Tellus (1996), 48A, 767–785
Printed in UK – all rights reserved

TELLUS
ISSN 0280-6495

Validation of modelled cloudiness using satellite-estimated cloud climatologies

By KARL-GÖRAN KARLSSON, *Swedish Meteorological and Hydrological Institute (SMHI), S-601 76 Norrköping, Sweden*

(Manuscript received 28 November 1995; in final form 22 April 1996)

ABSTRACT

A method to evaluate forecasts of total fractional cloud cover using satellite measurements is demonstrated. Cloud analyses in the form of monthly cloud climatologies are extracted from NOAA AVHRR data which are compared to corresponding cloud forecast information from the HIRLAM and ECMWF numerical weather prediction models. The satellite-based cloud information is extracted for a summer month in 1994 and a winter month in 1995 by use of the SMHI cloud classification model SCANDIA. Cloud analyses are conducted for an area covering a substantial part of northern Europe. Deficiencies in forecasted cloud amounts are found for both models, especially the underestimation of cloudiness for short forecast lengths with the HIRLAM model. Forecast improvements using the HIRLAM model are indicated when introducing a cloud initialisation technique using cloud fields from initial 6-hour forecasts (first-guess fields). Future systematic validations using this technique are, however, needed to make firm conclusions on the general model behaviour. SCANDIA-derived cloud information is proposed as a valuable complement to other datasets used for cloud forecast validation (e.g., the SSM/I- and ISCCP data sets).

1. Introduction

Studies of clouds form an essential part of investigations of the hydrological cycle in the earth-atmosphere system. This is obvious when considering the fundamental impact on radiation and precipitation conditions that is related to cloud processes. Atmospheric circulation models must therefore describe clouds and condensation processes on the resolved scale but also in a parameterised form to take into account effects on the sub-grid scale. The majority of clouds (except those connected to synoptic scale frontal systems) appear on the sub-grid scale which means that much work must be devoted to the construction of usable cloud parameterisation schemes in NWP (see acronym list in Section 7) models. During this process, validation of these schemes is of great importance. This paper addresses this subject and, in particular, the use of satellite data in model validation studies. The paper focuses on the modelling and validation of the total fractional cloud cover and the vertical extension of cloud layers by use of cloud information extracted from multispectral satellite imageries. Other cloud parameters are, although equally important, not discussed here.

A straightforward and often used method to validate cloud information in models from satellite data is to calculate the outgoing longwave radiation (often denoted OLR) from model state variables and compare it to satellite-measured OLR values (Slingo, 1987; Rizzi, 1995). An alternative approach is to use effective radiation temperatures (brightness temperatures) at specific infrared wavelengths instead of OLR (Morcrette, 1991). The latter method has an advantage in that it enables

email: kgkarlsson@smhi.se

use of infrared measurements from ordinary operationally available meteorological satellites instead of specifically designed instruments for earth radiation budget measurements. These two methods offer an appropriate means of detecting the presence of mid- and high-level clouds, especially in the sub-tropics and in the tropics. Their existence leads to decreased OLR and brightness temperature values. However, low-level cloudiness is not properly detected by these methods since their effective radiation temperatures are often close to surface temperatures. Furthermore, cold surfaces at high latitudes and near the poles may produce the same radiances as almost all cloud types. To solve this problem, radiation conditions in other parts of the electromagnetic spectrum must additionally be considered (e.g., visible and microwave regions). Differences in radiation characteristics between clouds and earth surfaces may then be utilised. The visible region is the most usable spectral region if the ability of analysing fractional cloud cover and low-level cloudiness is desired. Other cloud parameters (e.g., cloud water content) are, however, more readily extracted in the microwave region.

Unfortunately, methods comparing model-simulated and satellite-measured visible radiances have not yet become established. This is explained by the fact that the model set of state variables are generally not sufficient to describe and simulate visible cloud radiances as accurately as can be made in the infrared region. Visible radiances depend very much on microphysical conditions (water phase, droplet/ice crystal distributions and concentrations) and on the three-dimensional structure of individual cloud elements. Such information is not at present described by operationally used NWP models. Therefore, the validation of low-level cloudiness is most often made by using satellite-diagnosed cloud information which is compared directly to model cloud variables.

An often-used global satellite dataset is the ISCCP dataset (Rossow and Schiffer, 1991) which is based on processed information from one visible and one infrared spectral channel from the current operational geostationary and polar orbiting meteorological satellites. Drawbacks of using this dataset are that the information is available on a quite coarse grid (thus not providing information on model sub-grid scale cloudiness) and that the derived cloud cover information decreases in quality at high latitudes and near the poles (Mokhow and Schlesinger, 1994). Attempts have been made during recent years to improve validation datasets by utilising multispectral image processing techniques (Saunders, 1989; Raustein et al. 1991; Hou et al., 1993, Mölders et al, 1995). Here, data from the five channel AVHRR instrument onboard the polar orbiting NOAA satellites has been utilised. The inclusion of more spectral bands improves the separability between cloudy and cloud-free pixels, especially when using AVHRR channel 3 at 3.7 μm wavelength. Measurements in this channel are sensitive to both emitted terrestrial radiation and reflected solar radiation. Here, clouds behave very differently from earth surfaces (as discussed by Hunt (1973)). Reported model validation experiments have so far been performed on quite limited satellite datasets and detailed information on the quality of the satellite-retrieved cloud parameters has generally not been presented.

This paper presents a method to validate cloud forecasts from two well-established and heavily used NWP models by using cloud information extracted by a cloud classification model based on the processing of the full five-channel AVHRR dataset at its maximum horizontal resolution. The cloud classification model, named SCANDIA, is a well-established operational model and the quality characteristics of the derived cloud information have been carefully studied (Karlsson, 1994). Furthermore, as opposed to earlier studies based on AVHRR data, the satellite-derived validation dataset consists of a large number of satellite scenes which leads to possibilities to compile model error statistics valid for longer periods. The studied models are operationally used versions of the HIRLAM and ECMWF models. Mean cloud cover conditions for entire months are derived from satellite data which are compared to predicted mean cloud conditions by the two models.

The main objective of the study is to demonstrate the potential of this alternative validation method. In addition, some particular aspects of cloud modelling have been addressed, namely how mean cloud conditions are described by a model using an explicit and consistent treatment of cloud parameters compared to a model using only a diagnostic treatment of clouds (mainly for use in the radiation scheme). Here, the studied version of the HIRLAM model represents the former category while the ECMWF model represents the latter (however, the ECMWF model now uses an explicit prognostic cloud water scheme which was implemented in April 1995). Furthermore, special attention has been paid to the problem of cloud spin-up in HIRLAM, i.e. the fact that reasonable cloud amounts are not reached until several hours of model integration since no cloud initialisation is normally performed. The effect of introducing a simple cloud initialisation method is also demonstrated.

2. Cloud climate investigations with the SCANDIA model

2.1. *The SCANDIA model*

The method of estimating mean cloud conditions from satellite imagery is based on results from operational cloud classifications derived by the SMHI SCANDIA model. Principles of the model are described by Karlsson (1989) and by Karlsson (1995a). A full description can be found in Karlsson and Liljas (1990) and in Karlsson (1996).

The model makes use of calibrated and geometrically transformed imagery from all five spectral channels of the AVHRR instrument at maximum horizontal resolution (at nadir 1.1 km). AVHRR scenes are classified by use of seven image features (see detailed description by Karlsson, (1995a)). Classifications are made in two predefined areas covering the southern and northern parts of the Nordic area (Sweden, Denmark, Norway, Finland plus the Baltic Sea with its coastal areas). Each pixel is classified into one of 23 cloud and surface types. The SCANDIA model has been run and used as a tool in operational weather forecasting at SMHI since 1988.

2.2. *Estimation of mean cloudiness in the Nordic region by use of SCANDIA*

By selecting a subset of high-quality cloud classifications, it has been possible to estimate monthly means of cloud cover over the Nordic area with high horizontal resolution (Karlsson, 1994, and Karlsson, 1995a). Here, the used AVHRR scenes were restricted to those having maximum satellite zenith angles below approximately 40° at the reception site (Norrköping). Using this restriction, the most frequently found cloud classification errors due to high satellite zenith angles (discussed by Karlsson, 1994) could be avoided. The daily mean of cloud cover was determined from four remaining satellite observations valid approximately for conditions at night-time, in the morning, in the afternoon and in the evening (see Karlsson, 1995a, for more detailed description of passage times of the NOAA satellites). At the pixel level, with a horizontal resolution of, at best, 1.1 km, pixels were treated as fully cloudy or cloud-free in each individual AVHRR scene (no partial cloud cover was estimated).

Similar monthly analyses of mean cloudiness over Sweden are routinely made at SMHI by use of SYNOP observations made at 06, 12 and 18 UTC (e.g., SMHI, 1993). Comparisons with the satellite estimations showed a very good agreement although it was found that satellite estimations produced a few percent smaller cloud amounts than shown by SYNOP observations (Karlsson, 1994, and Karlsson, 1995a).

Three examples of satellite-derived monthly means of cloudiness are shown in Fig. 1. Cloud conditions in July are here shown for the three consecutive years of 1993, 1994 and 1995. The horizontal resolution has been reduced to 20 km by an averaging procedure. It can be noticed that cloud conditions have been extremely variable during these three years. July 1993 was extremely cloudy throughout the whole area, July 1994 showed very little cloudiness in the area and July 1995 exhibited very high cloudiness in the northern part while the southern part was much less cloudy. Naturally, cloud amount depends very much on whether the month is dominated by cyclonic (e.g., July 1993) or by anticyclonic (e.g., July 1994) circulation conditions. However, regardless of the mean circulation type, cloudiness was always found to be substantially suppressed over the Baltic Sea and the larger lakes in the area. Thus, sea surface temperatures are still cold enough during July to suppress the formation of convective clouds over sea areas. By contrast, cloud amounts were always high in the mountain regions. Again, comparisons with SYNOP-based cloud climatologies (SMHI, 1993, 1994, 1995) verify most of the features found in the satellite analysis over Sweden. From Fig. 1 and from earlier studies (Karlsson, 1994, 1995a), it is clear that the Baltic Sea acts as a strong suppressing moderator of the cloud climate in the region during the

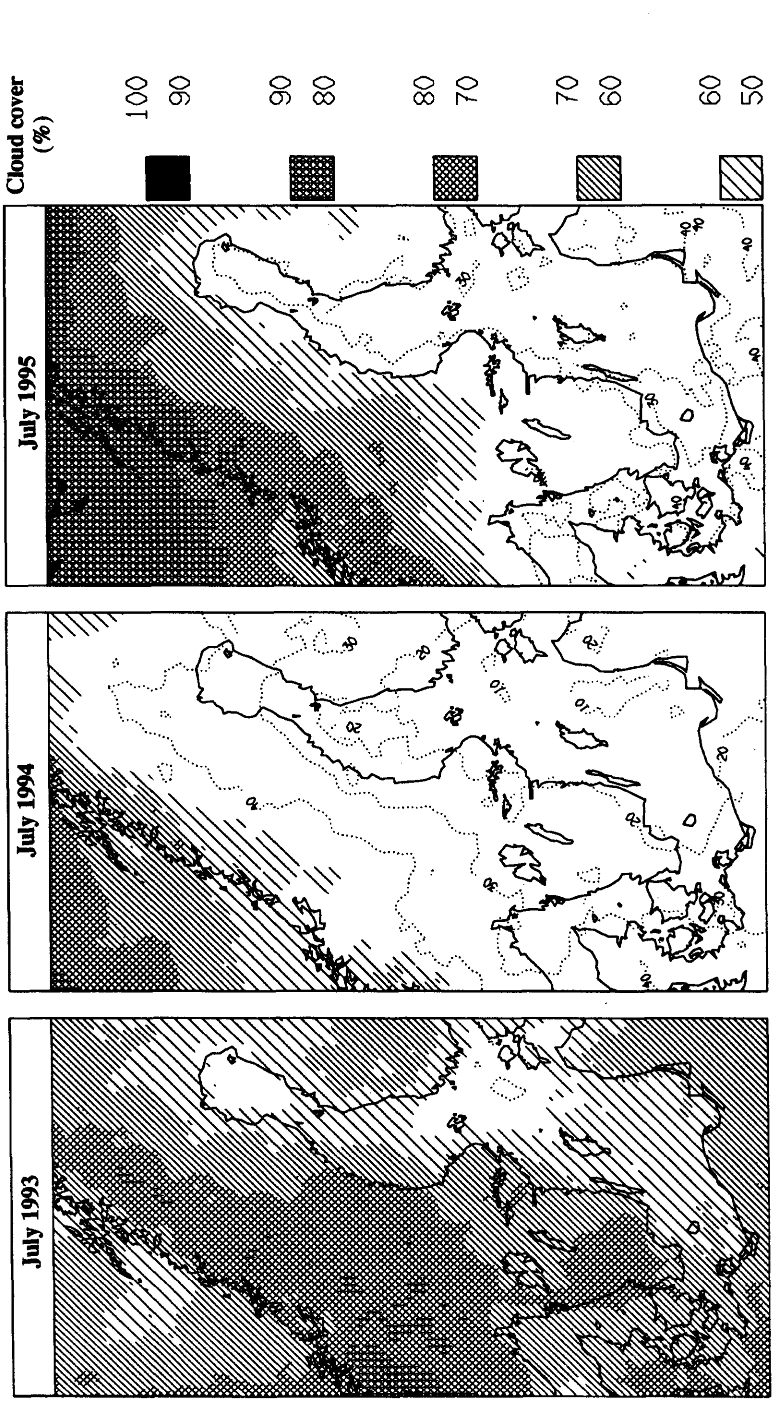

Fig. 1. SCANDIA-derived mean of cloud cover (%) for the month of July for the consecutive years of 1993 (left), 1994 (middle) and 1995 (right). Horizontal resolution 20 km.

summer season (see also Karlsson, 1995) under quite variable circulation conditions. At the same time, the land areas of the Scandinavian peninsula act in the opposite direction, increasing cloud amounts due to convective and orographic processes.

3. Validation of HIRLAM and ECMWF cloud forecasts

3.1. *Modification of SCANDIA cloud analyses*

In order to accomplish a meaningful comparison of SCANDIA cloud observations to NWP model output, the SCANDIA analysis area was enlarged to cover a substantial part of northern Europe. The horizontal image resolution was at the same time reduced from one to four km in order to reduce computational costs. The most important modification was related to the large variation of sun elevations introduced when applying SCANDIA on much larger areas. A segmentation of the area into segments with specific sun elevation intervals was made. The complete analysis over the entire area was then realised by the execution and merging of a sequence of classifications where each classification was valid for one specific sun elevation interval. Another important modification (perhaps somewhat controversial— as discussed later in section 5) of the SCANDIA model was the introduction of a priori surface temperature information provided by short-range (9–12 h) surface temperature forecasts from the HIRLAM model. This additional information was used to improve the cloud separation close to sunrise and sunset when the separability of low-level clouds is severely restricted (as discussed by Karlsson (1994)), compared to in situations with complete darkness at night or in good solar illumination during daytime.

The same technique for computing monthly means of cloud cover, as described in section 2, was applied. However, to ensure four good observations per day in the entire enlarged area (representing one observation at night, one in the morning, one in the afternoon and one in the evening), mosaics of two consecutive NOAA passages were frequently used. A single AVHRR scene does only just cover the entire area and since parts of each scene has to be discarded to avoid large satellite zenith angles, often two consecutive scenes had to be used. A maximum of eight NOAA passages over the area could then be used per day. For the model comparison, the satellite analysis was further transformed to the nominal horizontal grid resolution of the HIRLAM model (approximately 55 km) by computation of averages for grid squares.

The basic cloud classifications contain additional information about individual cloud types. Attempts were made to estimate contributions to the total cloud cover from the main cloud groups low-, mid- and high-level clouds. In the SCANDIA model, thick clouds are separated into these categories by comparing AVHRR channel 4 brightness temperatures to temperatures in the 700 and 500 hPa levels (derived from HIRLAM analyses or, here, from short-range HIRLAM forecasts). Thin Cirrus clouds are however separated by use of AVHRR channels 3 and 5.

3.2. *Studied cloud information from the HIRLAM and ECMWF models*

The present study makes use of results from the operational HIRLAM version run at SMHI during the years 1994, 1995. HIRLAM is a gridpoint model with a horizontal resolution of approximately 55 km and with 16 vertical layers. A general description of the model is given by Gustafsson (1991). The used version is basically the HIRLAM level 2.0 version (Gustafsson, 1993) extended with the Sundquist cloud parameterisation scheme (Sundquist et al., 1989). This scheme carries cloud water as a prognostic variable and treats release of latent heat, appearance of fractional cloud cover, cloud water content and precipitation/evaporation in a consistent way. For a detailed description of this scheme, the reader is referred to Sundquist et al., (1989).

In the first implementation of the Sundquist scheme at SMHI, no initialisation of cloud water and fractional cloud water was included, naturally resulting in a quite substantial under-estimation of cloud amounts for short forecast lead times. In February 1995, a simple cloud initialisation was implemented consisting of the utilisation of existing clouds in the first-guess fields (6-h forecasts) used in the HIRLAM analysis and data assimilation scheme. The mean of HIRLAM forecasted cloud cover for entire months was computed from four forecasts per day in analogy with the computation of satellite-estimated cloud climatologies from four satellite observations. Forecasts with different forecast lead times and with valid times separated by six-h intervals (valid at 00, 06, 12 and 18 UTC) were studied. The computation of total fractional cloud cover is based on the maximum-random overlap assumption: Maximum overlap is used if cloudy layers are contiguous, otherwise random overlap is used. Calculation is made from the top layer continuing downward.

To estimate the contribution to the total cloud cover from the main cloud groups low-, mid- and high-level clouds, a sub-division of the contributions from the 16 vertical HIRLAM layers was made in the following manner: layers 1–8 defined the contribution from high-level clouds, layers 9–11 from mid-level clouds and layers 12–16 from low-level clouds. The choice of layers corresponds in principle to the SCANDIA definition of these cloud groups (temperatures in the 500 hPa and 700 hPa layers are used for the separation). Also here, the calculation starts with the top layers and this means that the computed layer contributions should in principle correspond to the layer contributions estimated from the satellite data.

The ECMWF model is a global model with a spectral formulation of the prognostic equations based on the primitive equations for atmospheric circulation (ECMWF, 1991). Physics are computed on a Gaussian grid. In this study, results from the operational version run in 1994 and in early 1995 have been used. This version has a T213 spectral resolution and 31 vertical layers. Clouds are diagnosed using a revised version of the scheme described in detail by Slingo (1987). The diagnostic treatment means that clouds are diagnosed in every model layer from model state variables (basically humidity, stability and vertical velocity). The maximum-random overlap assumption is used when calculating total, low-, mid-and high-level fractional cloud cover. However, the three layer cloud groups are not additive (their sum is not equal to the total cloud cover) which means that only high-level clouds are directly comparable to the satellite-analysed layer cloud groups.

Interpolation of ECMWF forecasts to the HIRLAM grid was performed to make the results comparable. The T213 version of the ECMWF model has an effective horizontal resolution that does not differ substantially from the HIRLAM 55 km grid resolution. The study of ECMWF forecasts has been limited to deal only with 18- and 24-h forecast lengths. Monthly means of fractional cloud cover were computed in a similar way as for the HIRLAM forecasts. However, since operational ECMWF forecast runs were carried out only at 00 and 12 UTC, cloud forecasts valid at times 00, 06, 12 and 18 UTC were compiled by use of two 18-h and two 24-h forecasts per day. As in the HIRLAM case, individual contributions from the main cloud groups low-, mid- and high-level clouds were also studied.

3.3. Selected evaluation periods and data

The validation study was carried out for one month during the warm and bright part of the year (August 1994) and for one month during colder and darker conditions (March 1995). The reason for choosing March 1995 instead of earlier and darker months was that the simple cloud initialisation scheme for the HIRLAM model was implemented in the beginning of February 1995. Comparison of results in March 1995 with those achieved in August 1994 would then hopefully indicate if any improvement in cloud spin-up had been achieved. Some of the validation results from the August 1994 period have earlier been reported by Karlsson (1995b).

The reason for comparing forecasted clouds in the form of monthly means instead of as a sum of comparisons of individual forecasts and satellite scenes is that satellite observations do not occur with fixed and stable observation times every day. This is due to the present sun synchronous orbits of the NOAA satellites. The asynoptic satellite observation times make comparisons of individual forecasts quite cumbersome. It is thus difficult to find a sufficient number of usable observations when studying a particular forecast lead time and this led to the decision of using the monthly mean instead.

4. Results

The verification data set derived from SCANDIA cloud classifications was complete for the March period in 1995 but 3 days of data were missing for the month of August in 1994. These days were then excluded from the model data set. Some parts of a few individual AVHRR scenes (seven out of 204 scenes) had to be removed in August due to the presence of misclassified very strong sunglints. However, this loss of data was considered to be of marginal importance.

The general circulation type in August 1994 can be deduced from the monthly mean of MSL pressure over the European area as shown in Fig. 2. Higher pressure than normal is found in the studied area which indicates some anticyclonic dominance during the month, especially in the eastern part of the area. However, the latter half of the month changed to more cyclonic conditions with some low pressure systems passing eastward. Thus, the month had quite variable weather conditions. The same map for March 1995 is shown in Fig. 3. This month was dominated by several deep low pressure systems causing warm and very windy conditions, especially in the northern part of Europe. This caused also very high cloud amounts here. Colder and more stable periods occurred only temporarily.

Fig. 4 shows the satellite-derived mean of cloud cover for August 1994 which may be compared to the mean of cloud cover derived from HIRLAM 24-h forecasts for the same period in Fig. 5. Generally, the month was rather cloudy in this region, especially in the western part where cloudiness exceeding 70% was found. Much smaller cloud amounts are found over the Baltic Sea and nearby coastal areas. It is evident in Fig. 5 that there is, still after 24 hours of model integration, a substantial underestimation of cloudiness in the whole area. The horizontal distribution of cloudiness is generally in accordance with the satellite

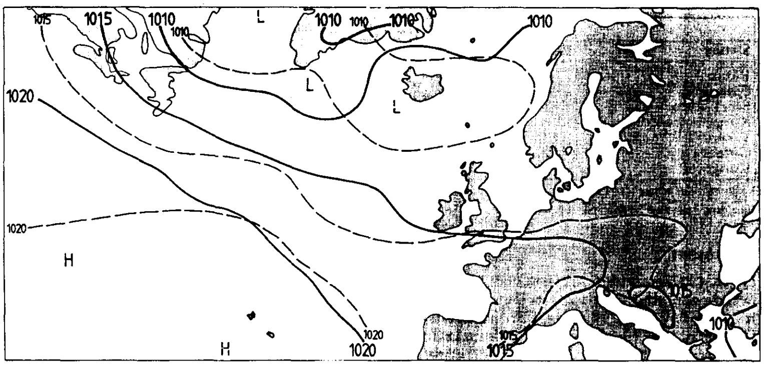

Fig. 2. Monthly mean of MSL pressure (hPa) for the European and North Atlantic area in August 1994 (solid line). Dashed line show average values for the period 1931–1960 (from SMHI, 1994).

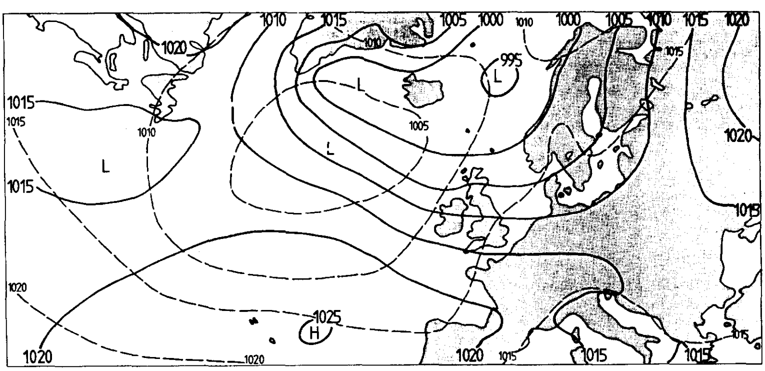

Fig. 3. Monthly mean of MSL pressure (hPa) for the European and North Atlantic area in March 1995 (solid line). Dashed line show average values for the period 1931–1960 (from SMHI, 1995).

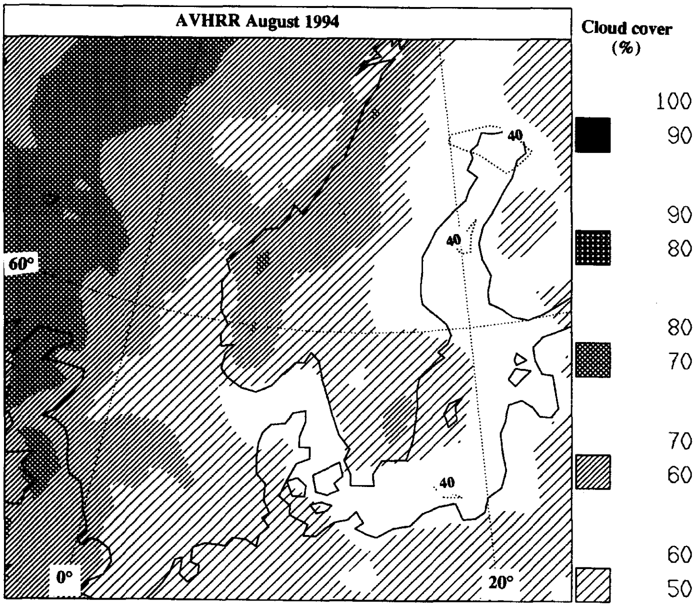

Fig. 4. SCANDIA-derived mean of cloud cover (%) for August 1994 in the northern European area. Different hatchings are used for values above 50% while isolines are used for values below 50%. Same presentation type is used below for Figs. 5–8. Some latitudes and longitudes for the area are also shown (however excluded in the following Figs. 5–14).

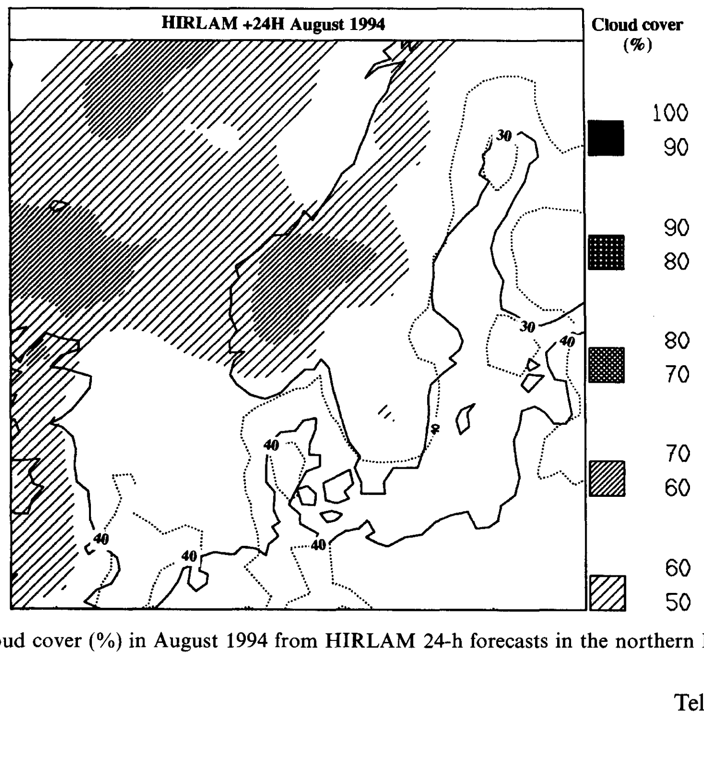

Fig. 5. Mean of cloud cover (%) in August 1994 from HIRLAM 24-h forecasts in the northern European area.

analysis. Table 1 summarises the results from comparisons with five different HIRLAM forecast lengths. It is seen that the underestimation of cloudiness is reduced from approximately 19% for 6-h forecasts to 10% for 48-h forecasts. Thus, the spin-up of cloudiness has not yielded values close to the satellite-estimated values within 48 h of model integration. The bias level appears to approach an equilibrium level close to −10% and this shows that also other defects than the spin-up effect hamper HIRLAM cloud forecasts.

The corresponding cloud information from the ECMWF model in August 1994 is shown in Fig. 6. A significant underestimation of cloud amounts is found also in this case. The horizontal distribution of cloudiness is quite similar to the HIRLAM results but minima in cloud amounts in the eastern part of the area are shifted to the east, covering parts of Finland and the Baltic states. This differs from both the SCANDIA information and the HIRLAM results which clearly shows minimum cloud amounts exclusively over the sea areas. The HIRLAM cloud information shows better agreement with satellite observations here, even if the positions of cloudiness minima are not exactly the same.

Table 1. *Area mean of monthly cloud cover for August 1994 from HIRLAM forecasts of varying lead times compared to SCANDIA-estimated cloud cover; resulting mean error and RMS error of the monthly mean are also shown*
August 1994: uninitialized clouds
(no initial cloud water and cloud cover)

	Satellite	HIR+06	HIR+12	HIR+24	HIR+36	HIR+48
cloudiness (%)	57.8	39.3	43.3	46.3	47.3	47.9
bias (%)	–	−18.5	−14.5	−11.5	−10.5	−9.9
RMS (%)	–	19.8	15.7	13.1	12.6	12.0

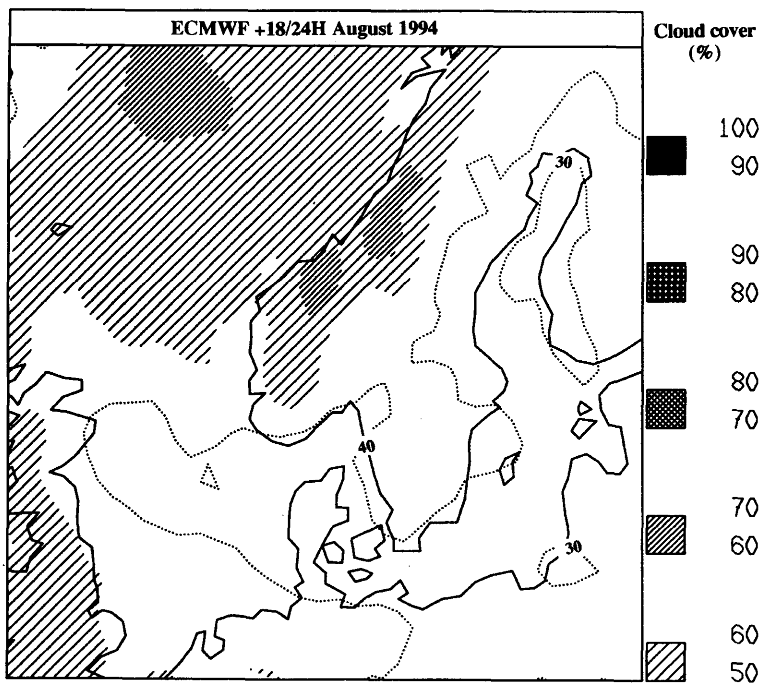

Fig. 6. Mean of cloud cover (%) in August 1994 from ECMWF 18/24-h forecasts in the northern European area.

AVHRR-derived cloud amounts for March 1995 are shown in Fig. 7 and can be compared with cloud amounts from 24-h HIRLAM forecasts in Fig. 8. It is evident that cloud amounts are now generally quite comparable to the satellite-derived amounts. Results for all five studied forecast lengths are shown in Table 2 where it can be seen that the negative bias for the six-hour forecast has improved to 9.7% and that final cloud amounts for 48-h forecasts exceed satellite-derived amounts by only 2.4%. This may be close to a realistic equilibrium level since SCANDIA-derived cloud amounts have been shown to give a small underestimation of cloud amounts (Karlsson, 1994). It can be noticed in Tables 1 and 2 that RMS errors are not large in comparison with bias errors (except for forecast lengths of 24 hours and longer in March 1995). This indicates again relatively small spatial phase errors of forecasted monthly mean cloudiness. However, quite large variations were observed on the grid point scale for individual forecasts and these were thus evidently suppressed when averaging. A test comparing a very limited sub-set of analysed AVHRR scenes in August 1994 with forecasts within an hour of the NOAA passages showed RMS errors of the order of 40%. Thus, large cloudiness variations from grid point to grid point may occur, especially in convective weather situations, whose effects are not seen in a validation material using monthly means of cloud cover.

ECMWF cloudiness for March 1995 showed approximately the same deficiencies as for August 1994. Table 3 summarises the results for these two months. A negative bias of 13% was found for both months.

Since only 2 months of data have been covered in this study, the dependence of the actual weather type is not clear from the results and this fact makes it difficult to draw firm conclusions. A simple way of investigating the sensitivity of the results to the dominating circulation type is to divide the material into shorter time periods. Tables 4 and 5 show such a partitioning of the results for HIRLAM 24-h forecasts into results for 10-day periods for the 2 months. The tables include a brief description of the weather type during each period. For August 1994, it can be seen that the bias is larger during the first third of the month than during the other two thirds. Since the first period was dominated by an anticyclonic weather type, this indicates that the bias problem may be worse for an anticyclonic weather type than for a cyclonic weather type during the

Table 2. *Area mean of monthly cloud cover for March 1994 from HIRLAM forecasts of varying lead times compared to SCANDIA-estimated cloud cover; resulting mean error and RMS error of the monthly mean are also shown*
March 1995: initialized clouds
(initial cloud water and cloud cover from 6-h forecasts)

	Satellite	HIR+06	HIR+12	HIR+24	HIR+36	HIR+48
cloudiness (%)	68.2	58.5	63.5	67.4	69.5	70.6
bias (%)	–	−9.7	−4.7	−0.8	1.3	2.4
RMS (%)	–	11.0	6.8	5.2	5.7	5.6

Table 3. *Area mean of monthly cloud cover for August 1994 and for March 1995 from ECMWF 18/24-h forecasts compared to SCANDIA-estimated cloud cover; resulting mean error and RMS error of the monthly mean are also shown*
ECMWF 18/24-h forecasts
(diagnosed total cloud cover)

	Satellite August 1994	ECMWF+18/24 August 1994	Satellite March 1995	ECMWF+18/24 March 1995
cloudiness (%)	57.8	44.6	68.2	54.9
bias (%)	–	−13.2	–	−13.2
RMS (%)	–	14.5	–	14.3

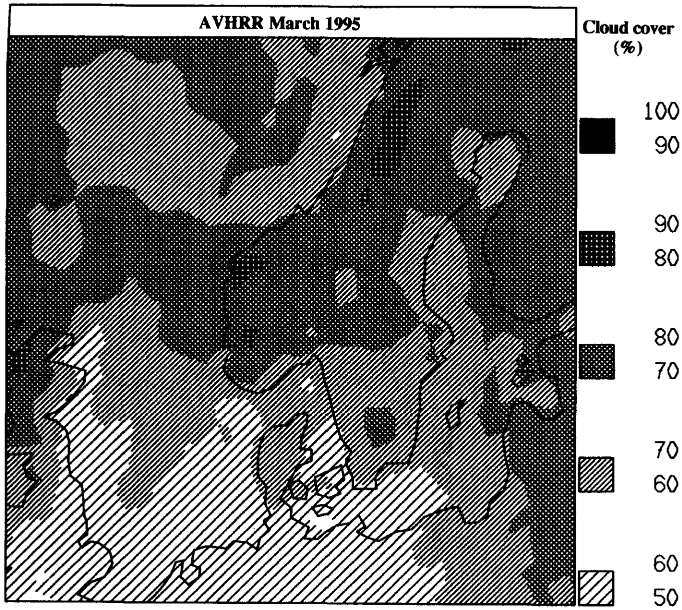

Fig. 7. SCANDIA-derived mean of cloud cover (%) for March 1995 in the northern European area.

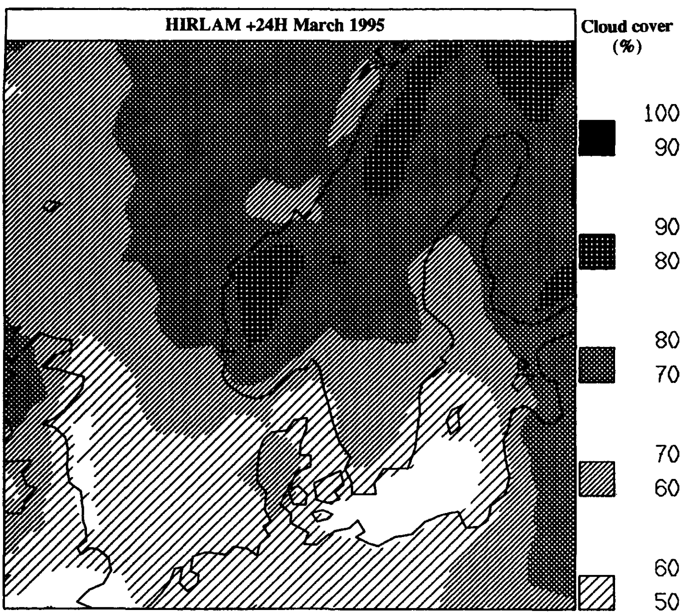

Fig. 8. Mean of cloud cover (%) in March 1995 from HIRLAM 24-h forecasts in the northern European area.

summer season. The three periods in March 1995 were unfortunately very similar in their dominating weather types making it difficult to assess the differences, however quite small, that were found. Notice that RMS errors are generally larger for the periods compared with the monthly values in Tables 1, 2. The reduced dataset means that phase errors for individual forecasts may now influence

Table 4. *Same HIRLAM validation results as in Table 1 (August 1994) but partitioned into 3 periods; the weather type in each period is briefly described*

Period (days)	Weather conditions	Cloudiness SCANDIA (%)	Cloudiness HIRLAM (%)	Bias HIRLAM (%)	RMS HIRLAM (%)
1–10	anticyclonic dominance, except for period 1–5 in the north-western region having cyclonic conditions	53.9	38.1	−15.8	19.4
11–20	a change to cyclonic conditions occurred; frontal as well as convective systems appear frequently	63.6	50.3	−13.3	16.2
21–31	continuing unstable and cyclonic weather type; only shorter periods with more stable weather occur	58.2	49.1	−9.1	12.7

Table 5. *Same HIRLAM validation results as in Table 2 (March 1995) but partitioned into 3 periods; the weather type in each period is briefly described*

Period (days)	Weather conditions	Cloudiness SCANDIA (%)	Cloudiness HIRLAM (%)	Bias HIRLAM (%)	RMS HIRLAM (%)
1–10	cyclonic dominance; strong zonal flow with frequently passing frontal systems; very cloudy in the eastern part	66.5	67.2	+0.7	8.7
11–20	same dominant weather type as during the first period of the month; very cloudy in the entire northern half of the area	74.9	71.2	−3.8	9.6
21–31	anticyclonic in the south-western part; cyclonic with only short anticyclonic periods in the rest of the area	64.3	62.7	−1.6	8.9

results more evidently (not smoothed out as efficiently as with a monthly mean). The noisy appearance at the gridpoint scale for individual forecasts (discussed earlier) may also explain the larger RMS values here.

Some results from the studies of the contributions to the total cloud cover from the main cloud groups low-, mid- and high-level clouds are shown in Figs. 9–14 for August 1994. Results for the low-level clouds are shown for SCANDIA in Fig. 9, for HIRLAM 24-h forecasts in Fig. 10. and for ECMWF 18/24 h forecasts in Fig. 11. Corresponding information for high-level clouds are shown in Figs. 12–14. Results for mid-level clouds were quite similar to those for high-level clouds and are not shown here. For the low-level clouds, it is seen that values are slightly larger than the satellite-analysed for both HIRLAM and ECMWF forecasts (although ECMWF underestimates low-level cloud amounts in the north-western part). For high-level clouds, the HIRLAM forecasts show a significant underestimation while the ECMWF model shows too large contributions, especially over the Norwegian Sea where an excess of up to 40% in contribution is found. The ECMWF overestimation of high-level clouds was also observed in March 1995 but it was not as pronounced as in August 1994. Results for March 1995 cannot be shown for the HIRLAM model since the complete HIRLAM

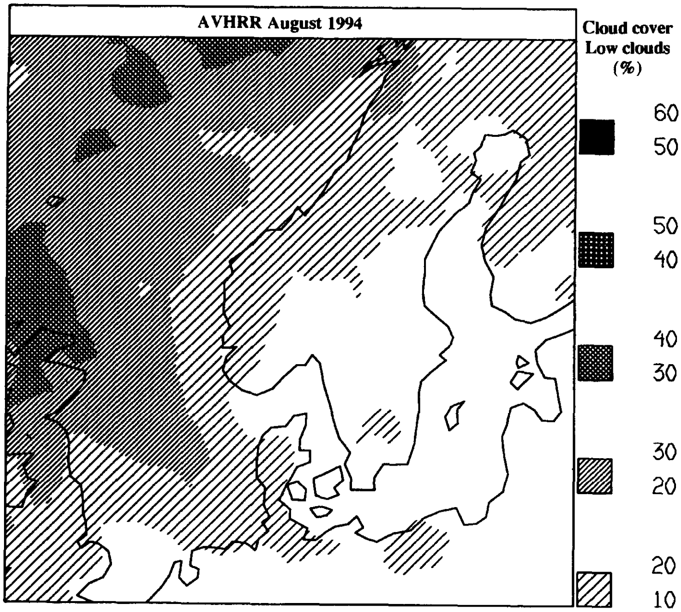

Fig. 9. SCANDIA-estimated contribution (%) from low-level cloud types in August 1994 in the northern European area. Observe the different meaning of hatching levels compared with those used in Figs. 4–8. This presentation type is also used below for Figs. 10–14.

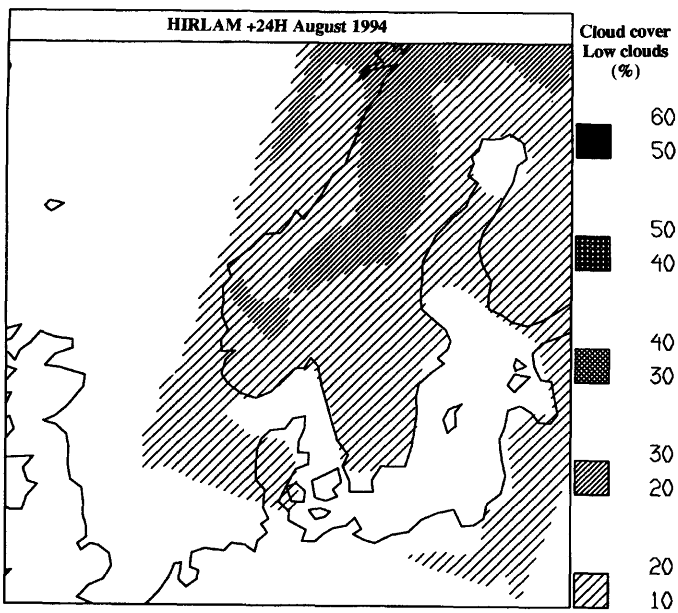

Fig. 10. Contribution from low-level clouds (%) in August 1995 for HIRLAM 24-h forecasts in the northern European area. Observe that the complete HIRLAM model dataset was only available over the Scandinavian area.

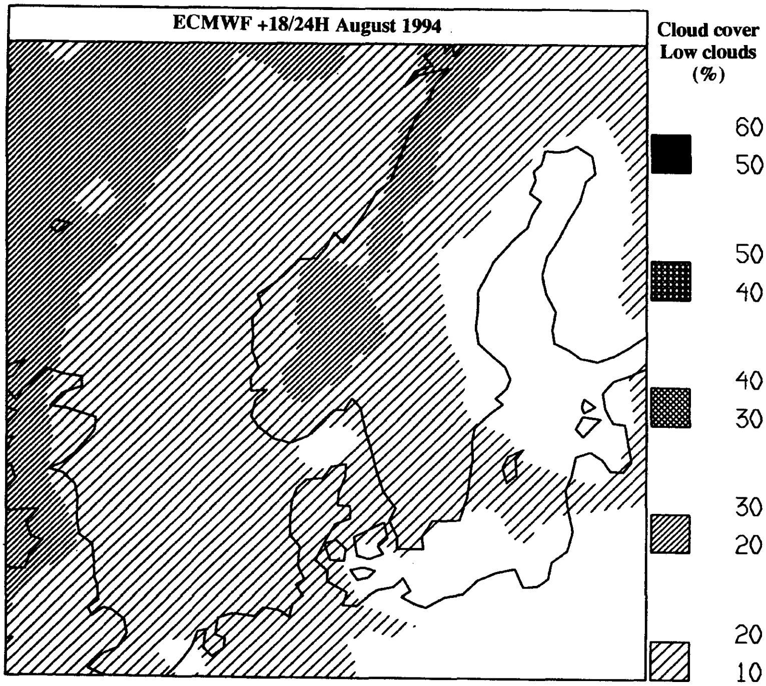

Fig. 11. Diagnosed amount of low-level clouds (%) in August 1995 for ECMWF 18/24-h forecasts in the northern European area.

dataset (data from all model layers) was not available. Interpretation of the results are not readily made here. Since HIRLAM cloudiness contributions from mid- and high-level cloud layers were found to be too small compared to satellite estimations, the contribution from low-level clouds has most probably been overestimated here (the degree of overlapping by higher cloud layers should have been larger). Thus, it is reasonable to assume an underestimation of cloudiness for all cloud layers, however most pronounced for high-level clouds.

5. Discussion

A method of comparing cloud forecast information with satellite-derived information on the total fractional cloud cover and on the distribution of different vertical cloud layers has been demonstrated. It has been possible to show and assess effects of the spin-up of cloud parameters in the HIRLAM NWP model, using a complete and consistent description of cloud parameters. Without any cloud initialisation, the HIRLAM forecasts suffered from a significant underestimation of cloud amounts. A 10% underestimation of cloudiness was found to remain also for longer forecast lengths (48 h) when cloud spin-up seemed to have approached an equilibrium level. Thus, deficiencies other than the spin-up problem (e.g., too dry forecasts) are indicated. Underestimation of cloud amounts was found in almost all vertical levels of the HIRLAM model but especially at high-levels. The underestimation of cloud amounts appeared to be most serious during anticyclonic conditions in the studied summer month. This could mean that the cloud parameterisation scheme has particular problems in the generation of realistic convective cloud amounts. Improvements of HIRLAM results were indicated when introducing a simple cloud initialisation scheme in March 1995. Cloud amount underestimation was then only observed for very short forecast lengths (less than 12 h).

Studied forecasts of the ECMWF model

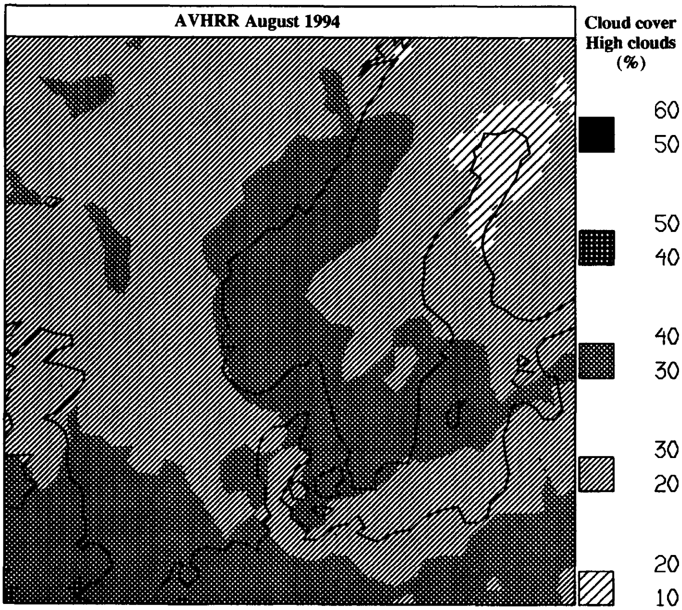

Fig. 12. SCANDIA-estimated contribution (%) from high-level clouds in August 1994 in the northern European area.

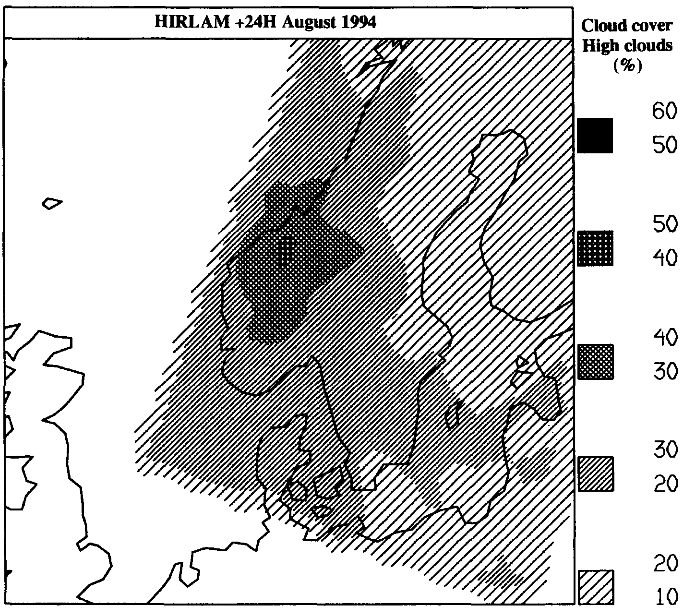

Fig. 13. Contribution from high-level clouds (%) in August 1995 for HIRLAM 24-h forecasts in the northern European area. Observe that the complete HIRLAM model dataset was only available over the Scandinavian area.

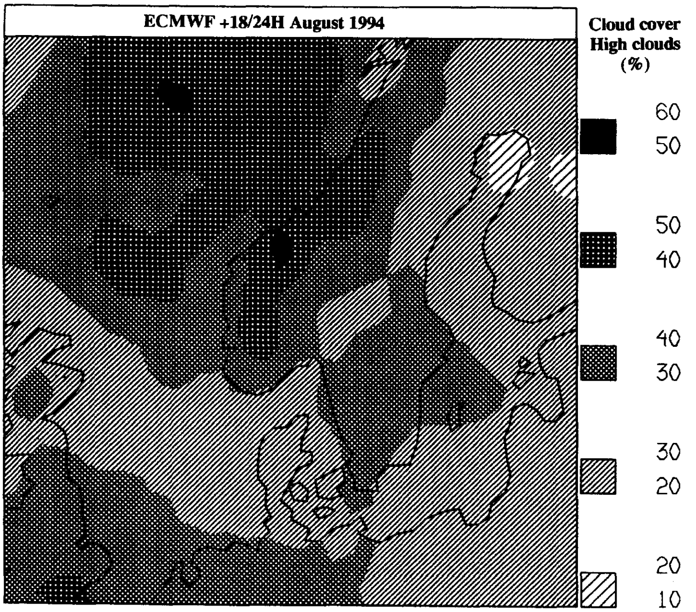

Fig. 14. Diagnosed amount of high-level clouds in August 1994 for ECMWF 18/24-h forecasts in the northern European area.

(18/24 h forecasts) were also found to underestimate the total fractional cloud cover. Interesting deficiencies in the diagnosis of high-level cloudiness for a purely diagnostic cloud scheme (as represented by the ECMWF model in this version which was operational until April 1995) have further been indicated. When considering the large impact on radiation conditions exerted by high-level cloudiness (especially the green-house effect caused by thin Cirrus clouds), these large deviations may have introduced serious errors in the ECMWF radiation calculations.

It is not possible to make overly general conclusions from this study since only two months of data have been investigated. This limitation of the study is explained by the fact that an immense satellite image processing is necessary for carrying out these kind of experiments. Automatic methods for image quality control, image mosaic generation and transfer to the model grid resolution are required in the future to enable a more efficient compilation of model validation datasets. Another limitation has been that only historic routinely archived model information has been available for the study. Several interesting and crucial aspects of model validation (e.g., the evaluation of different cloud initialisation methods using the same validation dataset and the comparison of forecasts close in time to satellite observations) have therefore not been possible to include. Consequently, the model validation experiment must be seen as a demonstration or a feasibility study. The validation method is proposed as a valuable complement to other model evaluation methods in the future, based on surface as well as on satellite observations.

A difficult problem to consider in all cloudiness studies is the problem of cloud cover representation, i.e., what do we mean with the quantity "fractional cloud cover"? This is relevant for the observation of clouds as well as for the modelling of clouds. The satellite-derived quantity used here is purely the horizontal coverage. Information on the true vertical distribution of cloud layers is generally not available from satellite measurements. The fractional cloud cover described by models is also expressed as the horizontal coverage in each grid square but it is additionally assumed that clouds are filling the grid box vertically in the cloudy portion of the grid square. This means that satellite-observed and modelled cloud cover are not truly comparable. A likely difference between the two datasets could be that very thin cloud decks (e.g., thin Cirrus clouds) may be easier to observe than to model because model layers in the upper troposphere are thick compared to satellite-detectable Cirrus cloud layers. A slight underestimation of typically thin clouds could therefore be anticipated which may partly explain the observed underestimation of high-level cloudiness for the HIRLAM model. However, these problems and drawbacks should become less important with the introduction of an increasing number of vertical levels in future NWP models. The indicated erroneous excess of high-level cloudiness in the ECMWF model is not understood at this stage.

Another aspect to consider is the quality of cloud observations. The SCANDIA model has been found to produce cloud cover information with a quality comparable to the SYNOP cloud information. However, it is obvious from many earlier studies that the SYNOP information has a limited quality which reduces its potential to be used as ground truth information. This is due to the problem for the surface observer to correctly estimate the horizontal cloud cover when viewing clouds at off-zenith angles. Furthermore, there are obvious problems when observing clouds during dark conditions. At the same time, also satellite observations have obvious limitations. The most evident problem is to describe and take into account cloudiness on a scale that is smaller than the pixel scale. A related problem here is also the treatment of very thin and transparent clouds. A serious defect of the SCANDIA model is an apparent underestimation of cloud amounts for low-level clouds in twilight conditions (Karlsson, 1994). In this validation experiment, an attempt to use a priori surface temperatures from short HIRLAM forecasts to improve the interpretation of satellite-measured infrared brightness temperatures have been applied. There are obvious risks in doing this since HIRLAM-surface temperatures evidently are influenced by HIRLAM cloud amounts. However, comparisons with available SYNOP observations have generally shown improved SCANDIA results (compared to the operationally used SCANDIA scheme) with only a few exceptions. For the future, a replacement of forecasted surface temperatures with analysed values are proposed and planned at SMHI.

For all the earlier mentioned reasons, it is not possible to make any definite statements on true levels of mean cloudiness. Despite this, it is believed that the quality of the satellite-derived cloud information presented here is at a level permitting the presented model comparisons, especially when considering the superior horizontal coverage of the satellite information compared to SYNOP information. This can be exemplified by mentioning that the present study has compared model grid values in almost 1300 grid points to daily observations. Only a very small fraction of these grid points could have been verified by use of SYNOP observations. Furthermore, satellite information provides coverage of sea areas which is a large advantage compared to SYNOP. Finally, it must be stressed that alternative high-quality validation material on cloud cover parameters is not easily found.

A more systematic use of this validation method is planned at SMHI, partly as a contribution to the BALTEX research programme. The effects on the cloud information when increasing the horizontal and vertical HIRLAM resolution will especially be studied. Studies of the parameterisation and description of boundary-layer clouds and convective clouds, using the detailed cloud information provided by the SCANDIA scheme, will be considered. Furthermore, cloud climate data over the Nordic area will be compiled for the period 1991–1998 in a research project sponsored by the Swedish National Space Board. This new data set will not be contaminated by any NWP model data since it will be based on results from the original SCANDIA model. In parallel, similar cloud climate analyses will be compiled for the years 1994 to 1998 from the latest version of the SCANDIA model including a priori temperature information from HIRLAM forecasts. Thus, comparisons of the two data sets and conventional cloud climate information from SYNOP observations will then be possible. They should indicate whether the quality of analysed cloud amounts does improve significantly when utilising a priori temperature information from HIRLAM forecasts. The availability of accurate information on surface temperatures is in any case considered as crucial if the very problematic conditions close to sunrise and sunset should be properly handled by AVHRR cloud analysis methods.

6. Acknowledgements

The author is very grateful to Lars Meuller for assisting in the compilation of HIRLAM and

ECMWF forecast information. Thanks also to Nils Gustafsson and Stefan Gollvik for valuable advice and discussions and to Daniel Michelson and Joakim Langner for useful comments on the manuscript.

7. Appendix A

Acronyms

AVHRR	Advanced Very High Resolution Radiometer (NOAA satellites)
BALTEX	The BALTic sea EXperiment
DMSP	Defence Meteorological Satellite Programme (USA)
ECMWF	European Centre for Medium-range Weather Forecasts (Reading, UK)
HIRLAM	High Resolution Limited Area Model (developed by weather services in the Nordic countries plus the Netherlands and Ireland).
ISCCP	International Satellite Cloud Climatology Project
MSL	Mean Sea Level
NOAA	National Oceanographic and Atmospheric Administration (USA)
NWP	Numerical Weather Prediction
OLR	Outgoing Longwave Radiation
SCANDIA	SMHI Cloud ANalysis model using DIgital AVHRR data
SMHI	Swedish Meteorological and Hydrological Institute
SSM/I	Special Sensor Microwave Imager (on DMSP satellites)
SYNOP	Synoptical weather observations

REFERENCES

ECMWF, 1991. ECMWF forecast model. *Research Manuals 2 (Forecast model, adiabatic part) and 3 (Physical parameterization),* (Available from ECMWF, Shinfield Park, Reading,RG2 9AX, U.K.).

Gustafsson, N. 1991. The HIRLAM model. *Proc. of Seminar on Numerical methods in atmospheric models, ECMWF, Reading, UK, 9–13 September 1991.* 115–146 (available from ECMWF, Shinfield Park, Reading RG2 9AX, UK).

Gustafsson, N. 1993. HIRLAM 2 final report, *HIRLAM Technical Report no. 9*, 126 pp. (available from SMHI, S-601 76 Norrköping, Sweden)

Hou, Y.-T. Campana, K. A. Mitchell, K. E. Yang, S.-K. and Stowe, L. L. 1993. Comparison of an experimental NOAA AVHRR cloud dataset with other observed and forecasted datasets. *J. Atmos. Oceanic. Tech.* **10**, 833–849.

Hunt, E. 1973. Radiative properties of terrestrial clouds at visible and infrared thermal window wavelenghts. *Quart. J. Roy. Meteor. Soc.*, **99**, 346–369.

Karlsson, K-G. 1989. Development of an operational cloud classification model. *Int. J. Remote. Sens.* **10**, 687–693.

Karlsson, K.-G. 1994. Satellite-estimated cloudiness from NOAA AVHRR data in the Nordic area during 1993. *SMHI Reports, Meteorology and Climatology*, no. 66, 51 pp (available from SMHI, S-601 76 Norrköping, Sweden).

Karlsson, K.-G. 1995a. Estimation of cloudiness at high latitudes from multispectral satellite measurements. *Ambio*, **24**, 33–40.

Karlsson, K.-G. 1995b. Validation of HIRLAM cloud cover forecasts using satellite-derived cloud cover statistics. *Proc. ECMWF/GEWEX Workshop on modelling, validation and assimilation of clouds*, Reading, UK, 31 Oct–4 Nov. 1994, 263–276 (available from ECMWF, Shinfield Park, Reading RG2 9AX, UK).

Karlsson, K.-G. 1996. Cloud classifications with the SCANDIA model. *SMHI Reports, Meteorology and Climatology*, no. 67, 36 pp (available from SMHI, S-601 76 Norrköping, Sweden).

Karlsson, K.-G.and Liljas, E. 1990. The SMHI model for cloud and precipitation analysis from multispectral AVHRR data. *SMHI PROMIS Reports*, no. 10, 74 pp (available from SMHI, S-601 76 Norrköping, Sweden).

Mokhov, I. I. and Schlesinger, M. E. 1994. Analysis of global cloudiness: (2). Comparison of ground-based and satellite-based climatologies. *J. Geophys. Res.* **99**, 17045–17065.

Morcrette, J.-J. 1991. Evaluation of model-generated cloudiness: Satellite-observed and model-generated diurnal variability of brightness temperature. *Mon. Wea. Rev.* **119**, 1205-1224.

Mölders, N. Laube, M. and Raschke, E. 1995. Evaluation of model generated cloud cover by means of satellite data. *Atmos. Res.* **39**, 91–111.

Raustein, E. Sundqvist, H. and Katsaros, K. B. 1991. Quantitative comparison between simu-lated cloudiness and clouds objectively derived from satellite data. *Tellus* **43A**, 306–320.

Rizzi, R. 1995. Validation of model clouds using satellite data. *Proc. ECMWF/GEWEX Workshop on Modelling, validation and assimilation of clouds.* Reading, UK, 31 Oct–4 Nov 1994, 263–276. (available from ECMWF, Shinfield Park, Reading RG2 9AX, UK).

Rossow, W. B. and Schiffer, R. A. 1991. ISCCP cloud data products. *Bull. Amer. Meteor. Soc.* **72**, 2–19.

Saunders, R. W. 1989. A comparison of satellite-retrieved parameters with mesoscale analyses. *Quart. J. Roy. Meteor. Soc.* **115**, 651–672.

Slingo, J. M. 1987. The development and verification of a cloud prediction scheme for the ECMWF model. *Quart. J. Roy. Meteor. Soc.* **113**, 899–927.

SMHI, 1993. *Monthly weather and climate bulletins* (in Swedish: Väder och Vatten), August issue (available from SMHI, S-601 76 Norrköping, Sweden).

SMHI, 1994. *Monthly weather and climate bulletins* (in Swedish: Väder och Vatten). August and September issue (available from SMHI, S-601 76 Norrköping, Sweden).

SMHI, 1995. *Monthly weather and climate bulletins* (in Swedish: Väder och Vatten), April and August issue (available from SMHI, S-601 76 Norrköping, Sweden).

Sundqvist, H. Berge, E. and Kristjánssón, J. E. 1989. Condensation and cloud parameterization studies with a mesoscale numerical weather prediction model. *Mon. Wea. Rev.* **117**, 1641–1657.