An Investigation of Diagnostic Relations between Stratiform Fractional Cloud Cover and Other Meteorological Parameters in Numerical Weather Prediction Models

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ABSTRACT

The main objective of this study has been to find model parameters that may be used to diagnose or parameterize the stratiform fractional cloud cover. Observational data are obtained from satellite radiance measurements. Cloudiness parameters are derived by use of the measurements in three channels: 0.58–0.68 \( \mu \text{m} \) (visible), 0.7–1.1 \( \mu \text{m} \) (near infrared), 10.5–11.5 \( \mu \text{m} \) (infrared).

The derived cloud parameters, fractional cloud cover, cloud-top height, and cloud depth have been put on a grid with 50-km resolution. The inferred cloud parameters have been investigated and compared to several quantities derived from analyzed fields on the same grid, nearly coincident in time to the two satellite passages. A fairly distinct relationship to cloud cover is found only for relative humidity. On this basis two parametric relations are discussed.

1. Introduction

A number of studies on the climatic effect of clouds (e.g., Shukla and Sud 1981; Melesko and Wetherald 1981; Ramanathan et al. 1983; Cess et al. 1989) have shown that the model’s simulation of general circulation is significantly sensitive to the specification of cloudiness. For short- and medium-range forecasts, the impact of cloud was generally considered to be less important, mainly because radiative time scales tend to be large. However, studies by Geleyn (1981) and Slingo (1984) have shown that simplifications of the cloud cover parameterization lead to weakening of the extratropical circulation during the forecast period (10 days) particularly in the synoptic scale. Furthermore, there is an important influence from insolation and cloud conditions on the daily variation of structure of the planetary boundary layer and thus on vertical eddy fluxes.

These facts emphasize the importance of having a realistic representation of cloud cover in numerical models. This way will better distribute cloud-associated physical processes, which in turn will influence the evolution of the circulation in a more realistic way.

One assumes that clouds form under certain conditions. Yet by the very fact that the cloud forming process is an interaction between several physical processes on different scales, and some of these are poorly understood as well, the complete conditions are not fully known. Since some of the physical processes (such as turbulence, radiation, and microphysics) in addition to cloud cover itself, are subgrid scale, it is impossible to design a scheme describing cloud cover in a numerical model, without making certain simplifications and assumptions. The basic premise of such schemes is that condensation on the smaller scale is part of a large scale such as the synoptic circulation. Qualitative support for this is evident in satellite pictures.

Many of today’s models for weather prediction and general circulation and climate simulation (henceforth denoted GCM) have become quite elaborate through inclusion of advanced boundary layer treatments and radiation calculations. However, treatment of condensation and especially associated cloudiness is not carried out to the same degree of refinement. Therefore, the statement in Wiscombe and Ramanathan (1985) that this problem must be given more attention than in the past in order to make it possible to achieve a substantial improvement in our prediction skill is still applicable.

To promote further development of parameterization of fractional cloud cover, the purpose of the present paper is to examine some plausible relations between cloud cover and other resolved meteorological parameters.

Today there are satellite measurements that afford the possibility to obtain cloud data both over land and sea areas. In the present paper, a statistical method is used to objectively obtain the fractional cloud cover, which in turn is adapted and put on a grid area of a numerical weather prediction model.

In principle the idea is to compare the fractional cloud cover with analyzed meteorological parameters.
However, the analyzed humidity field is usually a smoothed version of the actual humidity distribution. Therefore, in order to let the humidity field adjust itself to the circulation, predicted fields are used as analyzed data. The model outputs will later be referred to as analyzed quantities.

2. Ways of obtaining data

a. The analyzed data

To seek possible relations between two quantities, observations of both are needed in a geographic area. For reasons given in the Introduction, a numerical weather prediction model was chosen to produce the meteorological quantities to which cloudiness is to be related. At the University of Bergen Section of Meteorology, a numerical weather prediction model is used as a research tool for studies of atmospheric mesoscale circulation. This model is a modified version of the model in operational use at The Norwegian Meteorological Institute (DNMI). The major modification concerns the treatment of condensation and clouds. An elaborate description is given in Sundqvist et al. (1989). In this study the model has a horizontal resolution of 50 km, and lateral boundary values are obtained from a model at DNMI with a coarser grid mesh and larger prediction area. The model is a primitive equation model applied to a polar-stericographic map projection, true at 60°N. The so-called σ-coordinate is employed for the vertical resolution.

A more detailed description of the model may be found in Bratseth (1983), Grønås et al. (1987), Iversen and Nordeng (1987), and Sundqvist et al. (1989). The data assimilation is described in Grønås and Midtbø (1986).

The integration domain is a rectangular area and, with the present resolution, this area consists of 61 × 49 points. The model area is seen in Fig. 1. There are 10 sigma layers of the model atmosphere with the top at 200 mb. The layers are defined at $\sigma_1 = 0.0607$, $\sigma_2 = 0.1821$, $\sigma_3 = 0.3036$, $\sigma_4 = 0.4250$, $\sigma_5 = 0.5464$, $\sigma_6 = 0.6679$, $\sigma_7 = 0.7893$, $\sigma_8 = 0.9025$, $\sigma_9 = 0.9715$, and $\sigma_{10} = 0.9940$.

As mentioned earlier, the analyzed humidity field is considerably smoothed. When the initial relative humidity fields are generated, the lower levels are derived on basis of observed data. The upper-level fields (above 250–300 mb) are formed by an extrapolation of the relative humidity $U$ from lower levels in such a way that $U$ decreases with height and becomes horizontally smoother. This type of procedure is common practice. This circumstance has an impact on our “analyzed fields,” since the initial situation affects the results long after the beginning of the integration. Such effects may also be maintained or enhanced because the vertical diffusion is very weak in the upper layers of the model.

![Fig. 1. Satellite observed cloud cover 0900 UTC 27 August 1988. The scale to the left shows the shadings for the different fractional cloud covers.](image_url)
This might lead to unrealistically dry conditions in the upper part of the model atmosphere, not only in the early stages of the prediction but over a substantial part of the integration period. Experiments have shown that it takes about 4–5 h (Sundqvist et al. 1989), which may be somewhat situation-dependent, before the humidity field has adjusted to the motion system and is realistically distributed. Even if the spinup time is 4–5 h, the effects of the analysis procedure may last considerably longer, especially in the upper levels.

b. Clouds derived from satellite data

Observed cloud cover is obtained from satellite data with the aid of a cloud classification scheme (Raustein 1989). The method makes use of AVHRR data from NOAA satellites, and radiance measurements in three channels are utilized. The three channels are:

CH1 0.58–0.68 μm (visible);
CH2 0.7–1.1 μm (near infrared);
CH4 10.5–11.5 μm (infrared).

The measured radiances come from pixels covering about 1.1 × 1.1 km²; those radiances are averaged over unit areas consisting of 5 × 5 pixels. To obtain an objective cloud classification, the statistical method called clustering is applied. The method is based upon the assumption that the cloudy areas can be classified into several homogeneous areas (clusters) with different radiative properties. Each such area (cluster) is represented by either a group of pixels showing the radiation from the earth’s surface (surface cluster) or a certain cloud type (cloud cluster). Hence, the fractional cloud cover, b, of unit areas belonging to a surface cluster is 0. For unit areas belonging to a cloud cluster, it is assumed that b = 100%. This is a reasonable assumption, since a cluster contains a great number of unit areas with similar properties with respect to albedo and brightness temperature. Partly cloudy unit areas are not homogeneous over large areas, whereas overcast areas may well be extensive and rather homogeneous. Unit areas that do not belong to either of the two cluster types are assumed to have 0 < b < 100%. A method similar to the one Arking and Childs (1985) call “the maximal clustering technique” is used to find b for such unit areas.

After the unit areas are classified, the cloud-top temperature is found by using data from CH4 and Planck’s law. The cloud-top height is obtained by assuming a constant lapse rate, γ, and a surface temperature obtained from the measured radiances in the cloud-free areas. At present γ = 0.60°C (100 m)⁻¹ is adopted. Furthermore, expressions for reflectivity and transmittance of clouds as functions of optical thickness and solar elevation are employed (Arking and Childs 1985, Appendix). In this way an optical thickness corresponding to the actually measured reflectivity is found. The vertical extension of the clouds cannot be found from the optical thickness alone. This is also a function of the drop-size spectrum and the number of drops per unit volume in the cloud. Raustein assumes that the clouds consist of water drops with mode radius of r₀ = 4 μm and the same form of the drop-size spectrum as Arking and Childs (1985). The number concentration of drops per unit volume is assumed to be n = 10⁸ m⁻³. With these assumptions and knowing the optical thickness, a value of the cloud thickness may be obtained. A complete description of the method may be found in Raustein (1989) and Arking and Childs (1985).

Average values of the different cloud parameters are calculated for each 50-km grid square from the above mentioned unit areas. The average values for a grid square is calculated as the arithmetic mean of the values in every unit area within a distance of 25 km from the grid point.

The quality of this satellite cloud observation (SCO) is dependent on the solar zenith angle. If this angle becomes large, the roughness of the cloud tops will cause significant shadowing, which leads to erroneous interpretation of the measured reflectance. In addition, the bidirectional reflectance becomes increasingly anisotropic with increasing zenith angle (Taylor and Stowe 1984). Thus the optimal dataset would be obtained in the summer solstice at solar noon. A second serious problem is that it is difficult to distinguish between snow-covered surfaces and clouds when utilizing only the three above mentioned channels (Raustein 1989). Since the snow amounts reach a minimum in late summer/early autumn, a compromise must be made here. In addition, an interesting weather situation must be sought in the relevant time period. On the basis of these considerations, situations at 0840 and 1425 UTC 27 August 1988 were chosen.

3. Comparing fractional cloud cover with other quantities

Since the cloud observations are two-dimensional, comparisons are made with vertical integrals of other quantities, aᵢ, j, k. These quantities are treated as follows. First, the sigma levels K1 and K2 corresponding to cloud top and cloud base are found. Next an average value ᵦᵢ, j of the parameter aᵢ, j, k is calculated:

\[
\overline{a}_{i,j} = \frac{1}{K2 - K1 + 1} \sum_{k=K1}^{K2} a_{i,j,k}
\]  

(3.1)

where \(i, j, k\) denote the \(x, y, z\), and \(\sigma\) directions, respectively. In this way, a value \(\overline{a}_{i,j}\) that is representative for the column \((i, j)\) is found. One could also say that (3.1) represents a pressure weighted mean because the \(\sigma\) levels are defined so that each layer above the planetary boundary layer contain equal masses. To find \(\overline{a}_{i,j}\) in a cloud-free column, an artificial cloud top and cloud base are taken from the average cloud top \(\overline{K}1\) and cloud base \(\overline{K}2\). Here \(\overline{K}1\) and \(\overline{K}2\) are the arith-
metric mean values for the whole grid area of the $K_1$ and $K_2$ values of the columns with cloud cover. Thus, $\bar{a}_{ij}$ is also obtained for cloud-free columns. It is thus possible to compare observed cloud cover and any quantity $\bar{a}_{ij}$ column by column.

This method has its limitations. Multilayer clouds cannot be detected by the classification scheme. On the other hand there are ten layers in the model. In the specific situation used here, the values of $K_1$ and $K_2$ give an average cloud top and cloud base at $\sigma$-levels 5 and 7, respectively. This indicates that the majority of columns with cloud have a vertical extent of two or three grid boxes (or about 250 mb). If the clouds are multilayered, most of them will be of subgrid scale in the vertical (i.e., the grid is vertically too coarse to resolve them). The averaging represented by (3.1) may also smooth out important vertical variations in the quantities, especially if the cloud column is deep. But, since the majority of columns with cloud have a vertical extent of 2–3 grid boxes, one should believe that most of the average values are representative for the corresponding columns and that (3.1) does not change the picture severely.

4. Choice of situation

The situation chosen for this case study is a cyclone coming from the west and passing the Norwegian Sea between 0900 and 1500 UTC 27 August 1988. Satellite data from NOAA 10 was obtained for about 0840 UTC 27 August 1988 and NOAA 9 for about 1425 UTC 27 October 1988. None of the two datasets fully cover the model area; about 50% is covered by SCO in each case. However, the satellite data are not covering the same areas at the two times. The two SCO datasets coincide within about half an hour with the 21-h and 27-h forecast times. The cloud cover given by the SCO at the two times is shown in Figs. 1 and 2.

There are several factors that were considered when a situation suitable for this case study was chosen. It is important to avoid a too complicated type of situation. As stratiform cloud cover is to be studied, it is obviously an advantage to use a case with a minimum of convection.

It is very important that the model and observed atmospheres are closely in phase with regard to the motion systems when choosing to produce “analyses” by integrating the prognostic model. If this is not the case, a column-by-column comparison is of little use. Judging from studies done by comparing predicted and analyzed surface pressures, it is found that the model prognosis and the analysis agree quite well in both cases. Maps of the surface pressure analysis and the simulation are shown for both sampling times in Figs. 3a–d. It should be mentioned here that the rms error in the

Fig. 2. Satellite observed cloud cover 1500 UTC 27 August 1988. The scale to the left shows the shadings for the different fractional cloud covers.
5. Results from the comparisons

To investigate the correlation between different quantities derived from the analysis (model output) and the cloud cover of SCO, the column quantities are plotted in a scatter diagram. In this type of diagram, the vertical axis represents the SCO cloud cover $b$ of a column, while the horizontal axis represents the analyzed quantity. After an examination of a great number of scatter plots, it has been found that relative humidity, $U$, is the only quantity that provides useful signals of the cloud cover situation. This is contrary to the conclusion made by Slingo (1980). However, Slingo (1980) investigated data associated with convection (GATE). For convection, it is quite likely that a quantity other than $U$ shows a relation to the cloud cover. The scatter diagram from the 0900 UTC time is shown in Fig. 4. At first sight, the diagram seems to have too high a degree of scatter to be of any use. However, a more careful examination shows that there is a positive correlation between relative humidity and cloud cover. This feature is better visualized in a frequency distribution of cloud-cover occurrence as function of relative humidity. Figure 5 shows that the relative humidity value of the modes in the different frequency distributions increases as $b$ increases.

In order to explain the scatter, it is desirable to find some characteristics of the columns that have a large deviation from the mode of the different distributions. To do this, some general features of the atmosphere and the grid are focused on first. Another important factor that one should have in mind, is that there also

Fig. 3a. Analysis of surface pressure 0900 UTC 27 August 1988.
are uncertainties in the cloud classification method (Raustein 1989; Arking and Childs 1985).

The fact that the upper layers are generally very dry implies that small changes in the prognostic variable $q$ (specific humidity) may lead to large changes in the relative humidity $U$, which is a diagnostic variable. Provided that the cloud cover is dependent on $U$, such changes will also lead to large changes in the cloud cover of the upper levels. If the $q$ fields that are used for the comparison have small perturbations relative to the real fields, a relatively large degree of scatter will result. The grid-box geometry may also play a role. Since the volume of the higher grid boxes is large, there is obviously a greater probability for an unevenly distributed relative humidity within the box. This makes it more difficult to interpret the value representative of the grid box, thus causing a large scatter.

Figure 6 confirms this statement to some extent. Here, observed cloud top height as a function of analyzed relative humidity is plotted. Only columns with $b = 100\%$ are included. The plot shows that there is a greater variability in relative humidity for high- and mid-level clouds than for low clouds.

Figure 6 also leads to separation of the different scatter regions, namely one with columns with cloud tops higher than 3 km and one with cloud tops lower than 3 km. Columns in the latter region are plotted in Fig. 7.

The artificial cloud top and cloud base calculated for cloud-free columns (mentioned in section 3) were the average cloud top and cloud base computed on the basis of the total number of columns in the diagram. Since only the columns of the lower (or higher) levels are plotted, new values of $K_1$ and $K_2$ will appear. This explains the difference in the distributions of columns with $b = 0$, which is evident from Fig. 5 and Fig. 8. The scatter plot for the lower region contains considerably less scatter than the one including the total number of columns, especially for high cloud-cover values. Figures 4 and 7 show that the standard deviations are significantly reduced (in some cases by 50\%) by excluding columns with cloud top higher than 3 km. Both Figs. 4 and 7 contain three different measures for the centers in the frequency distributions. Namely, the mean value, the median, and the mode of the distribution. Figures 5 and 8 show that the distributions
become more skewed as cloud cover increases. This fact separates the mode from the mean value and the median for large cloud-cover values. Relative to the mode, the median lies out in the direction of the tail, and the mean lies even farther out. If the modes of the distributions are considered, Fig. 7 shows that there is a pronounced positive correlation between the cloud cover and the relative humidity. This correlation is weaker if the medians and the means are considered. The mode is defined as the most frequent value of the distribution. Since the cloud cover will be diagnosed, it is an advantage that a diagnosed value matches the most frequent value in an observation. Consequently, the modes in Fig. 7 give a basis of a formation of a parameterization expression.

The frequency distributions in the case with cloud tops lower than 3 km are shown in Fig. 8. Compared to Fig. 5, one can clearly see that the distributions here have become more narrow and that the $b = 100\%$ curve has no distinct maximum in Fig. 8, but rather generally increases with increasing $U$.

A feature that may contribute to the large scatter in the upper levels is, as mentioned in section 2a, that the initial humidity fields in the upper layers are markedly smoothed and may therefore lead to unrealistic values over a substantial part of the integration period. It will be shown in section 6 that there is no correlation between the true analyzed humidity fields and the satellite derived cloud cover at the two observation times. This indicates that the humidity field has become more realistic during the integration period as the model has had time to structure this humidity field. Thus, it is likely that the humidity analysis and, probably to a lesser extent, the humidity treatment in the model cause some of the large degree of scatter in Fig. 7. Furthermore, in the estimation of the cloud top, the assumption about a fixed lapse rate may lead to significant errors, especially for the upper levels. If it is assumed that $b = 100\%$ for a column and the estimated cloud top is too high, then the cloud may be unrealistically extended up into drier parts of the column, which leads to a too low $\tilde{U}_{i,j}$ value given from (3.1). The result would be a point in the scatter diagram that has maximum value but has a too low $x$ value. These factors definitely contribute to the large scatter in upper levels.

Figure 9 shows the same type of plots as Fig. 7, but...
for the 1500 UTC situation. One can clearly recognize the same features as those of the 0900 UTC situation. However, the rate of increase of $b$ with respect to $u$ seems to be smaller than in Fig. 7. Also the points in the cloud-cover interval $[10, 80]$ (in %) seem to be situated more to the left in Fig. 9 than in Fig. 7. It is difficult to find a reason for this. However, Figs. 1 and 2 show that there are a lot more SCOs over land in the 1500 UTC case than in the 0900 UTC case. This may indicate that there are different conditions for cloud formation over sea and land.

The results show that the data material contains fairly distinct features so a relation between relative humidity and fractional cloud cover is attempted to be found.

a. Specific relations between relative humidity and cloud cover

Consider the cloud-free columns in Fig. 8 (the full line). From this distribution, the mean value is found to be $\bar{U} \approx 67\%$ and the standard deviation $\sigma_u \approx 11\%$. For the 1500 UTC situation (Fig. 10), the corresponding values are $\bar{U} \approx 61\%$ and $\sigma \approx 13\%$. Note that the mean values, the medians, and the modes have approximately the same value in these distributions ($b = 0$).

If the full lines in the two distributions for $b = 0$ at 0900 UTC are replaced by the standard normal distribution, it is readily found that 90% of the columns lie within the interval

$$U \in [\bar{U} - 1.6\sigma, \bar{U} + 1.6\sigma],$$

where $\bar{U}$ is the mean relative humidity for the distribution of columns where $b = 0$. Here the upper limit of the interval may be used as the threshold value $U_{90}$ for condensation to appear. When the corresponding values of $U_{90}$ and $\sigma$ for the two data moments are put into the expression of the upper limit, $U_{90} = 85\%$ for the 0900 UTC data and $U_{90} = 82\%$ for the 1500 UTC data. These values for $U_{90}$ are quite close to the values used in Sundqvist et al. (1989). A visual inspection of the analyzed data shows that a simple linear relationship in relative humidity gives a reasonable description of the cloud-cover data:
Fig. 4. Predicted relative humidity and satellite observed cloud cover at 0900 UTC are plotted column by column in the scatter diagram. The y-axis represents the cloud cover in tenths and the x-axis represents the relative humidity in percent. The solid line passes through the medians of the data in each of the eleven cloud cover values. The dashed line passes through the modes of the frequency distributions for each cloud cover number. The open circles denote the mean values and the brackets indicate the standard deviation from the mean in each of the eleven cloud cover values.

\[
b = 0 \quad \text{when} \quad u < u_{00}
\]
\[
b = \frac{b_{\text{max}} - b_{\text{min}}}{U_s - U_{00}} (U - U_{00}) \quad (5.2)
\]

where \(b_{\text{max}} = 100\%\), \(b_{\text{min}} = 0\), and \(U_s = 100\%\).

In Sundqvist et al. (1989), the following diagnostic relation between relative humidity and fractional cloud cover is used:

\[
b = 0 \quad \text{when} \quad U < U_{00}
\]
\[
b = 1 - \left(\frac{U_s - U}{U_s - U_{00}}\right)^{1/2} \quad \text{when} \quad U > U_{00} \quad (5.3)
\]

where now \(U_{00}\) is a threshold value for when condensation is allowed to take place in a grid box.

In the present model version, the values \(U_{00} = 85\%\) over sea and \(U_{00} = 75\%\) over land were used. Both relation (5.2) and (5.3) yield good representations of the data both in Fig. 7 and Fig. 9. Relation (5.2) and (5.3) are shown in Fig. 7.

Considering the two suggested parameterizations, it is seen that the one suggested in (5.2) seems to make the best fit to the curve through the modes of the frequency distributions in Fig. 7. Correspondingly, (5.2), with a smaller value of \(U_{00} (75\%)\), seems to be the best representation for the data in Fig. 9. On the other hand, with \(U_{00} \in [75, 85]\) (in %), both parameterization expressions clearly underestimate \(b\) in the interval \(b \in [10, 70]\) (in %) in the 1500 UTC case. In this connection it may be observed that the cloud parameterization suggested by Slingo (1987) is qualitatively the same type of curve as (5.3).

Keeping in mind that Figs. 7 and 9 are based upon data where columns with cloud top higher than 3 km are removed, it is evident that the number of cloud-free columns is quite large relative to the total number of columns used. Thus, the distribution of columns where \(b = 0\) is statistically more reliable than the distributions where \(b \in [10, 70]\) (in %). Thus the interval...
Fig. 5. Normalized frequency distributions for three different cloud cover values at 0900 UTC. The solid line represents the distribution for \( b = 0 \). The dotted line represents the distribution for \( b = 50\% \). The dashed line represents the distribution for \( b = 100\% \). In each distribution the maximum and minimum relative humidity are found. The interval between these two values is divided into 20 even parts. These parts make the intervals in which the observations are summed.

Var. Of RH With Z

Fig. 6. Cloud-top height plotted against relative humidity (0900 case). Only columns with \( b = 100\% \) are included.
Fig. 7. Scatter plot of cloud cover versus relative humidity where only columns with cloud top lower than 3 km are included. The solid line represents (5.2) and the dashed line represents (5.3) (see text). The filled circles denote the mean values and the brackets indicate the standard deviations. The open circles denote the medians of the distributions and the open triangles denote the modes.

Fig. 8. Same as Fig. 5, but only columns with cloud top lower than 3 km are included.
Fig. 9. Same as Fig. 7, except that 1500 UTC data are used here and only columns with cloud top lower than 3 km are included. (The mean values and standard deviations are not included here.)

Fig. 10. Same as Fig. 8, except that 1500 UTC data are used here.
(5.1) should be a quite satisfying way to determine $U_{oo}$. Based on this limited material, (5.2) seems to fit the data slightly better than (5.3). However, investigations of several cases should be carried out to make a more confident determination of a parameterization expression. Additionally, it should be mentioned that linear relationships, and also (5.3), are used in several NWPs. Thus it is believed that these data (to some extent) justifies the use of them.

Even though the examined parameterization relations are based upon columns with cloud top lower than 3 km, it is assumed that the relations apply to the whole model atmosphere. With regard to the scatter in the upper levels, a more confident assumption for those layers requires larger samples and a thorough consideration of the humidity analysis.

b. Other quantities than relative humidity

The other quantities have been found to have had little relationship to the cloud cover. Among others, the vertical velocity, advection of thickness, advection of equivalent potential temperature, relative vorticity, and stratification have been treated in the same manner as $U$. An example is shown in Fig. 11. This is a scatter plot of equivalent potential temperature advection and SCO data. In addition to the fact that there is a high degree of scatter, the frequency distributions of the individual values of the cloud cover (not shown here), corresponding to those in Fig. 10, show that all the modes $X_m$ in the distributions have values $X_m \approx 0$.

An explanation may be obtained as to why there is so (unexpectedly) little information in those other quantities by studying the relative humidity and the map of equivalent potential temperature in Fig. 12. The horizontal gradients are sharp in a narrow area in the vicinity of the frontal zones. However, this area is small compared to the cloudy areas. Therefore, for example, a quantity involving the horizontal equivalent potential temperature gradient has a broad spectrum of values where the cloud cover has little variation. This leads to a large spread in the scatter diagrams.

6. Humidity analysis

The Introduction notes that the humidity analysis might not represent the actual situation as well as predicted humidity fields do. Therefore, a comparison of the actually analyzed humidity fields and the SCO data have been promoted at 0900 UTC and 1500 UTC. The results of these comparisons (0900 UTC case only) are shown in Fig. 13. This figure corresponds to Fig. 4

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**Fig. 11.** Scatter plot of cloud cover and advection of equivalent potential temperature. Total number of columns are included.
(the predicted case), while Figs. 14 and 15 correspond to Figs. 5 and 7, respectively.

From these figures it is seen that there is not much difference in the degree of scatter in the two cases. But, if the modes in the frequency distributions of each cloud-cover value at 0900 UTC are considered, the rather monotonic increase in cloud cover with relative humidity is not found in the comparisons with the true analyses. In fact, Fig. 14 shows that the peak relative humidity is lower for \( b = 100\% \) than for \( b = 50\% \). Figure 15 shows that columns with cloud cover \( b > 90\% \) have \( U \) values about 80%–90%. Since more than half of the total number of columns have cloud cover \( b > 90\% \), such a distribution indeed indicates that the analyzed humidity field is drier than the predicted humidity field.

This is also the case for the 1500 UTC situation. Here the scatter diagrams and frequency distributions show that only a few of the columns have \( U > 85\% \) and there is no (or very weak) coupling between cloud cover and relative humidity in the interval \( b > 30\% \). Like the situation at 0900 UTC, the modes in the different distributions are more or less situated on a vertical line in the diagram (Fig. 13). This fact is also illustrated in Fig. 15.

The effect of excluding the columns with cloud top higher than 3 km has been investigated also in this case. It is interesting to find that in both the 0900 and 1500 UTC cases (0900 UTC case is shown in Figs. 13–15), the degree of scatter is reduced with a magnitude that is more or less the same as in the cases where predicted fields were used as analyses. But, there is still a less distinct coupling in the analysis fields than in the predicted fields.

These results indicate that the humidity field, predicted with the present model, is more realistic than the analyzed humidity at the corresponding time. This implies that the conventional humidity analyses cannot be used for verification of humidity from model simulations. Obviously a general improvement of the humidity analysis is needed. To make progress in that respect, it will probably turn out to be advisable to utilize cloudiness quantities derived from satellite measurements in combination with first guess fields obtained from integrations of models with advanced condensation treatment.
Fig. 13. Same as Fig. 4, but with use of the actually analyzed relative humidity.
(Mean values and standard deviations are not included here.)

Fig. 14. Same as Fig. 5, but with use of the actually analyzed relative humidity.
7. Conclusions

In the present study, possible relations between fractional cloud cover and other (synoptic scale) meteorological quantities have been investigated. The fractional cloud cover was obtained from satellite measurements (Raustein 1989), and the other parameters were derived from analyses and from predictions that have been utilized as analyses. The objective of the work has been to use satellite data to contribute to an enhanced insight into relations between stratiform cloud cover and other meteorological variables on resolvable scales in a model.

The results have shown a quite pronounced correlation between fractional stratiform cloud cover and relative humidity. Comparing the cloud quantities obtained from satellite data with the other quantities analyzed on the model grid, it is found that the relative humidity is the only parameter that shows an unambiguous relation with the fractional cloud cover. Consequently, two specific relations for description of the stratiform cloud cover in the model are discussed in section 5a.

A linear relation in relative humidity (5.2) and a relation described in Sundqvist et al. (1989) seem to make a good fit to the data investigated. It should be noted here that these proposals are based on data from the lower troposphere (0–3 km) and a confident assumption of the upper layers requires larger samples and a thorough consideration of the humidity analysis. One should also note that this study is limited to one weather situation. Hence, larger continuous samples of data, including time periods between storms, are required to make a more confident verification of the validity of the relationships obtained here.

Since the humidity analysis has turned out to be somewhat unrealistic, prediction fields were utilized as analyses. As the prediction field is connected with small phase errors, this might contribute to a somewhat fuzzy coupling between fractional cloud cover and relative humidity.

Since this use of satellite measurements appears to give valuable information of the stratiform cloud cover, there is reason to assume that encouraging results could be obtained in a corresponding study of convective clouds, in which case probably some other resolved parameter(s) (e.g., stratification) will turn out to show the highest degree of correlation.

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