NOTES AND CORRESPONDENCE

Determination of Cloud Amount and Level from Radiosonde Soundings

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ABSTRACT

A method developed in the former Soviet Union for predicting cloud amounts is supplemented with a new method of determining the base and tops of clouds. Criteria for predicting a cloud layer are $0 \leq T''(z)$ and $R''(z) \leq 0$, where T'' is the second derivative of the vertical profile of temperature and R'' is the second derivative of the relative humidity. This test was found from an analyses of United States radiosonde data.

Cloud amount (sky cover) is predicted from a relationship between cloud amount and dewpoint depression within the predicted cloud layer and the temperature at that level. This relationship is based on data from the former Soviet Union and data from the Indian Ocean and divides cloud amount into four categories: 0%–20%, 20%–60%, 60%–80%, and 80%–100% coverage.

The new composite method is evaluated using data from several United States radiosonde stations within different climates. Evaluation data was selected to include only situations in which the observer (providing the "truth") could see only one cloud layer. Consequently, the evaluation is biased toward stratified cloud conditions. The method will provide cloud information that can be used in models of radiosonde sensors to adjusted temperature data.

1. Introduction

The National Climatic Data Center (NCDC) and the Russian Research Institute of Hydrometeorological Information are conducting a joint project to produce the Comprehensive Aerological Reference Data Set (CARDS, see Eskridge et al. 1995, 1996). The CARDS dataset will contain data from the late 1930s to the present. The CARDS project has developed numerical algorithms for adjusting upper-air temperature data for radiation errors (e.g., Luers and Eskridge 1995). The adjustment algorithms require knowledge of cloud amounts and heights. The sensitivity of the various algorithms to clouds varies; the VIZ radiosonde temperature at high elevations is very sensitive to clouds. Surface reports are frequently inaccessible or deficient (low clouds obscuring high clouds) for many radiosonde soundings. This paper presents a method for predicting cloud height and amounts from the radiosonde soundings. The method can be applied to both operational and climatological analyses.

The United States Air Force Air Weather Service Manual (AWSM 1969) presents guidelines for predicting clouds and cloud bases and tops. The method, which uses only dewpoint depression, is based on at least two unpublished studies conducted in the 1950s with United States radiosondes using lithium chloride hygristors. The AWSM (1969) does not present a statistical analysis of how well the rules work.

Predicting clouds from radiosonde soundings was a topic of interest in the former Soviet Union. Arabey (1975), Dmitrieva-Arrago and Koloskova (1969), Dolgin (1983), and Zavarina (1966) have worked to develop methods for determining cloud amounts and heights of different cloud types from radiosonde sounding data. In these studies, the change of temperature or the vertical temperature gradient and the dewpoint or its vertical gradient were used.

Moshnykov's method (described in Arabey 1975) for predicting cloud amounts from radiosonde data using temperature and dewpoint depression was improved by Arabey (1975), who developed a technique that can be summarized graphically. Arabey evaluated the method with data from the former Soviet Union and

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a voyage of the scientific research vessel *Akademik Korolev* in the Indian Ocean. Arabey reports a success rate of 87% during the day and 83% during the night in correctly predicting cloud level. Arabey correctly predicted the cloud amounts 69% of the time during the daytime and 67% during the nighttime.

2. Clouds and radiosonde humidity measurements

Cloud occurrences are very sensitive to changes of temperature and humidity, so temperature and humidity need to be measured with a very high accuracy (Matveev 1981) in order to predict cloud existence and heights. The accuracy of relative humidity measurements depends on the magnitude and/or sign of the gradient of temperature, relative humidity, pressure, cloud water, and solar radiation (Ivanov et al. 1991).

Different nations use different relative humidity sensors. For example, Finland uses a thin film capacitor sensor called a Humicap; Space Data Corp (SDC), VIZ, and AIR radiosondes use a carbon hygristor manufactured by the VIZ company; and the Soviet and the Chinese radiosondes use goldbeater's skin sensors (Ivanov et al. 1991). There are no international standards for the transformation of relative humidity observations to dewpoint depression. Different methods of data reduction (relative humidity to dewpoint depression) for the same radiosonde model are used in different countries. Canada and the United States both use the same VIZ radiosonde but apply different data reduction procedures. This is the reason the tails of the dewpoint depression distributions are quite different in the United States and Canadian data (Garand et al. 1992).

The time constant of all widely used humidity sensors depends on temperature and pressure (Ivanov et al. 1991). Sensor response is also affected by factors such as the relative humidity and ascent rate of the radiosonde (Trischenko and Sherstyukov 1988).

The implication of these facts is that the historical upper-air humidity data records are inhomogeneous in most countries and regions. Since temperature and humidity sensors respond rapidly to changing conditions when they enter or exit a cloud layer (Pietrowicz and Schiermeir 1978; and Lawson and Cooper 1990), changes in the vertical gradient of temperature and humidity are potentially better parameters to use to identify clouds than humidity and temperature. The tests used in the method described below involve the derivatives of temperature $T(z)$ and humidity $R(z)$, with respect to height. The second derivatives $T''(z)$ and $R''(z)$ characterize the change in the gradients.

The measured values of temperature and humidity contain errors including those due to the time constant of the instruments (lag error). By using $T'(z)$ and $R'(z)$, the sensors' systematic errors are minimized. Errors in the gradients of temperature and humidity are frequently smaller than the errors in temperature and humidity since systematic errors are removed or reduced in calculating the difference ΔR or ΔT.

3. Cloud prediction method

A method is presented that determines cloud boundaries and cloud amounts from vertical profiles of temperature, relative humidity, and dewpoint depression. This method incorporates the graphical method of predicting cloud amount (Arabey 1975) and a new method

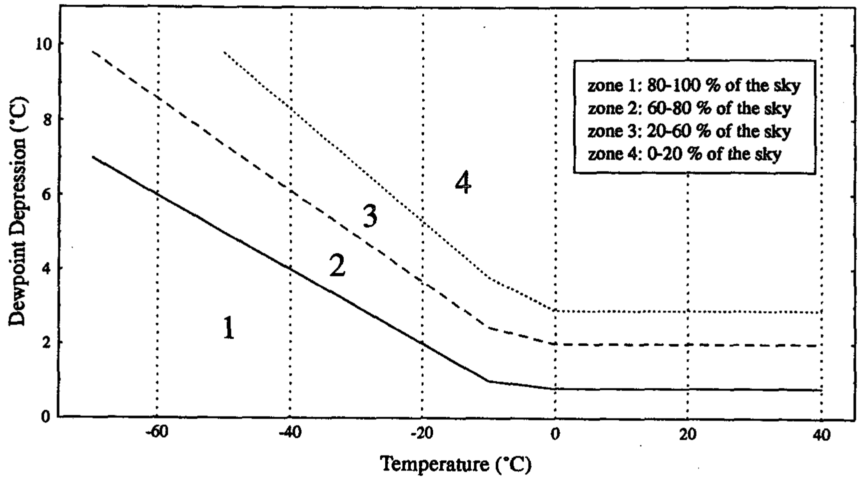

FIG. 1. Piecewise linear approximation to the Arabey diagram, which is used to predict cloud amounts from radiosonde dewpoint depression and temperature. The plane is divided into four zones: 1—area of complete saturation with cloud cover of 80%–100%; 2—area of near saturation with cloud cover of 60%–80%; 3—area of partial saturation with cloud cover of 20%–60%; 4—area of dry air with cloud cover of 0%–20%.

TABLE 1. Percent of correctly diagnosed cloud level, PL (low, middle, or high), and correctly diagnosed cloud level and cloud cover, PC, by this method. Here N is the number of surface observations with one visible layer. Total sample size is approximately 3650 for each location.

Station		Cloud levels			
		Low	Middle	High	Total
Brownsville, Texas	PL	97.5	88.4	96.9	96.1
	PC	84.3	71.3	61.5	80.0
	N	681	129	96	906
Cape Hatteras, North Carolina	PL	94.7	93.4	89.8	93.7
	PC	78.2	79.3	51.6	74.3
	N	495	198	128	821
Amarillo, Texas	PL	94.4	93.2	96.7	94.5
	PC	87.4	73.5	53.8	79.6
	N	396	117	91	604
Albany, New York	PL	97.0	100.0	96.2	97.1
	PC	84.2	62.9	36.5	79.7
	N	755	70	52	877
Spokane, Washington	PL	95.2	99.3	90.9	96.1
	PC	87.3	81.4	42.4	82.7
	N	331	145	33	509
Medford, Oregon	PL	96.9	95.8	96.5	96.6
	PC	80.6	87.4	52.6	80.0
	N	490	167	57	714

of locating the base and tops of clouds. The method is defined as follows: the temperature T, relative humidity R, and dewpoint depression profiles are approximated by cubic splines (Bartels et al. 1987). Therefore, the second derivatives $T''(z)$ and $R''(z)$ are approximated by linear functions over each segment. A necessary condition for the existence of clouds in atmospheric layers is that

$$0 \leqslant T''(z) \quad \text{and} \quad R''(z) \leqslant 0. \qquad (1)$$

The conditions, $0 \leqslant T''(z)$ and $R''(z) \leqslant 0$ for the existence of cloud layers, were developed by comparing the spline approximations of the temperature and humidity sounding profiles, the first derivatives $T'(z)$ and $R'(z)$, and second derivatives $T''(z)$ and $R''(z)$, with surface cloud observations. The magnitude of the second derivatives in (1) are not important.

While the test for the presences of clouds given in (1) was developed from a purely statistical analysis, it makes physical sense. In a region of the atmosphere containing clouds, one expects higher relative humidities than in the layer above and below the cloud layer. Hence, a local maximum of R means $R''(z) \leqslant 0$ in the region above and below the cloud layer. If $R(z)$ is near saturation, it is expected that $R''(z) = 0$ between the cloud base and top. At the top of a cloud the emission of infrared radiation will act to produce marked cooling of the top of the cloud. Layer clouds ordinarily have a more defined top than base and nearly always form under a temperature inversion. Hence, $0 \leqslant T''(z)$. Condensation of water vapor and its accompanying release of latent heat make it reasonable for temperature to stop decreasing with height or to increase with height near the base of a cloud. Hence, a local minimum below the cloud base means $0 \leqslant T''(z)$.

In each layer satisfying (1), the minimum dewpoint depression is determined from the sounding. This minimum value and the corresponding temperature are used to estimate the cloud amount in this layer via a computerized approximation of the Arabey diagram, which is shown in Fig. 1. In the Arabey diagram, the dewpoint depression and temperature plane is divided into four regions: first, a saturated region with cloud coverage of 80%–100%; second, a nearly saturated region with cloud coverage of 60%–80% or with thin cloud layers with thickness less than 500 m; third, a relatively drier region with cloud coverage of 20%–60%; fourth, a region of dry air with cloud coverage of 0%–20%.

Arabey developed this diagram for the temperature range of −70°C to +30°C. The diagram has been extend to +40°C by a linear extrapolation of the linear segments from 0° to +30°C.

Cloud cover for three cloud-level types: low (surface–2000 m), middle (2000–6100 m), and high (above 6100 m) is predicted as the maximum cloud amount of the cloud layers in a level type.

4. Model evaluation

a. Cloudy skies

To verify the proposed method, twice-daily radiosonde sounding data and surface-based cloud observations for the 1975–80 period were studied at the following six United States radiosonde stations: Brownsville, Texas; Cape Hatteras, North Carolina; Amarillo, Texas; Albany, New York; Spokane, Washington; and Medford, Oregon. These stations sample several different climatic regions in the United States. Predicted cloud heights and cloud cover were compared with surface cloud observations. Cloud bases and types from the surface airways hourly database were quality controlled for permissible values (NCDC 1991). Cloud bases were controlled to be consistent with the cloud classification system (MO 1982). Only those cases where the surface observer could see only one cloud layer were selected for the analysis. The results of this analysis are shown in the Table 1. Cloud amounts are said to be predicted correctly if the observed and predicted cloud cover both fall within one of the following intervals (0%–20%, 20%–60%, 60%–80%, 80%–100%).

It is important to note that the visually measured cloud ceiling is generally higher than the condensation level. The observer's eyes or ceilometer begins to detect the cloud only after the droplets' size and concentration surpass some limiting value. The difference between the observed cloud height and condensation level can be several hundreds of meters (Shmeter 1972).

When a middle- or high-level visible cloud layer was predicted correctly, underlying moist layers (greater than 20% coverage and less than 600 m in total thickness) identified as clouds by the model were ignored in the analysis. False positives, as in this case, are evaluated in sections 4b and 5c.

Cases in which the predicted cloud base was at the next higher reported level (middle, high) and the difference between the predicted base and reported cloud ceiling was less than 500 m were considered to be correctly predicted. This situation is frequently due to the lower boundary of stratus and stratocumulus clouds being ragged, resulting in rapid height variations of the ceiling (Borovikov and Khrgian 1963).

Table 1 shows the frequency or probability (probability is estimated empirically by relative frequency) of predicting cloud level correctly is generally independent of level type (low, middle, or high) and location. The frequency of correctly predicting all cloud levels varies from a high of 97.1% at Albany to a low of 93.7% at Cape Hatteras.

The frequency of correctly predicting both cloud level and cloud amount varies with the level: at low levels it varies from 87.4% at Amarillo to 78.2% at Cape Hatteras; for middle levels it varies from 87.4% at Medford to 62.9% at Albany; and at high levels it varies from 61.5% at Brownsville to 36.5% at Albany. For all levels, the skill varies from 74.3% at Cape Hatteras to 82.7% at Spokane. The limited ability to correctly predict both cloud level and cloud amount for high clouds may be due, in part, to the lower accuracy of humidity sensors at low temperatures and the difficulty of observing high thin clouds from the ground, especially at nighttime (WMO 1983).

b. Clear skies

To evaluate the tendency of the proposed method to predict cloud layers when none are observed (false positives), the method was applied to data when clear skies were reported. The set of observations and predictions was divided into four groups for atmospheric layers in which $0 \leqslant T''(z)$ and $R''(z) \leqslant 0$. The frequencies or estimated probabilities were calculated for each group. The first group contains the cases of predicted atmospheric layers of less than 20% cloud cover (P1). The second group contains the cases of predicted thin cloud layers with a total thickness $dh \leqslant 300$ m and more than 20% cloud cover (P2). Here P3 is the sum of the first two groups (P1 and P2) and P4 is the frequency of predicting a cloud layer with thickness between 300 and 500 m. Term P5 is the frequency of clear skies or thin cloud layers with a total thickness of less than 500 m (P1 + P2 + P4). The results of this analysis are shown in Table 2.

TABLE 2. Analysis of the predictions when a clear sky is observed. Here No. is the number of clear sky observations, P1 is the frequency of a prediction of 0%–20% cloud cover; P2 is the frequency of predictions of cloud layers with thickness less than 300 m and cloud cover greater than 20%; P3 is the combined frequency of the first and second classes; P4 is the frequency of predictions of cloud layers of 300–500 m in thickness and cloud coverage greater than 20%; and P5 is the frequency of predictions of clear skies or thin cloud layers with total thickness less than or equal to 500 m (P1 + P2 + P4).

Station	P1	P2	P3	P4	P5	No.
Brownsville, Texas	42.1	42.5	84.6	8.0	92.6	525
Cape Hatteras, North Carolina	48.2	39.9	88.1	7.8	95.9	913
Amarillo, Texas	75.3	15.3	90.6	5.4	96.0	1083
Albany, New York	42.6	41.9	84.5	9.6	94.1	434
Spokane, Washington	55.1	30.6	85.7	7.3	93.0	523
Medford, Oregon	62.5	22.6	85.1	7.2	92.3	871

TABLE 3. Frequency of observations with one to four visible cloud layers, cloudy sky, cloud cover of 0%–10%, clear skies, and the number of observations.

Station	One layer (%)	Two layers (%)	Three layers (%)	Four layers (%)	Cloudy sky	<10%	Clear sky	No. obs.
Brownsville, Texas	34.5	24.4	6.3	0.2	65.4	14.6	20.0	2628
Cape Hatteras, North Carolina	29.5	26.1	6.4	0.2	62.2	4.9	32.9	2778
Amarillo, Texas	22.8	18.0	4.0	0.0	44.8	14.3	40.9	2647
Albany, New York	32.8	33.6	9.6	0.7	76.7	7.1	16.2	2674
Spokane, Washington	22.1	32.3	14.6	0.4	69.4	7.8	22.8	2300
Medford, Oregon	26.6	21.1	6.1	0.4	54.2	13.4	32.4	2686

The indicator P3 = P1 + P2 has been adopt as a measure of correctly predicting a clear sky. Thin moist layers less than 300 m are haze layers or cloud layers containing cloud droplets frequently too small to be seen from the surface. Hence, we believe that thin layers are frequently not reported.

Table 2 shows that the frequency P4 of predicting thin cloud layers (300 m < total thickness < 500 m), which are not observed, is not strongly dependent on the location: the maximum is 9.6% at Albany and minimum is 5.4% at Amarillo.

Table 2 shows that the frequencies, P1 and P2, of predicting cloud amounts of 0%–20% and predicting thin cloud layers with total thickness $dh \leqslant 300$ m are dependent on location: the maximum for P1 is 75.3% at Amarillo and the minimum is 42.1% at Brownsville; the maximum for P2 is 42.5% at Brownsville and the minimum is 15.3% at Amarillo. For other stations P1 varies from 62.5% at Medford to 42.6% at Albany; P2 varies from 41.9% at Albany to 22.6% at Medford. But P3 is almost independent of location and averages about 87% (e.g., 13% false positives). The maximum for P3 is 90.6% at Amarillo and the minimum is 84.5% at Albany. The frequency P5 of predicting clear skies or thin cloud layers with total thickness of no greater than 500 m is independent of location and averages about 94%. The maximum for P5 is 96.0% at Amarillo and the minimum is 92.3% at Medford.

Table 3 shows the percentage of observations with one to four visible cloud layers, percentage with cloudy sky, percentage of observations with cloud cover of 0%–10%, and percentage with a clear sky.

The results presented in Tables 2 and 3 show that P1 and P2 depend of the local climate and hence location. The greater the percentage P1 the smaller P2, and vice versa. In a dry climate, the greater the probability of a clear sky at a station the larger P1 and smaller P2.

Assuming P3 represents correct predictions, the number of false positives ranges from 9.4% at Amarillo to 15.4% at Brownsville.

5. Application of the method

The results of applying this technique of predicting clouds (see section 3) to data from several radiosonde sites are presented. Table 4 shows the numbers of observations by cloud type when only one cloud layer was visible from the surface. Stratocumulus and stratus were the most common cloud types observed. It was found that for stratus and stratocumulus clouds, the range of values for $T''(z)$ and $R''(z)$ was very large, but their signs in cloud layers were consistent with (1).

TABLE 4. Numbers of observations of different cloud types from surface observations when only one visible layer was reported. The standard cloud abbreviations are used: Cu—cumulus, St—stratus, Sc—stratocumulus, Cb—cumulonimbus, Ns—nimbostratus, As—altostratus, Ac—altocumulus, Ci—cirrus, Cs—cirrostratus, Cc—cirrocumulus.

Station	Cu	St	Sc	Cb	Ns	As	Ac	Ci	Cs	Cc	Total
Brownsville, Texas	31	205	437	8	2	15	112	34	61	1	906
Cape Hatteras, North Carolina	134	120	229	12	0	28	170	31	97	0	821
Amarillo, Texas	2	221	157	16	0	12	105	13	78	0	604
Albany, New York	8	207	538	2	0	16	54	2	47	3	877
Spokane, Washington	17	216	94	4	3	26	116	12	21	0	508
Medford, Oregon	47	91	341	11	5	44	118	12	45	0	714

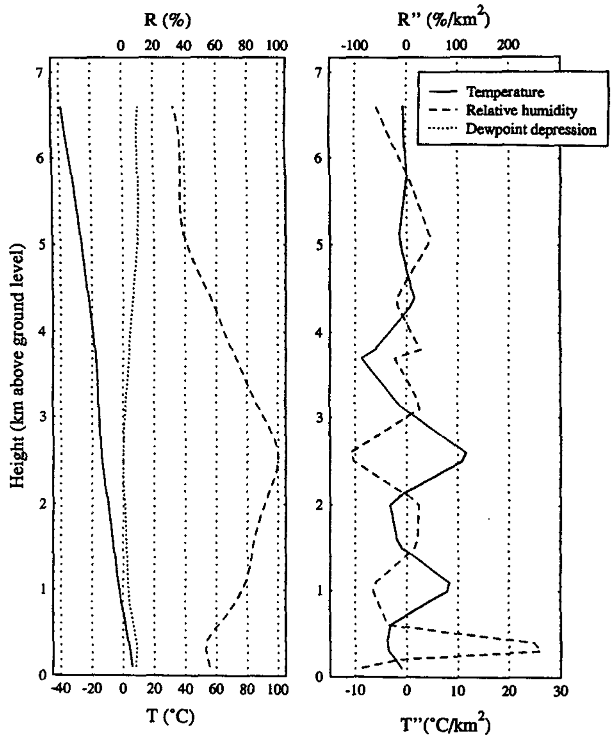

Fig. 2. Distribution of temperature, dewpoint depression, and relative humidity and their second derivatives. Sounding at Medford at 0000 UTC 21 March 1975. Prediction is four cloud layers: a low layer (800 m, 1400 m) with 20%–60% cloud cover, a layer of middle clouds (2200 m, 3000 m) with 80%–100% cloud cover, and two high layers (4300 m, 4500 m), (5850 m, 5900 m) with 0%–20% cover.

In the following sections, examples will be presented for low-, middle-, and high-level clouds.

a. Low and middle clouds

Figures 2 and 3 show atmospheric layers where $0 \leq T''(z)$ and $R''(z) \leq 0$ and the predicted cloud cover is less than 20%. These layers are not discussed.

Figures 2 and 3 show the distribution of temperature, relative humidity, and their second derivatives with respect to height together with the dewpoint depression. These two figures show cases of multiple layers of low or middle clouds. An ordered pair notation will be used to denote the base and top of a layer.

Figure 2 shows the 0000 UTC 21 March 1975 sounding at Medford. The prediction is a layer of low clouds (800 m, 1400 m) with 20%–60% cloud coverage. The minimum dewpoint depression in this layer is 2.4°C at −5.5°C. There is a single layer of middle clouds (2200 m, 3000 m) with a 80%–100% cloud cover. The minimum dewpoint depression in this layer is 0.0°C at −13.6°C. The NCDC airways database reports a stratocumulus layer with a base at 975 m and 30% cloud cover with scattered clouds. Airways also reports an altocumulus layer with base at 3048 m and a 50% cloud cover. The reported total cloud cover was 80%.

The example shown in Fig. 2 shows that the method was able to correctly predict the low cloud deck and the cloud amount. A midlevel cloud was also predicted.

Figure 3 shows the distribution of temperature, relative humidity, and their second derivatives together with the dewpoint depression at Spokane for the 0000 UTC 10 March 1975 sounding. Multiple cloud layers were present with three visible cloud layers of stratus, stratocumulus, and altocumulus clouds. The prediction is two layers of low clouds (600 m, 900 m) and (1400 m, 1600 m); and four layers of middle clouds at (2200 m, 2300 m), (3200 m, 3400 m), (3900 m, 4000 m), and (4900 m, 5200 m) with 80%–100% cloud cover for all these layers. The NCDC airways database reports a stratus layer with base at 610 m and 20% cloud cover, a stratocumulus layer with base at 1373 m and 70% cloud cover and broken cloud cover (60%–90%), and altocumulus clouds with base at 2591 m and 20% cloud cover with overcast (100%) cloud cover.

Based on our experience, we believe that correctly predicting stratus cloud cover with 20% or less cloud

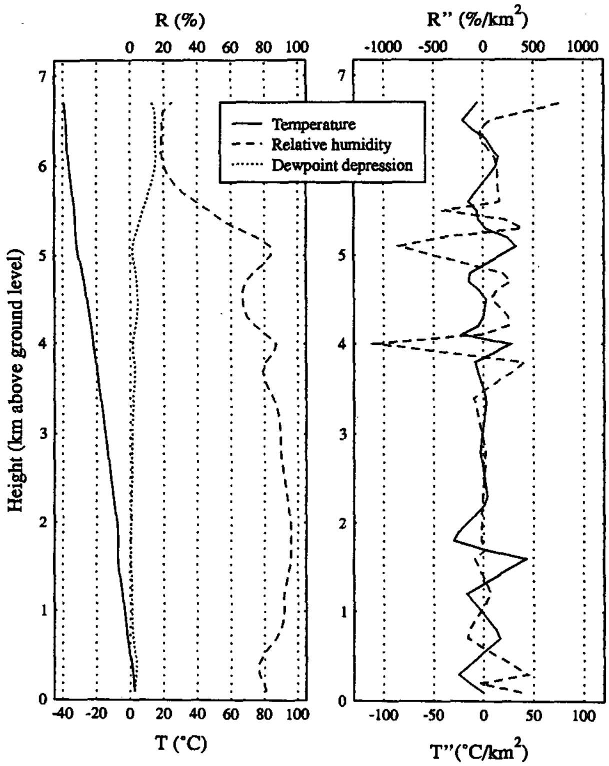

Fig. 3. Same as Fig. 2 except sounding at Spokane at 0000 UTC 10 March 1975. Prediction is six cloud layers with cloud cover of 80%–100% with bases and tops at (600 m, 900 m), (1400 m, 1600 m), (2200 m, 2300 m), (3200 m, 3400 m), (3900 m, 4000 m), (4900 m, 5200 m). Also a high layer is predicted (6250 m, 6300 m) with 0%–20% cover.

cover depends on whether the radiosonde was within the clouds or between them.

b. *High clouds*

Figure 4 shows the distribution of temperature, relative humidity, and their second derivatives together with the dewpoint depression for a 0000 UTC 12 February 1975 sounding at Cape Hatteras when cirrostratus were reported.

The prediction for the Cape Hatteras sounding are several low and middle layers: (1100 m, 1300 m), (1900 m, 2200 m), (2700 m, 3200 m), (3650 m, 3700 m), (4300 m, 4600 m), (5400 m, 6100 m) with cloud cover of 0%–20% and a layer of high clouds (7300 m, 7700 m) with 80%–100% cloud cover. The minimum dewpoint depression in the highest layer is 1.8°C at −32°C. A cirrostratus layer with a base at 7620 m and cloud cover of 100% was reported in the airways database.

c. *Clear sky*

Figure 5 shows the distribution of temperature, relative humidity, and their second derivatives, together with the dewpoint depression for the 1200 UTC 3 January 1975 sounding from Amarillo. The sounding contains several layers in which $0 \leqslant T''(z)$ and $R''(z) \leqslant 0$: (500 m, 800 m), (950 m, 1000 m), (1450 m, 1500 m), (2100 m, 2300 m), (4400 m, 4700 m), (5500 m, 5600 m). The predicted cloud amount in all of the layers is 0%–20%. The NCDC airways database reports a clear sky. The reported value of 19% for relative humidity at all heights higher than 3200 m is due to the previous United States practice of censoring data when the humidity drops below 20%.

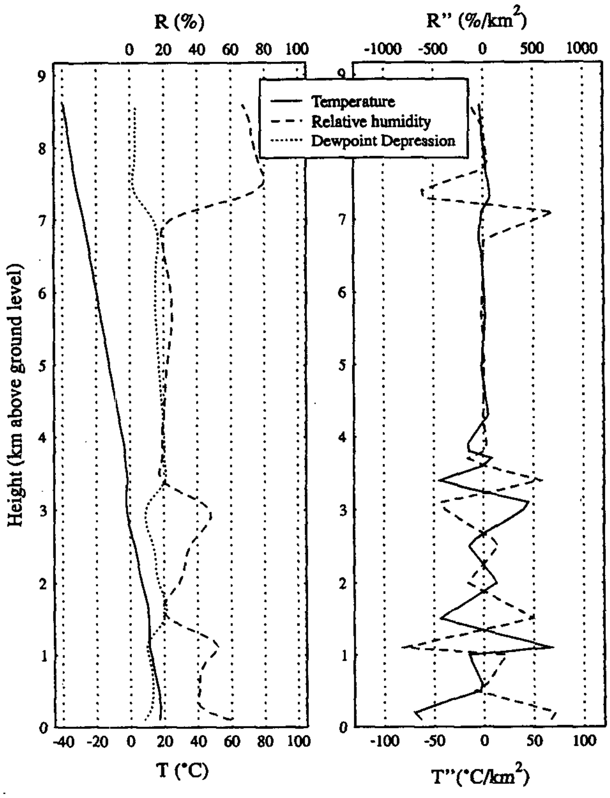

FIG. 4. Same as Fig. 2 except sounding at Cape Hatteras at 0000 UTC 12 February 1975. Prediction is several cloud layers: (1100 m, 1300 m), (1900 m, 2200 m), (2700 m, 3200 m), (3650 m, 3700 m), (4300 m, 4600 m), (5400 m, 6100 m) with 0%–20% cover and a high cloud layer (7300 m, 7700 m) with 80%–100% cloud cover.

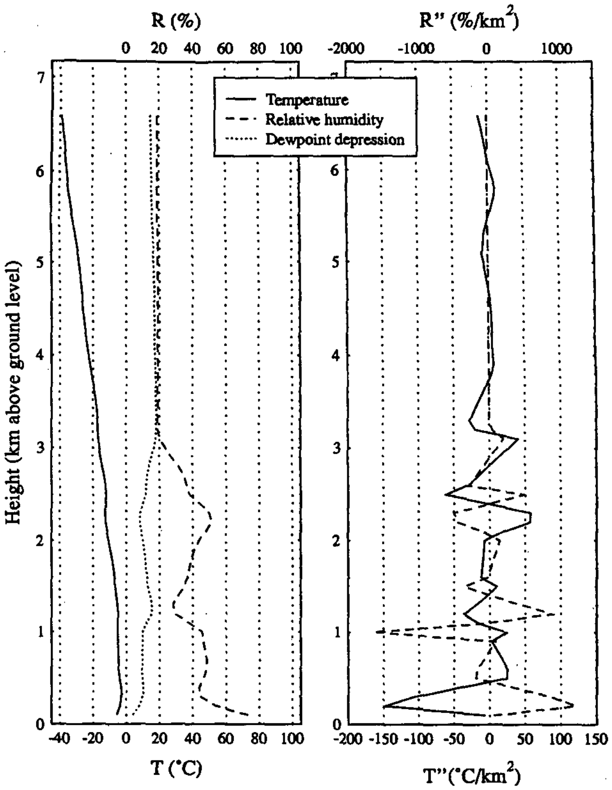

FIG. 5. Same as Fig. 2 except sounding at Amarillo at 1200 UTC 3 January 1975. Prediction is five layers with 0%–20% cloud cover.

6. Conclusions

This paper presents a method for predicting cloud level and cloud cover from radiosonde measurements of temperature and relative humidity. The analysis indicates the probability of predicting cloud level correctly is independent of level type and location. There is a 90% or greater probability of correctly predicting cloud level. The probability of predicting both cloud level and cloud amount varies with the level. The probability is highest for low clouds and lowest for high clouds.

Table 4 shows that, for the stations studied the most, typical cloud types with one visible layer are stratus, stratocumulus, and altocumulus. For nimbostratus, altostratus, and cumulonimbus, further research should be done, because the stations selected had too few observations of these cloud types.

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