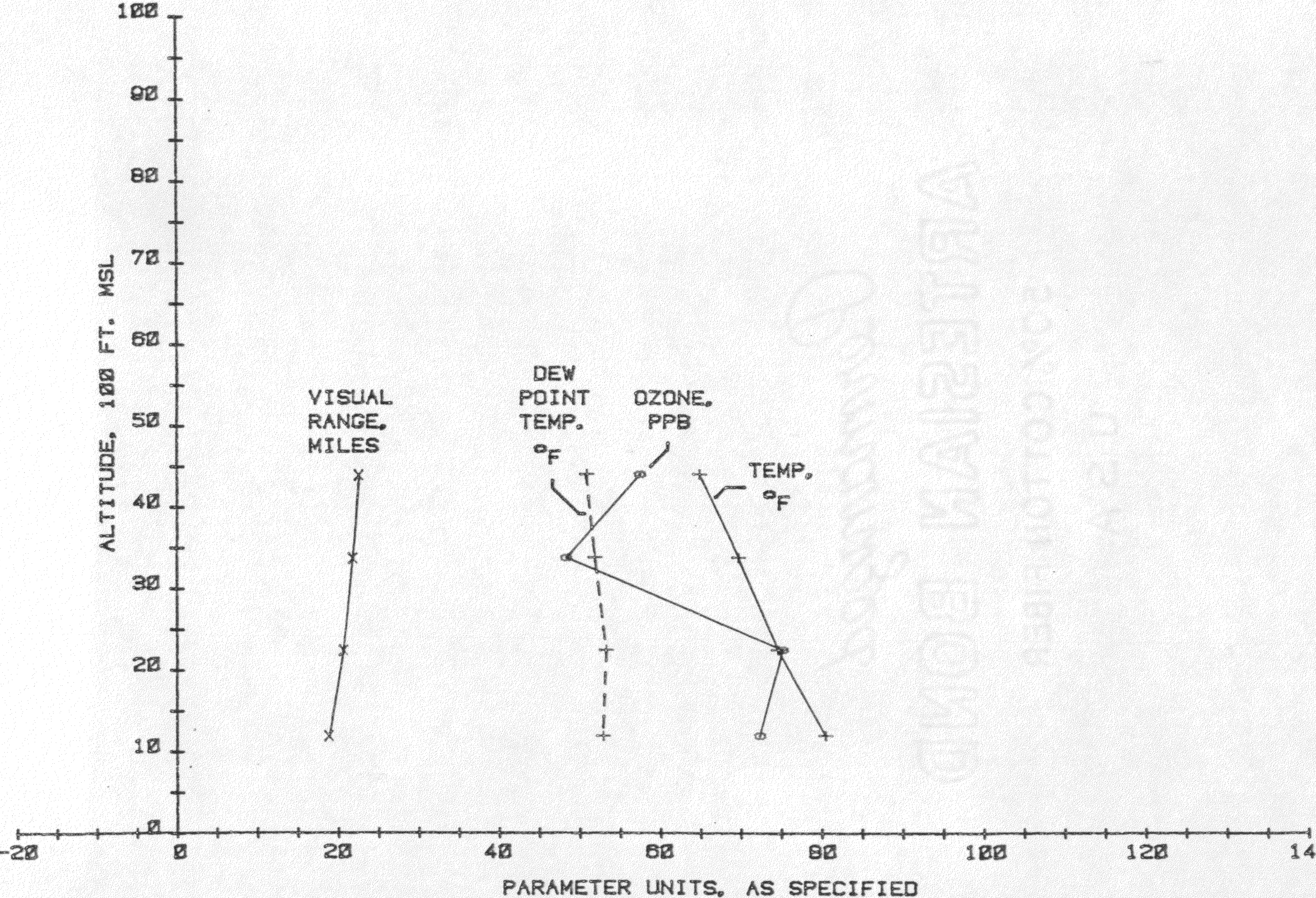


FIGURE 17. SPIRAL OVER NORTH SIDE OF GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 14, 1979

Table 15

Spiral on north side of Great Smoky Mountain National Park

on June 14, 1979 (see Figure 18)

Time (EDT)	Altitude (ft. MSL)	Temp. (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
15:16	5889	60	43	53	1.40	21	66	104.3	NDA[1]
15:17	5467	62	44	51	1.37	21	62	99.9	NDA
15:19	4860	63	47	55	1.54	19	61	100.6	NDA
15:21	4407	66	51	58	1.53	19	75	125.1	NDA
15:24	3822	68	52	56	1.43	20	61	103.4	NDA
15:26	3373	71	51	49	1.47	20	69	119.0	NDA
15:29	2347	78	53	41	1.63	18	66	118.3	NDA
15:31	1682	79	52	38	1.63	18	69	126.6	NDA
15:36	1318	82	52	35	1.60	18	66	123.9	NDA

[1] no data available

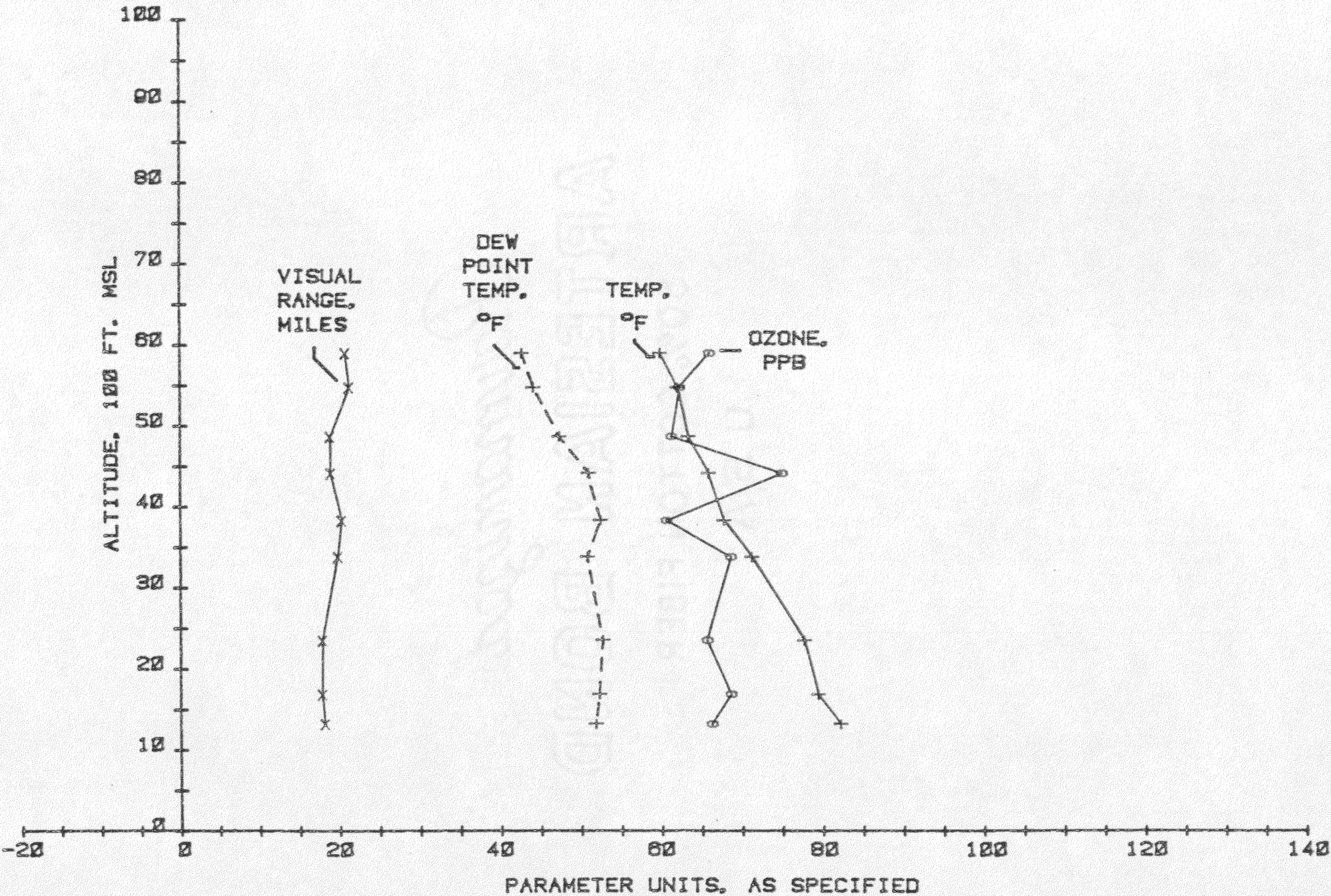


FIGURE 18. SPIRAL OVER NORTH SIDE OF GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 14, 1979

The temperatures for the two spirals are approximately the same at corresponding altitudes. Dew point temperatures are low for the two and the relative humidity is less than 70 percent throughout the flights.

Visual ranges indicated during the two spirals are uniformly distributed at around 20 miles. Ozone concentrations are somewhat different for the two spirals. A high concentration at low elevations and lower concentrations at the higher altitudes are evident in the first spiral. The concentrations become more uniform at approximately 65 PPB during the second flight. The uniform distributions which are evident would indicate fairly good mixing which often exists in the afternoon.

Data from the south side spiral, reported in Table 16 and plotted versus altitude in Figure 19, show a nearly adiabatic temperature lapse rate and low dew point temperatures. The relative humidity never exceeds 70 percent during this spiral.

As was evident on the north side of the park, a fairly uniform distribution of pollutants is indicated by the south side data. The visual range is between 20 and 25 miles. The O_3 concentration is approximately 65 PPB.

A comparison of the north side spirals with the south side spirals reveals that a uniform distribution of pollutants exists

Table 16

Spiral on south side of Great Smoky Mountain National Park

on June 14, 1979 (see Figure 19)

Time (EDT)	Altitude (ft. MSL)	Temp. (^oF)	Dew Pt. Temp. (^oF)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
14:57	2284	76	49	38	1.35	22	63	114.0	NDA[1]
14:59	2880	74	49	41	1.36	21	60	106.1	NDA
15:01	3378	73	47	39	1.45	20	65	113.0	NDA
15:03	3902	70	45	40	1.40	21	66	112.6	NDA
15:05	4580	67	47	48	1.43	20	66	109.6	NDA
15:07	5093	66	41	39	1.26	23	63	102.3	NDA
15:09	5880	61	39	44	1.25	23	66	104.2	NDA

[1] no data available

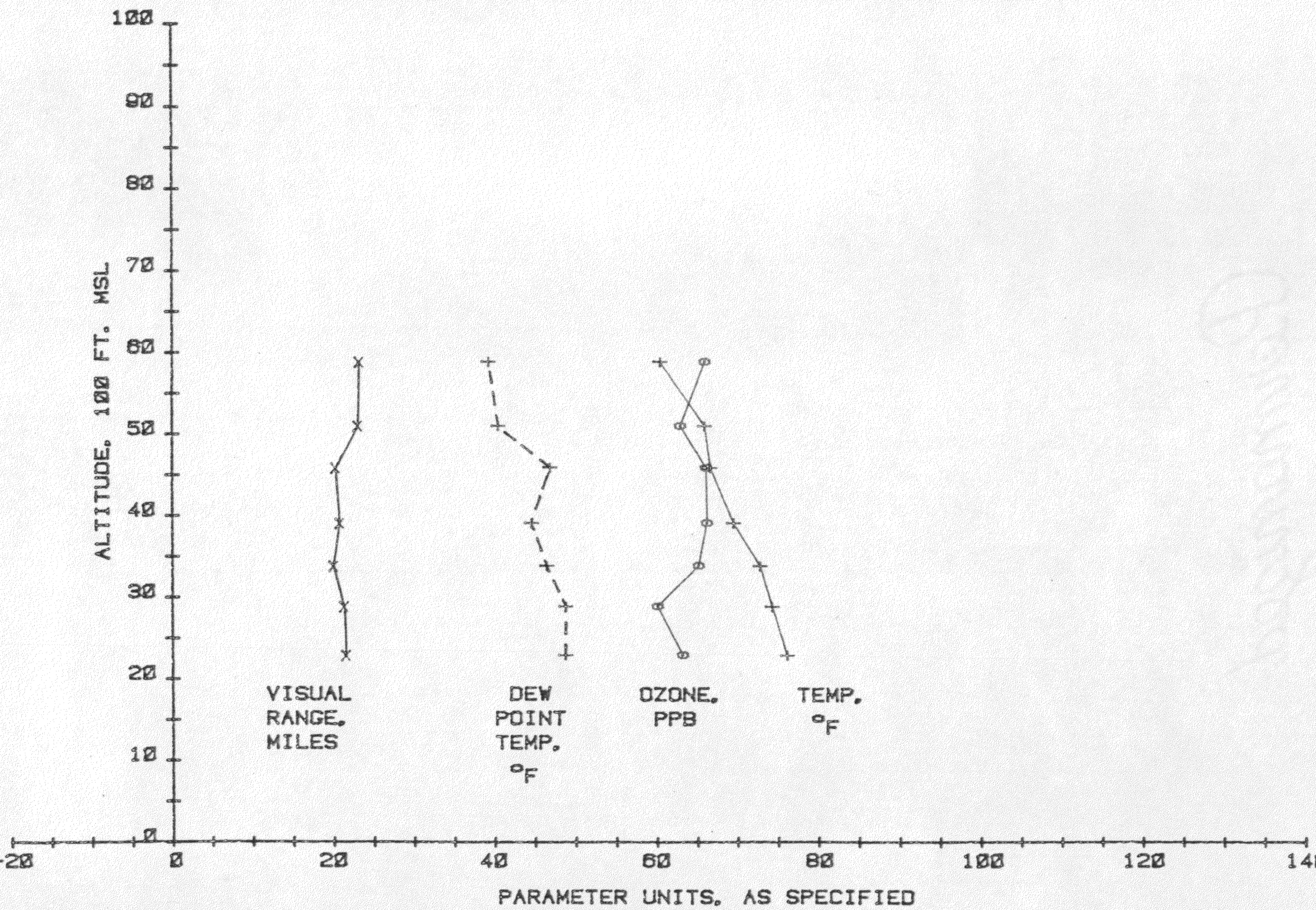


FIGURE 19. SPIRAL OVER SOUTH SIDE OF GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 14, 1979

throughout the park. The high concentrations may again be the result of transport by the northwesterly wind of pollutants emitted or formed to the north of the park.

A comparison of afternoon data with morning data indicates lower visibility occurring in the afternoon, probably due to the formation of aerosols through secondary photochemical reactions. Ozone concentrations are approximately the same, except under the influence of the morning inversion.

The park experienced northwesterly winds at 15 to 20 knots and clear skies on the morning of June 15, 1979.

No horizontal flights were taken in the park on this date, however, two vertical spirals were flown in the morning at the north side of the park. The first of these spirals was flown between Sevierville and Cades Cove. Data for this flight are presented in Table 17 and are plotted versus altitude in Figure 20.

Temperature data indicate the presence of an inversion between 2000 and 2500 feet MSL. Dew point temperatures are low and the relative humidity remains below 70 percent at all times.

A haze layer is indicated by the data at approximately 6500 feet MSL. The visual ranges below this elevation are around 20 miles while they increase to over 60 miles at higher elevations. A sharp decrease in visual range occurs at 8500 feet MSL. This, accompanied with an increase in dew point temperatures and a de-

Table 17

Spiral between Cades Cove and Sevierville on the north side of the Great Smoky Mountain National Park on June 15, 1979 (see Figure 20)

Time (EDT)	Altitude (ft. MSL)	Temp. (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
6:14	1569	68	52	56	2.13	14	33	61.2	NDA[1]
6:19	1989	67	53	60	2.42	12	34	61.1	NDA
6:22	2598	68	48	48	2.16	14	34	61.2	0
6:28	3156	67	47	48	2.14	14	34	59.9	0
6:32	3531	65	45	48	2.10	14	NDA	NDA	0
6:36	4067	63	44	49	1.78	16	57	95.5	0
6:39	4624	61	42	49	1.62	18	61	100.1	0
6:42	5200	59	41	51	1.49	20	61	98.2	0

[1] no data available

Table 17 (Continued)

Spiral between Cades Cove and Sevierville on the north side of the Great Smoky Mountain National Park on June 15, 1979 (see Figure 20)

Time (EDT)	Altitude (ft. MSL)	Temp. (^{o}F)	Dew Pt. Temp. (^{o}F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
6:45	5693	57	39	50	1.27	23	56	89.3	1
6:48	6111	55	39	54	1.32	22	58	90.5	0
6:51	6680	54	33	44	0.84	35	53	81.8	0
6:53	7087	53	26	33	0.45	65	48	72.0	0
6:56	7600	53	22	28	0.42	70	52	76.6	1
6:59	8044	51	18	25	0.40	73	56	80.8	1
7:02	8422	47	21	33	0.65	45	57	81.5	1

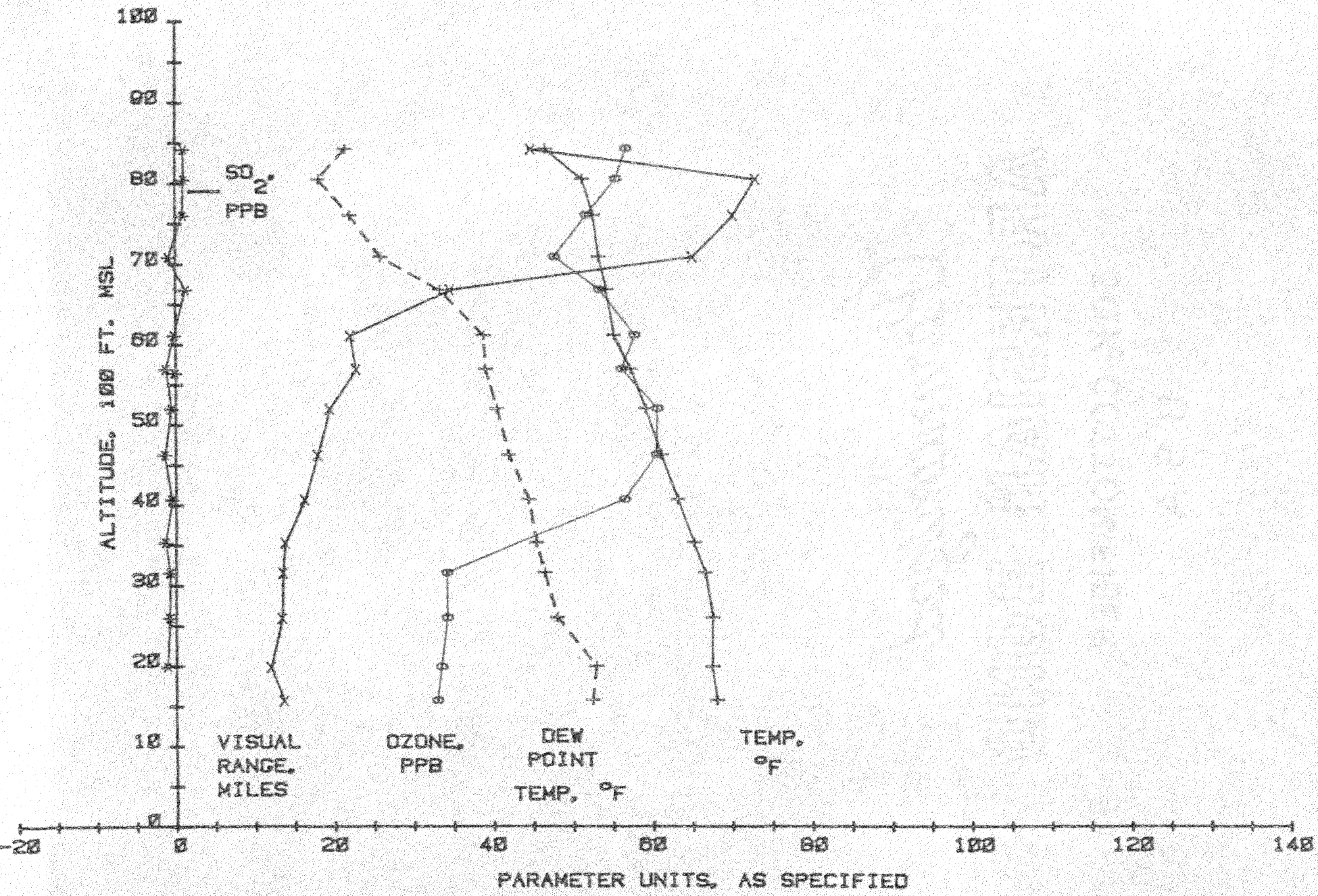


FIGURE 20. SPIRAL OVER NORTH SIDE OF GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 15, 1979

crease in ambient temperature, may suggest that a more complex relationship between these three parameters exists.

Ozone concentrations are approximately 35 PPB at elevations below 3500 feet MSL. However, the concentrations increase to roughly 60 PPB at higher altitudes. Sulfur dioxide concentrations never exceed 1 PPB during this spiral.

The second spiral of the day was flown over Sevierville, Tennessee just north of the park. Data for this spiral are reported in Table 18 and are shown graphically in Figure 21.

Data for this spiral resemble data for the previous spiral on this date. Relative humidities are all below 70 percent. The inversion which was evident during the earlier spiral has dissipated for this spiral.

The visual ranges are approximately 15 to 20 miles at low altitudes and a haze layer is evident at around 7000 feet MSL. Above this altitude the visual range is nearly 75 miles, however, as in the previous spiral, the visual range drops off at around 8500 feet MSL. This time the dew point temperature does not increase, nor does the ambient temperature decrease, which suggests that other factors may cause drastic changes in atmospheric light scattering properties.

Ozone concentrations are nearly the same, at around 60 PPB, as the previous spiral, however, the higher concentration is experienced at lower elevations than witnessed previously. The

Table 18

Spiral over Sevierville, Tennessee, north of the Great Smoky Mountain National Park on June 15, 1979 (see Figure 21)

Time (EDT)	Altitude (ft. MSL)	Temp. (°F)	Dew Pt. Temp. (°F)	Rel. Hum. (%)	b_{scat} ($10^{-4}m^{-1}$)	L_v (miles)	O_3 (PPB)	O_3 ($\mu g/m^3$)	SO_2 (PPB)
7:02	8422	47	21	33	0.65	45	57	81.5	NDA[1]
7:04	7756	49	28	43	0.40	73	48	71.2	NDA
7:06	6611	53	42	66	1.29	23	56	85.9	NDA
7:07	5473	59	39	47	1.12	26	53	84.4	NDA
7:09	4073	63	45	51	1.80	16	66	111.5	NDA
7:11	2609	65	49	56	2.23	13	64	114.6	NDA
7:12	2009	67	50	54	2.34	12	68	123.5	NDA
7:14	1776	67	51	56	2.25	13	59	108.8	NDA
7:16	996	68	20	15	2.34	12	44	82.4	NDA

[1] no data available

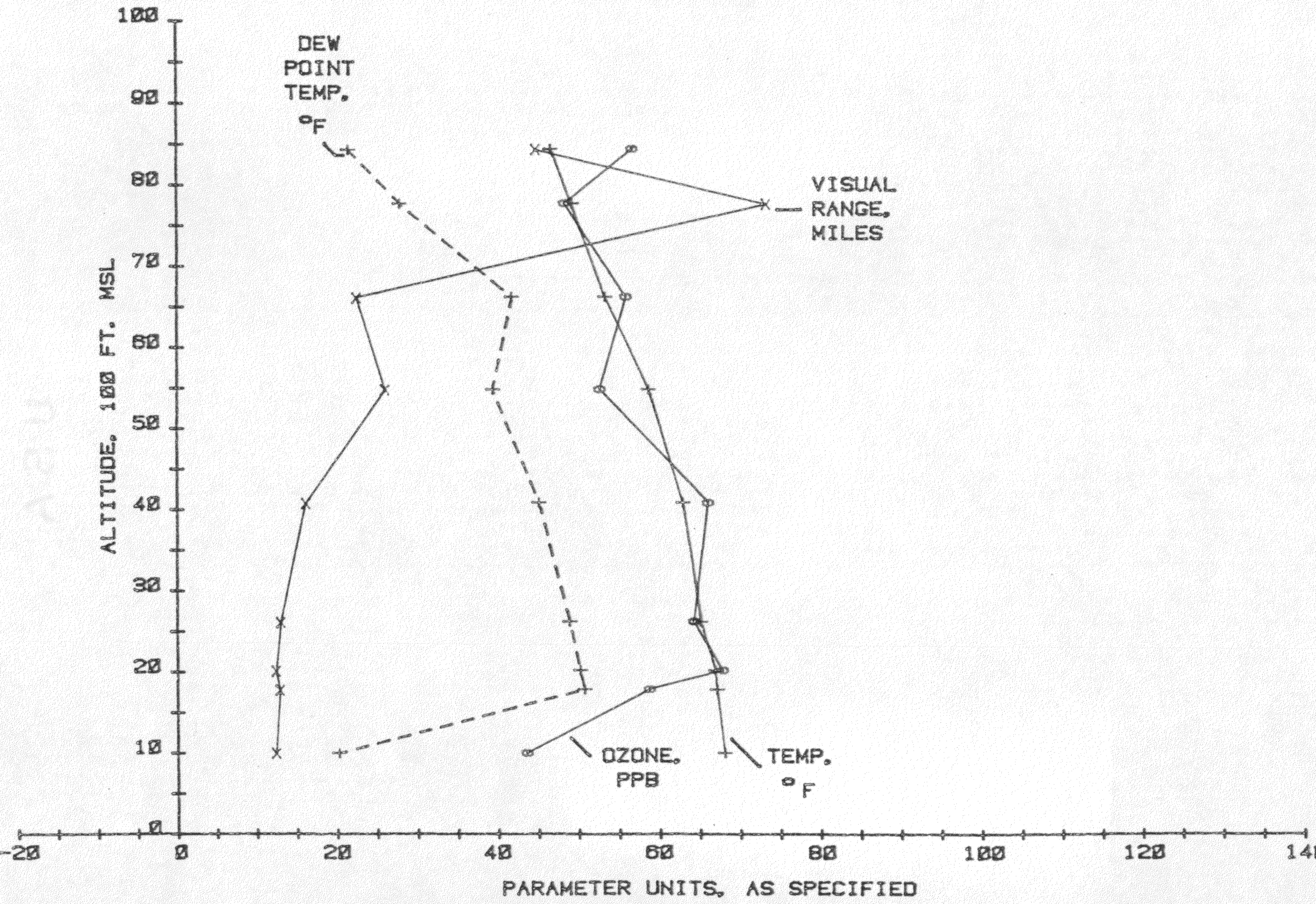


FIGURE 21. SPIRAL OVER SEVIERVILLE, TENNESSEE, NEAR GREAT SMOKY MOUNTAIN NATIONAL PARK ON JUNE 15, 1979

concentration decreases to between 40 and 45 PPB at 1000 feet MSL.

A comparison of these spirals with those recorded on the previous afternoon reveals that visual ranges were approximately the same for the two days. Ozone concentrations decreased overnight indicating the effects of natural scavenging which took place.

Conclusions

Data derived in this investigation may be useful in determining air quality in the Great Smoky Mountains and Shenandoah National Parks. It is important to note, however, that these data were not collected in what is generally considered to be the peak season for reduced visibility. Late spring and early summer months typically exhibit high visual ranges, whereas the later summer months may have much lower visual ranges. In addition, sampling flights were taken only when favorable visual flight conditions existed such as a minimum cloud ceiling of 1000 feet above ground and a minimum visibility of three miles. These conditions may restrict sampling during periods when extremely low visibility exists.

The results of this study tend to support the hypothesis that visibility levels in the two national parks vary vertically and horizontally. In most cases the data indicated a well defined haze layer in which light scattering was increased by aerosols present in the atmosphere. This haze layer usually correlated well with that which was observed visually by the author during sampling flights.

The results usually indicated a distinct stratification in pollutant concentration levels from one side of a park to the other. This is probably due to the "barrier" effect on prevailing winds, created by the mountain peaks which divide each park. If the prevailing winds are responsible for outside transport of air pollutants into the parks, then this barrier may alter the pollutant distribution patterns in the parks, depending on the direction of the prevailing winds. Uniform distributions of pollutants at all altitudes could indicate internal generation of these pollutants in the parks, again depending on the direction of the prevailing winds. In this study the concentrations tended to become more uniform at elevations higher than the mountain peaks. Air mass transport of pollutants into the parks is further suggested by meteorological conditions and varying diurnal pollutant concentrations which existed in the two parks on sampling days.

The integrating nephelometer has been shown to be useful in determining the presence of aerosols which scatter light, thus obscurring vision, in ambient air. This instrument is lightweight and portable, and is relatively easy to calibrate, thus making it well suited for mobile use.

By outfitting a light aircraft with instrumentation such as the integrating nephelometer and other ambient air monitoring equipment, much can be learned about both horizontal and vertical distributions of ambient air pollutants. This becomes even more practical in areas such as those studied in this report where the rugged terrain may restrict adequate ground placement of the necessary monitoring equipment.

A consistent relationship between light scattering and ozone concentrations was not evident during this investigation. Therefore, it is recommended that further study be encouraged to determine the relationship between gaseous or particulate pollutants and light scattering itself or the formation of light scattering aerosols. Further study into the effects of relative humidity on light scattering is also recommended.

Additional research is necessary to determine the various causes and effects, both physical and psychological, of decreased visibility in Federal class I PSD areas such as the national parks. Research of this type will assist the Federal land managers and legislators in promulgating air pollution control policy necessary to preserve our environmental resources for public enjoyment and welfare.

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PRELIMINARY INVESTIGATION

OF

LIGHT SCATTERING

AND

VISIBILITY

IN

TWO EASTERN NATIONAL PARKS

by

THOMAS F. ALBEE

(ABSTRACT)

Light scattering, ambient temperature, dew point temperature and altitude were measured in the Great Smoky Mountain National Park and Shenandoah National Park, two mandatory Federal class I prevention of significant deterioration (PSD) areas. Instruments for measuring these parameters and other air quality related parameters were mounted in a twin engine light aircraft.

Data obtained from horizontal and vertical profiles flown in the two parks on six days between April and June 1979 were utilized in this study. However, these data are not conclusive in that sampling flights were performed under ideal visual flight conditions, and not in the peak season for reduced visibility.

Horizontal and vertical variability in visual range is calculated from the measured light scattering and relative humidity data. Results of this study indicate horizontal stratification in visual ranges

measured from one side of a park to the other possibly due to the "barrier" effect of mountain peaks which divide each park. Data also indicate the existence of a distinct upper aerosol boundary layer which correlates well with the observed haze layer.

The presence and distribution of light scattering aerosols as well as other pollutants such as ozone and sulfur dioxide, measured by the airborne instrument system, indicate the potential for adverse impacts of anthropogenic emissions and secondary pollutants due to meteorological and topographic conditions existing in and around the two parks.

The results of this study will aid Federal land managers and legislators in developing environmental policy for the two parks.