

Cloud Cover and Its Relationship to Relative Humidity during a Springtime Midlatitude Cyclone

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ABSTRACT

Vertical distributions of fractional cloud coverage derived from the U.S. Air Force 3DNEPH satellite, aircraft, and surface-based analysis are compared with related standard meteorological observations over the eastern United States. Cloud cover and related observations are interpolated onto the identical three-dimensional grid consisting of 15 tropospheric levels at various horizontal resolutions ranging from $(80 \text{ km})^2$ to $(800 \text{ km})^2$ for five local noon periods during a springtime midlatitude cyclone. During the period analyzed, cloud cover maximizes near 900 mb at 35% cloud cover and decreases to near-zero cover at the surface. Above 900 mb, fractional cloudiness gradually decreases to 10%–20% cover at 200 mb. Cloud cover is positively correlated with relative humidity and large-scale vertical velocity, and negatively correlated with wind shear and temperature lapse rate, except in the lowest 100 mb, where cloud cover is weakly correlated with relative humidity, vertical velocity, wind shear, and temperature lapse rate. Mean fractional cloud coverage observed at various relative humidities and pressures is derived from these observations, and resolution-dependent algorithms for estimating cloud coverage from relative humidity are suggested. This analysis suggests that there is considerable uncertainty in measuring or calculating cloud cover and other meteorological factors averaged over large areas, especially in the upper troposphere. However, cloud cover appears to decrease exponentially as humidity falls below 100%, and relative to other layers in the troposphere, the layers 2.5–5 km above the surface contain the highest cloud amounts at the lowest relative humidities, with mean cloud amounts of 30% near 50% humidity at 650 mb. In the upper troposphere, cloud amounts are greater under convectively unstable conditions relative to stable conditions at high relative humidities. In the lower troposphere, high humidity environments where convection is possible contain lower cloud amounts relative to stable conditions at the same relative humidity, which may result from cumulus-induced subsidence of dry air into the lower troposphere under convectively unstable conditions. Using relative humidity alone as an indicator of cloud coverage, cloud amount can be assessed only to within a root-mean-square difference of 15%–30% from the 3DNEPH cloud cover, depending on the resolution at which calculations are performed. Many meteorological, climate, and chemical models of the atmosphere specify cloud amounts less than reported by these observations when relative humidities are less than 90%–95% during this analysis period. This is especially true in the midtroposphere (850–600 mb), where most algorithms specify zero cloud amounts at relative humidities below 60%–80%, while observed cloud amounts range from 20% to 60% at these height and humidity ranges. At humidities close to saturation, current algorithms probably overestimate cloud coverage.

1. Introduction

Microphysical and dynamical processes occurring within clouds significantly influence numerous larger-scale dynamic, radiative, and chemical processes in the troposphere (e.g., Arakawa and Schubert 1974; Ramanathan et al. 1983; Walcek et al. 1990). At any point in the atmosphere, clouds form when the vapor pressure of water exceeds the vapor pressure that would be saturated with respect to liquid water or ice. However, when averaging over large air masses, it is not unusual to observe cloud formation at humidities well below 100% saturation. Small-scale fluctuations in tempera-

ture and/or water vapor concentration can lead to areas where condensation (clouds) occurs even though the concentration of water averaged over a larger air mass may not be saturated at the mean air mass temperature.

In large-scale numerical models of the atmosphere, chemical or meteorological properties can be explicitly resolved only over relatively large air masses, typically several tens to hundreds of kilometers horizontally and approximately 1000 m vertically. It is not unusual to observe temperature and moisture fluctuations within air volumes of this size because of turbulent or convective motions, surface inhomogeneities, terrain, and other factors. These perturbations induce cloud formation on a scale that cannot be resolved by larger-scale models of the atmosphere, requiring regional or global-scale meteorology models to parameterize the radiative, dynamic, and chemical processes of these subgrid-scale clouds. In most parameterizations of

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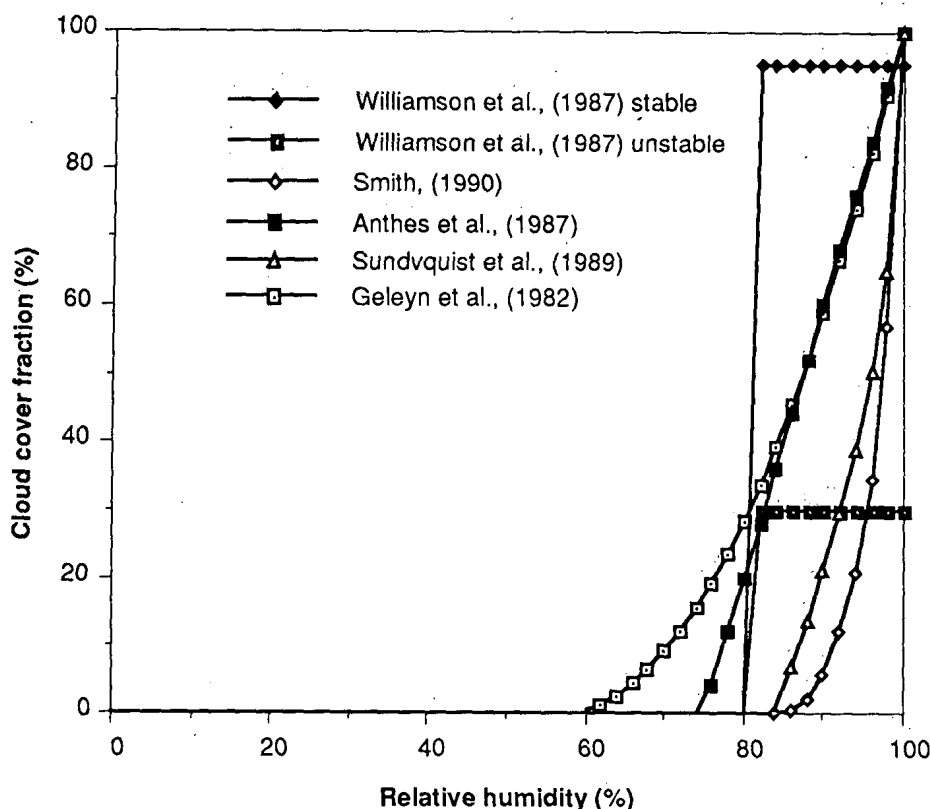


FIG. 1. Fractional cloud coverage as a function of relative humidity at 800 mb according to various formulations used by meso- and global-scale atmospheric models.

cloud-scale processes, the heterogeneous (or subgrid scale) nature of cloudiness is approximated by assuming that a fraction f of each grid area is occupied by clouds. This cloud fraction is used to apportion a significantly different cloud "forcing" into a "grid-averaged" forcing in areas that contain a mixture of clear and cloudy regions.

For this study, cloud cover fraction is defined as the fraction of a given *horizontal* plane in the atmosphere where condensed water is "visibly present" according to standard surface, aircraft, or satellite reports. This definition becomes somewhat vague when "thin" or low condensed water content clouds are present, conditions that commonly occur in the upper troposphere, where it will be difficult to explicitly define or quantify the fractional area of cloud coverage. This definition implies that cloud cover is *vertically varying* and under many conditions may not be directly measurable from either looking up from the surface or down from an aircraft or satellite. The fraction of a downward-looking satellite photograph that is covered with clouds represents a top-down vertical integral of the nonoverlapping fractional area of cloud coverage and essentially ignores lower-level clouds that are covered by higher-level clouds. Similarly, a surface-based observer "sees" a bottom-up integral of the fractional area of

cloud coverage that does not include overlying clouds obscured by lower-level clouds. Deriving a readily observable single cloud cover for one column of the atmosphere would entail knowing information about the overlapping characteristics of f at all levels.

Many studies of clouds and their effects on tropospheric processes have concluded that even small cloud amounts can exert a significant influence on larger-scale processes. Under these conditions, the net impact of clouds on many physical or chemical processes will be proportional to the fractional area of cloud coverage. Most models of tropospheric dynamics assume that the fractional area of cloud coverage is determined by the grid-averaged relative humidity. Figure 1 shows the functional dependence of cloud coverage within a particular atmospheric layer from a survey of formulations currently used by various researchers. All formulations assume a "critical relative humidity" of between 60% and 90%, above which partially cloudy conditions can occur. Below this critical humidity, all algorithms specify totally clear skies. At humidities above the critical humidity, cloud fraction increases by differing functional forms to 100% cloud cover at 100% humidity. Figure 1 shows considerable differences between alternate formulations in assessing cloud coverage within current meteorology and climate models. At 80% hu-

midity, the National Center for Atmospheric Research (NCAR) Community Climate Model (Williamson et al. 1987) specifies 95% cloud cover (under stable conditions), the British Meteorological Office climate model (Smith 1990) uses 0% cloud cover, while other algorithms specify cloud coverage between these extremes.

The uncertainty exhibited in Fig. 1 has motivated researchers to evaluate and improve methods for diagnosing cloud cover. Many researchers have suggested that factors in addition to relative humidity should influence cloud coverage. Using a detailed cumulus ensemble model, Xu and Krueger (1991) find correlations between cloud cover and convective mass flux, convective precipitation rate, and vertical velocity averaged over a large area. To correctly simulate stratiform clouds near large-scale temperature inversions within a global meteorological model, Slingo (1980) hypothesized that cloud cover is influenced by temperature lapse rate. In a study of eastern Pacific marine boundary layer clouds, Betts and Boers (1990) find a correlation between "mixing line stability" and cloud amount. Using a physically intuitive description of cumulus growth and evaporation, Albrecht (1981) finds correlations between trade-cumulus cloud cover and relative humidity and a "virtual saturation ratio," defined approximately as the ratio of the below-cloud water vapor mixing ratio to the saturation mixing ratio within a partially cloudy layer.

In summary, researchers have proposed a wide variety of formulations for estimating cloud cover from related meteorological parameters. Most formulations are derived from a limited set of observations used in conjunction with physically intuitive models of cloud formation. Tunable parameters within cloud cover formulations are empirically adjusted to match a particular (and usually limited) set of observations, or are adjusted within the framework of a larger-scale climatological simulation. For example, Slingo and Slingo (1991) adjust the threshold relative humidities within their cloud cover formulations in order to match climatological estimates of cloud cover and satellite-derived measurements of outgoing longwave radiation.

Relationships between cloud cover and other meteorological factors can be quantified and evaluated using observations of cloud cover and associated meteorology (e.g., Slingo 1980; Sundqvist et al. 1989), or cloud cover can be inferred using fine-resolution dynamic models capable of explicitly resolving cloud-scale dynamics (Xu and Krueger 1991). The primary problem with using observations to infer relationships between cloud cover and other meteorological factors is the difficulty of accurately measuring highly variable and uncertain quantities of interest over relatively large areas. Accurate measurements capable of vertically resolving cloud coverage require high-density vertical soundings, together with satellite and relatively expensive aircraft observations. Due to the expense associated with such

measurement programs, there are only limited observational datasets under a few meteorological environments from which to evaluate and improve cloud cover algorithms.

When models capable of resolving cloud-scale processes are used to ascertain cloud coverage, the accuracy and reliability of the modeling techniques are subject to an independent evaluation, which ultimately relies on observations. Sensitivities of model calculations to the model dimensionality, turbulence and microphysical parameterizations, and other factors must also be evaluated.

As part of an atmospheric chemistry research effort, cloud cover information and related standard meteorological measurements were collected during 20–25 April 1981. This period was chosen since numerous precipitation chemistry and air quality measurements were made during a field experiment over the northeast United States, allowing one to evaluate an atmospheric chemistry model (Middleton et al. 1988). Chemical processes in the troposphere are strongly influenced by clouds, and therefore, it is important to quantify the location, fractional coverage, and vertical distribution of cloud coverage during an atmospheric chemistry simulation. After reviewing several possible mechanisms for specifying cloud coverage within this atmospheric chemical modeling system, it was decided that the cloud observations archived by the U.S. Air Force (3DNEPH) were the best available, and they were already in a format that could be readily used. These cloud cover observations were compiled together with wind, temperatures, and moisture observations into a regularly spaced, simultaneously sampled format during 20–24 April 1981, allowing us to easily compare the cloud cover and related meteorological observations during this period. After reviewing previous studies of clouds and their relationships to other meteorological factors, we concluded that these aggregated observations could possibly contribute to the limited body of simultaneously paired (in time and space) cloud and meteorological observations, and could thus be used to infer relationships between clouds and related meteorological factors.

In this study, we attempt to ascertain the relationships between cloud coverage and other meteorological factors using simultaneous observations of these parameters. Recent attempts to relate *observations* of cloud cover with *observations* of other meteorological factors are limited to a relatively restricted set of meteorological conditions. Much of Slingo's (1980) formulations are inferred from tropical GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment (GATE) observations. Albrecht (1981) considers Atlantic trade-wind cumulus, while Betts and Boers (1990) rely on a single Landsat image of a transitional trade-wind cumulus–stratocumulus area. Sundqvist (1989) qualitatively compares several satellite images with model-calculated cloudiness during

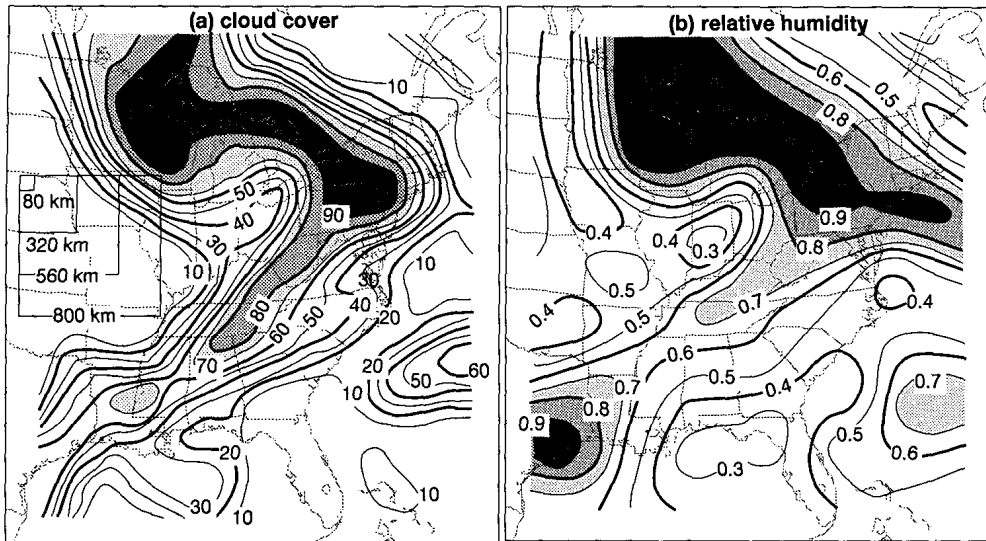


FIG. 2. (a) Cloud cover and (b) relative humidity averaged over $(320 \text{ km})^2$ areas in the layer 800–730 mb at 1800 UTC 23 April 1981. Cloud cover extracted from the U.S. Air Force 3DNEPH compilation of surface reports, aircraft observations, and satellite-derived data. Inset boxes show averaging scales used in this study. Relative humidity interpolated from radiosonde observations in time and space using a hydrostatic mesoscale meteorology model.

a midlatitude cyclone period. We acknowledge beforehand that the standard meteorological parameters and the cloud cover measurements used in this analysis contain a level of uncertainty that is difficult to quantify. However, we feel that the large size of our observational database (relative to previous studies) will allow us to more accurately ascertain the qualitative relationships that may exist between cloud cover and other meteorological factors. By using observations to infer relationships between cloud cover and other meteorological factors, the global-scale influence of cloud microphysical and dynamical processes can be more accurately treated in larger-scale studies of meteorology and atmospheric chemistry.

Meteorological observations used for this analysis are described in section 2. Section 3 provides a summary of the meteorological conditions present during this analysis period, and in section 4, we perform several preliminary statistical surveys of the observations and suggest algorithms for calculating cloud coverage.

2. Description of cloud and meteorology observations

a. Cloud cover

The U.S. Air Force Environmental Technical Applications Center has been receiving and storing Air Force Global Weather Central (AFGWC) cloud data since January 1971. From 1971 to 1983, the AFGWC used an operational real-time three-dimensional analysis of cloud cover referred to as 3DNEPH (Fye 1978). The 3DNEPH is a global analysis of cloud cover that uses surface-based and aircraft reports, together with visual

and infrared satellite imagery, to produce three-dimensional cloud cover information on a routine basis. Cloud fractional coverage is apportioned into 15 different tropospheric levels between the surface and approximately 16 km above the surface based on routine surface reports of the base and top elevation, and cloud cover in the standard low, middle, and high cloud layers. In areas where surface reports are lacking, satellite imagery and aircraft reports are used to estimate cloud coverage and vertical placement. During periods when satellite or surface data are lacking, clouds are inferred from rawinsonde temperatures and dewpoints. The data are mapped onto a polar-stereographic global grid from which we have extracted observations over the northeast United States. Horizontally, the grid size varies from about 25 km near the equator to 60 km at the poles. The 3DNEPH stores cloud cover information every 3 h.

Figure 2a shows an example of the 3DNEPH-analyzed cloud cover averaged over approximately $(320 \text{ km})^2$ areas in the layer 800–730 mb at local noon, 23 April 1981. A broad region of greater cloud coverage corresponding to a warm-frontal region is present over the Great Lakes, and a cold-frontal region extends from Pennsylvania to Texas.

Any cloud cover database will contain a level of uncertainty that is difficult to explicitly evaluate. The 3DNEPH assimilates virtually all routinely available cloud observations, making an independent evaluation impossible. In addition, numerous unevaluated algorithms are used to consolidate surface-based and aircraft observations together with visible and infrared satellite imagery. Hughes and Henderson-Sellers

(1985) performed an analysis of the air force cloud archive for 1979, and although numerous areas of obvious but minor errors were discovered, they found that the cloud observations were generally reliable and in good agreement with known features of tropospheric meteorology. Problems were found when satellite data were gathered over highly variable backgrounds or backgrounds with snow or sea ice. Also, periods of missing data occur, although they are identified. At a minimum, we expect that cloud cover estimates at any given instant in time will contain a level of uncertainty comparable to the uncertainty of surface reports, which report only cloud cover to the nearest octa (12.5%). Chang and Coakley (1993) find that alternate algorithms for extracting cloud cover from infrared satellite imagery over oceanic areas produced mean differences of 18%–25%, depending on the averaging area considered. We expect that this uncertainty is also present in the 3DNEPH algorithms for extracting cloud cover from satellite imagery. Additional errors will be introduced as these cloud amounts are vertically apportioned based on uncertainties in identifying the tops and bases of cloudy layers. Buriez et al. (1988) compared two different methods of analyzing cloud cover from satellite information and found uncertainties ranging from 1.3 to 2.4 octas (16%–30%). When comparing three satellite-derived cloud cover analyses averaged during monthly periods, Mokhov and Schlesenger (1993) find spatial correlation regression coefficients r in cloud cover estimates ranging from 0.52 to 0.85, suggesting a considerable level of uncertainty.

b. Standard meteorology observations

Temperature, moisture, and dynamical data used in this analysis are taken from observations and spatially and temporally interpolated onto an $(80 \text{ km})^2$ Lambert-conformal grid using a hydrostatic mesoscale meteorology model. Observations are derived from the National Meteorological Center global meteorological analysis and further enhanced using 3-h surface observations and 12-h vertical rawinsonde measurements. Vertically, these meteorological data encompass the surface and 100-mb pressure surface ($\sim 16 \text{ km}$), and horizontally, they span the contiguous United States. The vertical grid size of the meteorology data is about 80 m near the surface and on the order of a kilometer or more aloft. These observations are provided as initial and boundary conditions to the NCAR mesoscale meteorological model (MM4, Anthes and Warner 1978). In addition, during model execution, observations are incorporated into the model calculations in regions near observation locations. Differences between observed and calculated temperatures, humidities, and wind speeds are continuously minimized through the use of additional tendency terms in the momentum, moisture, and thermodynamic equations that “nudge” the calculation toward the observations (Stauffer and Seaman

1990). The mesoscale meteorological modeling system is not used to “predict” or “forecast” meteorology. Rather, in a manner suggested by GEWEX (1993), the model interpolates in space and time several meteorological variables of interest in a dynamically and physically reasonable manner. Thus, model calculations agree closely with observations when and where observations are available, and when no observations are available, the meteorological data are dynamically consistent. Under some conditions, meteorology interpolated and analyzed from observations in this manner provides data of superior temporal and spatial resolution relative to “raw,” point observations.

Figure 2b shows the relative humidity in the 800–730-mb layer interpolated from observations using the mesoscale meteorology model described above at the identical time as Fig. 2a. For this figure, temperature and moisture calculations are aggregated into overlapping $(320 \text{ km})^2$ areas, representing a 4×4 average of the 80-km grid used by the MM4. The domain shown in Fig. 2 represents approximately one-half of the domain simulated by the mesoscale meteorological analysis. Comparisons of Figs. 2a,b qualitatively show positive correlations between cloud cover and relative humidity.

Since nearly all routinely available measurements are incorporated into the model calculations, the temperatures, moisture, and dynamic variables resulting from this analysis agree with the measurements to within the instrumental uncertainty. Standard radiosondes are designed to measure temperature within 0.5°C , and relative humidity with an accuracy of 5%–7% (Golden et al. 1986). In addition, radiosonde humidities are known to consistently undermeasure relative humidity under saturated conditions by 2%–4%. Hoehne (1980) found that differences between dewpoint depressions measured by identical radiosondes launched at the same time deviated from one another by $\pm 3.2^\circ\text{--}3.7^\circ\text{C}$. These dewpoint uncertainties alone translate into uncertainties of $\pm 15\%\text{--}20\%$ in relative humidity for a typical sounding.

Any method of extrapolating “point” measurements to larger averaging areas will introduce additional uncertainties into the area-averaged “observations.” If a particular radiosonde rises through a cloudy region of a layer of the atmosphere containing a mixture of clear and cloudy areas, it will report approximately 100% humidity for an area where the mean relative humidity would be well below 100%. How often these conditions occur, and just how “noisy” the temperature and water vapor fields are within areas the size of larger-scale model grid areas, is highly variable and (for the period analyzed in this study) uncertain. However, the cloud cover data itself suggests that there is considerable variations from the mean relative humidity within averaging areas larger than $(80 \text{ km})^2$. For example, according to Fig. 2, it is not unusual to see 50% cloud cover at 800 mb when the relative humidity is 60%–

80%. This suggests that within $(320 \text{ km})^2$ averaging areas, when the relative humidity is approximately 70%, fully 50% of the area actually has a relative humidity of 100% (i.e., the cloudy fraction of the grid). Therefore, the likelihood that a radiosonde will rise through an approximately saturated region within this layer is high. At a minimum, the relative humidities used in this analysis contain a level of uncertainty that is probably considerably greater than the raw measurement precision ($\pm 15\% - 20\%$).

3. Description of analysis period

Cloud observations and related meteorology were analyzed over the eastern United States domain during five local noon periods during 20–24 April 1981. At noon, we expect the maximum utilization of aircraft and surface reports together with visual and infrared satellite imagery by the 3DNEPH analysis. Figure 3 shows 700-mb heights and temperatures during the analysis period. On 20–22 April, a ridge of high pressure moved from west to east across the study domain. A trough entered the western portion of the domain on

22 April and rapidly intensified by 23 April. This mid-latitude cyclone continued to intensify and move into the eastern portion of the domain by 25 April. A wide variety of airmass types and temperature regimes were represented during this period. Temperatures at 700 mb ranged from -20° to 15°C , and continental and maritime air with tropical and polar histories were involved in this cyclone.

Figure 4 shows the vertical distribution of relative humidity and cloud cover fraction averaged over the entire domain during the five noon periods shown in Fig. 3. Relative humidities throughout the atmosphere ranged from 20% to 100%, although a majority of the humidities ranged $\pm 30\%$ of the mean humidity. Also shown in Fig. 4a is the global mean relative humidity extracted from an NCAR present-day climate simulation (extracted from a simulation by Wang et al. 1992), showing that the vertical distribution of relative humidity aggregated during this period closely resembles the global mean humidity distribution, suggesting that the meteorological conditions considered in this study do not widely deviate from conditions encountered globally as far as relative humidity is concerned. Figure

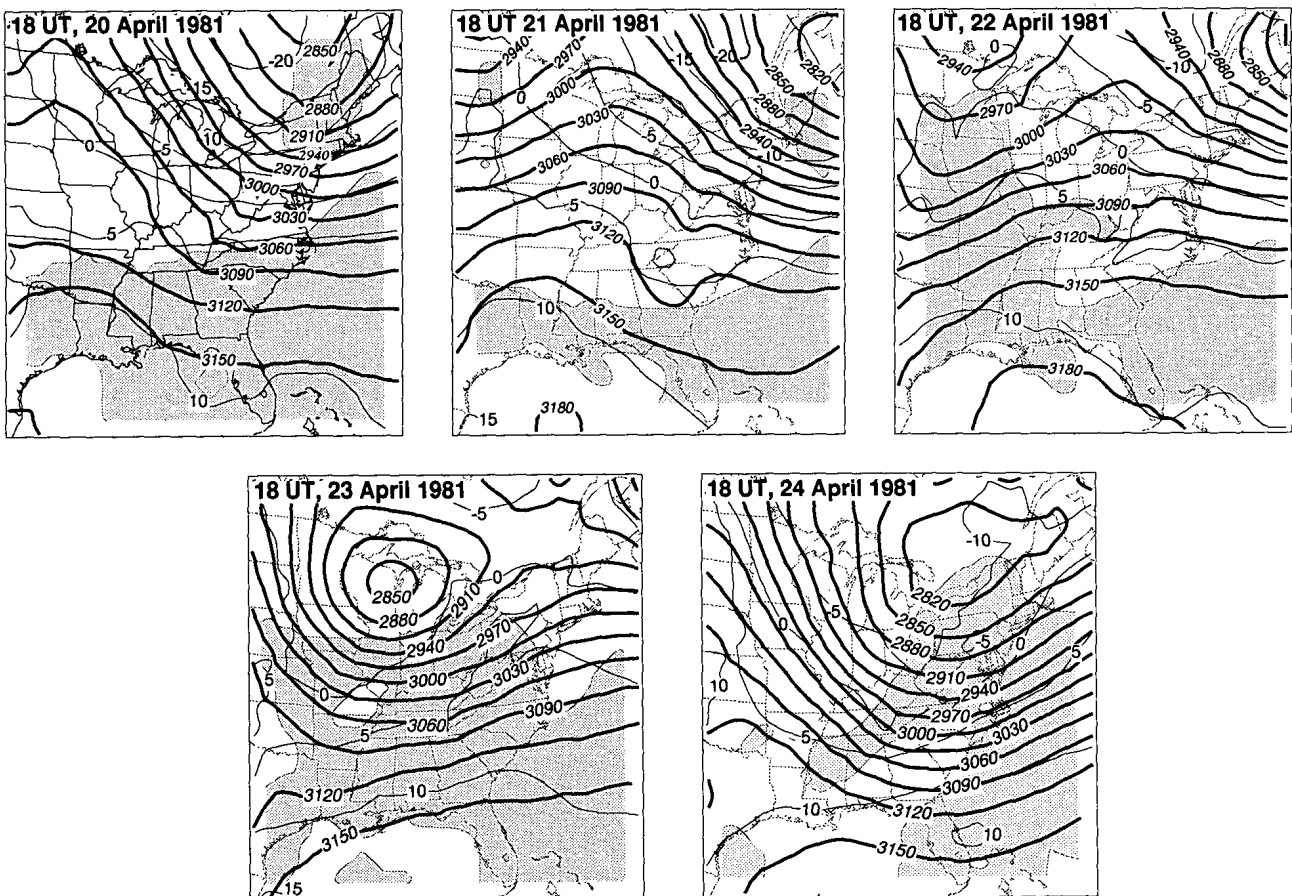


FIG. 3. The 700-mb heights (m, thick solid contours) and temperatures ($^\circ\text{C}$, thin lines) during 20–24 April 1981. Gray areas denote regions where convective motions can potentially occur.

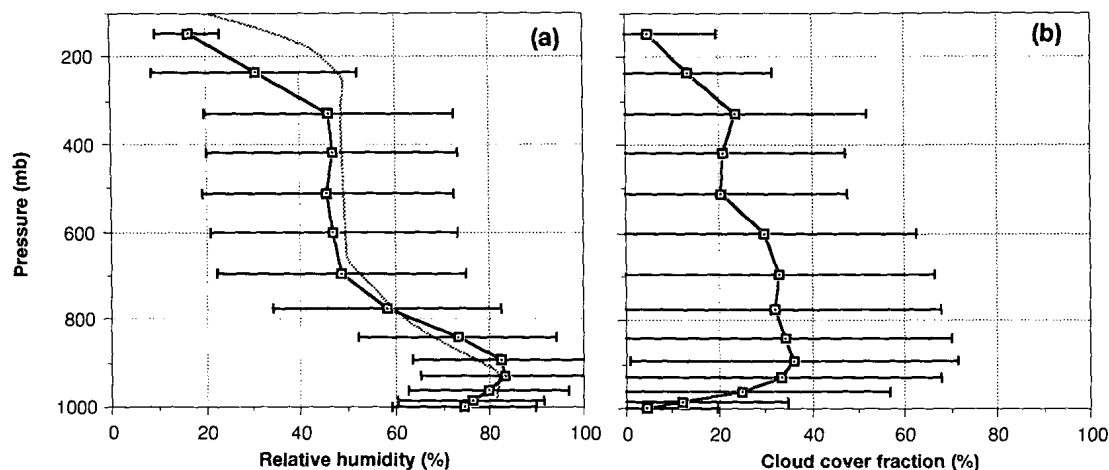


FIG. 4. Vertical distribution of (a) relative humidity and (b) cloud cover fraction averaged over the domain shown in Fig. 3 during 20–24 April 1981. Error bars denote standard deviations about the mean.

5b shows that cloud cover maximizes at about 35% near 900 mb, and gradually decreases to 10%–20% at 200 mb. Cloud amounts ranged from clear to 100%, with a majority of the cloud coverages clustered between 20% and 35% of the mean cloud cover.

Figure 5 shows the temporal deviations from the mean cloud cover and relative humidity averaged over the domain shown in Fig. 3 during 20–24 April 1981.

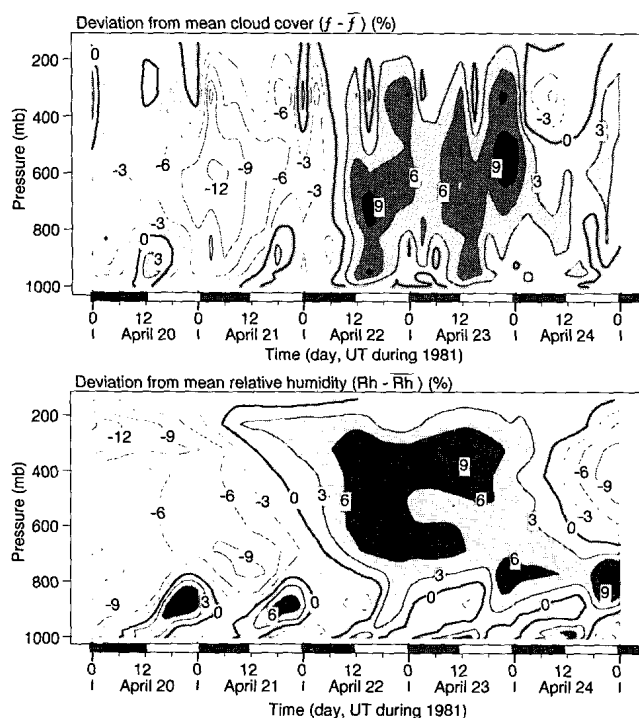


FIG. 5. Temporal variation of (a) cloud cover and (b) relative humidity from the mean values shown in Fig. 4 as a function of height in the troposphere during 20–24 April 1981. Day and night periods are shown as a light or dark strip along time axis.

Dry air is initially present within this domain, and the relative humidity gradually increases downward from upper levels beginning on 21 April. On 24 April, the relative humidity in the upper troposphere rapidly decreases as the cyclone moves out of the domain. The lower atmosphere exhibits a diurnal trend in relative humidity, with peak moistening near the top of the planetary boundary layer during the afternoons. This diurnal pattern is interrupted by the passage of the cyclone through the domain during 22–24 April. Variations in cloud cover correlate approximately with relative humidity variations, with lowest cloud amounts present before the arrival of the midlatitude cyclone, and generally greater cloud fractions during the time when the cyclonic system is centered in the analysis domain.

4. Comparisons between cloud cover and related meteorology

a. General comparisons

Cloud cover and related meteorological observations were mapped onto the identical grid at various horizontal resolutions by area averaging the raw temperature, moisture, or cloud cover data. Horizontal averaging areas were changed from $(80 \text{ km})^2$ to $(800 \text{ km})^2$, corresponding to the approximate range of horizontal resolutions employed by various regional- or global-scale models in use today. Relative humidities are defined relative to the saturation mixing ratio over liquid water, calculated using the mean water vapor mixing ratio and temperature within an averaging area. Saturation with respect to ice could have been defined, but subsequent analysis showed that relative humidity defined with respect to ice did not correlate any better with cloud amounts than relative humidity defined with respect to liquid water. Vertically, the cloud cover and

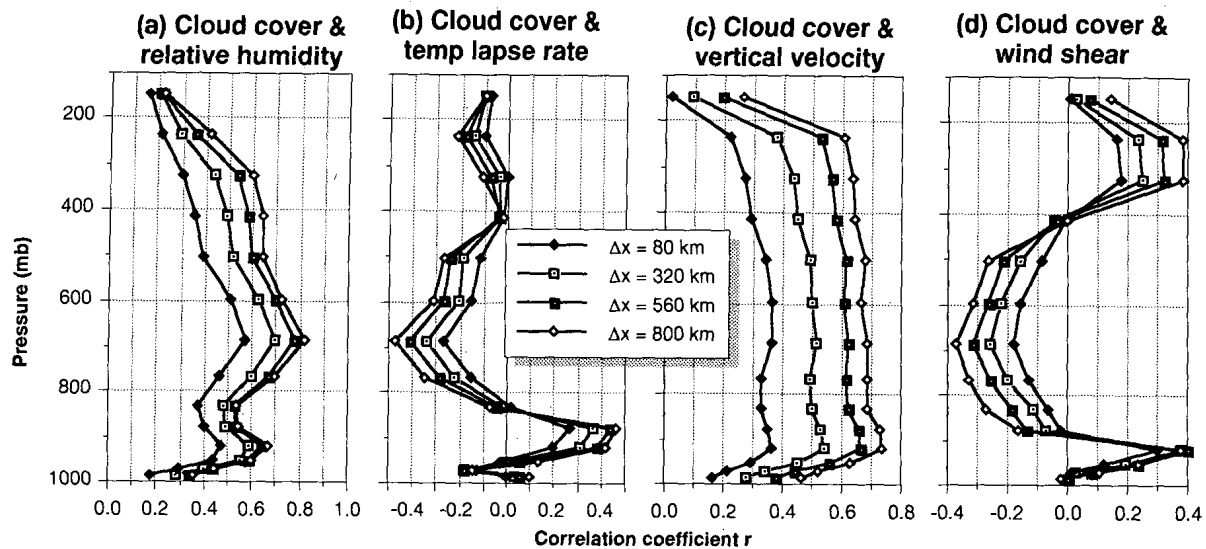


FIG. 6. Correlation coefficient at various atmospheric levels for the best-fit linear relationship between cloud cover and (a) relative humidity, (b) potential temperature lapse rate, (c) vertical velocity, and (d) wind shear. Different curves on each figure denote varying horizontal averaging areas ($80\text{--}800\text{ km}^2$).

mesoscale interpolation model grids are slightly different, and the cloud cover grid was transposed onto the meteorology model pressure-based coordinate using a cloud-volume-conserving mapping. As a result, a total of 3370–6650 (depending on averaging resolution) data points at 15 tropospheric levels are available for comparison during the five noon periods studied.

The most commonly used indicator of cloud coverage is the mean relative humidity of an air mass. As noted earlier, local potential temperature lapse rate and vertical velocity have also been shown to influence cloudiness. Here we hypothesize that vertical shear of the horizontal wind may also affect cloud cover. Other meteorological factors have been hypothesized to influence cloudiness, although many of these factors are actually model-generated parameters and thus difficult to directly “measure” with routine observations considered in this study. For example, cumulus mass fluxes or “convective” precipitation rates have been used to assess cloud coverage. However, these parameters are difficult to measure directly and will generally have a model-dependent (or resolution dependent) character. In this study, we restrict our comparisons to those parameters that can be readily inferred from routine observations in a straightforward manner.

To evaluate whether any of these parameters are correlated with cloud coverage, we calculate the correlation coefficient for the best-fitting linear regression between cloud cover and each of these meteorological factors for the observations gathered over the domain shown in Fig. 2 for five noon periods during 20–24 April 1981. While we do not expect that any of these parameters will be linearly related to cloud amount, we use this correlation analysis as a means to initially iden-

tify how strongly each of these factors correlates with cloudiness.

Figure 6 shows the vertical distribution of the correlation coefficient for the best-fit linear relationship between cloud cover and humidity, temperature lapse rate, wind shear, and vertical velocity. Correlation coefficients are calculated using all paired observations at each level. Correlation coefficients with magnitudes greater than 0.8 are considered “excellent” according to standard statistical texts, while correlations between 0.6 and 0.8 are considered “good,” and correlations between 0.4 and 0.6 are considered only “moderate.” Correlation coefficients less than 0.4 indicate poor or no relationship between parameters. This figure shows that cloud cover is most strongly correlated (positively) with relative humidity, followed by vertical velocity, which shows moderate to good positive correlations at most tropospheric levels. There is also evidence for a weaker negative correlation between cloud cover and both wind shear and potential temperature lapse rate. Within the planetary boundary layer (lowest 100 mb), cloud cover is weakly positively correlated with nearly all meteorological factors considered here [$0.4 < r < 0.75$ for an averaging area of $(800\text{ km})^2$]. Absolute values of the correlation coefficients increase as the horizontal averaging areas increase, reflecting the decrease in the deviations within the total sample population as larger averaging areas are considered.

Above about 300 mb, we find almost no correlation between cloud cover and other meteorological variables, reflecting the relatively low relative humidity (10%–20%) and cloud cover (0%–20%). At these heights, measurement uncertainty is very large. Routine water vapor measurements are rare above 300 mb, and

therefore, we are relying on purely model-calculated humidities here. In addition, the highest “layers” in this analysis dataset are actually averaged over 3–4-km depths of the atmosphere, and therefore, the “cloud area fraction” defined above actually becomes more like a “cloud volume fraction.” Because of this high uncertainty, any trends reported here for the upper troposphere must be interpreted with caution until better measurements are available.

Based on this cursory analysis of factors influencing cloudiness, we conclude that relative humidity and vertical velocity are the best candidates for calculating cloud coverage. However, relative humidity and vertical velocity are themselves strongly correlated, with higher relative humidities usually occurring with upward motions. Even small upward motions will rapidly increase the relative humidity of an atmospheric column since there is such a strong negative gradient of water vapor concentration in the atmosphere. Since relative humidity is a simpler parameter to measure or estimate within larger-scale atmospheric models, we concentrate the following analysis on further studying the relationship between cloud cover and relative humidity.

b. Cloud coverage and relative humidity

The relationship between cloud cover and relative humidity during this analysis period is assessed by aggregating the observations into increments of relative humidity and cloud cover at each level. Figure 7a shows a joint probability distribution (a “smoothed” scatter diagram) of the 3DNEPH cloud cover and interpolated relative humidity observations in the layer between 800 and 730 mb, averaged over $(320 \text{ km})^2$ areas. Contours in this figure show the percent probability of observing relative humidity and cloud cover within a particular 5% increment of either of these parameters.

A high degree of scatter is immediately evident in this comparison between cloud cover and humidity. For example, at 80% relative humidity, Fig. 7a shows a nearly uniform probability of observing any cloud fraction, and the average cloud cover at 80% humidity is about 50%. The correlation coefficient for the best linear relationship between cloud cover and relative humidity at this level is 0.6. When averaging over regions of this size, this scatter is not unexpected and is comparable to deviations found with cloud-resolving models (Xu and Krueger 1991). Similarly, using a statistical approach to modeling subgrid-scale variability, Lewellen and Yoh (1993) find up to 20% deviations in cloud cover at the same relative humidity depending on the skewness of the subgrid distribution of water vapor and temperature within averaging areas. In addition, we fully expect cloud amount to be influenced by factors in addition to relative humidity. Finally, as discussed earlier, the uncertainty in these measured

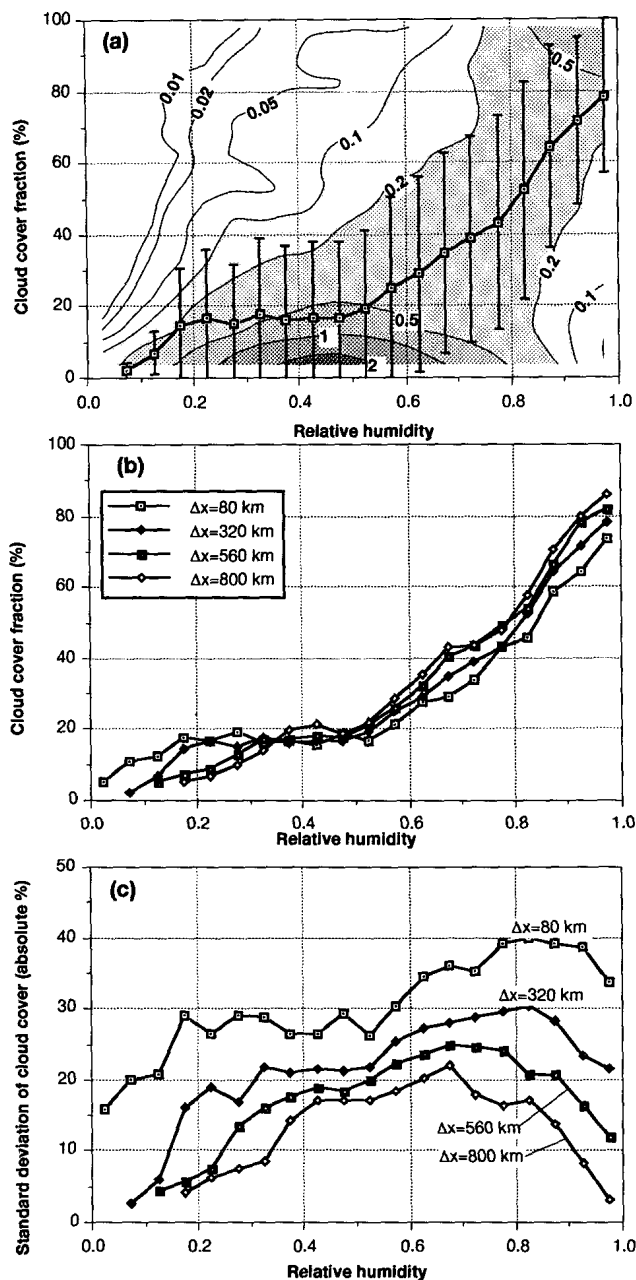


FIG. 7. (a) Joint frequency distribution showing the probability (%) of observing various relative humidity and cloud cover combinations averaged over $(320 \text{ km})^2$ areas in the layer 800–730 mb at five noon periods during 20–24 April 1981. Curve with error bars shows the mean and standard deviation of cloud cover within 5% increments of relative humidity. (b) Mean cloud cover as a function of relative humidity in the 800–730-mb layer for various averaging areas. (c) Standard deviation of the cloud cover within restricted relative humidity ranges at various averaging areas.

cloud amounts and relative humidities is comparable to the range of deviations shown in Fig. 7. However, this high uncertainty does not imply that existing measurements cannot be used to assess relationships between cloud cover and related meteorological factors. If the

sample size for this study is large and covers a wide range of meteorological environments, then trends in cloud cover may be discernible, and the functional relationship between cloud cover and related meteorological parameters may be at least qualitatively revealed.

To assess trends in the measurements shown in Fig. 7a, we aggregate the observations into 5% relative humidity increments at each atmospheric level, then average the cloud coverage within these restricted humidity ranges. Using this averaging technique, trends become apparent in the highly scattered observations. The average and standard deviation of the cloud coverage within 5% relative humidity increments are shown as a curve with error bars in Fig. 7a. As expected, cloud amount increases as humidity increases. At humidities 20%–40%, there is 10%–20% cloud cover on average. We hypothesize that if cloud coverage is related to relative humidity, then that relationship should fall within the range of (and most likely near the middle of) the mean and deviations shown in Fig. 7a.

Figure 7b shows the mean cloud cover within 5% relative humidity increments for horizontal averaging areas ranging from $(80 \text{ km})^2$ to $(800 \text{ km})^2$. All trends show a gradual falloff of cloudiness as relative humidity decreases, and when extrapolated to 100% relative humidity, we see that cloud cover does not necessarily approach 100%. Cloud amounts less than 100% are frequently reported when relative humidities are 100%. At humidities greater than 50%, cloud amount tends to increase as the averaging area increases, since the probability of encountering larger deviations from the mean increases as one averages over a wider area. Figure 7c shows the standard deviations of cloud cover within each increment of relative humidity for the entire population of samples considered in this study. As one averages over larger areas, the ranges of the averaged relative humidities and cloud cover encountered decrease substantially within this fixed domain. Within $(80 \text{ km})^2$ averaging areas at 80% humidity, we see approximately 45% cloud cover, $\pm 40\%$. In contrast, within $(800 \text{ km})^2$ averaging areas at the same relative humidity, we see about 53% cloud cover, $\pm 15\%$.

This process of averaging is repeated at all tropospheric levels to obtain the average cloud cover within each layer at any particular relative humidity, shown in Fig. 8a. At a particular relative humidity, cloud amounts are greatest in the 800–500-mb layer of the troposphere, a trend that is consistent with earlier approximations (Buriez et al. 1988; Geleyn et al. 1982). The highest cloud amounts occur under high humidities at 800–700 mb, but this figure shows that 10%–20% cloud coverage occurs at humidities as low as 20%, in contrast to the formulations shown in Fig. 1, which all specify zero cloud cover at humidities below 60%–80%. Standard deviations of cloud coverage within these 5% humidity increments (Fig. 8b) fall between

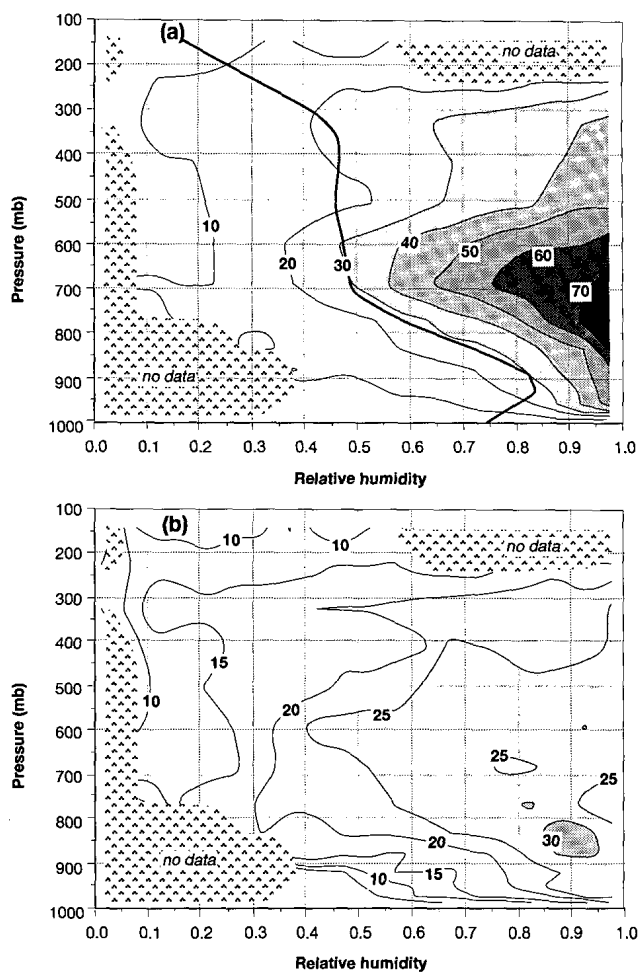


FIG. 8. (a) Mean fractional cloud coverage and (b) standard deviation of fractional cloud coverage observed at various relative humidities and pressures during 20–24 April 1981 over the northeast United States (domain shown in Fig. 2). Curve shown in Fig. 2a shows mean relative humidity during analysis period.

20% and 30% in absolute cloud cover, which in many cases is comparable to the mean cloud cover at this averaging resolution $[(320 \text{ km})^2]$.

The trends in the average cloud amount shown in Figs. 7 and 8 suggest that fractional area of cloud coverage decreases exponentially as the relative humidity falls below 100%, and that there is no clear “critical relative humidity” where cloud coverage is always zero. Also, these trends suggest that at 100% humidity, cloud cover can be significantly lower than 100%. As noted previously, there is a consistent undermeasurement in relative humidity by 2%–4% under saturated conditions, a bias that cannot account for the larger deviations (0%–40%) from 100% cloud cover observed here. Cloud amounts significantly less than 100% at saturation were also noted by Xu and Krueger (1991) within a field of simulated convective clouds. Using a cumulus ensemble model, they found, when averaging over an individual layer of the atmosphere

at resolutions ranging from $(60 \text{ km})^2$ to $(256 \text{ km})^2$, stratiform cloud amounts at 100% humidity well below 100%. The trends in the average cloud amount shown in Figs. 7 and 8 suggest the following approximation for cloud amount f as a function of relative humidity RH ($\text{RH} < 1$):

$$f(\%) = \min \left[f_{100} \exp \left(\frac{\text{RH} - 1}{1 - \text{RH}_e} \right), 100 \right], \quad (1)$$

where f_{100} is the cloud cover extrapolated to or at 100% relative humidity, and RH_e (e -folding relative humidity) is qualitatively similar to the "critical humidity" used in previous cloud cover formulations, although here it represents the relative humidity depression below 100% where cloud amount decreases to 37% (e^{-1}) of its value at 100% humidity.

Using (1) as the functional form that appears to match the qualitative trends noted in Figs. 7 and 8, we calculated the root-mean-square difference between calculated and observed cloud cover for all observations using all combinations of f_{100} and $(1 - \text{RH}_e)$. Figure 9 shows the best values for f_{100} (Fig. 9a) and $(1 - \text{RH}_e)$ (Fig. 9b), along with the corresponding root-mean-square difference $\{[n^{-1} \sum (\text{calculated} - \text{observed})^2]^{1/2}\}$ between the calculated and observed cloudiness. Both of these parameters exhibit a pressure dependence, which we quantify here as the ratio of the pressure P to the surface pressure P_s , and are also slightly influenced by the averaging area $(\Delta x)^2$. The optimum values for f_{100} maximize near about 700 mb and also increase as the averaging dimension increases. The peak value for f_{100} can be approximated by

$$f_{\max}(\%) = 78 + \frac{\Delta x (\text{km})}{15.5},$$

$$80 \text{ km} < \Delta x < 800 \text{ km}. \quad (2)$$

Above about 700 mb, f_{100} falls off from this peak value linearly to zero at $P/P_s = 0.1$:

$$f_{100} = f_{\max} \frac{(P/P_s - 0.1)}{0.6}, \quad 0.7 > \frac{P}{P_s} > 0.1. \quad (3)$$

Below 700 mb, f_{100} decreases to about 30% at the surface:

$$f_{100} = 30 + \frac{(1 - P/P_s)(f_{\max} - 30)}{0.3}, \quad 1 > \frac{P}{P_s} > 0.7. \quad (4)$$

The $(1 - \text{RH}_e)$ term in (1) shown in Fig. 9b linearly increases throughout the depth of the troposphere and is also influenced slightly by the grid resolution. We suggest the following form:

$$(1 - \text{RH}_e) = 0.196$$

$$+ \left[0.76 - \frac{\Delta x (\text{km})}{2834} \right] \left(1 - \frac{P}{P_s} \right). \quad (5)$$

The linear forms for (2)–(5) at a 560-km resolution are shown as lines in Figs. 9a,b. Using (1)–(5) to calculate cloud cover from relative humidity produced cloud cover estimates that on average contained a root-mean-square difference of 20–30 percentage points from the 3DNEPH observations, depending on the tro-

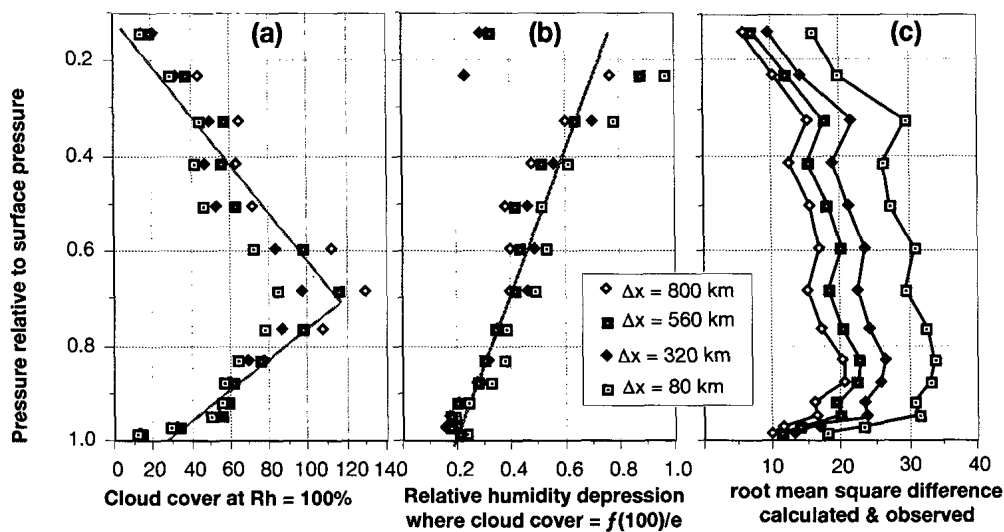


FIG. 9. Optimum values of parameters used to calculate cloud cover from relative humidity. (a) Cloud cover when relative humidity is extrapolated to 100% [Eqs. (3) and (4)]. (b) Relative humidity depression where cloud cover is $1/e$ of cloud cover at 100% humidity [Eq. (5)]. (c) Root-mean-square difference between observed cloud cover and cloud cover calculated using Eqs. (1)–(5). Shaded line in (a) and (b) shows suggested linear fit to optimum values for a horizontal resolution of 560 km.

pospheric level and horizontal averaging area considered. This difference is comparable to previously cited uncertainties in measurements of cloud cover; however, the functional form and sensitivity of cloud cover to changes in relative humidity mimic the observations gathered in this study.

c. Cloud coverage and convective instabilities

We expect cloud coverage to be influenced by the presence of buoyantly induced convection that is not resolved by the coarse resolution of the interpolated observations used in this analysis. Local stability ($\partial T / \partial z$) at any point in a sounding is not a sufficient indicator of the presence of convective activity, since convection can often penetrate into atmospheric layers that are absolutely stable with respect to vertical perturbations (Stull 1991). To define areas and layers where buoyantly induced convection can occur, we provide a 1 m s^{-1} "push" to air with a slightly higher temperature and moisture content from each point on a vertical sounding. In a conditionally unstable environment, the "pushed" parcel will accelerate upward. Ignoring frictional forces and pressure perturbations, the parcel velocity at levels above the layer where it is perturbed can be obtained by integrating the vertical equation of motion for a parcel rising under the influence of buoyant accelerations:

$$\frac{dw}{dz} = \frac{g}{w} \left(\frac{T_{vp} - T_{ve}}{T_{ve}} - q_l \right), \quad (6)$$

where w is the parcel vertical velocity, T_{vp} is the virtual temperature of the rising parcel, T_{ve} is the virtual temperature of the surrounding environment through which the parcel rises, and g is the gravitational acceleration. The condensed water content of the parcel (q_l) is the total water content (assumed to remain constant) of the parcel minus the saturated vapor mixing ratio at any level above the lifting condensation level. For this study, we define a given layer to have a potential for convective clouds if any parcel is capable of rising adiabatically into or through that layer from lower layers under the influence of buoyant forces. These convectively unstable areas at 700 mb are shaded in Fig. 3.

Figure 10 shows the average cloud cover subdivided into $(320 \text{ km})^2$ stable (Fig. 10a) and convectively unstable (Fig. 10b) areas as a function of the layer relative humidity and pressure. Figure 10c shows the difference between the stable and unstable cloud covers ($f_{\text{stable}} - f_{\text{unstable}}$) at the same relative humidity and pressure. Shaded areas in Fig. 10c denote regions where unstable cloud amounts are greater than stable cloud amounts. Since the observations from which these figures are constructed contain a high level of scatter, some of the differences between stable and unstable cloud covers may not be statistically significant. Therefore, we perform a chi-square analysis of these differences. At each

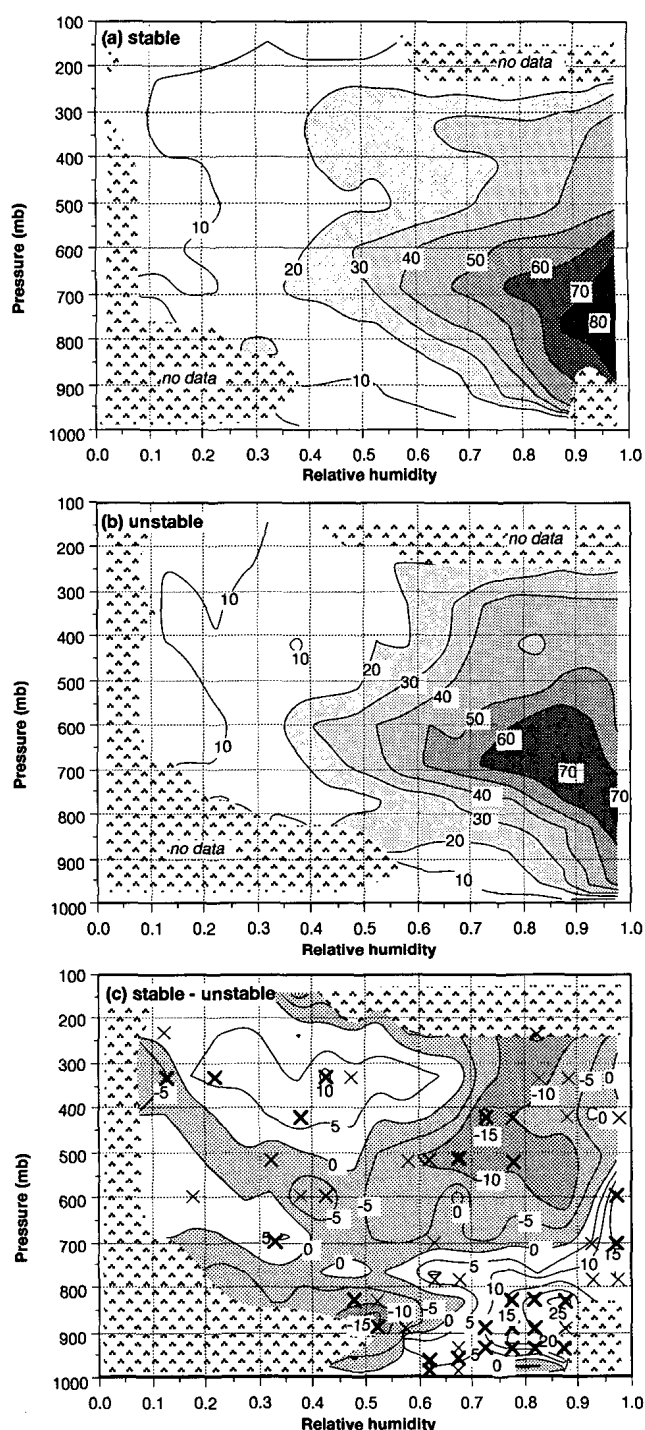


FIG. 10. Comparison of fractional cloud coverage under (a) stable and (b) convectively unstable conditions as a function of relative humidity and pressure during 20–24 April 1981 over the northeast United States (domain shown in Fig. 2). (c) Difference between stable and unstable cloud cover ($f_{\text{stable}} - f_{\text{unstable}}$). Boldface crosses denote differences that are significant with greater than 95% confidence, and lightface crosses denote differences that are significant above only 90% confidence. All other areas contain differences that are significant at less than 90% confidence. Shaded areas in (c) show areas where cloud cover is greater under convectively unstable conditions relative to stable conditions at the same pressure and relative humidity.

atmospheric level, relative humidity and cloud cover data pairs were aggregated into 10% cloud cover increments and 5% humidity increments. The unstable and stable cloud cover frequency distributions were then subjected to a chi-square confidence limits test. Differences between stable and unstable cloud cover that are significant at greater than the 95% confidence limit are denoted by boldface crosses in Fig. 10c, and differences that are significant at greater than the 90% limit are denoted by lightface crosses. Differences that are not close to a cross in Fig. 10c are usually small and may not be statistically significant.

Figure 10c shows that under relatively humid convectively unstable conditions, we see greater cloud amounts relative to stable conditions at the same humidity in the upper troposphere. In the lower troposphere, high humidity environments where convection is possible contain lower cloud amounts relative to stable conditions at the same relative humidity, which may result from cumulus-induced subsidence of dry air into the lower troposphere under convectively unstable conditions. At lower humidities in the lower troposphere, the presence of buoyantly induced convection leads to greater cloud cover. These differences seem physically reasonable. However, under unstable conditions there is a region of significantly *lower* cloud amounts when humidities are below 65% in the upper troposphere that cannot be easily explained. This anomalous behavior prompted a further investigation of the cloud cover and humidity data. Further analysis of the MM4 interpolation system showed that under unstable conditions, the upper troposphere is calculated to become rapidly saturated when observations are *not* assimilated into the model forecast equations (i.e., the MM4 is run in a "forecast" mode away from the model initial conditions and boundaries). The MM4 calculates humidities approaching 80%–100% in the layer from 500 to 100 mb over regions of mean upward motion and convective activity associated with transient cold and warm fronts. Simultaneous observations show much smaller regions of humidities in excess of 80% between 500 and 300 mb, and there are no measurements above 300 mb, suggesting a bias (overprediction) of relative humidity. Any biases introduced by the model physics into the interpolation of water vapor are partially deleted since water vapor calculations are continuously "nudged" toward the observations for the version of the model used in this analysis. However, above 400–300 mb, there are few humidity observations. Even below 300 mb, despite this "nudging," there may be a residual bias in the MM4 interpolated moisture calculations in these areas. If the "interpolated" relative humidities above 400 mb are higher than were actually present, then this could account for the analyzed reduction in cloud cover under unstable, dry conditions in the upper troposphere. Because of these apparent discrepancies, we feel that the observation–interpolation system described above may introduce a moist bias

in relative humidity in the upper troposphere under unstable conditions. This apparent discrepancy may also influence humidity "measurements" reported here under stable conditions in the upper troposphere, since this is an integrated observation assimilation system, although these errors would be continuously minimized in areas where observations are available. However, as noted earlier, direct measurements of water vapor in the upper troposphere are not available, and we suspect a model-induced bias only because of the apparently lower cloud amounts observed at heights above 400 mb under unstable conditions. Whether this bias is real can be ascertained only with better measurements and evaluations of the MM4 mesoscale meteorology model.

These comparisons of stable and unstable areas at constant heights and relative humidities suggest that convective motions induce large and statistically significant changes in cloud cover. In the lower troposphere, convection increases cloud cover under dry conditions ($RH < 60\%$ – 70%) and decreases cloud cover under moist conditions ($RH > 60\%$ – 70%). In the moist upper troposphere ($RH > 60\%$), cloud cover is greater when convection is occurring, although these trends may be biased due to an apparent bias in our ability to infer relative humidities in the upper troposphere. As noted by previous researchers, there is most likely a relationship between convective mass fluxes or convective precipitation rate and cloud cover under unstable conditions. However, using routinely available meteorological measurements, it is difficult to quantify either of these measures of convective intensity. When we analyze cloud cover within a relatively constant and narrow relative humidity range, we find no correlations between cloud cover and convective available potential energy (CAPE), a standard measure of convective instability. These initial comparisons suggest that diagnosing the effects of convection on cloud cover is very complicated, requiring further study using more accurate measurements of cloud cover and relative humidity.

5. Discussion and conclusions

In this study, we have compared satellite observations of fractional cloud coverage with related meteorological observations over the northeast United States during a springtime midlatitude cyclone. Cloud cover observations were derived from the U.S. Air Force 3DNEPH analysis of satellite imagery, aircraft reports, and surface-based observations. Other meteorological measurements were interpolated from radiosonde observations using a hydrostatic mesoscale meteorology model. Collocated comparisons of the cloud cover with other meteorological measurements show considerable uncertainty, although we find moderate to good correlations between cloud cover and relative humidity and vertical velocity. An analysis of the relationship between observed cloud cover and humidity

suggests that cloud cover decreases exponentially as humidity falls below 100%. Relative to other layers in the troposphere, the midtroposphere (700–500 mb) contains higher cloud amounts at the lowest humidities, with mean cloud amounts of approximately 30% near 50% humidity. Cloud cover also exhibits weak negative correlations with potential temperature lapse rate and vertical shear of the horizontal wind in the middle atmosphere. Throughout most of the troposphere, relative humidity is the best *single* indicator of cloud coverage, and resolution-dependent formulations that calculate the cloud cover from relative humidity are presented.

Under conditions when buoyantly forced vertical motions are possible, cloud cover is greater in the upper troposphere and smaller in the lower troposphere when relative humidity is greater than about 60%. However, anomalous low cloud amounts under unstable conditions are recorded at low humidities above about 400 mb, suggesting that model-interpolated relative humidity may be biased there. Thus, the 3DNEPH cloud observations are being used as an evaluation tool. In a manner similar to Nehr Korn and Hoffman (1990), this analysis suggests that cloud coverage may be a useful tool for inferring relative humidity, contrary to the underlying purpose of most cloud cover algorithms: to infer cloud coverage from other “easy to estimate” meteorological factors. For inferring upper-tropospheric water vapor concentrations, perhaps cloud observations are easier to estimate with greater accuracy than relative humidity.

Despite the high level of uncertainty present in this analysis of cloud cover, most parameterizations of cloud coverage used by current meteorology and climate models yield smaller cloud amounts than reported by the 3DNEPH at particular relative humidities, especially in the midtroposphere. Near 800 mb when the relative humidity is near 70%–90%, many cloud cover formulations (shown in Fig. 1) specify cloud cover fractions considerably lower than the mean minus one standard deviation from the measurements presented in Fig. 7. At humidities below 60%–80%, nearly all algorithms specify zero cloud coverage, while the 3DNEPH reports 10%–20% cloud cover at humidities as low as 20%, although the zero cloud amount used by most algorithms falls within the standard deviations (and uncertainties) of the observations.

We find no evidence for “threshold” relative humidities below which cloud cover is always zero. Previous observational analyses and modeling studies have actually extrapolated the trends measured within relatively narrow (and moist) humidity ranges outside the ranges where measurements were available, thus generating a need for a “threshold humidity.” For example, Slingo (1980) noted a trend in low cloud cover when the relative humidity was 65%–90%. However, Slingo’s cloud observations were confined to periods when relative humidities were confined to the 65%–

90% range, making it impossible to infer cloud cover under drier conditions. In this study, the relative humidity at any atmospheric level showed considerably greater range than reported in previous studies, and in particular we have sampled periods and areas when relative humidities are considerably lower than 70%. Thus, the observations presented here do not necessarily disagree with previous observational studies, but these observations are gathered over a wider range of environmental conditions.

Many of the formulations for cloud cover used by climate models are not actually based on short-term observations of cloud cover and relative humidity. Rather, these formulations along with their “critical humidities” are “tuned” within the context of their host model physics and dynamics to yield reasonable estimates of the global, long-term planetary outgoing longwave radiation or albedo. Thus, cloud cover formulations are “backed out” of their host model, and represent a functional form that when used in the particular climate model for which they were tuned, yield a reasonable planetary albedo and/or outgoing longwave radiation. The danger of this method of assessing cloud cover is that other model uncertainties or errors may be concealed by an incorrect cloud cover formulation. For example, forcing model clouds to be smaller can conceal excessively large optical depths. Slingo and Slingo (1991) find that when increasing the resolution of a climate model, it was necessary to reduce the “critical relative humidities,” thus increasing cloud amounts at humidities above 70%–90% and allowing clouds to form at lower humidities. This behavior is the opposite of the results presented in this study. Figure 7 shows that at a fixed relative humidity, as the averaging resolution increases (Δx smaller), cloud amounts decrease since the dispersion about the mean relative humidity decreases as one reduces the averaging area, decreasing the likelihood that saturated conditions exist within the averaging area.

These results suggest that current methods of calculating cloud coverage within large-scale climate simulations or atmospheric chemical modeling studies are probably underestimating cloud amount at most relative humidities. More importantly, current climate models probably cannot adequately estimate the potentially significant *changes* in cloud cover that can result from small changes in relative humidity. As clearly shown in Fig. 1, a small change in relative humidity can result in large or small changes in cloud coverage, depending on which cloud cover algorithms are used. This analysis of the 3DNEPH cloud archive shows an exponentially decreasing cloud cover as relative humidity decreases, and no clear “critical relative humidity” below which there are no clouds. According to the trends revealed by this analysis, cloud amount probably changes as relative humidity changes at *any* relative humidity, unlike current formulations, where cloud cover changes when relative humidity is greater than

the 60%–90% “critical” humidities used by current cloud cover formulations.

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