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## Low-Level Cloudiness in the Appalachian Region

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### ABSTRACT

Low-level (<2 km) cloud frequencies have been derived for the Appalachian Mountain region for the period 1985–88 based on in situ measurements by optical cloud and relative humidity sensors, and regional analyses incorporating the U.S. Air Force Real-Time Nephelometer (RTNeph) database. Statistics include cloud frequency as a function of elevation, season and time of day. The in situ results reveal that the higher Appalachian peaks (>1400 m) were in cloud an average of 29%–37% during the period, while peaks near 1000 m experienced cloud 11%–19% of all hours. RTNeph regional results indicate that low-level cloud was most frequent between 900 m and 1300 m with a maximum at 1100 m. Orographic effects are probably responsible for the difference in these findings. Drought conditions during the period reduced overall cloudiness in the southern portions of the Appalachians, while more normal amounts were observed in northern areas. Cloud was found to be more abundant at night over the mountains in contrast to trends observed at regional airport sites.

### 1. Introduction

The wet deposition of pollutants by clouds on high elevation forests in the eastern United States has been proposed as a contributing factor in spruce–fir decline (Lovett et al. 1982; Woodman and Cowling 1987). The Environmental Protection Agency's Mountain Cloud Chemistry Project (MCCP) was implemented by the Forest Response Program of the National Acid Precipitation Assessment Program (NAPAP) to provide air chemistry and meteorological support data to address the hypothesis that acidic and other airborne chemicals contribute to this forest decline. The MCCP has worked closely with the Spruce–Fir Research Cooperative and the Forest Response Program Synthesis and Integration Group to assess the impact of the results on forest ecosystems. Measurement and research stations were established in 1986 at six remote sites along the Appalachians from Maine to North Carolina. In Canada, the Chemistry of High Elevation Fog (CHEF) program was started in late 1985 with similar goals in mind (Schemenauer 1986).

The forest die-back problem appears to be extremely sensitive to elevation and is primarily confined to elevations above 900 m (Woodman and Cowling 1987). The decline may be related to stresses imposed by pol-

lution, climate, pathogens, or possibly a combination of all three (Dasch 1988). Chemical inputs from wet deposition, particularly cloud water, may be important for the following reasons: 1) the higher-elevation sites are often immersed in cloud; 2) the higher wind speeds at these elevations result in a higher interception potential; and 3) the concentrations of chemical species in cloud water have been found to be higher than those found in precipitation (Falconer and Falconer 1980; Waldman et al. 1982; Lovett et al. 1982; and Dollard et al. 1983). The cloud-water acidity of a particular cloud event at a mountain site is dependent on a number of factors including the source region of air over the mountain as well as the air mass in which the clouds are embedded (Vong et al. 1990). Although these results are quite variable from site to site and by event, an overall analysis of cloud distribution within the Appalachians may prove to be a useful first step in determining the role, if any, that cloud water may have on forest decline.

Prior to the birth of the MCCP, mountain cloud observations along the Appalachians were very limited both temporally and spatially. Estimates of cloud impaction frequency ranged from 30% of all hours in the Great Smoky Mountains to 40% at the summit of Mount Mitchell. Estimates for the northern Appalachians were 50% at Whiteface Mountain, New York (Nicholson and Scott 1969), 55% at Mount Washington, New Hampshire (NOAA, 1975) and 40% at the summit of Mount Moosilauke, New Hampshire (Lov-

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ett et al. 1982). Siccama (1974) estimated that the upper slopes of the Green Mountains are in cloud 30%–50% of all hours. The installation of meteorological instrumentation at the MCCP sites provided the first opportunity to directly monitor the presence of cloud.

In the absence of direct mountaintop cloud observations, other sources of regional information can be used to infer cloud frequency within the mountains themselves. These include airport observations, satellite data, pilot reports, and rawinsonde data. For example, Warren et al. (1986) developed global cloud climatology statistics from surface airport observations for the 1971–81 period on a  $5^\circ$  lat  $\times$   $5^\circ$  long grid. The Real-Time Nephanalysis (RTNEPH), a global climatological cloud archive produced by the U.S. Air Force (Fye 1978), incorporates all of the above sources enabling the user to conduct a variety of cloud analyses. Schulz and Samson (1988) utilized the 3DNEPH, an earlier version of RTNEPH, to determine the nonprecipitating low cloud frequency in central North America for 1982.

In this paper, cloud statistics for the Appalachian region are presented based on site-specific results from the MCCP during the warm seasons of 1986–88 and regional findings for 1985–87 derived from the RTNEPH database. Statistics include cloud as a function of latitude, longitude, elevation, and time of day. In addition, the percentages of low cloud types and the ratio of precipitating to nonprecipitating cloud are also investigated. Section 2 briefly describes the MCCP network while section 3 discusses the methods of cloud detection at each of the sites. Cloud statistics from the MCCP sites and the RTNEPH database are contained in sections 4 and 5, respectively. Finally, a summary is presented in section 6.

## 2. MCCP network and site descriptions

The MCCP network encompasses an area from Maine to North Carolina and consists of five primary mountain summit sites ranging in elevation from 1000 to 1950 m, and one primary nonmountain site at a much lower elevation. The locations of the mountain sites are shown in Fig. 1.

The five summit sites include Whiteface Mountain, New York; Mount Moosilauke, New Hampshire; Shenandoah, Virginia; Whitetop Mountain, Virginia; and Mount Mitchell, North Carolina. Given their elevation and location, these sites are frequently impacted by cloud. The sixth, a low elevation site, Howland Forest, Maine, does not experience cloud. Brief site-specific descriptions for the primary mountain sites are presented below.

### a. Whiteface

Whiteface Mountain is situated in the northeastern Adirondack Mountains in New York. The MCCP site, located at the summit, is above the tree line at an ele-

1. Whiteface Mtn., NY
2. Mt. Moosilauke, NH
3. Shenandoah Nat'l Park, VA
4. Whitetop Mtn., VA
5. Mt. Mitchell, NC

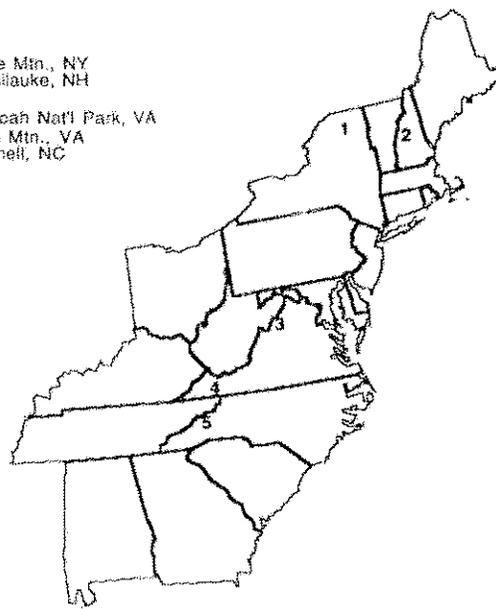


FIG. 1. Locations of the primary summit sites of the MCCP network.

vation of 1483 m. The prevailing wind direction is from the west-southwest, which also corresponds to the steepest terrain on the mountain. The research facilities on Whiteface have been in place since 1961 under the guidance of the Atmospheric Sciences Research Center (ASRC) of the State University of New York.

### b. Moosilauke

Mount Moosilauke, New Hampshire is located in the southern portion of the White Mountains. The MCCP site, operated by Dartmouth College, is located on a spine of the main mountain approximately 7 km southeast of the summit. The site elevation is 1000 m compared with the summit elevation of 1465 m. The terrain falls off significantly to the east-southeast of the site and the predominant wind direction is from the west-northwest.

### c. Shenandoah

The Shenandoah site (elevation 1015 m) is located in the Shaver Hollow watershed in the northern end of the central section of Shenandoah National Park, Virginia. The topography of Shaver Hollow is extremely steep (average slope is 47%). The prevailing wind direction is west-northwest, which is essentially perpendicular to the ridgeline. The westerly winds must travel over the main Appalachian chain, the beginning of which is roughly 35 miles to the west, before reaching the site. Research at the site is conducted by the University of Virginia.

#### d. *Whitetop*

Whitetop Mountain is located at the Mount Rogers National Recreation Area of the Jefferson National Forest in southwestern Virginia, approximately 6 km southwest of Mount Rogers, the highest peak in the state at 1746 m. The Tennessee Valley Authority (TVA) summit research station is at an elevation of 1689 m. The prevailing wind direction is from the west-northwest, thus the site is strongly influenced by air originating from the Tennessee Valley region. The steepest slopes on the mountain are on its southwestern side.

#### e. *Mitchell*

The southernmost MCCP site is located in the Mitchell State Park, North Carolina, one mile southwest of Mount Mitchell, which is the highest peak in the eastern United States (2038 m). The MCCP meteorological tower is installed on Mount Gibbs at an elevation of 1950 m. Wind direction frequency distributions indicate a pronounced peak from the west-northwest.

### 3. Methods of cloud detection at MCCP sites

#### a. *Instrument description*

Three different techniques for estimating the frequency of cloud impaction were utilized by the MCCP beginning in 1986. From the project's onset, relative humidity was used at most sites to determine cloud presence. At Whitetop Mountain a reflectometer was used to detect cloud but its high cost precluded its use throughout the network. Beginning with the 1988 field season, an optical cloud detector was installed at all sites. A description of the techniques along with their measurement uncertainties is presented below.

##### 1) RELATIVE HUMIDITY

Relative humidity (RH) is sensed by a Rotronics MP-100 combination temperature-RH probe housed in a naturally aspirated radiation shield. Cloud presence is determined subjectively by analyzing the time series trace during saturated and near-saturated conditions. The tendency for the sensor's response in these conditions to drift upward over an extended period of time precluded the use of a wholly objective RH cloud threshold, such as a minimum RH value, to define cloud events. Average RH values are recorded hourly based on 5-s samples. As verified by field observations, the onset of cloud is typically marked by a sharp rise in RH to near 100% followed by a leveling off. Cloud dissipation is marked by an abrupt drop of at least several percentage points. Figure 2 depicts a typical RH pattern for a cloud event derived from data at Mount Mitchell.

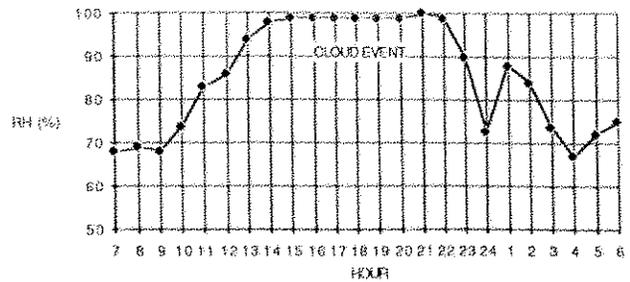


FIG. 2. Hourly time series for relative humidity showing a cloud event from Mount Mitchell, 9-10 June 1988.

The uncertainties inherent in the RH technique are several: the element of subjective interpretation, the instrument's 5% accuracy specification, the use of hourly averaged values, and its slow response time relative to the two optical techniques. Overall, it is suspected that this technique may somewhat overestimate the frequency of cloud due to the fact that near saturated conditions can occur when the cloud base is above the site but is accompanied by heavy or prolonged rain events.

##### 2) REFLECTOMETER

A backscatter reflectometer (visibility sensor Weathertronics Model 8340) has been used by the Tennessee Valley Authority (TVA) since 1980 as a cloud detector. According to Valente et al. (1989), "observations at Whitetop have shown that by using a signal strength of 0.15 (5% of the output range) as the definition of the presence of cloud, haze and liquid precipitation are not mistaken for cloud impaction." The instrument has a visibility range of 1000+ to 10 m, corresponding to a signal output of 0%-100% of scale, respectively. The detection threshold of 5% of scale corresponds to a visibility of 260 m according to the manufacturer's literature.

The uncertainties with the reflectometer are not well defined. However, the method used to obtain hourly signal values will tend to overemphasize the presence of cloud within an hour in which cloud was present less than half the time. This occurs because the signal's scale is logarithmic whereas hourly averages are derived arithmetically. Hourly average reflectometer values are based on 5-min intermediate average values derived from 20-s samples. Given that the first 5% of scale (cloud absent) corresponds to a visibility range of about 740 m while the remaining 95% of scale (cloud present) corresponds to about a 250-m visibility range, arithmetic averaging of percent of scale values within an hour will give greater weight to "cloud present" signals. This can be a source of discrepancy when comparing different measurement techniques during variably cloudy hours.

### 3) OPTICAL CLOUD DETECTOR

The optical cloud detector (OCD) is a forward-scattering optical device originally developed by the Energy Research Foundation in the Netherlands (Mallant and Kos 1990). Following successful laboratory and field tests (see Valente et al. 1989), a modified design was built by AWS Scientific, Inc. (AWS) and deployed at all summit sites in 1988. It has an adjustable detection threshold corresponding to liquid-water content (LWC) at an assumed mass median-droplet diameter. Hourly recordings indicate the percentage of time with cloud present based on 5-s samples. Each sample produces a binary signal corresponding to cloud presence (=1) and absence (=0). Based on laboratory tests conducted at the Energy Research Foundation, the instrument's detection threshold is set at an equivalent LWC value of approximately  $0.04 \text{ g m}^{-3}$  for a droplet mass median diameter of about  $11 \mu\text{m}$ , roughly equivalent to a visibility of 350 m (Atlas and Bartnoff 1953). The uncertainty in this threshold is estimated to be  $\pm 0.02 \text{ g m}^{-3}$  due to the uncertainties in the FSSP-based laboratory calibrations and on the imprecision of the adjustment potentiometers. The instrument can be calibrated in the field through the use of neutral density filters.

Under ambient field conditions, the actual detection threshold will also be a function of the cloud's drop-size distribution. Therefore, this instrument's response to cloud, especially "thin" clouds, is variable. It has also been observed that this instrument can be susceptible to droplet accumulation on the optical lenses, which results in a reduction in the sensitivity to the presence of cloud. The original version of the detector did not contain heaters and therefore was suitable only for above-freezing cloud conditions.

#### *b. Summary of intercomparison tests*

##### 1) OCD VERSUS REFLECTOMETER

Several intercomparisons of the OCD and the TVA reflectometer have taken place, beginning with a 1987 liquid-water content instrument "shoot-out" at Whitetop Mountain (Valente et al. 1989). This first intercomparison used an original prototype whereas all later intercomparisons used the AWS-modified design. In all intercomparisons, in lieu of an absolute cloud detection technique, the TVA reflectometer was arbitrarily designated the "standard" to define periods when cloud was present or absent. The first intercomparison, covering a two-week period in 1987, found that the prototype had 98% agreement with the reflectometer during cloud events and 93% agreement during noncloud hours.

Four other intercomparisons were conducted during 1988 and 1989 using four different AWS-built instruments. These tests comprised over 5700 field hours. The OCD agreed with 96%–99% of the cloud/no cloud

observations taken by the reflectometer. When clouds were indicated by the reflectometer, the OCDs agreed 92%–95% of the time for three of the instruments, and 80% for the other. The lower agreement of this one instrument was the result of it not responding to cloud for a 24-h period within one extended cloud event. It is expected that water droplets accumulated on its lenses, reducing the instrument's sensitivity. When the reflectometer indicated that clouds were absent, agreement with all four OCDs ranged from 98% to 100%.

##### 2) RELATIVE HUMIDITY VERSUS OCD

Concurrent estimates of hourly cloud presence using the RH and OCD techniques were made throughout the 1988 field season at four MCCP summit sites: Mitchell, Moosilauke, Shenandoah and Whiteface. A minimum of 2300 h of simultaneous values were taken at each site. Based on its favorable intercomparison results with the TVA reflectometer, the OCD was designated the standard in the intercomparisons with RH. An hour with cloud as defined by the OCD required the instrument to be detecting cloud for at least 50% of the hour. Overall agreement between techniques on an hourly basis ranged from 87% to 96%. During cloud conditions as defined by the OCD, agreement ranged from 81% to 94%.

##### 3) OCD VERSUS RH VERSUS REFLECTOMETER

The 1988 field season provided the first opportunity for the RH sensor to operate together with both the OCD and reflectometer instruments at Whitetop Mountain. In summary, RH agreed with the reflectometer 91% of the time, and 90% with the OCD. During cloudy conditions the agreement was 86% and 85%, respectively. Based on these results, error estimates for relative humidity derived cloud frequencies for the MCCP sites would range from  $\pm 2\%$  to 6%.

The results of the comparison tests indicate that the OCD gives the most conservative estimate of seasonal cloud frequency. The differences between the OCD and RH are larger than those for the OCD and reflectometer, suggesting that RH may give the most liberal estimate of cloud frequency.

#### 4. MCCP cloud statistics

The MCCP dataset consists of both chemical and meteorological data beginning in the warm season of 1986. These data were collected under the auspices of an EPA approved Quality Assurance Plan (NADP Quality Assurance Steering Committee 1984; MCCP Quality Assurance Project Plan 1988). The following meteorological parameters were routinely monitored across the network: air temperature, pressure, insolation, wind speed and direction, relative humidity, cloud detector (1988 only), and precipitation amount. Data were collected during the growing season, the onset of

which varies with site location. In this paper, cloud results are presented only for the period 1 June–30 September, hereafter referred to as the field season, during which all sites were fully operational.

### a. Cloud frequency

The frequency of cloud on a particular mountain can be a function of several factors: latitude, longitude, elevation, mountain shape and orientation, and aspect. The mechanisms responsible for cloud formation in mountainous areas can be attributed to three primary processes: 1) large-scale weather systems (cold fronts, warm fronts, cyclonic activity) which usually produce widespread regional cloudiness; 2) orography (forced uplifting by terrain) which leads to localized cap cloud formation; and 3) solar heating, typically exemplified by the formation of cumulus clouds.

Table 1 presents the percent frequency of cloud impaction for the combined 1986–88 field seasons at each of the MCCP summit sites. The top half of the table indicates the percent of time that the sites were impacted by cloud while the lower half presents the percent of days with at least 1 h of cloud. Cloud frequency estimates at all sites, except Whitetop, were based on relative humidity data during the 1986 and 1987 field seasons and optical cloud detector results in 1988. Whitetop results were derived from the reflectometer throughout the period.

The 3-yr mean of cloud impaction frequency ranged from a high of 37% at Whiteface to a low of 11% at Shenandoah. Whitetop experienced cloud 30% of the time, Mitchell 29% and Moosilauke 19%. Noteworthy is the observation that the three higher elevation sites experienced cloud two to three times more frequently than the two lower sites. On a day to day basis, at least

one hour of cloud was observed between 32% to 42% of the days at the lower elevation sites and between 68% to 77% of the days on the three higher mountains.

Overall, observed cloud impaction was a maximum during the first year of the project and decreased thereafter. The general decline in cloudiness between 1986 and 1988 is a reflection of the drought conditions which affected portions of the region, especially the southern half of the network (Bergman et al. 1986; Cook et al. 1988). Section 4e will further discuss the spatial and temporal representativeness of the MCCP cloud data.

### b. Diurnal trends

In the absence of synoptic-scale cloud producing mechanisms, the diurnal trend in cloudiness is strongly driven by surface heating. Warren et al. (1986) showed a maximum in cloudiness during the afternoon hours using regional airport observations. An analysis of the general diurnal trend of cloud frequency at the mountain sites was conducted by dividing cloud observations into 6-h intervals (0100–0600 LST, 0700–1200 LST, etc.). Figure 3 presents a summary of the diurnal trends for the summit sites.

Diurnal cloud activity at mountaintop indicates a preference for cloud impaction at night (1900–0600 LST). The most pronounced day-to-night differences during this period occurred at the higher sites, while flatter diurnal trends are apparent at the lower peaks. This pattern of cloud activity was also observed by Schemenauer (1986) for a mountain site in Quebec. In that particular study cloud frequencies were determined twice daily, 0800 EST and afternoon hours, for three different elevations. One suspected reason for the higher amplitude curves at Mitchell, Whitetop and Whiteface is the occurrence of orographic cloud. On-site observations by technicians at these sites have indicated that orographic cloud can occur quite regularly under certain synoptic conditions such as a Bermuda High situation. Moosilauke and Shenandoah, being lower in elevation, infrequently experience orographic cloud.

A year-to-year breakdown of diurnal trends at the higher sites revealed a maximum in amplitude in 1987 and a distinct minimum in 1988. Yearly changes were less subtle at Moosilauke and Shenandoah. The significant flattening of the curves during 1988 may be attributed to two factors: 1) the extreme drought conditions over the Appalachians which probably inhibited cap cloud formation and 2) the switch to the optical cloud detector as a means of determining cloud presence at the majority of the sites. The tendency for relative humidity to approach saturation as a result of nighttime mountaintop cooling may have led to a slight overestimate of nocturnal cloudiness during 1986 and 1987. Comparisons between the two techniques during 1988 indicate a 9% higher cloud frequency during the 0100–0600 LST period using the relative humidity

TABLE 1. Cloud frequency\* at the MCCP summit sites during June–September, 1986–88.

Cloud frequency (% of hours in cloud)				
Site	1986	1987	1988	3-yr mean
Whiteface (1483 m)	44	42	25	37
Moosilauke (960 m)	29	22	6	19
Shenandoah (1015 m)	19	8	6	11
Whitetop (1689 m)	35	30	26	30
Mitchell (1950 m)	32	32	23	29

Percentage of days with at least 1 h of cloud				
Site	1986	1987	1988	3-yr mean
Whiteface	79	80	73	77
Moosilauke	52	51	22	42
Shenandoah	46	25	25	32
Whitetop	76	67	62	68
Mitchell	84	75	68	76

\* Error estimates for 1986–87 based on relative humidity data are  $\pm 2\%$ –6%.

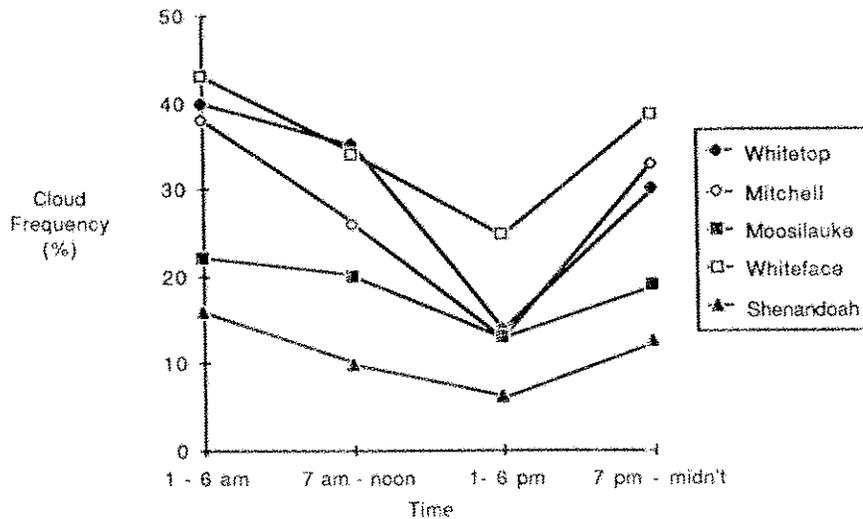


FIG. 3. Diurnal trends in cloudiness at the MCCP summit sites 1986-88 field season.

technique. Whitetop results, which were based solely on the reflectometer, did indicate nearly a 50% reduction in diurnal amplitude during 1988 suggesting that the drought was an important factor.

#### c. Precipitating versus nonprecipitating cloud

The collection and chemical analysis of cloud water was one of the major activities within the MCCP. Collectible cloud events required  $\leq 1$  km visibility and a collection rate of  $> 10$  ml over a 20-min period. Cloud samples were taken at 1-h intervals. All sites operated the ASRC omnidirectional, passive cloud collector (Falconer and Falconer 1980) or CAL TECH active collector (Daube et al. 1987) and followed the established QA/QC protocol for cloud collection and LWC measurements. Frequency distributions for the four major ions ( $H^+$ ,  $NH_4^+$ ,  $SO_4^{2-}$  and  $NO_3^-$ ) based on cloud events collected during the 1986-88 period indicate that their concentrations are lower during precipitating cloud than during periods containing cloud only as a result of dilution by rain droplets (Mohnen 1990). Given these findings, an attempt was made by the MCCP to determine the frequency of exposure of forests to nonprecipitating cloud.

Hourly cloud and precipitation records were compared to determine the relative frequencies of precipitating and nonprecipitating cloud. Table 2 summarizes the results for each of the MCCP sites by year for the 1986-88 period. In general, between 60% and 90% of the observed cloud hours were nonprecipitating. The highest percentage of nonprecipitating cloud ( $\sim 90\%$ ) was found at Mount Mitchell. Values were generally higher in the southern portions of the network, possibly a reflection of the drought conditions observed during the period.

#### d. Vertical cloud distribution

Regional differences in the vertical distribution of cloudiness are governed primarily by synoptic-scale weather features and large geographical factors such as the proximity of large water bodies. In the case of site-specific distributions in mountainous terrain, smaller scale effects such as a particular mountain's shape and orientation and its position relative to surrounding peaks may also play a significant role. An understanding of the distribution of cloud with height is important for estimating cloud-water impaction potential. In addition, the identification of zones of typical cloud base may be important since there appears to be a significant elevational gradient for pollution related ions in cloud with the highest concentrations at or near cloud base (Petrenchuk and Drozdova 1966; Daum et al. 1984; Romer et al. 1985; Lazrus et al. 1983; ten Brink et al. 1987; and Scott and Laulainen 1979).

Vertical distributions of cloud frequency were available for only two MCCP sites, Whitetop and Whiteface. At Whitetop the observed frequency of daytime cloud exposure versus elevation was obtained from a time-lapse video recorder sited 4.5 km to the north-northwest

TABLE 2. Annual and composite percentage of cloud at the MCCP summit sites that are nonprecipitating.

Site	1986	1987	1988	3-yr mean
Whiteface	65	76	*	—
Moosilauke	67	51	70	61
Shenandoah	74	61	69	69
Whitetop	84	85	77	84
Mitchell	99	88	84	90

\* Precipitation data unavailable.

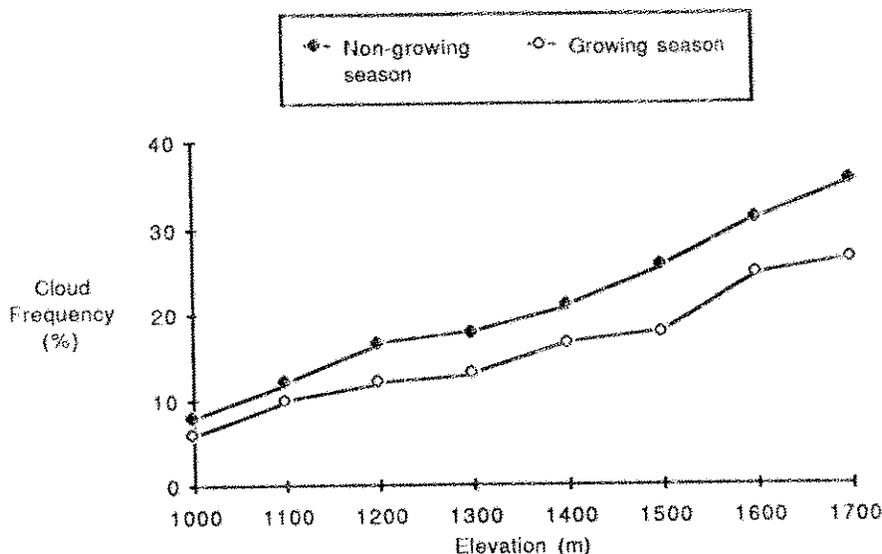


FIG. 4. Whitetop cloud frequency as a function of elevation based on video camera data (daytime only).

of the summit at an elevation of 915 m. The dataset consists of hourly cloud-base information for the period October 1985–December 1988. Figure 4 presents the daytime cloud impaction frequency versus height at Whitetop for both the growing seasons (May 1–August 31) and nongrowing seasons during the 3-yr period. For a particular observation, a low overcast resulted in all higher elevations being considered in cloud. The results indicate a gradual increase in cloud impaction frequency with elevation throughout the year. The nongrowing season had a higher cloud frequency. The summit daytime cloud frequency during the nongrowing season was approximately 36%, or nearly 9% higher than that observed during the growing season.

Cloud-base frequency distribution results for Whiteface for the 1986–88 field seasons were determined from relative humidity data, site technician observations (primarily daytime) and the optical cloud detector (1988 only). Figure 5 presents the 3-yr mean

cloud frequency at Whiteface in 100-m intervals ranging from below 800 m to the summit. Cloud impaction frequency ranged from 5% at the lowest elevations to approximately 37% at the summit.

*e. Representativeness of MCCP cloud results*

Beginning in the latter half of 1984 and continuing into the 1988 field season, the southernmost portions of the Appalachians experienced prolonged drought conditions as determined by the Palmer drought severity index (Palmer 1965). In addition, extremely dry conditions were observed throughout the entire Appalachian region during the first half of the 1988 field season. Given these overall anomalous conditions, it is important to put into perspective how representative the cloud frequency data derived from the MCCP compares to the long-term mean.

One potential source of long-term cloud information is the hourly observations taken by National Weather Service airports. Cloud-base heights at the airports are determined primarily through the use of ceilometers; however, pilot reports are also used in some instances. The fixed or rotating beam ceilometers have an estimated accuracy of  $\pm 30$  m up to 1000 m in elevation and  $\pm 10\%$  above 1000 m (WMO 1976). These data are available in various forms from the National Climatic Data Center. In this study, 3-h observations were analyzed for eight airports along the Appalachians for the period 1965–85. The locations of the airports used in the analysis are presented in Fig. 6. Cloud-base height observations were grouped into 150-m (500-ft) intervals extending to 2134 m (7000 ft) above sea level in order to obtain the vertical distribution of cloudiness. The 2134-m level was chosen as a cap in this study

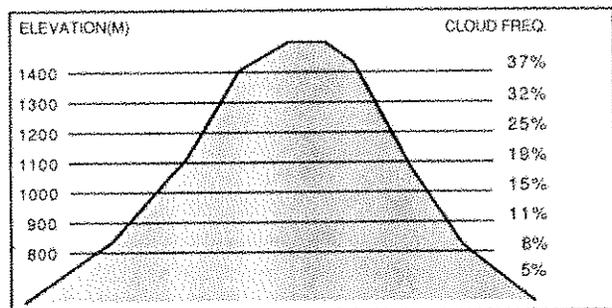


FIG. 5. Vertical profile of cloud impaction at Whiteface (1986–88) based on RH, site technicians, and cloud-detector observations.

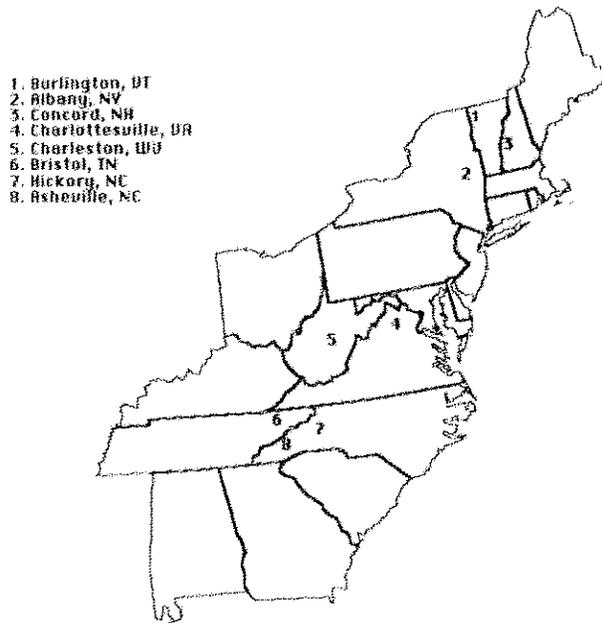


FIG. 6. Locations of airports used in 1965-85 cloud climatology.

since it roughly corresponds to the elevation of the highest peak within the Appalachian chain. Cloud-base observations above 2134 m were combined into a single category and clear conditions were also noted.

All cloud-base height observations below 2134 m were summed to produce the percentage of observations with cloud base below that particular level. The results do not indicate the percentage of time with cloud below 2134 m since multiple cloud layers below this level can exist at one observation period. The results were used only to highlight relative differences in low cloud frequency. Similar calculations were performed for the 1986-88 seasons and then compared to the long-term values. The 3-yr composite departure from the long-term mean for the eight airports is presented in Fig. 7.

The synoptic-scale patterns during the period produced marked differences in regional cloudiness. In the northeast, above normal cloudiness was observed during both 1986 and 1987. The departures for these two years were +9% and +6%, respectively. Extremely dry conditions in 1988, particularly during the early portion of the field season, resulted in a departure of -8%. The five southern airports reported consistently below normal cloudiness throughout the period. On average, the departures for the three years were -4%, -8% and -5%, respectively. The 3-yr composite departure from the long-term mean for both regions is presented in Fig. 7. On the basis of regional cloud only, these findings imply that cloud frequency results for the northern MCCP sites may be higher than normal. In contrast, the southern MCCP sites probably experienced below normal cloudiness. However, whereas

trends in regional-scale cloud are evident, it is not possible to determine the effects on local orographic clouds. Clouds at the MCCP sites were not distinguished between regional and orographic types.

## 5. RTNEPH

The Real-Time Nephanalysis (RTNEPH) is a global climatological cloud archive produced by the U.S. Air Force (Fye 1978). An earlier version, called 3-Dimensional Nephanalysis (3DNEPH) was begun in 1971 and replaced in 1984 by the improved RTNEPH version. Both versions use all conventional surface and rawinsonde data, pilot reports, and satellite data to produce three-dimensional cloud information. The RTNEPH data are organized according to a horizontal grid system superimposed upon a polar stereographic projection. Gridpoint spacing is 47.7 km at 60° latitude where projection is true. Each grid point contains the following data parameters for every 3-h period: type of low, middle, and high clouds; present weather; maximum cloud top; minimum cloud base; total percent sky coverage; and percent coverage for 15 fixed layers. Hughes and Henderson-Sellers (1985, 1986) have compiled a global cloud climatology for 1979 from the 3DNEPH archives while Schulz and Samson (1988) used the same database to determine nonprecipitating low-cloud frequencies for central North America for 1982.

The uncertainties in the RTNEPH data archives consist of the limitations inherent to each of the data sources which have been synthesized. First, airport cloud-base heights are measured by a ceilometer whose accuracy has been previously discussed. Secondly, the



FIG. 7. Three-year (1986-88) low-level cloud frequency departures (%) from 1965-85 normals at eight NWS airports.

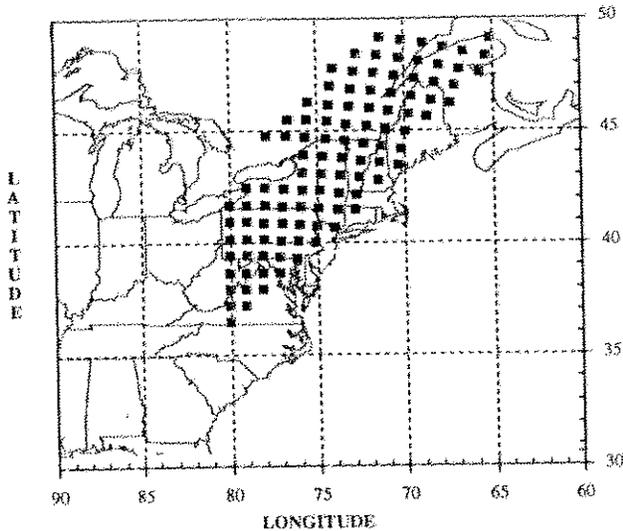


FIG. 8. Area covered by RTNEPH cloud analyses in the northeastern United States (squares represent locations of grid cells).

conditions, are best detected by surface and rawinsonde observations and least by satellites. In areas where airport station density is low, low-cloud information may not be well represented. Quality assurance has been upgraded in RTNEPH by the use of source flags, improved quality control algorithms and weighting factors for the age of the data and distance from a gridpoint.

For this study the RTNEPH database was used to examine the spatial and temporal variations of low-level clouds (<2.1 km MSL) in eastern North America for the 1985–1987 period. The region analyzed encompasses an area from Virginia northeastward into southern Canada. Results for the southernmost portions of the Appalachians were not available since this required the analysis of data from a different grid box. Roughly 50% of the grid cell within the analysis area were used in this study. The area of interest and the position of the grid cells are presented in Fig. 8.

satellite data processors may misinterpret cloud information under certain conditions. For example, the visual data processor cannot distinguish between clouds and bright areas of snow or ice. Therefore, unless accurate snow or ice data are available, the analyses may be in error. In addition, the infrared data processor may underestimate cloud-top heights for thin cirrus clouds or small cloud elements due to the large field of view of the instrument. The 47.7-km grid spacing precludes resolution at smaller space scales and thus the RTNEPH analyses are best used for regional analysis. Low-level clouds, particularly for multilayer cloud

*a. Cloud frequency*

Regional low-cloud frequency over the northeastern Appalachian domain as determined by the RTNEPH database is presented in Fig. 9. In this figure the frequency of cloud is calculated by multiplying the frequency of low-cloud occurrence by the amount-when-present.

Low-cloud frequency ranged from nearly 50% in the winter of 1985 to just over 20% in the summer of 1987. Values were greatest during 1985 and gradually decreased with time through 1987. On a seasonal basis, cloud frequency was highest during the winter months (December–February) and lowest during the summer (June–August).

*Percent of Cloud Coverage over NE Appalachian Domain*

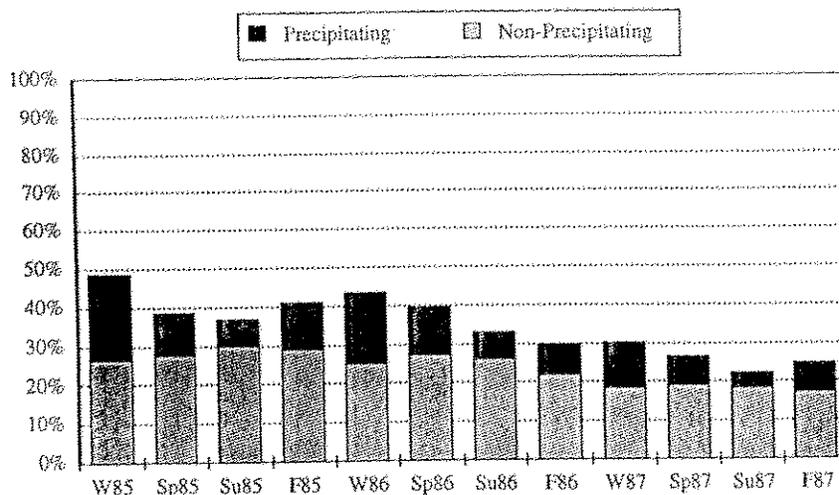


FIG. 9. Percent cloud coverage over northeast Appalachian domain.

### b. Diurnal trends in cloudiness

In Fig. 10, the diurnal trends in cloudiness during 1985–87 for the Appalachian domain are presented using 3-h mean cloud cover values. In contrast to the MCCP results, the regional analysis shows a preferred maximum at 1500 LST and a minimum around sunrise. The trend in mean cloud cover closely resembles the diurnal temperature curve and may reflect the production of cumulus clouds as a result of surface heating.

Warren et al. (1986), using airport observations exclusively, presented the time of maximum cloud amount for several low cloud types, including cumulus and cumulonimbus. The results for cumulus clouds showed a time of maximum between 1300 and 1500 LST, the latter value being observed during the summer months. The peak in cumulonimbus clouds, which contributed a much smaller percentage to the overall cloud coverage, was between 1700 and 1800 LST. These results support the conclusions drawn from RTNEPH.

### c. Precipitating versus nonprecipitating cloud

A seasonal analysis of the relative frequency of precipitating versus nonprecipitating cloud was conducted by comparing gridded cloud and precipitation data. Schulz and Samson (1988) conducted a similar analysis using the 3DNEPH database. The seasons were defined as follows: winter (December–February); spring (March–May); summer (June–August) and fall (September–November). Figure 9 presents the seasonal percentage of cloud over the Appalachians broken into precipitating and nonprecipitating components.

Seasonal tendencies reveal a minimum in nonpre-

cipitating cloud during the winter, a maximum during the summer months and comparable values in the spring and fall. The percentage of nonprecipitating cloud was approximately 80% and 57% during the 1985–87 summer and winter months, respectively. The percentages of nonprecipitating cloud derived from RTNEPH for the summers of 1986 and 1987 are comparable to those observed at the MCCP sites (79% vs 75%). Finally, despite the decrease in overall cloudiness throughout the period, the ratio of precipitating to nonprecipitating cloud remained essentially constant. Annual percentages of nonprecipitating cloud for the three years ranged from 69% to 71%, the highest being observed in 1987.

### d. Cloud type

RTNEPH analyses of the percentage of low-cloud type was conducted for the entire northern Appalachian domain. The cloud types included stratus (st), stratocumulus (sc), cumulus (cu) and cumulonimbus (cb).

Figure 11 shows the percentage of cloud occurrence by type for the summer months. It is apparent that stratus clouds are the predominant low cloud type. The frequency of stratus clouds peaked in 1985 at nearly 65% and then dropped substantially in both 1986 and 1987. The percentages of both stratocumulus and cumulus ranged from 5% to 10% during this period and showed less interannual variability. The amount of cumulonimbus clouds were negligible during the 3-year period. By combining all four cloud categories, low clouds were present 75% of the time in the summer of 1985, 66% in 1986 and only 51% in 1987.

The same analysis for the winter months (not shown) indicated a similar percentage of overall cloud

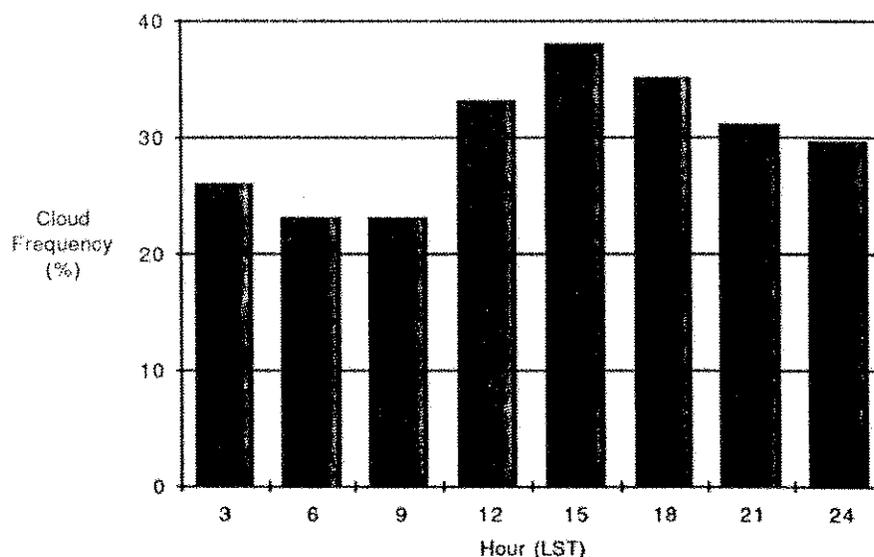


FIG. 10. Mean cloud cover by hour over entire Appalachian grid.

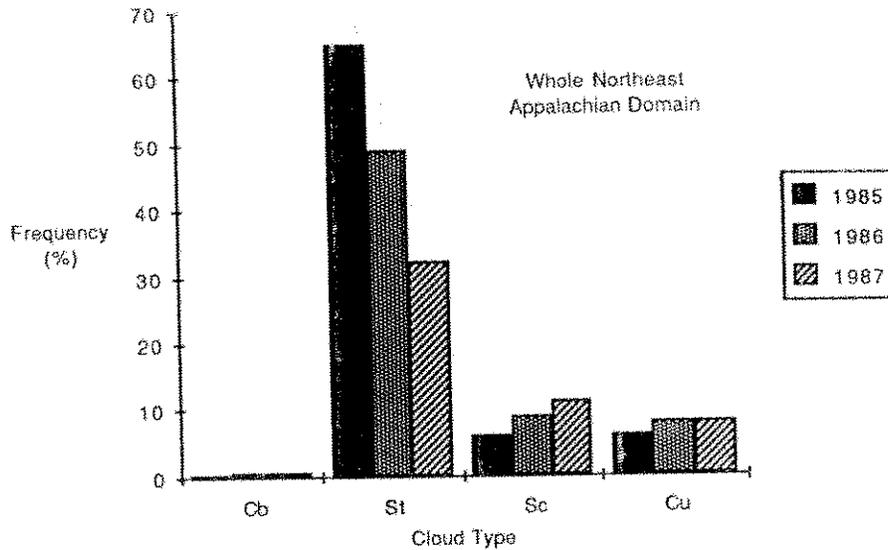


FIG. 11. Percent cloud occurrence by type (summer only).

frequency. There was, however, an annual increase of roughly 5% for stratus and a similar decrease for the cumulus type. The percentages of stratocumulus remained essentially unchanged from summer to winter.

*e. Vertical distribution of cloudiness*

The importance of determining elevations which are most likely to experience cloud impaction has been previously discussed. This section presents RTNEPH regional and grid-specific results of cloud probabilities versus height.

Figure 12 presents the relative probability of low cloud for the northern Appalachian region during the

summers of 1985 through 1987. Cloud-base height during this period was found to average between 700 and 900 m. This height interval agrees with the findings of Warren et al. (1986) who determined an average cloud base of 800–900 m for stratus/stratocumulus during the 1971–81 period. This typical cloud base combined with cloud thickness produced the results shown in Fig. 12. The probability of cloud as a function of elevation was largest in a range between 900 and 1300 m with a maximum at 1100 m.

The results in Fig. 12 contrast with the findings at both Whitetop and Whiteface presented earlier and with other estimated mountaintop cloud distributions. The mountaintop results suggest a continued increase

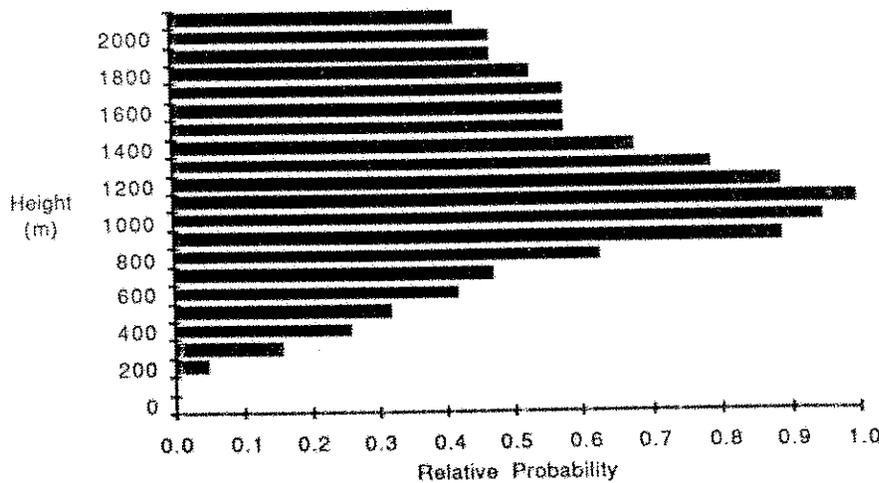


FIG. 12. Relative probability of low cloud (<2100 m) for the northern Appalachian region (Virginia to Canada)—summers 1985–87.

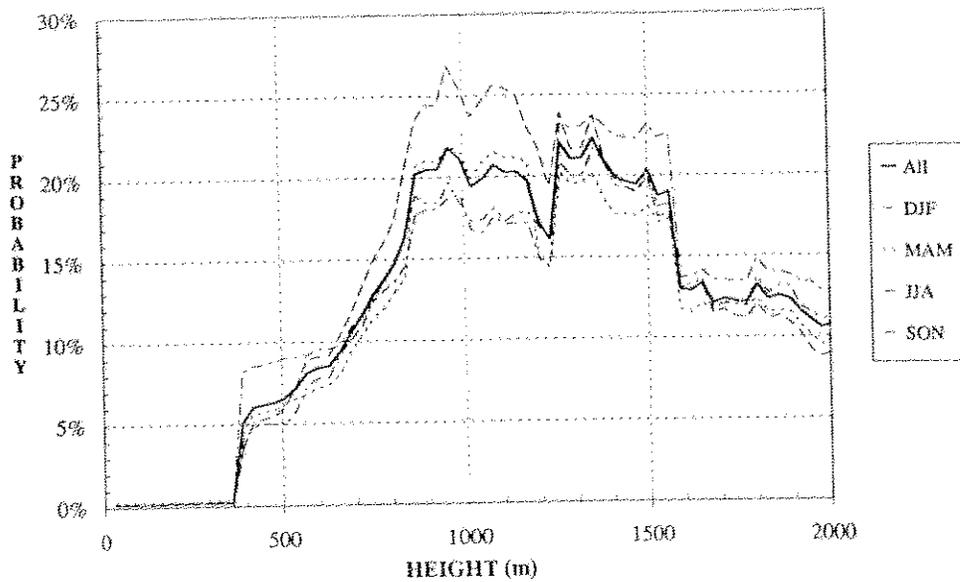


FIG. 13. Probability of cloud by height and season at Whiteface Mountain based on RTNEPH results (1985-87).

m. On a seasonal basis the maximum probabilities are in cloud frequency well above the 1100 m peak derived from regional reports. This discrepancy highlights both the effects of orography in producing cloud on mountains and also the difficulty in making site-specific cloud estimates using regional observations.

The probability of cloud as a function of height and season was analyzed for grid cells near three of the

MCCP sites. The results for Whiteface, Moosilauke and Shenandoah are presented in Figs. 13-15, respectively. It should be kept in mind that RTNEPH cloud height values apply to relatively large-scale elements in the general vicinity of the referenced mountains and are not necessarily representative of site-specific cloud elevations. Near Whiteface the highest annual cloud probabilities are within a broad range from 800 to 1600

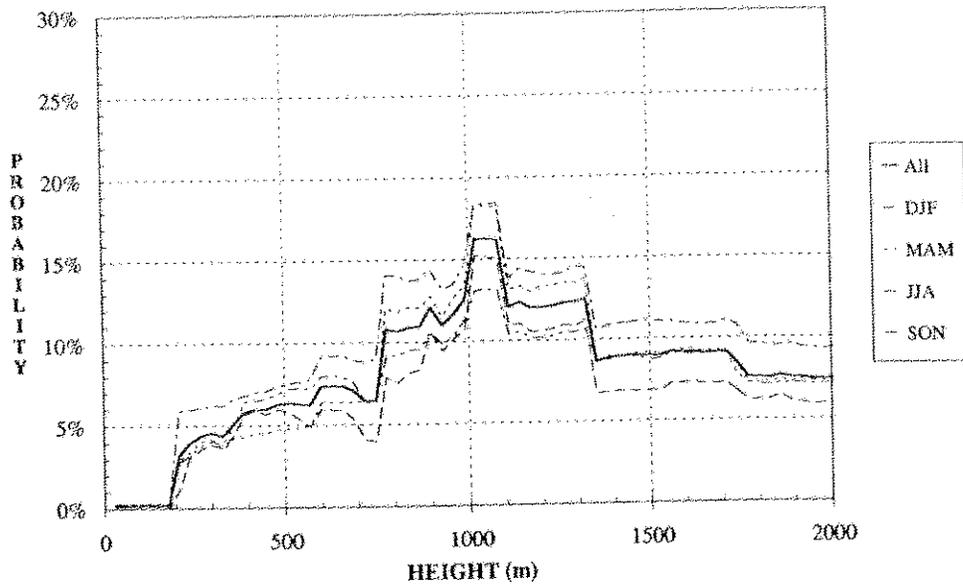


FIG. 14. Probability of cloud by height and season at Shenandoah, Virginia based on RTNEPH results (1985-87).

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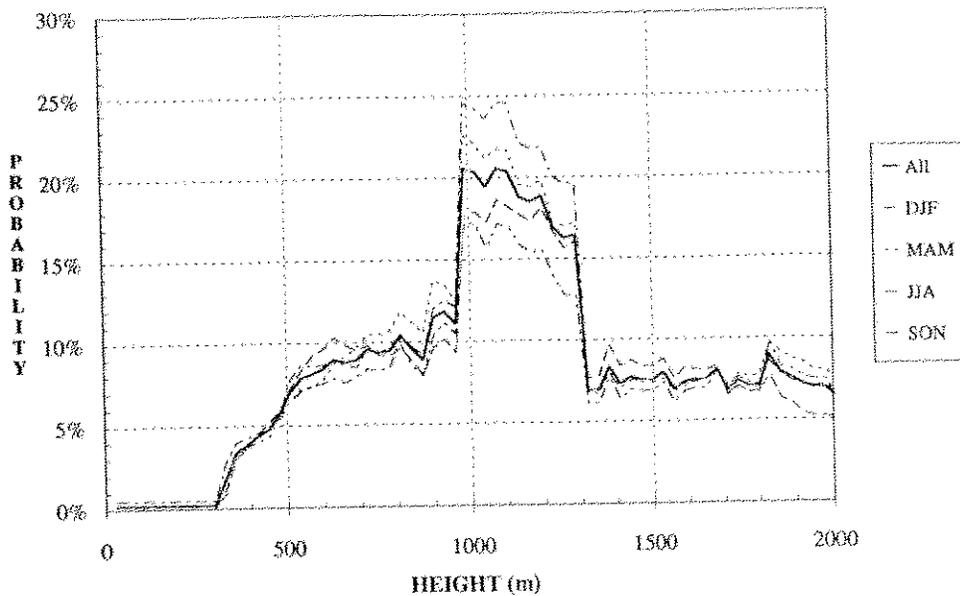


FIG. 15. Probability of cloud by height and season at Moosilauke, New Hampshire based on RTNEPH results (1985-87).

observed during the winter at an elevation of approximately 1000 m. During the summer and fall the probabilities are several percent lower, consistent with a decline in synoptic-scale activity, and the maximum occurs at an elevation between 1300 and 1400 m. Cloud probabilities near Moosilauke increase sharply above 900 m to a peak between 1000 to 1100 m during all four seasons. An abrupt decrease in cloud probability occurs above 1300 m. Cloud is most frequently observed during the summer months. Results from Shenandoah indicate that cloud probabilities are roughly half those near Whiteface and are strongest in the 800-1300 m range, particularly between 1000 and 1100 m. Again, the highest probability was observed during the summer months.

Figure 16 presents the location of three transects of cloud probability across the Appalachians for the summers of 1985-87 using the RTNEPH database. These transects were chosen so as to complement the site-specific vertical distributions presented above. The individual plots are presented, from north to south, in Figs. 17-19, respectively. The northernmost cross section spans from 70° to 78°W at a latitude of 44.5°N, while the second is located approximately 85 km to the south and covers nearly 5° longitude (70°-75°W). The final transect is along a line from eastern West Virginia across northern Virginia. The vertical dimensions of all cross sections are 0-2 km. Finally, the locations of other mountains near the transects are presented for reference purposes.

Figure 17 indicates a zone of maximum cloudiness at a height of 800-1000 m from southern Ontario

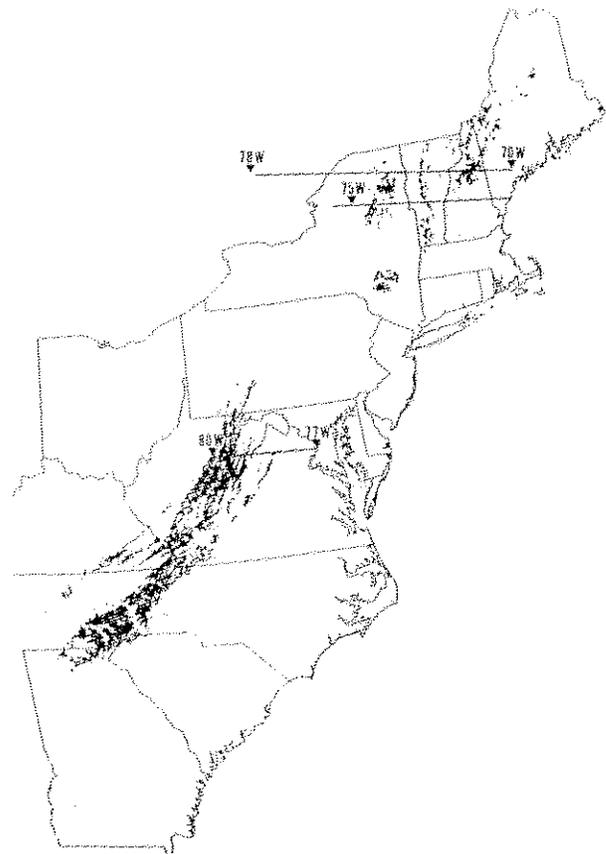


FIG. 16. Locations of transects of cloud probability using the RTNEPH database. (Darkened areas depict land areas above 800 m.)

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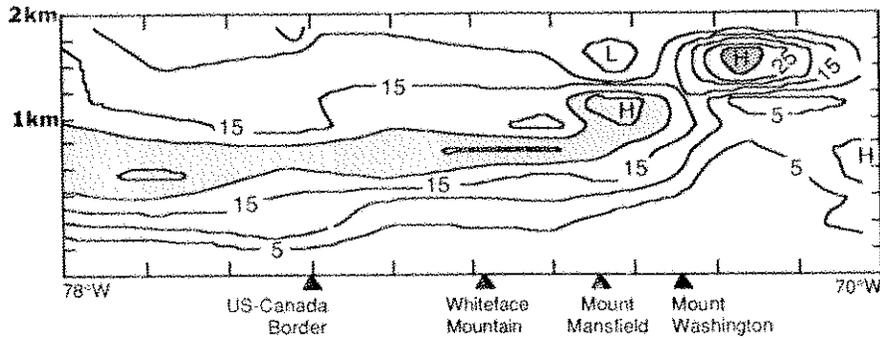


FIG. 17. Summer (1985–87)—probability of cloud occurrence (RTNEPH data) for the west-east transect across the northern Appalachians at approximately  $44.5^{\circ}\text{N}$ . Cross section represents a height of 0–2 km and width of  $70^{\circ}$ – $78^{\circ}\text{W}$ .

province across the northern Adirondacks into the Green Mountains of Vermont. The zone lifts to near 1200 m across New Hampshire and to near 1600 m over southwestern Maine. Figure 18 spans the central Adirondacks and the Mount Moosilauke area. The trends in cloudiness along this transect are similar across New York, Vermont and New Hampshire. This suggests that the preferred zone of cloudiness over the high mountain regions of the northern Appalachians is between 800 and 1200 m, with a tendency for clouds in the lower portion of the range over the Adirondacks and Green Mountains.

The results in Fig. 19 suggest a slightly higher zone of preferred cloudiness—1000 to 1400 m—over the higher mountains of West Virginia, but a lowering of the zone into the 700–1000 m range east of the Appalachians major axis. It is likely that the lowering of the zone on the eastern end of the transect is in response to the influence of low-level cloudiness off the Atlantic.

## 6. Summary and conclusions

The low-cloud characteristics of the Appalachian region have been described using two unique cloud da-

taset, site-specific findings from the MCCP and regional results using the RTNEPH archives. MCCP data indicate that the higher Appalachian peaks ( $>1400$  m) were in cloud an average of 29% to 37% of the time during the summer 1986–88 period while peaks near 1000 m experienced cloud 11%–19% of all hours. Year-round data from one site, Whitetop Mountain, revealed a higher frequency of cloud during the nongrowing season. Both regional and mountaintop results indicated that approximately 25% of the cloud hours were precipitating. The higher elevation mountains had a greater frequency of cloud at night, in contrast to a predominance in the afternoon over surrounding lower terrain. The magnitude of the diurnal trend appeared to be reduced in 1988 in response to widespread drought conditions. Regional cloud observations suggest that the drought resulted in 5% less cloudiness throughout the southern portion of the MCCP network, while more normal cloud amounts were observed in the northern Appalachians.

The RTNEPH regional-scale database indicates that stratus is the dominant low-cloud type in the Appalachian Mountain region. Its typical cloud-base elevation is 700–900 m. This cloud base combined with

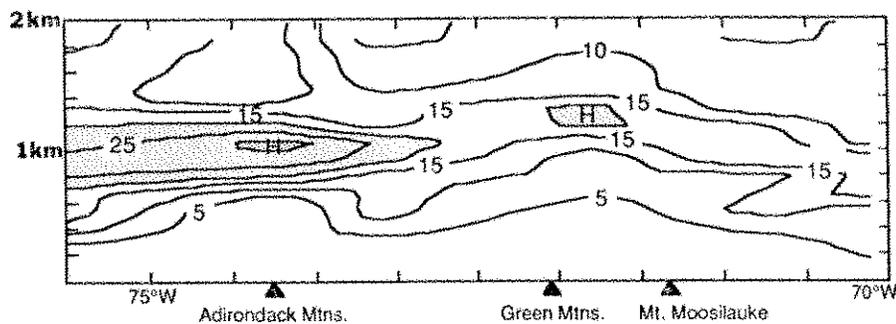


FIG. 18. Summer (1985–87)—probability of cloud occurrence (RTNEPH data) for the west-east transect across the northern Appalachians at approximately  $43.5^{\circ}\text{N}$ . Cross section represents a height of 0–2 km and width of  $70^{\circ}$ – $75^{\circ}\text{W}$ .

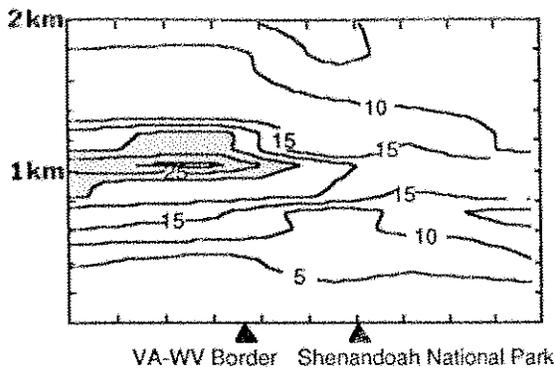


FIG. 19. Summer (1985-87)—probability of cloud occurrence (RTNEPH data) for the west-east transect across the northern Appalachians at approximately 38.5°N. Cross section represents a height of 0-2 km and width of 77°-80°W.

cloud thickness produced the highest probability of cloud between 900 and 1300 m with a maximum at 1100 m. Actual mountaintop cloud distributions may be somewhat different due to orographic effects.

The cloud results from this study imply that high elevation forests (>800 m) are susceptible to significant periods of cloud-water deposition. Forest canopies near 1100 m may be particularly vulnerable to adverse effects from cloud water since this elevation zone is typically just above cloud base where concentrations of major ions are found to be highest.

Future site-specific studies of forest decline need to determine the primary cloud-producing mechanisms in the region of interest, for example, the frequency of regional versus orographic cloud. In addition, detailed cloud-base measurements over an extended period of time would prove useful in determining the distribution of cloud water on a particular mountain.

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