Factors Influencing Regional-Scale Cloud Cover: Investigations Using Satellite-Derived Cloud Cover and Standard Meteorological Observations

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Introduction

Large-scale numerical models of the atmosphere approximate the heterogeneous or subgrid-scale nature of cloudiness by assuming that a fraction of each grid area is occupied by clouds. This cloud cover fraction is used to apportion cloud effects into a "grid-averaged" forcing within areas that contain a mixture of clear and cloudy regions. Most models of tropospheric dynamics assume that the fractional cloud coverage is determined by the grid-averaged relative humidity, stability, or resolvable-scale vertical motions (e.g., Slingo 1980).

In this study, we investigate the relationship between cloud cover and other related meteorological factors by comparing observations of clouds and relative humidity, temperature lapse rates, wind shear, and large-scale vertical velocity within various tropospheric levels.

Cloud Cover Observations

Cloud observations are derived from the U.S. Air Force operational real-time three-dimensional analysis of cloud cover (3DNEPH). 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 3-D cloud cover information every 3 hours at 15 vertical layers between the surface and ~16 km above the surface. Horizontally, the grid size varies from ~25 km near the equator to ~60 km at the poles.

In this study, we use five noon-time spring periods (20 to 24 April 1981) analyzed over the northeast United States by the 3DNEPH. During this 5-day period, a relatively intense midlatitude cyclone developed and traversed this domain, allowing one to investigate cloud cover under a wide variety of meteorological environments.

Related Meteorology

Temperature and moisture observations used in this analysis are taken from the National Meteorological Center global analysis and spatially and temporally interpolated onto an (80 km)^2 grid using a hydrostatic mesoscale meteorology model (MM4). During model execution, observations are incorporated into the model calculations in regions near the observation locations. Differences between observed and calculated temperatures, humidities and wind speeds are continuously minimized by "nudging" the calculations towards the observations. In this manner, model calculations agree closely with observations when and where observations are available, and when no observations are available, the meteorological data are dynamically consistent.

Comparisons

Figure 1 shows contours of the average 3DNEPH cloud cover at 15 tropospheric levels and at various relative humidities. Typically, 1000 to 5000 (320 km)^2 observation pairs were available at each layer, representing cloud cover under cold and warm maritime and continental air masses during this period. The cloud observations are averaged within 5% relative humidity increments at each level.

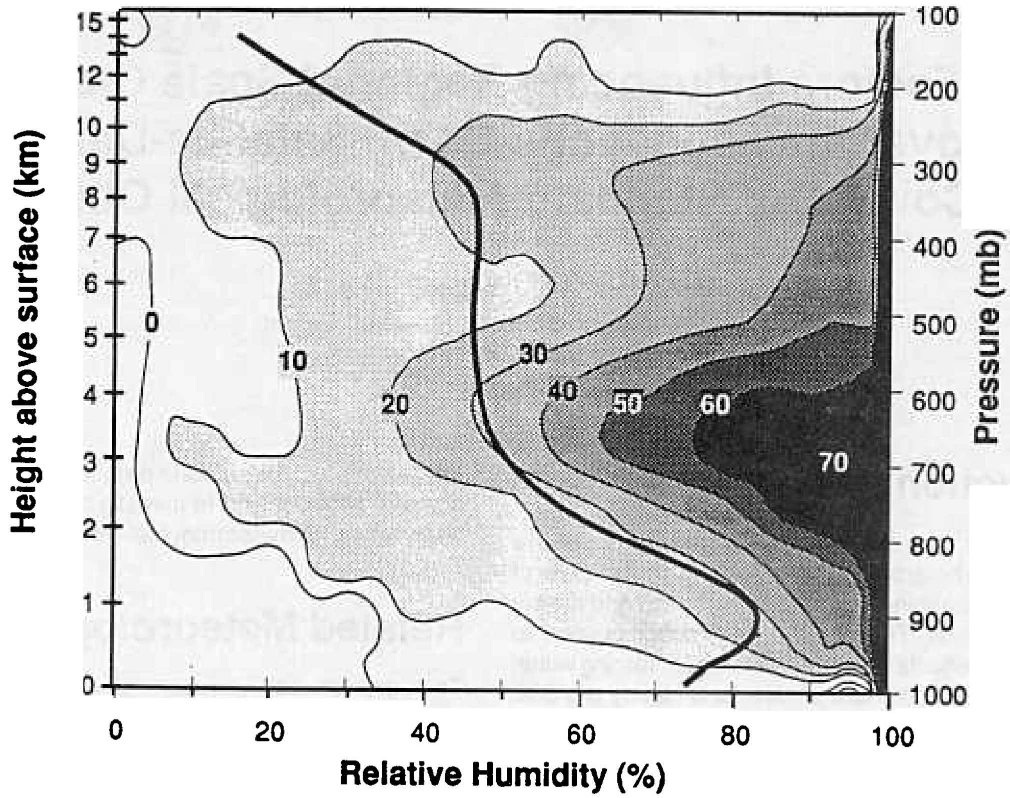

Figure 1. Fractional cloud coverage versus relative humidity and pressure over the northeast United States during 20 to 24 April 1981.

As expected, cloud amount increases as humidity increases. At a particular relative humidity, cloud amounts are greatest in the 800- to 600-mb layer, a trend that is consistent with earlier approximations (Buriez et al. 1988). The highest cloud amounts occur under high humidities at 900 to 800 mb. This figure shows, however, that 10% to 20% cloud coverage occurs at humidities as low as 15%, in contrast to many formulations, which all set zero cloud cover at humidities below 50% to 80%.

These results suggest that fractional area of cloud coverage decreases exponentially as relative humidity falls below 100% and that there is no clear "critical relative humidity" where cloud coverage is always zero. We suggest the following approximation for cloud amount f as a function of relative humidity Rh (Rh<1) and vertical velocity:

$$f = \exp\left\{\frac{Rh - 1}{\alpha + 0.1\sigma^2 w}\right\} \quad (1)$$

where α is a function of height in the troposphere and represents the relative humidity depression from 100% at which cloud amount falls off to 37% (e^{-1}):

$$\alpha = \begin{cases} 0.2 + \sigma/3 & \sigma < 0.75 \\ 1.8(1-\sigma) & \sigma \geq 0.75 \end{cases} \quad (2)$$

In Equations (1) and (2), σ is the pressure relative to surface pressure. Using Equations (1) and (2) to calculate cloud cover from Rh and w (averaged over [320 km]^2 areas) produces cloud cover estimates that differ by 10 to 30 percentage points from the 3DNEPH observations.

Based on climate model sensitivity studies, Slingo (1990) estimates that a 15% change in low cloud cover could potentially counter a double-CO_2 warming. If cloud cover changes in response to a change in relative humidity, then there is an important feedback between changing relative humidity and changing cloud cover.

The dark curve on Figure 1 shows the relative humidity averaged during the observation period considered in this study. The vertical distribution of relative humidity agrees closely with the global mean relative humidity according to various analyses and the NCAR climate model. The averaged cloud cover at any vertical layer can be very accurately calculated from the average relative humidity of the layer simply by choosing the cloud cover corresponding to the mean relative humidity shown in Figure 1. If relative humidity changes slightly in a future climate, then the cloud cover change associated with that changing humidity can be approximated by looking at the sensitivity of cloud cover to relative humidity in the present climate.

Figure 2 shows the change in relative humidity that is correlated with a 15% change in the mean cloud cover. This figure shows that near the middle and top of the planetary boundary layer (950-900 mb), changes in the relative humidity of less than 2% are correlated with 15% changes in cloud cover.

Conclusions

We find that an increase in relative humidity of ~2% at 950 to 900 mb could lead to a 15% increase in cloud cover at these layers. Thus, small changes in relative humidity could counter a CO_2-induced global warming. These conclusions are based on our comparisons of satellite observations of fractional cloud coverage with collocated related meteorological parameters over the northeast United States.

We find significant correlations between cloud cover and relative humidity and vertical velocity. These comparisons suggest that cloud coverage decreases exponentially as humidity falls below 100%. Relative to other layers in the troposphere, the middle troposphere contains higher cloud amounts at lower humidities. Most parameterizations of cloud coverage calculate smaller cloud amounts than reported by the 3DNEPH observations, especially in the middle troposphere. Furthermore, all cloud cover

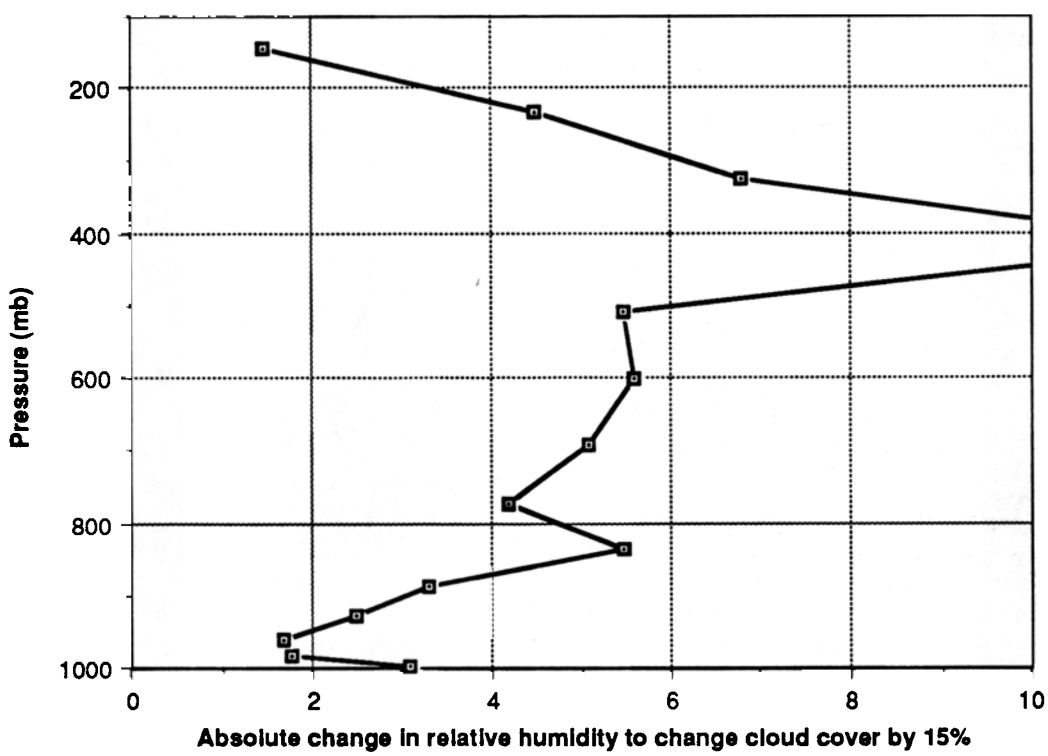

Figure 2. Sensitivity of cloud cover to changes in the relative humidity according to the trends reported in Figure 1. This figure shows the change in relative humidity that correlates with a 15% change in cloud cover.

parameterizations assume that cloud amount is always zero below a "critical" relative humidity, an assumption that is not discernible from this analysis.

These results suggest that current methods of calculating cloud cover within large-scale climate simulations or atmospheric chemical modeling studies are significantly underestimating the effects of clouds. 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 under dry conditions.

Acknowledgments

The author is grateful to the U.S. Department of Energy for supporting the research presented here.

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