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Analyses and short range forecasts of cloud cover.

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Abstract

The issue of analysing and predicting cloud cover accurately is considered in the context of the numerical road condition model 'ROCMO' (ROad Condition MOdel) used operationally at the Danish Meteorological Institute (DMI). A procedure for analysing cloud cover is presented. The analysis is based on the combination of information from synoptic observations and a 'first guess' from an atmospheric forecast model. Current developments are based on a coupled model system where ROCMO is called from the 3-D atmospheric model. The new cloud analysis scheme is used in the data assimilation procedure of the atmospheric model to improve the initial state of the atmospheric model, and is also used inside ROCMO to specify the initial cloud cover. The cloud cover analysis utilizes detailed information from synoptic reports which provide the basis for analysing a vertical cloud structure. A strategy for further development of the 3-D cloud analysis and short range cloud cover forecasts is outlined.

Resumé

Problemet at analysere et 3-D skydække præcist behandles i denne rapport, som skal ses i forbindelse med en udvikling af modelprognosesystemet 'ROCMO' for glatførevarsling, anvendt ved Danmarks Meterologiske Institut (DMI). En ny metode præsenteres til analyse af det 3-dimensionale skydække. Metoden er baseret på en kombination af skydækkeprognoser fra den operationelle numeriske vejrprognosemodel 'DMI-HIRLAM' og detaljerede skydækkeobservationer fra synoptiske vejrstationer i Danmark. Flere informationer giver grundlaget for at analysere en mere detaljeret vertikalstruktur for skydækket. Den igangværende modeludvikling er baseret på et koblet modelsystem hvor ROCMO kaldes fra den 3-dimensionale atmosfæriske model. Den nye skyanalyse kan anvendes i ROCMO samt under data-assimilering i DMI-HIRLAM til at forbedre atmosfæremodellens begyndelsestilstand. Strategien for den videre udvikling af 3-D skydækkeanalyser og prognoser diskuteres.

1. Introduction

Clouds are an essential part of daily weather. Physically clouds may be defined as a volume of saturated air containing cloud condensate , e.g., cloud droplets, ice crystals and/or other hydrometeors in a certain concentration.

The present report is concerned with cloud analysis and short range cloud predictions in the context of the Road Condition Model (referred to as ROCMO =ROad Condition MOdel) used operationally at the Danish Meteorological Institute (DMI). This numerical model (Sass, 1997) predicts road conditions including the road surface temperature, using forecast input from the atmospheric model DMI-HIRLAM used operationally at DMI (Sass et al., 2002). A realistic and detailed cloud cover prediction is essential for the quality of the predictions with ROCMO. This has been revealed clearly by case studies and is also consistent with the general knowledge that the radiative impact of clouds on the energy budget at the surface is strong, both with respect to longwave radiation and solar radiation. Reports including verification of operational forecasts with the ROCMO system are available, (Kmit and Sass, 1999; Sass and Petersen, 2000). A verification of cloud cover, however, has not been included in these reports on the operational verification.

From satellite pictures it is evident that cloud structures can be quite complex showing a large variability down to very small scales in the horizontal. Frequently, the vertical variation is also large with several distinct cloud layers as clearly verified from aircrafts. This emphasizes the importance of analysing a 3-D cloud structure and not only total cloud cover as seen from the ground, because the radiative impact of high clouds is quite different from the impact of low level clouds, due to different radiative temperatures involved and different optical properties.

Also the cloud cover variability in time is very pronounced involving local cloud cover changes down to less than an hour. This is because the evolution of individual clouds or cloud sheets depends strongly on both the dynamical processes, e.g. on adiabatic compression or expansion of air, and on the physical processes such as turbulent mixing of air with different properties and the heating rate due to radiation inside clouds. In particular, the small scale circulations associated with turbulence and shallow convection may give rise to significant variations of cloud cover, implying large fluctuations in the net radiation at the ground. This may consequently lead to critical temperature changes, implying that, for example, frost with slippery road conditions will occur.

The first versions of the cloud description used in ROCMO from the 1990s did not treat the vertical cloud structure in a realistic way, as will be mentioned in the section 2. Hence, a revised strategy for cloud analysis and short range cloud prediction has been designed and is documented in the present report.

An accurate forecast of clouds at a given location obviously requires observations of cloud cover at that site, and also that the changes of cloud cover can be predicted. One may claim that an atmospheric model involving the dynamical advections and the relevant physical processes connected to cloud evolution is a natural framework for cloud prediction. Hence it is natural to devote efforts on 3-D cloud analysis to be used in the atmospheric forecast model which provides input to the local site specific ROCMO.

Traditionally, the key data source in connection with cloud analysis in atmospheric models has been the moisture profiles achieved from radiosondes which are horizontally sparse compared to the model resolution needed for short range cloud prediction. In recent years it has become possible to run operational models with high resolution, e.g. with a grid size of 15 km or less. Then it becomes vital to make use of several data sources associated with moisture information, e.g., surface based reports related to cloud, and data from satellites.

There are potential problems associated with the application of synoptic observations of cloud cover together with cloud information from an atmospheric model, in this case DMI-HIRLAM. The problems can be summarized as follows:

The atmospheric model defines fractional cloud cover in every model layer in the vertical. It is defined as the fraction of the air volume covered by cloud assuming that the cloud is filling the grid box from bottom to top. Manual cloud cover observations, on the other hand, report total cloud cover, cloud base heigth and cloud types. The total cloud cover is defined as the fraction of a complete hemispheric sky view covered by cloud. Hence it is a challenge to convert the information in the cloud cover observation to a correction that can be applied for the cloud cover in the model layers of the atmospheric model.

Moreover, in order to analyse the cloud cover profile at a given location, e.g., at a road station site, it is generally considered necessary to combine a model cloud prediction in some mesh of grid points and observations at other locations.

Furthermore, a traditional quality control on cloud cover observation data is difficult due the large cloud variability in space and time. For this reason, and due to a generally good quality of synoptic cloud cover observations, some meso-scale analysis systems (Häggmark et al., 2000) do not apply quality control to synoptic cloud cover observations.

On the other hand, a quality control of satellite data is considered necessary (Häggmark et al., 2000; Macpherson et al., 1996). Work on the combination of atmospheric model forecast fields with cloud cover related observations e.g. from satellites has been published in recent years, e.g., Macpherson et al. (1996). This work applies to the U.K. Met. Office meso-scale model and describes a cloud cover analysis procedure which is a part of the socalled Moisture Analysis Preprocessing System (MOPS). The two main steps in the analysis procedure of cloud cover may be summarized as follows:

First a correction to the complete cloud cover field is made using satellite radiation data, mainly the infrared radiation information. This step is in particular devoted to locate the cloud tops. Another step is that local cloud observations are used to correct the interpolated cloud field from the first step to form a modified cloud profile which in turn is needed to construct a relative humidity profile. This profile is used in the data assimilation in a way similar to a radiosonde observation. It has been shown (Macpherson et al., 1996) that data assimilation along these lines in the U.K. Met. Office mesoscale model, using the socalled 'nudging' approach (Harms et al., 1992), leads to improved cloud cover predictions at forecast ranges up to about 12-18 hours. This is a confirmation that cloud analysis procedures can lead to improved short range forecasts of clouds. The 3-D cloud analysis is still a development issue (Watkin, 2001).

A similar activity to make a 3-D cloud cover analysis which is subsequently assimilated into an atmospheric model has started at DMI (Sass and Petersen, 2002). The 3-D cloud analyses of the revised ROCMO system does currently not utilize satellite data although such data will be increasingly useful in the future with the growing availability of satellite data. An accurate prediction of road surface temperature is particularly sensitive to a precise specification of cloud base and the cloud amounts of low level, medium- and high level clouds. This information is provided by synoptic observations of cloud cover which are used in the present cloud analysis and checked for internal consistency.

In section 2 the ROCMO cloud scheme for analysis and short range forecasts is described. The cloud analysis procedure may be used both to improve data-assimilation in the dynamical atmospheric model and for local cloud analysis in ROCMO. The problem of analysing a vertical cloud cover structure is discussed, and a strategy for possible future developments is outlined in section 3.

2. A scheme for local cloud analysis and forecast

In the 1990s the ROCMO 3-D cloud cover was not available from the DMI-HIRLAM. Hence a diagnostic cloud cover was developed as a part of ROCMO. This cloud cover was a function of relative humidity and precipitation intensity from DMI-HIRLAM. Moreover, the total cloud cover in a vertical air column was determined from a maximum cloud overlap assumption from fractional cloud cover at individual model levels. Any detailed vertical variation of cloud cover was discarded from a radiative point of view. Physically, the total cloud cover was assumed to be present just above the lowest cloud base reported from synoptic observations.

For applications such as surface temperature prediction, it is not only important to know about total cloud cover, but also the vertical distribution of clouds. As a consequence, it seems necessary to utilize the full information on the vertical dependency of cloud cover, both in the atmospheric model and in the observations. As regards the model, the full information is the fractional cloud cover at all model levels. For the observations most reports contain more information than just the cloud base height for the lowest clouds and the total cloud cover. We may utilise reports about cloud base, height and cloud amount on different levels.

Moreover, the issue of combining the background atmospheric forecast with observations at the analysis time needs to be addressed. The quality of the background model forecast is also very important as regards the time evolution of the cloud cover. ROCMO has recently been integrated to the framework of the atmospheric model DMI-HIRLAM supplying the input data. This means that data can be easily exchanged between the two model systems during a forecast. For this reason it is natural to replace the diagnostic cloud cover formulation of ROCMO by the cloud scheme of the atmospheric model (Sass et al., 2002) which is under continued development and improvement.

2.1. Computational procedure

A revised analysis and forecast procedure taking into account the ideas mentioned above are presented below:

We divide the atmosphere into 3 parts representing low level clouds, medium level clouds and high level clouds, respectively. We attempt to analyse 3 separate cloud categories: C_{La}, C_{Ma}, C_{Ha} for low clouds, medium level cloud and high clouds, respectively. The analysed cloud cover for each part of the atmosphere is a linear combination of a model derived cloud cover and an observation based value. The weight function takes into account the age of the observations and the presence of clouds closer to the ground (valid for C_{Ma} and C_{Ha}) For the corrections of the model level cloud covers at the analysis time we adopt the principle that the DMI-HIRLAM cloud cover background value should not be corrected strongly unless a substantial modification is clearly supported by the observational data. In order to use the observations efficiently we also need to take into account situations where not all cloud categories are observed while a total cloud cover valid for the entire vertical air column is available. A preliminary assessment of the cloud covers associated with the medium- and high level cloud amounts may be adjusted if the total cloud cover determined from an overlap assumption disagrees significantly with the observed total cloud cover. The different steps in the computational procedure is described below.

1) We first interpolate a background HIRLAM full 3-dimensional cloud field C_{hir} to the sites of the synoptic cloud cover observations using bi-linear interpolation. The cloud cover formulation has been brought in agreement with the current operational cloud cover parameterization from the operational DMI-HIRLAM.

2) The atmospheric model determines the 3 cloud covers, C_{Lhir}, C_{Mhir} and C_{Hhir}, respectively, from a maximum cloud overlap assumption.

$$C_{Lhir} = Max\{C_{hir}(k)\}; 0 < Z_k \leq Z_L \quad (1)$$

$$C_{Mhir} = Max\{C_{hir}(k)\}; Z_L < Z_k \leq Z_M \quad (2)$$

$$C_{Hhir} = Max\{C_{hir}(k)\}; Z_M < Z_k \leq Z_H \quad (3)$$

In (1), (2) and (3) Z_k is the height above ground of the model level and Z_L, Z_M and Z_H are threshold heights defining the intervals for the three different cloud types. In order to be compatibel with traditional observational reports we currently set $Z_L = 1000m$, and $Z_M = 2500m$. Z_H is the top model level height which is high enough to contain all high clouds in the troposphere and in the stratosphere.

3) In the next step we assign an observed fractional cloud amount for low, medium and high clouds. Such assignment is most easily done in the case there are cloud reports in the relevant height intervals mentioned above. These cloud covers are named C_{Lob}, C_{Mob} and C_{Hob}, respectively. In addition we expect always that a total cloud cover C_{tob} is available. First it is demanded that any cloud report consists of a cloud amount and an associated cloud base height. Otherwise the information is disregarded. The situation is such that there may be 3 cloud cover reports, but these do not necessarily include all the 3 mentioned cloud categories. Up to 3 reports may apply to the same cloud category. In this case the cloud cover for that category is taken to be the sum of the reports in the relevant height interval with the restriction that the result must not exceed the total cloud cover C_{tob} reported. Furthermore, the average of multiple cloud base reports for a given category is taken as the reported cloud base.

If the lowest cloud cover reported belongs to the high or medium cloud category we infer a zero cloud cover observation at the cloud base level(s) for medium and/or low level clouds closer to the ground. The associated cloud base height is then taken to be the HIRLAM model level just below the level of the maximum fractional HIRLAM cloud cover (C_{Mhir} and/or C_{Lhir}). In case that all the HIRLAM fractional cloud covers are zero the model level closest to the middle of the relevant height interval is chosen for the considered cloud category.

We have now assigned *observed* couples of cloud cover and cloud base for the different cloud categories.

4) We then need to *analyse* cloud covers and cloud base heights for the 3 categories.

In the procedure to analyse these values the associated weight factors are W_L, W_M and

W_H, respectively. In the case of missing observational values for a specific category the weight factor is set to zero which implies that the background HIRLAM cloud cover is given full weight.

In the first analysis step we take into account the effect of clouds between the ground and the cloud category to be observed. The following formulae are used:

$$C_{La} = C_{Lob} \cdot W_L + C_{Lhir} \cdot (1 - W_L) \tag{4}$$

In (4) the weight factor is described as

$$W_L = J_{obL} \cdot exp\Big(- b_w \tau_{ob}\Big) \tag{5}$$

In (5) J_{obL} is an indicator being either 1 (observation is available) or zero (no observation is available). The exponential factor reflects the auto correlation coefficient. From observed cloud cover data it is estimated that $b_w = 2 \cdot 10^{-5} s^{-1}$. τ_{ob} is the age of the observation at that site.

$$C_{Ma} = C_{Mob} \cdot W_M + C_{Mhir} \cdot (1 - W_M) \tag{6}$$

In (6) the weight factor also depends on the low level clouds preventing to some extent observations of medium level clouds:

$$W_M = J_{obM} \cdot (1 - C_{La}) \cdot exp\Big(- b_w \tau_{ob}\Big) \tag{7}$$

J_{obM} is an indicatior similar to J_{obL}. Finally we compute for high level clouds

$$C_{Ha} = C_{Hob} \cdot W_H + C_{Hhir} \cdot (1 - W_H) \tag{8}$$

In (8)

$$W_H = J_{obH} \cdot (1 - C_{La})(1 - C_{Ma}) \cdot exp\Big(- b_w \tau_{ob}\Big) \tag{9}$$

In (9) an assumption of arbitrary cloud overlap of low and medium clouds has been made when computing the fraction of the sky for the high cloud interval that can be seen from the ground. J_{obH} is an indicator similar to J_{obL}.

For the *analysis* of cloud base heights we accept the observed values. In case of no cloud observations for a given category we still assign a cloud base height since it is in general necessary to analyse clouds of all categories. If the cloud cover of the HIRLAM model is larger than zero for some levels belonging to that category we select the level just below the maximum fractional cloud cover in the relevant model layers to be the cloud base height. This HIRLAM cloud base estimate is also used to 'overrule' the observed cloud base provided that the model level agrees well with the reported level (a tolerance of ± one model level is accepted). In case of zero HIRLAM cloud cover everywhere the model level closest to the middle of the height interval of the cloud layer is chosen.

As alredy indicated, specific assumptions have been made in the equations (4), (6) (8) , related to the weighting of the 'background' value from DMI-HIRLAM and the observation. The weight factor should take into account that medium- or high level clouds above low level clouds cannot be properly observed. For observations having zero age we assume that the weight assigned to the higher level clouds equals the fraction of the sky that can be seen from the ground observer. This assumption will automatically guarantee that no weight is given to medium- or high level clouds above an overcast sky due to low level clouds while maintaining the cloud cover from the atmospheric model. Also the value of the switch being zero or 1 assures that the cloud cover from the atmospheric model is used with full weight if there is no observation available.

Applying the random overlap principle between all three categories we get the following formula for the total cloud cover

$$C^*_{ta} = 1 - (1 - C_{La}) \cdot (1 - C_{Ma}) \cdot (1 - C_{Ha}) \tag{10}$$

It is emphasized that (10) will not strictly agree with the observed total cloud cover from the synoptic observation. Instead C^*_{ta} may be considered as a first guess value of the analysed total cloud cover C_{ta}.

There is not a general unique relation to convert observed low, medium and high cloud amounts to a total cloud cover. It is reasonable to use some combination of random and maximum overlap between all model layers, for the following reason: A completely random overlap between the cloud covers of all model levels is not invariant to the number of model levels and will tend to give loo large cloud amounts with an increasing number of model levels. Also the maximum overlap assumption of all model levels as used in the original ROCMO scheme is not ideal, because it does not account for the possibility of independent horizontal positioning of different cloud layers which inherently influence the observed value of total cloud cover.

The largest possible difference between a maximum overlap assumption of all cloud levels and a combination of a maximum and a random overlap according to eq.10 equals

$$f(C_{tm}) = 1 - C_{tm} - (1 - C_{tm})^3$$

This maximum difference is shown in figure 1. It occurs only if the three analysed cloud covers C_{La}, C_{Ma} and C_{Ha} are all equal. For most atmospheric states the difference will be considerably smaller than shown in figure 1.

5) A preliminary analysis of all 3 cloud categories including associated cloud base heights for each category is available at this stage. The last correction step serves to improve the analysis in case that the observation of total cloud cover provides a substantial additional information to make a correction to the preliminary analysis reasonable.

In analogy with the analysis of the individual cloud categories we determine the total cloud cover C_t as a combination of the observed value C_{tob} and the HIRLAM based value C_{thir} determined from a random overlap assumption, that is,

$$C_t = W_t \cdot C_{tob} + (1 - W_t) \cdot C_{thir} \tag{11}$$

In (11)

$$W_t = \exp(-b_w \tau_{ob})$$

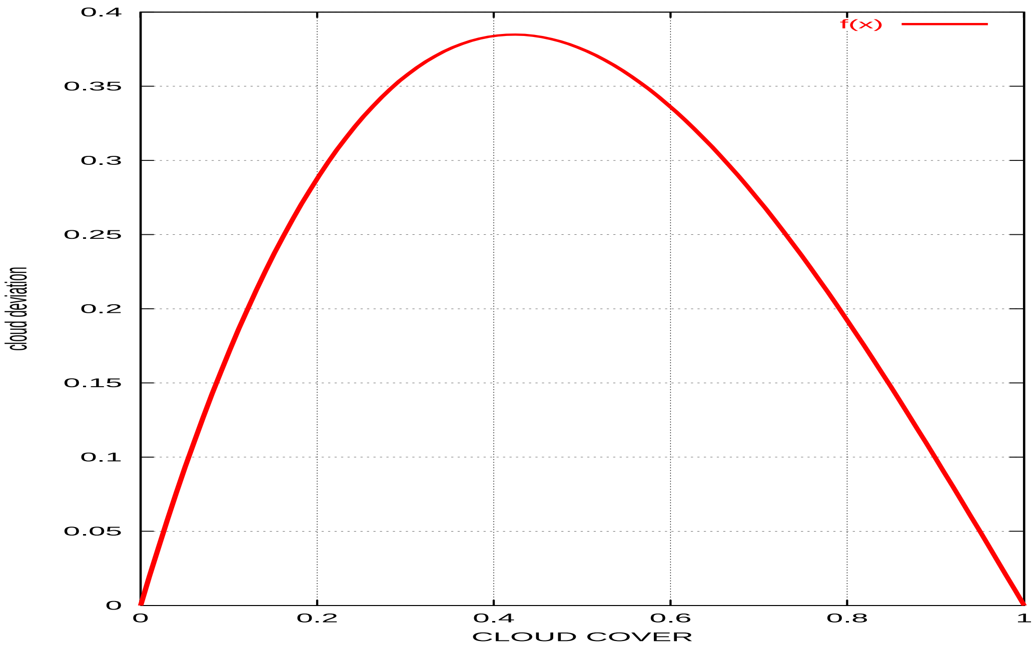

Figure 1: Maximum cloud difference $C_t - C_{tm}$ between the two formulations for total cloud cover.

$$C_{thir} = 1 - (1 - C_{Lhir})(1 - C_{Mhir})(1 - C_{Hhir})$$

Before deciding on a possible cloud correction a comparison is made between the estimated total cloud cover C^*_{ta} according to eq.10 and the observation estimate according to eq.11. In general we may consider the observed value of the lowest occurring cloud category as being most accurate. This is in agreement with previous arguments because there are no lower level clouds to prohibit a full sky view. Hence the decision has been to correct only medium and high level cloud cover provided that the two estimates according to eq.10 and eq.11 differ by a certain value which should reflect observation uncertainty. The assignment of an observation uncertainty for total cloud cover is of some importance in a correction procedure using the current cloud formulae. This is mainly important close to saturation conditions and overcast skies. We demand that the true analysed total cloud cover C_{ta} should lie in the interval

$$C_t - \epsilon_c \leq C_{ta} \leq C_t + \epsilon_c \tag{12}$$

In eq.12 ϵ_c is an estimate of the maximum uncertainty accociated with the total cloud observation. Currently it is estimated for all observations that $\epsilon_c = 0.125$ (1 octa). If the preliminary estimate C^*_{ta} is within the interval according to eq.12 no further modifications of the analysed cloud covers C_{Ma} and C_{Ha} will be made. However, if C^*_{ta} is outside the uncertainty interval we solve the following equation for the corrections of type $X \cdot C_{Ma}$ and $X \cdot C_{Ha}$, with X being a common factor for multiplying the preliminary cloud covers.

$$C_{ta} = 1 - (1 - C_{La})(1 - X \cdot C^*_{Ma})(1 - X \cdot C^*_{Ha}) \tag{13}$$

In eq.13 C_{ta} is chosen to be the value in the uncertainty interval closest to the preliminary value C^*_{ta}.

The equation (13) has always a physical solution for the correction factor X provided that C_{ta} is larger than C_{La}. The relevant solution is given in eq.14:

$$X = \frac{(C^*_{Ma} + C^*_{Ha})}{B} - \frac{\sqrt{\left((C^*_{Ma} + C^*_{Ha})^2 - 2B \cdot \frac{(C_{ta} - C_{La})}{(1 - C_{La})}\right)}}{B} \tag{14}$$

In eq.14 $B = 2C^*_{Ma} \cdot C^*_{Ha}$.

6) We finally need to establish an analysed cloud profile $C_{an}(k)$ at the road station sites for all model levels in order to make cloud cover forecasts at the road stations. The same problem exists when we want to establish analyses at the DMI-HIRLAM grid from the analyses at the synoptic observation points.

At this point it is important not to make an unrealistic smoothing of the vertical structure during the interpolation. When making interpolations for individual model levels to the DMI-HIRLAM model grid there is indeed a risk of a substantial reduction of the cloud cover maxima analysed at the synoptic stations. Displacements between neighbouring synoptic station sites of levels with maximum cloud cover, by one or more vertical levels, contributes to a reduction of the cloud cover maxima. To overcome this problem we interpolate the maximum cloud cover from each of the three cloud categories of low, medium level and high clouds, respectively. Also the corresponding cloud heights are interpolated. For example, an analysed low cloud cover C_{La} at a road station point p taking into account the synoptic observations is currently obtained from a horizontal interpolation function according to (15):

$$C_{La} = \frac{\sum_{i=1}^{l} F_p(i) \cdot C_{La}(i)}{\sum_{i=1}^{l} F_p(i)} \tag{15}$$

The weight function $F_p(i)$ declines strongly with increasing distance between analysis position and observation position:

$$F_p(i) = exp\Big(- \frac{d_p(i)^2}{d_{00}^2} \Big)$$

d_{00} is a scale distance chosen to be 50 km which appears to be consistent with observational studies, e.g., Macpherson et al. (1996). A corresponding interpolation is used for medium and high level clouds.

If interpolation takes place to a DMI-HIRLAM grid, the problem exists that the distance to synoptic observation points may be too large for any significant influence. In this case the original value is retained in the model grid. Currently the background cloud cover of DMI-HIRLAM is not corrected if the distance to all synoptic observations exceeds 150 km.

The total cloud cover C_{tan} analysed at the road station (or DMI-HIRLAM grid) is then computed according to the previously mentioned random overlap assumption.

The interpolated analysed cloud amounts for the 3 categories are assigned to the model level closest to the interpolated analysed cloud base heights. Currently an additional constraint is imposed on cloud depth of the different types. It is demanded that low clouds are at least 200 m thick. The corresponding thresholds for medium level and high level clouds are 600 m and 1000 m respectively. These fairly high threshold values for cloud thickness implies that the present implementation of the cloud analysis makes no attempt to analyse very thin cloud covers.

In case that more than a single model level is needed to fulfil this requirement the level(s) above and below having the highest effective relative humidity (determined as total specific humidity divided with the saturation value) will be chosen as an additional level carrying the cloud amount associated with that cloud category.

At all the remaining model levels we first interpolate the original HIRLAM cloud covers using bi-linear horizontal interpolation (valid for road station sites). For levels belonging to a given cloud category the interpolated HIRLAM cloud covers are constrained to be no larger than the analysed value for that category. Below the analysed cloud base for low clouds all model cloud covers are set to zero. After having carried out these steps an analysed cloud profile has been determined.

For consistency, the specific humidity is adjusted for levels where cloud cover has been significantly modified. This adjustment is made in order to make the relative humidity approximately consistent with the cloud cover. The actual adjustment should depend on the cloud parameterization of the atmospheric model.

It is noted that the lowest cloud base has a significant effect on the analysis because of the possible removal of HIRLAM cloud covers below the analysed cloud base. For medium and high clouds the present procedure allows for non-zero cloud covers below the main levels containing the maximum cloud covers. This may be justified to some extent by noting that it is most easy to observe the lowest cloud base height.

7) If the forecasted cloud cover of DMI-HIRLAM were perfect, the cloud cover forecast supplied to ROCMO could also be perfect apart from inaccuracies introduced in connection with interpolation procedures. In reality the cloud cover is not perfect. It is natural to allow for a prognostic formulation in ROCMO which combines locally analysed cloud cover, at the specific site considered, with forecast information from DMI-HIRLAM. For this purpose eq. 16 has been successfully used (see the next subsection). This equation describes a cloud cover $C(p, k, \tau)$ valid at point p in the horizontal, at the level k in the vertical and at time τ. The formula is used for all model levels, except at the levels representing the maximum cloud cover of each cloud category (low, medium and high clouds).

$$C(p, k, \tau) = C_{hir} + (C_{an}(k) - C_{hir}) \cdot exp\Big(- \frac{b_{c1} + b_{c2} \cdot |V(k)|}{(1 + b_{c3}|C_{hir0}(k) - C_{an}(k)|)} \cdot (\tau - \tau_0)\Big) \quad (16)$$

In (16) $b_{c1} = 1.0 \cdot 10^{-5} s^{-1}$, $b_{c2} = 2.0 \cdot 10^{-6} m^{-1}$, and $b_{c3} = 3$. τ_0 signifies the initial time of the prediction and $\tau - \tau_0$ is the forecast length. C_{hir}=$C_{hir}(p, k, \tau)$.

The reasoning behind (16) is that the transition to the atmospheric background field should perhaps be slower if there initially is a large deviation between first guess $C_{hir0}(k)$ (interpolated HIRLAM cloud cover at the road station) and the analysed value $C_{an}(k)$, expressed by the term in the denominator. The term proportional to the numerical value of the model wind speed $|V(k)|$ at that level expresses qualitatively that advection effects are potentially more important as the wind speed increases (the local observation will not last for long periods in the case of a strong cloud cover advection). Finally, a local source term b_{c1} is included in the nominator. If, for example, the cloud cover exhibits a diurnal cycle which the atmospheric model is able to describe it is reasonable to choose a value of b_{c1} larger than zero. The values given above for b_{c1}, b_{c2} and b_{c3} should be regarded as tuning constants depending on the atmospheric forecast model.

For the remaining levels, representing analysed (maximum cloud cover) of each cloud category, an equation similar to (16) is used, except that the analysed and first guess values of the cloud cover, representing the cloud category, appear instead of the local values. The time variation described at these levels represents the time evolution of maximum cloud cover for each cloud category.

For long forecast lengths the atmospheric model's cloud cover profile is uniquely guiding the solution.

2.2. Examples and verification tests

In the following two examples we briefly illustrate some basic properties of the cloud analyses made with the ROCMO analysis scheme. The option of a maximum cloud overlap configuration (old ROCMO system) is compared with the results of combining random and maximum overlap (new ROCMO configuration).

The first example is illustrated in figure 2 which illustrates a fictitious situation where medium level clouds have not been observed. Low level cloud cover and high level cloud cover have been observed to be 25 % and 50 %, respectively. In this case the model background field (10 percent) for high clouds is clearly in disagreement with observations. The result of the basic analysis for the 3 cloud categories is shown for the old ROCMO analysis (third column) and for the new analysis (fourth column). The results are displayed such as to illustrate the consequences of a maximum overlap and a random overlap of the cloud amounts for the individual cloud categories. In this figure the random overlap principle is also used to display the results of the DMI-HIRLAM cloud data.

It is seen that the old ROCMO diagnosis is in significant disagreement with the observed cloud structure. For the new scheme the preliminary analysis of the high clouds is slightly affected by the medium level and low level cloud amount ($C^*_{Ha} = 0.37$), and the preliminary analysis of medium level clouds is equal to the model's background value (C^*_{Ma} =0.10). Then the preliminary total cloud cover becomes C^*_{ta}=0.58 which is too far away from the observed and analysed total cloud cover (0.80) to prevent a correction by means of (14). The final analysis then leads to a reestablishment of C_{Ha}=0.50 while C_{Ma}=0.13, C_{La}=0.25 and C_{ta}=0.675

The second example is illustrated in figure 3. In this case the observed low level cloud amount is still 25 %, but observations are missing for both medium level and high level clouds. However, the total cloud amount (100 percent) has been observed. This situation is shown in the first column. In the second column we assume the same low cloud amounts for DMI-HIRLAM as in the first example. The third column show how the cloud information will be interpreted by the old ROCMO cloud scheme. A 100 percent cloud cover will be analysed for low cloud amount while the HIRLAM first guess values higer up will be unaffected.

The new scheme on the other hand will retain the low cloud cover according to observations and will analyse a preliminary cloud cover $C^*_{ta} = 39\%$. for both medium and high clouds. Again the correction according to eq.14 has been applied since the total cloud cover observed is far from the preliminary analysis.

The two examples above illustrate that the vertical cloud structure of the cloud analyses may become quite different with the two analysis schemes. It has been confirmed from actual test cases with the ROCMO system that the vertical structure of cloud cover can lead to significantly different surface temperatures in a short range forecast. For example, an erroneous assignment of high clouds instead of low clouds may lead to a degradation of short range surface temperature predictions by several °C.

These findings are consistent with objective verification over longer time periods. The new cloud analysis used in ROCMO has been compared with the old version using max-

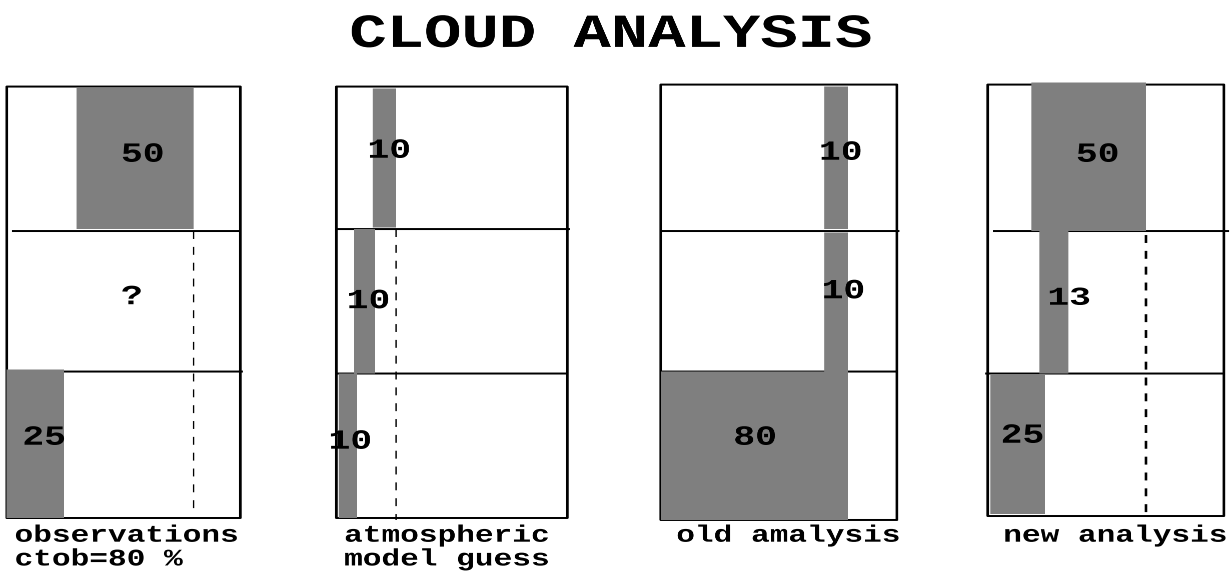

Figure 2: Example of a possible cloud analysis case (see text) where high , low clouds and total cloud amount (80 %) have been observed (first column). The other columns show the fictitious estimate from HIRLAM, from old cloud analysis scheme (third) and from new analysis scheme (fourth).

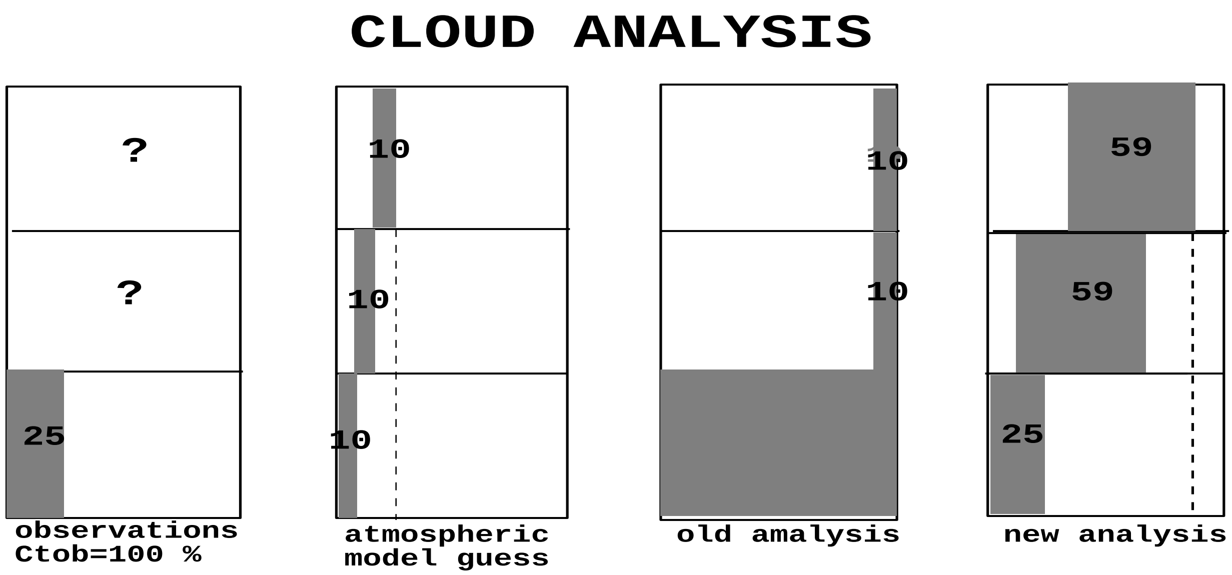

Figure 3: Example of a possible cloud analysis case (see text) where only low clouds and total cloud amount (100 %) have been observed (first column). The other columns show the fictitious estimate from HIRLAM (second column), from old cloud analysis scheme (third) and from new analysis scheme (fourth).

imum cloud overlap in parallel tests where the modified cloud analysis was the main difference in the two parallel model systems. The test period was October 2001 - March 2002. The verification shows that the percentage of forecasted surface temperatures with an error no larger that 1 °C has been increased from 82.67 % to 84.04 %. This verication is valid for 3 hour forecasts of road surface temperatures and includes the effect of all station forecasts which may be used in the verification (new forecasts every hour with more than 300 road station sites).

3. Concluding remarks

A new scheme for analysing 3-D cloud cover has been documented. The scheme provides the vertical cloud structure with some detail, in contrast to the previous scheme used in ROCMO. This has been possible because of the more detailed use of information from synoptic reports. Case studies and parallel runs with ROCMO during the winter season 2001-2002 confirm the increased potential of the new cloud analysis scheme.

The analysis of a realistic vertical cloud structure at a given model resolution is indeed a challenge due to the limited amount of detailed information on a vertical cloud structure. As a consequence, the combination of observations and first guess information from the model is vital for 3-D cloud analysis in the framework of an atmospheric model.

The present quality of the cloud analysis scheme is not only limited by the quality of the first guess from the atmospheric model, but also from the fact that only synoptic, surface based observations are used at present. New observation types should be used in the future to enhance the quality of the cloud analysis. Satellite data, becoming of better quality and with improved resolution, is the most obvious data source to be used as additional input in some form. The advantage of using more data types is that it offers improved possibilities to reduce uncertainties. As regards satellite data the view from above provides a natural way of reducing the uncertainty with respect to the analysis of high clouds. The introduction of more observational data implies that basic work on how to combine more data sources with the atmospheric first guess should be undertaken. From a forecasting point of view the full benefit of a cloud analysis should be seen in the context of a data-assimilation scheme. To enable further progress it is important to continue the current activities in this context.

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