Evidence for a Rising Cloud Ceiling in Eastern North America*

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ABSTRACT

Data from 24 airport weather stations along the north–south axis (35°–45°N) of the Appalachian Mountains are used to show a significant rising trend in cloud-ceiling height over the past three decades. The mean change in cloud-ceiling height was 4.14 ± 1.03 m yr^{-1} [mean ± 1 SE (standard error), $p \leq 0.001$] across all stations. The trend was negative (-2.22 ± 0.67 m yr^{-1}) for the six stations south of 37.5°N, but positive (6.26 ± 0.89 m yr^{-1}) for the 18 stations north of this latitude. Mean ceiling height for broken cloud cover was higher and rising faster than mean ceiling height for overcast cloud cover. There were strong seasonal patterns that varied between the northernmost and southernmost stations; differences were most pronounced during the spring and summer months. Some of the potential ecological effects on high-elevation forests, where the transition from deciduous to coniferous forest is thought to be controlled by the height of the cloud base, are discussed.

1. Introduction

At a global scale, cloud height plays a critical role in cloud-radiative forcing (Ramanathan et al. 1989). At a local scale, cloud-base height is an abiotic factor known to be important for montane ecosystems, where fog drip contributes to the deposition of atmospheric pollutants (Miller et al. 1993) and represents a major hydrologic input (Vogelmann et al. 1968).

Regional increases in cloud cover have been associated with global warming (Croke et al. 1999), and Malanson and Cairns (1995) used simulation models to demonstrate that increased cloud cover could result in decreased net primary productivity (NPP) and reduced species diversity in montane ecosystems. Simulation models (Still et al. 1999) and indirect evidence, such as dry season mist frequency (Pounds et al. 1999), have been used to support the hypothesis that the cloud base in tropical montane cloud forests has risen over the last few decades. Lawton et al. (2001) have proposed that lowland deforestation has had a significant effect on cloud formation, resulting in rising cloud bases and reduced hydrologic inputs to some tropical montane cloud forests. In contrast to these studies, analysis of radiosonde data (Chernykh et al. 2001) suggested that the mean global cloud base has decreased in height over the last four decades, but mean cloud top has increased in height.

Airports routinely measure the cloud-base height, or cloud ceiling, because it is essential for aerial navigation. In this paper, data from 24 airport weather stations in the eastern United States are used to document recent changes in cloud-ceiling height in the immediate vicinity of the Appalachian Mountains. We are not aware of any studies that have used direct observations of cloud-ceiling height to assess this particular aspect of climate change, which is potentially just as critical in temperate high-elevation ecosystems as it is in tropical cloud forests.

2. Data and method

Hourly surface data (temperature, dewpoint, cloud-ceiling height, wind speed, and visibility) from 1973 to 1999 were obtained from the National Climatic Data Center of the National Oceanic and Atmospheric Administration (NOAA). These measurements have been made following the detailed guidelines and rules set out in the Federal Meteorological Handbook (FMH-1). For these data, cloud ceiling is defined to be the height of the lowest sky cover layer that, in summation with all lower layers, covers more than 50% of the sky. The 24 stations used in this study were located along the entire length of the north–south axis of the Appalachian Mountains (Fig. 1). For uniformity across years and stations, synoptic data recorded every third hour were used. At five stations for which complete synoptic data were not available, observations taken at 0100 and 1300 local time (LT) were used. Relative humidity was calculated

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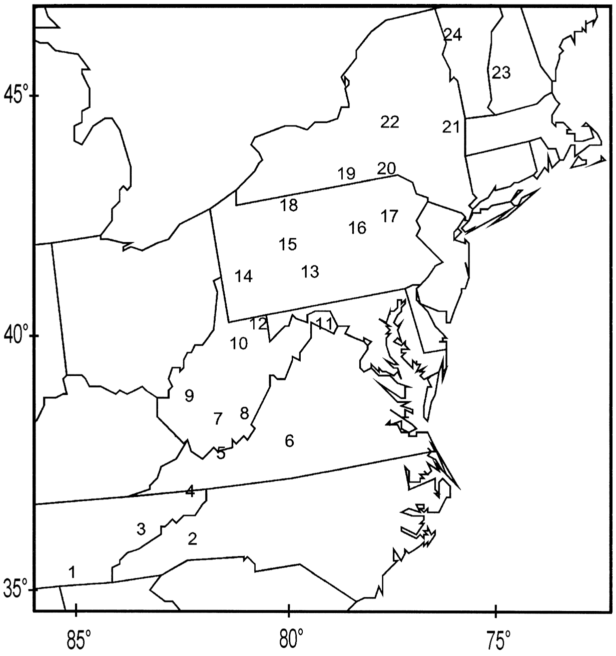

FIG. 1. Locations of the 24 climate stations along the Appalachian Mountains used in this study. Station numbers correspond to those in Table 1.

using the temperature–dewpoint pair for each observation.

When the cloud ceiling is above a certain altitude, it is classified as "unlimited ceiling." The cutoff height at which this occurs has varied over time and between stations, but for the period under study has always been at least 3658 m above ground level (AGL). The ceiling was therefore defined to be unlimited whenever 1) the data explicitly specified an unlimited ceiling; or 2) the measured cloud ceiling was above 3658 m. Ground fog (cloud ceiling = 0 m) was included in the dataset. The effect of using different upper (1829, 2438, 3048, and 3658 m), and lower cutoffs (0, 30, 152, and 305 m) on the estimates of the annual rate of change in cloud-ceiling height was investigated. For all 16 possible combinations of upper and lower cutoff, the overall results were essentially unchanged from the result when clouds between 0 and 3658 m were used.

To determine temporal trends in cloud-ceiling height, linear regressions using quarterly (Q1, January–March; Q2, April–June; Q3, July–September; Q4, October–December) mean ceiling-height data from each station were calculated. Only those observations when the ceiling was not classified as unlimited were used to calculate the mean. The slope of the trend lines in Fig. 2 represents the annual change in cloud-ceiling height (ΔC), in m yr^{-1}. For 13 of the 24 stations, the Durbin–Watson test statistic indicated significant first-order autocorrelation; in most cases, moreover, plots of the sample autocorrelation function indicated significant higher-order serial correlation as well. Least squares regression, when the error terms are serially correlated, will produce unbiased and consistent coefficient estimates, but the standard error (SE) estimates will be biased downward (Pindyck and Rubinfeld 1981); consequently, calculated *p* values

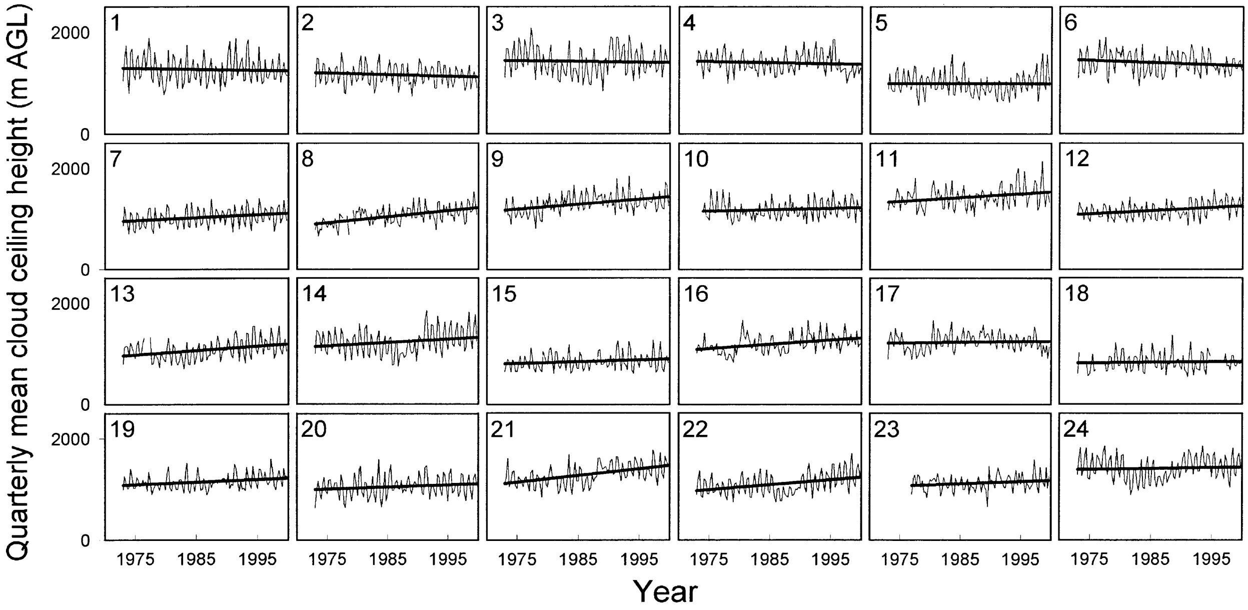

FIG. 2. Time series of cloud-ceiling height at each station. Solid lines indicate time trend, calculated by linear regression. Station numbers correspond to those in Table 1. The analysis is limited to 1973–99, for which continuous records at most stations are available. Data plotted are quarterly mean ceiling heights. The mean was calculated for each quarter using synoptic data, including only those observations when the ceiling was not recorded as unlimited (roughly 50% of the time). Thus each point represents the average of approximately 360 observations. For stations numbered 5, 8, 10, 18, and 23, complete synoptic data were not available and data from 0100 and 1300 LT were used instead.

TABLE 1. Annual changes in cloud-ceiling height and frequency of unlimited ceiling observations at 24 airport weather stations along the Appalachian Mountains, 1973–99. Here ΔC is the annual change in cloud-ceiling height; ΔU is the annual change in the frequency of unlimited ceiling observations. Footnotes indicate the significance level of the calculated rates of change. These must be interpreted cautiously as significant first-order autocorrelation was present for most of the time series; hence, regression P values likely overestimated the actual significance. All results were calculated from quarterly means using synoptic data recorded every third hour.

	Station	Lat (°N)	Lon (°W)	Elev (m)	ΔC (m yr^{-1})	ΔU (% yr^{-1})
1	Chattanooga, TN	35.0	85.2	205	−2.02	0.24[b]
2	Asheville, NC	35.4	82.5	652	−3.03	0.11
3	Knoxville, TN	35.8	84.0	293	−1.50	0.18[a]
4	Bristol, TN	36.5	82.4	457	−2.36	0.13
5	Bluefield, WV[d]	37.3	81.2	881	0.03	0.07
6	Roanoke, VA	37.3	80.0	350	−4.46[a]	0.18[a]
7	Beckley, WV	37.8	81.1	763	5.75[c]	0.33[c]
8	Lewisburg, WV[d]	37.9	80.4	698	12.35[c]	0.01
9	Charleston, WV	38.4	81.6	277	9.97[c]	0.31[c]
10	Clarksburg, WV[d]	39.3	80.2	367	2.82	0.11
11	Martinsburg, WV	39.4	78.0	162	7.42[c]	0.14
12	Morgantown, WV	39.7	79.9	378	6.42[c]	0.23[b]
13	Altoona, PA	40.3	78.3	450	9.07[c]	0.24[b]
14	Pittsburgh, PA	40.5	80.2	351	6.61[c]	0.17[b]
15	DuBois, PA	41.2	78.9	553	3.37[a]	0.07
16	Williamsport, PA	41.3	76.9	159	8.72[c]	0.24[b]
17	Wilkes-Barre, PA	41.3	75.7	284	1.26	0.46[c]
18	Bradford, PA[d]	41.8	78.6	645	0.80	0.20[a]
19	Elmira, NY	42.2	76.9	291	5.26[c]	0.15[a]
20	Binghamton, NY	42.2	76.0	488	4.17[b]	0.28[c]
21	Albany, NY	42.8	73.8	84	12.92[c]	0.26[c]
22	Utica, NY	43.2	75.4	217	9.87[c]	0.23[b]
23	Lebanon, NH[d]	43.6	72.3	181	4.35	0.00
24	Burlington, VT	44.5	73.2	101	1.59	0.12[a]
	Mean				4.14	0.19
	±1 SE				1.03	0.02

[a] $P \leq 0.05$.

[b] $P \leq 0.01$.

[c] $P \leq 0.001$.

[d] Synoptic data were not available and data from 0100 and 1300 LT were used instead.

for the individual regression coefficients will tend to overestimate significance. Thus, to test for the overall significance of the calculated rates of change, we focus not on the reported significance of the regression coefficients, but rather utilize a t test on the sample (of 24 stations) from what might be considered a ‘‘population’’ of climate stations. The use of nonparametric statistics (one-sample sign test) did not change the interpretation of results.

3. Results

a. Overall trends in cloud-ceiling height

In spite of large inter- and intra-annual variability, there was a clear and consistent rising trend in the mean cloud-ceiling height for most of the stations (Fig. 2). A linear regression with time as the independent variable indicated a mean (±1 SE) ΔC of 4.14 ± 1.03 m yr^{-1} across all 24 stations, which was significantly different from zero ($p \leq 0.001$ by the t test). At individual stations, ΔC ranged from -4.46 m yr^{-1} (Roanoke, Virginia) to 12.92 m yr^{-1} (Albany, New York; Table 1). The increase in cloud-ceiling height was also accompanied by an annual increase ($\Delta U = 0.186 \pm 0.021$% yr^{-1}) in the frequency of unlimited ceilings. This is not necessarily in contradiction with the general observation that cloudiness has been increasing globally (Parungo et al. 1994; Croke et al. 1999; Sun et al. 2001), since cloudiness is a distinctly different parameter.

Using the quarterly median (instead of the quarterly mean) cloud-ceiling height resulted in a somewhat higher annual rate of change (5.9 ± 0.9 m yr^{-1}), but the interpretation of results was unchanged.

b. Cloud-ceiling height in relation to sky cover

Ceiling height was analyzed in relation to the degree of cloud cover. In these data, cloud cover is described by one of four categories: clear (no cloud cover), scattered (1/8–4/8 cover), broken (5/8–7/8 cover), and overcast (complete cover). Because cloud cover must be greater than 4/8 for a ceiling height to be recorded, ceilings can only be compared for broken and overcast conditions. Mean ceiling height for broken cloud cover (1625 m) was higher than that for overcast cloud cover (1071 m). Furthermore, the annual rate of change in ceiling height was 4 times larger when cloud cover was broken (8.80 ± 0.33 m yr^{-1}) than when the sky was overcast (2.10 ± 0.19 m yr^{-1}). Annual rates of change in ceiling height for broken and overcast conditions were well correlated with each other ($r = 0.66$, $p \leq 0.001$). Results further indicate a small relative increase in the frequency of broken cloud cover observations during the 1973–99 period, however this trend is not correlated with the rates of change in ceiling height ($r = -0.09$, $p = 0.71$). Thus, increases in ceiling height under both broken and overcast sky conditions contribute to the general increase in ceiling height, but the overall pattern appears to be driven more by changes during broken (generally higher clouds) rather than overcast (generally lower clouds) conditions.

c. Regional patterns

The annual change in cloud-ceiling height appeared to vary regionally (Table 1). At all six stations south of 37.5°N (hereafter referred to as the ‘‘southern’’ stations), ΔC was negative or close to zero, suggesting that the mean cloud-ceiling height has been steady or falling over the last three decades. The mean ΔC at these stations was -2.22 ± 0.67 m yr^{-1}, which was significantly different from zero ($p = 0.02$). In contrast to this, at each of the 18 stations north of 37.5°N (hereafter referred to as the ‘‘northern’’ stations), ΔC was positive. The mean ΔC at these stations was 6.26 ± 0.89 m yr^{-1}, which was also significantly different from zero ($p \leq 0.001$). When broken down by sky cover class, rates of change in ceiling height also followed regional patterns. For example, with broken cloud cover, there was no trend in ceiling height at the six southern stations (0.15 ± 3.46 m yr^{-1}, $p = 0.97$), whereas there was a very strong trend at the 18 northern stations (11.69 ± 1.37 m yr^{-1}, $p \leq 0.001$).

d. Seasonal patterns

Strong seasonal patterns were detected in ΔC (Fig. 3). At the six southern stations, ΔC was positive only in the winter months (Q1, 1.13 ± 0.69 m yr^{-1}); ΔC was most negative in the summer (Q3, -5.79 ± 1.72 m yr^{-1}). In contrast to this, ΔC was positive in all quarters at the 18 northern stations, and reached a maximum in the spring (Q2, 7.95 ± 1.26 m yr^{-1}). The difference between the 6 southern and 18 northern stations was most pronounced during the spring and summer months of Q2 and Q3.

e. Potential effects of methodological changes

Because these data spanning almost 30 yr were collected at 24 different stations, by different observers, and possibly using different methodologies, we considered the possibility that some of the temporal trends we observed are influenced by artifacts introduced by changes in the measurement protocol. The most significant change in observational practices has occurred within the last decade (Steurer and Bodosky 2000) with the introduction of a completely automated system. Phasing in of the Automated Surface Observing System (ASOS) began in September 1992, and complete conversion to ASOS has taken over 8 yr. It is acknowledged that there might be a tendency for ASOS measurements of cloud-ceiling height to be different from those made by a human observer. To demonstrate that the apparent trends in cloud-ceiling height could not be attributed just to this new instrumentation, the annual change in cloud-ceiling height was recalculated using a dataset restricted to pre-ASOS measurements (1973–92). The estimated annual rate of change over the years 1973–92 (3.6 ± 1.4 m yr^{-1}, significantly different from zero at $p \leq 0.01$ by the t test), was some 15% lower than ΔC calculated using all 27 yr of data. However, this does not alter the conclusion that, at least for the 18 more northerly stations (5.7 ± 1.4 m yr^{-1}), the cloud ceiling appears to be rising.

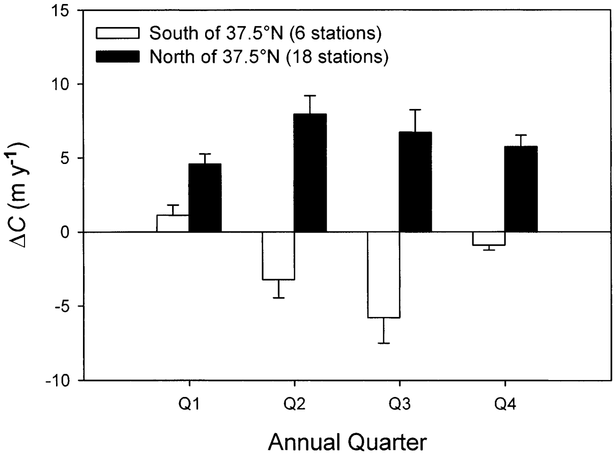

FIG. 3. Quarterly patterns in the annual change of cloud-ceiling height (ΔC, m yr^{-1}) for the 18 northernmost (above 37.5°N) and 6 southernmost (below 37.5°N) stations in this study. Error bars represent ±1 SE of each mean.

f. Trends in other meteorological variables

At each station, the synoptic data indicated significant correlations of cloud-ceiling height with temperature (Pearson correlation r, mean of 0.21 ± 0.01 across 24 stations), relative humidity ($r = -0.43 \pm 0.01$ across 24 stations), and visibility ($r = 0.42 \pm 0.01$ across 24 stations). The correlation with wind speed was weak ($r = -0.05 \pm 0.01$). Concurrent with increases in cloud-ceiling height, there were significant trends in temperature (mean annual rate of increase across all stations 0.028 ± 0.001°C yr^{-1}, significantly different from zero at $p \leq 0.001$ by the t test), wind speed (decreasing at a rate of 0.065 ± 0.003 km h^{-1} yr^{-1}, $p \leq 0.001$), and visibility (increasing at a rate of 0.101 ± 0.008 km yr^{-1}, $p \leq 0.001$). There was not a significant time trend in relative humidity ($p = 0.17$). There was a modest correlation between station latitude and the trend in visibility ($r = 0.35$, $p = 0.09$), but station latitude was only weakly correlated with the trend in temperature ($r = 0.24$), wind speed ($r = 0.14$), or relative humidity ($r = -0.01$).

Although there were no significant correlations (all $p > 0.10$) between the time trend in ceiling height and the time trends in any of these other meteorological variables, we do not believe that this proves that the trend in ceiling height is unrelated to trends in other meteorological variables. It is important to note that it is the vertical profile of temperature and humidity, for example, that determines the occurrence of clouds, and not the conditions on the ground. For example, Sun et al. (2001) used the fact that the relative frequencies of different cloud types has changed over the last five decades to propose that the vertical profiles of temperature and humidity may have changed, too. However, we do not have the data to test a similar hypothesis here.

Data from other sources (NOAA Climate Prediction Center, more information available online at http://www.cpc.ncep.noaa.gov/charts.htm) show regional trends in precipitation over the period 1966–98. During the summer months of July, August, and September, precipitation at the northern end of the Appalachians (e.g., New York, Vermont, New Hampshire) has increased, whereas in West Virginia there was no clear time trend, and in the vicinity of stations 1–6 (eastern Tennessee, western North Carolina, and western Virginia), precipitation has decreased. The spatial patterning of the trends in precipitation are similar to those for the trends in ceiling height, especially during the summer months when north–south differences were most pronounced.

4. Discussion

a. Comparison with other studies

In a recent paper, Chernykh et al. (2001) used radiosonde data from 795 stations around the world to calculate recent trends (1964–98) in cloud-base height and cloud-top height. Globally, cloud bases were shown to be decreasing at 4.4 m yr^{-1}, and cloud tops increasing at 15.4 m yr^{-1}. In eastern North America, cloud bases were shown to be decreasing at a rate of approximately 1 m yr^{-1}, whereas cloud tops were shown to be rising at 3–5 m yr^{-1} (July observations only). These results appear to contradict our finding that the cloud ceiling is rising in the northeastern United States. However, other studies (Still et al. 1999; Pounds et al. 1999; Lawton et al. 2001) have also found a rising cloud base in areas where the data of Chernykh et al. indicate the reverse. Notably, the latitude pattern we observed appears to be consistent with the observation of Chernykh et al. (2001); that is, in North America, the rate of increase in cloud-top height is strongly related to latitude, with greater increases at higher latitudes.

FIG. 4. West aspect of Mt. Abraham (44°7′N, 72°56′W, summit 1247 m ASL), in the Green Mountains of VT, illustrating the well-defined boundary between the low-elevation deciduous northern hardwood forest and the high-elevation spruce–fir forest at about 800 m ASL.

However, differences in methodology between the present study and that of Chernykh et al. (2001) make it difficult to directly compare results. The radiosonde method they use may detect the presence of ‘‘clouds,’’ which are not visible to a human observer, or to a ceilometer, as the latter two methods implicitly require that thresholds of droplet size and concentration be met before clouds are detected (Chernykh and Eskridge 1996). Also, Chernykh et al. (2001) show that the change in cloud-base height is strongly related to both season and cloud amount. In the dataset used in the present study, the definition of ‘‘cloud ceiling’’ explicitly requires cloud cover to be more than 50% for a ceiling to be detected. Although Chernykh et al. (2001) show that global cloud base has been declining at 3.1 m yr^{-1} when cloud cover is between 0% and 20%, their results also show that when cloud cover is 60%–80%, global cloud base has been rising at a rate of 6.0 m yr^{-1} since 1964, a rate similar to ours (4.1 m yr^{-1}) for cloud cover above 50%. These differences may explain the apparent contradiction between the two studies.

b. Potential effects on montane ecosystems

A rising cloud ceiling may have a significant impact on the mountain ecosystems of the Northeast. Both frog extinctions and avian range shifts in the highland forests at Monteverde, Costa Rica, have been associated with increases in cloud-base height (Pounds et al. 1999). Similar ecological shifts could result in the Appalachians. We expect that the greatest effects of a rising cloud ceiling will occur at the transition from deciduous to spruce–fir forest.

In the northern Appalachians, cloud ceiling is thought to control the boundary (Fig. 4) between low-elevation deciduous and high-elevation coniferous forests [Siccama (1974); Cogbill and White (1991); Miller et al. (1993); Kupfer and Cairns (1996); frequent fog immersion is thought to also control the extent of spruce–

fir forests in coastal Maine, see Davis (1966)], although the precise mechanism remains unclear. The annual rates of cloud-height change in our study are probably much faster than this temperate forest ecotone can shift. The timescale required for significant upslope species' movements is on the order of a century or so (Weinstein 1992), as significant conifer mortality would have to occur before a deciduous invasion could begin. Thus, a possible scenario is that a rising cloud ceiling could result in what Dyer (1995) described as a disequilibrium between climate and vegetation.

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REFERENCES

Chernykh, I. V., and R. E. Eskridge, 1996: Determination of cloud amount and level from radiosonde soundings. *J. Appl. Meteor.,* **35,** 1362–1369.

——, O. A. Alduchov, and R. E. Eskridge, 2001: Trends in low and high cloud boundaries and errors in height determination of cloud boundaries. *Bull. Amer. Meteor. Soc.,* **82,** 1941–1947.

Cogbill, C. V., and P. S. White, 1991: The latitude–elevation relationship for spruce–fir forest and treeline along the Appalachian mountain chain. *Vegetatio,* **94,** 153–175.

Croke, M. S., R. D. Cess, and S. Hameed, 1999: Regional cloud cover change associated with global climate change: Case studies for three regions of the United States. *J. Climate,* **12,** 2128–2134.

Davis, R. B., 1966: Spruce–fir forests of the coast of Maine. *Ecol. Monogr.,* **36,** 79–94.

Dyer, J. M., 1995: Assessment of climatic warming using a model of forest species migration. *Ecol. Model.,* **79,** 199–219.

Kupfer, J. A., and D. M. Cairns, 1996: The suitability of montane ecotones as indicators of global climatic change. *Prog. Phys. Geogr.,* **20,** 253–272.

Lawton, R. O., U. S. Nair, R. A. Pielke Sr., and R. M. Welch, 2001: Climatic impact of tropical lowland deforestation on nearby montane cloud forests. *Science,* **294,** 584–587.

Malanson, G. P., and D. M. Cairns, 1995: Effects of increased cloud-cover on a montane forest landscape. *Écoscience,* **2,** 75–82.

Miller, E. K., A. J. Friedland, E. A. Arons, V. A. Mohnen, J. J. Battles, J. A. Panek, J. Kadlecek, and A. H. Johnson, 1993: Atmospheric deposition to forests along an elevational gradient at Whiteface Mountain, NY, U.S.A. *Atmos. Environ.,* **27A,** 2121–2136.

Parungo, F., J. F. Boatman, H. Sievering, S. W. Wilkison, and B. B. Hicks, 1994: Trends in global marine cloudiness and anthropogenic sulfur. *J. Climate,* **7,** 434–440.

Pindyck, R. S., and D. L. Rubinfeld, 1981: *Econometric Models and Economic Forecasts.* McGraw-Hill, 630 pp.

Pounds, J. A., M. P. L. Fogden, and J. H. Campbell, 1999: Biological response to climate change on a tropical mountain. *Nature,* **398,** 611–615.

Ramanathan, V., R. D. Cess, E. F. Harrison, P. Minnis, B. R. Barkstrom, E. Ahmad, and D. Hartmann, 1989: Cloud-radiative forcing and climate: Results from the Earth Radiation Budget Experiment. *Science,* **243,** 57–63.

Siccama, T. G., 1974: Vegetation, soil, and climate on the Green Mountains of Vermont. *Ecol. Monogr.,* **44,** 325–349.

Steurer, P., and M. Bodosky, 2000: Data documentation for surface airways hourly (TD-3280) and airways solar radiation (TD-3281). National Climatic Data Center, Asheville, NC, 52 pp.

Still, C. J., P. N. Foster, and S. H. Schneider, 1999: Simulating the effects of climate change on tropical montane cloud forests. *Nature,* **398,** 608–610.

Sun, B., P. Y. Groisman, and I. I. Mokhov, 2001: Recent changes in cloud-type frequency and inferred increases in convection over the United States and the Former USSR. *J. Climate,* **14,** 1864–1880.

Vogelmann, H. W., T. Siccama, D. Leedy, and D. C. Ovitt, 1968: Precipitation from fog moisture in the Green Mountains of Vermont. *Ecology,* **49,** 1205–1207.

Weinstein, D. A., 1992: Use of simulation models to evaluate the alteration of ecotones by global carbon dioxide increases. *Landscape Boundaries: Consequences for Biotic Diversity and Ecological Flows,* A. J. Hansen and F. di Castri, Eds., Springer-Verlag, 379–393.