Cloud Cover in the ECMWF Reanalysis

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ABSTRACT

Data from reanalyses recently carried out by several climate and numerical weather prediction centers will find a variety of applications in different branches of atmospheric science. A careful evaluation of the many aspects of these datasets is a prerequisite for their successful use.

This paper describes the implementation of a fully prognostic cloud scheme into the ECMWF reanalysis system and provides a first assessment of the simulation of cloud cover by comparing it with monthly mean cloud cover derived from satellite observations in the context of the International Satellite Cloud Climatology Project for the years 1983–90. Special emphasis is put on the major cloud regimes and their intra- and interannual variation.

The main deficiencies identified are an underestimation of extratropical cloud cover over the oceans by 10%–15%, an overestimation of trade wind cumulus cover by about 10%–15%, an underestimation of stratocumulus off the west coasts of the subtropical continents by 15%, and an underestimation of the summer maximum in cloud cover over the Eurasian continent. Despite these deficiencies it is shown that the reanalysis system is able to capture the main aspects of the interannual variability, especially those connected to the major El Niño events in the observation period.

1. Introduction

It has been widely acknowledged that clouds are important regulators of the climate system. They interact with the atmosphere in a variety of ways influencing its dynamical behavior on many scales from the cloud scale itself to the general circulation. Randall (1989) categorized the direct effects of clouds on the atmosphere into three “cloud forcing” mechanisms: the cloud radiative forcing, the cloud latent forcing, and the cloud convective forcing. The cloud radiative forcing (Ramathan 1987) describes the modulation of the solar and terrestrial radiative fluxes by the clouds; the cloud latent forcing describes the latent heat effects of condensation and evaporation in clouds and precipitation; the cloud convective forcing describes additional effects due to transport of heat, moisture, and momentum in convective clouds, which are associated with latent heat release but can be seen distinct from it. Through the combination of the three forcings, clouds profoundly influence the distribution of energy in the atmosphere and at the surface, the hydrological cycle, and thus the general circulation of the atmosphere.

The representation of the influence of clouds on the resolved scales is the key task of their parameterization in GCMs used for both numerical weather prediction (NWP) and climate research. In recent years great efforts have been undertaken to improve cloud parameterizations. Initially the three forcings were treated by separate parameterization schemes, with a large-scale condensation scheme representing the latent heat effects of grid-scale condensation, a convection scheme describing the nonradiative effects of convective clouds, and a cloud scheme describing the cloud radiative effects. Diagnostic cloud schemes used then (e.g., Slingo 1987), derived cloud cover and cloud water/ice content from empirical relationships to large-scale parameters with the only purpose of providing parameters for the estimation of the cloud radiative forcing. In a next step, pioneered by Sundqvist (1978), cloud schemes combined the description of cloud radiative and cloud latent forcing by introducing a prognostic equation for cloud water/ice (e.g., LeTreut and Li 1988; Roeckner et al. 1990; Smith 1990). However, the generation of condensate in the cloud was limited to large-scale processes with no direct coupling of the clouds to convection. More recent cloud schemes link all three forcing terms. A first step in that direction is the coupling of convection to the clouds by using condensate generated in the convective updrafts and detrained into the environment as the source of cloud water/ice as applied in a variety of schemes today (e.g., Ose 1993; Tiedtke 1993; Fowler et al. 1996; Del Genio 1996).

A fully prognostic cloud scheme (Tiedtke 1993) has
recently been implemented in the ECMWF operational forecasting system. The scheme is prognostic for both cloud cover and cloud water/ice, linking cloud generation and dissipation directly to physical processes like convection, vertical motion, radiative heating, and turbulence. Representing the strong links between the clouds and the rest of the model is desirable to describe the main feedback processes connected to them. At the same time it is these strong links that make it difficult to assess the global performance of the scheme because errors in one part of the model formulation will be reflected in the cloud parameters, which will themselves feed back on the rest of the model.

Data assimilation systems run at operational NWP centers are an ideal test bed for cloud parameterizations. Here short-range forecasts performed with the numerical model are corrected by introducing observations in a statistically optimal way. Hence, the general circulation of the atmosphere is to a large extent controlled by observations so that the clouds are forced by the “best possible” large-scale flow.

Several climate and NWP centers have carried out projects to reanalyze the state of the atmosphere for a considerable period of time with a data assimilation system that remains fixed over the whole analysis period (Schubert et al. 1993; Kalnay et al. 1996; Gibson et al. 1997). The main advantage over analyses operationally produced is the consistency in the analysis system when creating a long-term dataset.

ECMWF has carried out a reanalysis for the period 1979–93 (Gibson et al. 1997) using an analysis and forecasting system similar to the one that was operational for most of 1995. The Tiedtke prognostic cloud scheme was an integral part of that system. Since no observational data is used in the analysis to directly alter the cloud, a comparison of the simulated clouds to those observed is a stringent test of the realism of the cloud parameterization.

This study describes the implementation of the prognostic cloud scheme (Tiedtke 1993) into the ECMWF reanalysis (ERA) system and provides a general overview over the quality of the representation of cloud cover by comparing the ERA results with satellite observations provided by the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer 1983). The main emphasis is on timescales longer than a month. The study attempts to achieve two main goals. First, the major problem areas for the cloud representation are identified. Because of the chosen timescales the comparison cannot reveal erroneous details of the parameterization that need to be investigated in detailed process studies. The second and equally important goal of the study is to assist in the interpretation of other studies that use reanalysis fields influenced by clouds such as precipitation (e.g., Stendel and Arpe 1997), radiative fluxes at the top of the atmosphere or at the surface, and turbulent surface fluxes. The study does not attempt an in-depth statistical analysis of the results as those carried out for other datasets by Mokhov and Schlesinger (1993, 1994), Weare et al. (1995), or Weare (1997).

Section 2 describes the analysis system including the implementation of the prognostic cloud equations into the analysis system and possible spinup effects. A short description of the data used for comparison is given in section 3, section 4 includes the major results of the comparison, and section 5 provides an overall summary.

2. The analysis system
a. General

The ERA was carried out with ECMWF’s Integrated Forecasting System (IFS) as it was used operationally for most of 1995. An extensive description of that system can be found in Gibson et al. (1997). Its main characteristics are the following:

- intermittent optimum interpolation analysis with 6-h cycling (ECMWF 1992)
- one-dimensional variational (1DVAR) physical retrieval of TOVS cloud cleared radiances (Eyre et al. 1993)
- diabatic, nonlinear normal mode initialization (Wer-gen 1988)

The model used to determine the background fields in the data assimilation is the ECMWF model cycle CY13R4. Its main characteristics can be summarized as follows:

- global spectral model at resolution T106
- equivalent reduced Gaussian grid of 1.125° maximum resolution (Hortal and Simmons 1991)
- 31 vertical eta levels (Simmons and Struening 1981)
- semi-Lagrangian advection scheme (Ritchie et al. 1995)
- model physics
  - radiation scheme (Morcrette 1990, 1991)
  - planetary boundary layer scheme (Louis et al. 1982; Beljaars and Holstlag 1991; Beljaars and Betts 1993; Beljaars 1995a,b)
  - four-layer land surface scheme (Viterbo and Beljaars 1995)
  - subgrid-scale orography scheme (Lott and Miller 1997)
  - mass-flux convection scheme with moisture confluence closure (Tiedtke 1989)
  - fully prognostic cloud scheme (Tiedtke 1993; Jakob 1994).

b. Clouds in the analysis system

The cloud parameterization used in the ERA system is described in detail in Tiedtke (1993) with further changes discussed in Jakob (1994). The scheme predicts both cloud cover a and cloud condensate l (water/ice) with prognostic equations; that is,
are separated from the other prognostic model variables, end of the first guess forecast the two cloud variables shows a flow diagram of two analysis cycles. At the beginning of the analysis process, the cloud variables, especially radiative fluxes throughout the atmosphere, would be in serious error (Jakob 1994). Significant processes determining the hydrological cycle of the model might undergo a typical evolution in the first few hours of a forecast, which is usually referred to as “model spinup” (Illari 1987).

Because this study uses 6-h forecasts of cloud cover (see section 3), it is necessary to examine whether these are significantly affected by model spinup. The method of finding the initial conditions for clouds outlined above does not in itself guarantee a small spinup because, in the course of the analysis and the initialization, all model fields except the cloud fields undergo modifications. Hence, the balance between the temperature, moisture, and cloud fields that exists at the end of a first guess forecast does not necessarily hold anymore at the beginning of the next forecast. Figure 2 shows the evolution of cloud cover averaged over different geographical regions for an individual 24-h forecast. For comparison the cloud cover of the same forecast starting with zero initial clouds is also shown. It is evident that there is no spinup in cloud cover and hence the use of short-range forecasts of this quantity is justified.

3. Data
a. ISCCP

ISCCP uses radiances measured by operational weather satellites to deduce a variety of cloud properties. Two channels, 0.6 µm and 11 µm, common to both the geostationary and polar-orbiting satellites are used. A detailed description of the algorithms is given in Rossow and Garder (1993a). From the initial interpretation of the instantaneous radiances fields a variety of different products with varying spatial and temporal resolution are derived (Rossow and Schiffer 1991). In this study
Fig. 2. Development of global (solid), Northern Hemisphere (dashed), and Southern Hemisphere (dot-dashed) mean cloud cover in a 24-h forecast when starting with (thick lines, ic) and without (thin lines, nic) initial cloud. The length of one time step is 30 min.

Table 1. Area and time-averaged cloud cover for ISCCP, ERA, and OPS. (The averaging period for OPS is only from 1987 to 1990.)

<table>
<thead>
<tr>
<th></th>
<th>ISCCP</th>
<th>ERA</th>
<th>OPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Globe</td>
<td>63.06</td>
<td>62.30</td>
<td>53.40</td>
</tr>
<tr>
<td>NH</td>
<td>59.34</td>
<td>57.26</td>
<td>52.55</td>
</tr>
<tr>
<td>SH</td>
<td>68.71</td>
<td>66.42</td>
<td>53.87</td>
</tr>
<tr>
<td>Tropics</td>
<td>61.21</td>
<td>63.17</td>
<td>53.75</td>
</tr>
</tbody>
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Fig. 3. Time series of global-mean cloud cover from Jul 1983 to Dec 1990 for ERA (solid), ISCCP C2 (dashed), and ECMWF operational 24-h forecasts (dot-dashed).

The monthly mean cloud cover as provided in the ISCCP-C2 dataset for the months from July 1983 to December 1990 at a horizontal resolution of $2.5^\circ \times 2.5^\circ$ is used.

b. ERA

For the comparison to the satellite data a monthly mean dataset of total cloud cover has been created from the ERA at the same horizontal resolution as ISCCP. Total cloud cover is calculated from the cloud cover predicted for each of the model levels by integrating from the model top using the maximum-random overlap assumption (Morcrette and Fouquart 1986). As shown in section 2, there is no noticeable spinup in total cloud cover in the assimilation system. Therefore results of the 6-h first guess forecasts have been used for the comparison, in order to have the best possible representation of the large-scale flow.

4. Results

a. Global mean

Table 1 shows the average cloud cover for July 1983 to December 1990 for the whole globe and separated into Northern Hemisphere (NH) ($90^\circ$–$20^\circ$N), Southern Hemisphere (SH) ($20^\circ$–$90^\circ$S), and Tropics ($20^\circ$N–$20^\circ$S). The datasets included are the ISCCP-C2 data, ERA, and the operational analysis for which the averaging period is from 1987 to 1990.

The ERA shows very good agreement with the observations with a slight underestimation of global cloudiness mainly resulting from an underestimation of cloud cover in the extratropics; the tropical cloud cover is slightly overestimated. The difference in cloud cover between Northern and Southern Hemispheres is also very well simulated. As a reference the values as given by the operational 24-h forecasts from 1987 to 1990 are included in the table. The then operational diagnostic cloud scheme (Slingo 1987) strongly underestimated cloud cover in all areas and showed no large hemispheric difference.

Figure 3 shows the temporal evolution of the global cloud cover. Again the correspondence between ERA and ISCCP is striking. The interannual variability in cloud cover is well simulated with maxima in 1984 and 1985. However, the ERA cloudiness exhibits a strong annual cycle that is not supported by the observations. The cloudiness in the 1987–1990 operational system shows an even larger annual signal and a strong underestimation of cloudiness. There is a marked increase in cloudiness in the end of the period, which is related to a change to the cloud parameterization in the operational model in 1990. One of the purposes of the reanalysis projects was to eliminate such discontinuities arising from model/assimilation system changes.

b. Zonal means

Figure 4 shows the zonal distribution of cloudiness averaged over the entire period. The first three panels show the annual, July, and January averages. There is fairly good agreement in the Tropics and subtropics, but
the extratropical cloud cover between $30^\circ$ and $60^\circ$ is underestimated in both hemispheres with an overestimation poleward of $60^\circ$. The significance of the differences poleward of $60^\circ$ is difficult to assess due to difficulties in the ISCCP cloud detection over snow and ice (Rossow and Garder 1993b). Further discussion is therefore concentrated on the areas between $60^\circ$N and $60^\circ$S.

The fourth panel of Fig. 4 shows the difference in zonal-mean cloud cover between July and January as an estimate of the annual cycle of cloudiness. There is good agreement between ERA and observations except for the NH extratropics, where a summer maximum in cloud cover is not simulated by the analysis. This will be investigated in the next subsection.

Figure 5 shows the time evolution of zonal-mean cloud cover for both ISCCP and ERA. The general distribution of clouds, with high cloud cover in both the tropical and extratropical belts and low cloud cover in the subtropics is well captured in the ERA. The month-by-month variation in cloud cover in the Tropics, which is governed by variations in the location of the intertropical convergence zone (ITCZ) is very well represented, although the overall level of cloud cover is higher than observed. Some interannual variations such as the maximum in cloud cover around $10^\circ$S in winter 1986/87, are well captured, although the ERA shows a similar maximum in 1989/90, which is not present in the observations. Subtropical cloudiness appears to be underestimated; seasonal variations are, however, well described with minima in the respective winter season. Extratropical cloudiness is strongly underestimated especially in the bands between $40^\circ$ and $50^\circ$N/S. The annual migration of maximum values of cloudiness from $40^\circ$N in late winter to $50^\circ$N in summer, which is an annually recurring feature in the NH, is not captured at all in the ERA, which instead shows cloud cover maxima at around $55^\circ$N in autumn.

c. Selected areas

To assess the geographic distribution of the cloud cover differences, the spatial distribution of cloud cover averaged over the entire period of the study is shown in Fig. 6. The top two panels show the average cloud cover for ISCCP and ERA, respectively, whereas the bottom panel shows the difference of ERA minus ISCCP. The general spatial patterns agree reasonably well. The underestimation of extratropical cloud cover noted already in the zonal-mean figures is quite evident with the largest errors occuring over the oceans. The good agreement of zonal-mean cloud cover in the subtropics is due to a cancellation of errors, with an underestimation of the cloudiness in the stratocumulus ar-
Fig. 5. Time evolution of monthly averaged zonal-mean cloud cover for ISCCP (top panel) and ERA (bottom panel).

Tropical cloudiness is generally well represented with a slight overestimation over Africa and the Maritime Continent.

To investigate the spatial and temporal evolution of different climatological cloud regimes Hovmoeller diagrams of the mean annual cycle of cloud cover for selected latitude bands are presented. The averaging period is 1984–1990. Cloud cover is averaged over a 10° latitude band and the annual cycle is plotted as a function of longitude. The areas chosen are 50°–40°N representing extratropical cloudiness, 30°–20°N as an example for subtropical cloud regimes, and 10°–0°N as a tropical area.

Figures 7 and 8 show the evolution of cloud cover in the latitude band 50°–40°N for both ISCCP and ERA. The most pronounced feature of the cloudiness at those latitudes is the strong land–sea contrast with continuous cloud cover above 70% over the oceans and considerably lower values over land. There are particularly sharp gradients on the west coast of North America and on the west coast of the Eurasian continent, especially in summer. The land–sea contrast in general is well captured by the ERA although the gradients appear to be weaker mainly due to a general underestimation of cloud cover over the oceans by more than 10%, which is further enhanced off the coast of North America in summer and autumn. In the ISCCP there is a pronounced annual cycle in cloudiness over the Pacific with a maximum in summer. This is mainly due to the annual cycle of low stratus clouds (Klein and Hartmann 1993) and is well captured by the ERA. Over the Atlantic the maximum cloud cover occurs in winter. In this region the low stratiform clouds exhibit their summer maximum farther north (Klein and Hartmann 1993), so the influence of baroclinic developments, which peak in winter, dominates the annual cycle. Over western Europe the ERA generally underestimates cloud cover by more than 15% but reproduces well the pronounced annual cycle with a cloud cover minimum in late summer. Over central Eurasia a very strong annual cycle exists with a distinct summer maximum in the observations. Although ERA captures the low winter cloud amounts in this region very well, the summer maximum is underestimated by up to 20%. This behavior could be explained by a lack of convective clouds over land in summer, which form the bulk of the cloudiness for those regions. This may include both fair-weather shallow cumuli and deep convective systems. Over the North American continent the predicted cloud cover matches the observed better although the winter maximum over the eastern part of the region is stronger in the ERA than in ISCCP. Care has to be taken in the interpretation of these differences because of the difficulties in the detection of clouds over snow-covered areas in ISCCP. Revised ISCCP datasets that are currently being produced (Rossow et al. 1996) will include better estimates of cloudiness over snow.

Figures 9 and 10 show the same quantities as Figs. 7 and 8 but for the latitude band 30°–20°N. Those latitudes are dominated by stratocumulus and trade wind cumulus regimes over the oceans, but features like the Indian summer monsoon are also apparent in the observations. Two major deficiencies in the ERA cloudiness are immediately evident. First of all, the trade cumulus regime cloud cover that dominates in summer over both the Pacific and the Atlantic Oceans is overestimated by about 10%–15%. However, the very pronounced continuously large cloud cover off the North American continent, representing mainly stratocumulus clouds, is underestimated in the ERA by about 15%. The cloudiness connected to the Indian summer monsoon is very well simulated with a 10% overestimation of the peak values.

Figures 11 and 12 show the tropical cloud cover evolution averaged over 0°–10°N lat. This region is dominated by the ITCZ for most of the year. Regions of special interest are the western Pacific warm pool, the eastern Pacific, and the African continent. The western Pacific region is characterized by large cloud amounts throughout the year, which ERA generally overestimates by 10%–15%.
Figure 6. Annual mean of total cloud cover averaged from Jul 1983 to Dec 1990 for ISCCP (top), ERA (middle), and ERA minus ISCCP (bottom). Positive differences are depicted by thick solid lines negative by thin dashed lines.
Fig. 7. Mean annual cycle of cloud cover for ISCCP averaged over 40°-50°N for the years 1984-90.

Fig. 8. Mean annual cycle of cloud cover for ERA averaged over 40°-50°N for the years 1984-90.
Fig. 9. Mean annual cycle of cloud cover for ISCCP averaged over 20°–30°N for the years 1984–90.

Fig. 10. Mean annual cycle of cloud cover for ERA averaged over 20°–30°N for the years 1984–90.
Fig. 11. Mean annual cycle of cloud cover for ISCCP averaged over 0°–10°N for the years 1984–90.

Fig. 12. Mean annual cycle of cloud cover for ERA averaged over 0°–10°N for the years 1984–90.
The eastern Pacific off the coast of South America is characterized by a strong annual cycle with a marked late summer maximum. Over the continent the annual cycle is of opposite phase with the cloudiness maximum occurring in winter and spring. This leads to a pronounced dipole structure of cloudiness between land and sea, which is most likely caused by annually recurring changes in the Walker circulation. ERA generally captures this dipole structure and the phase of the annual cycles both over land and sea. There is, however, a general overestimation by 10% of the cloudiness minima.

Over the African continent the signal is dominated by the movement of the ITCZ in and out of the region. In summer there is a pronounced maximum in the observations, which is reasonably well captured. Cloud cover over the central part of the continent is, however, overestimated, pointing to too intense convection over land. This is confirmed by a study by Stendel and Arpe (1997), who found an overestimation of precipitation in the ERA over tropical land.

It has been shown so far that the ERA system captures many of the important annual variations in cloud cover. In order to investigate whether the system is also able to capture some of the observed interannual variability, Figs. 13 and 14 show the evolution of the annual-mean cloud cover in the latitude band 0°–10°N from 1984–90. The strongest interannual signal in the Tropics is that of the El Niño phenomenon. A moderate El Niño event occurred in 1987 and is clearly visible in the ISCCP observations. The cloud cover maximum normally located in the western Pacific Ocean follows the eastward shift in maximum sea surface temperature (SST) to the date line. The cloud cover in the eastern Pacific is enhanced. This is followed by a cloud cover minimum near the date line in the following year characterized by cold SSTs in the region. Although generally overestimating cloud cover over the western Pacific, the ERA captures both the shift of the cloud cover maximum and the minimum in 1988, indicating that the parameterization schemes that influence the simulation of cloud cover, most prominently the cloud and convection parameterizations, are able to respond reasonably to the SST forcing.

An interesting feature in Fig. 14 is the the continuous reduction in cloud cover over the African continent. This trend has also been noticed in precipitation by Stendel and Arpe (1997). Its reason is unknown since there are no obvious trends in data availability in that region.

5. Summary and discussion

The study described the implementation of a fully prognostic cloud scheme into ECMWF’s reanalysis system and compared the representation of cloud cover on timescales of months and longer against data from ISCCP for the years 1983 to 1990. The purpose was twofold: (i) to identify general areas of deficiencies in the cloud cover parameterization and (ii) to provide guidance in the interpretation of results of other studies that use data from the ERA sensitive to clouds. The use of a data assimilation system in the assessment of a parameterization scheme is clearly superior to a long climate simulation because of the better representation of the large-scale conditions. With the method adopted to determine the initial values for the cloud parameters, spinup problems have been shown to be negligible.

The representation of cloud cover in the prognostic cloud scheme used in the ERA is a great improvement compared to the diagnostic scheme that was still operationally used when the reanalysis project went into its production phase. There are, however, several areas of erroneous simulation of cloud cover even on long timescales. The major deficiencies are:

- an underestimation of extratropical cloud cover over the oceans by 10%–15%
- an overestimation of trade wind cumulus cover by about 10%–15%
- an underestimation of stratuscover off the west coasts of the subtropical continents by 15%
- an underestimation of the summer maximum in cloud cover over the Eurasian continent.

The comparison presented here cannot reveal the detailed reasons for the problems identified. However, it points strongly to the cloud regimes that require further research with detailed process studies (e.g., single column simulations). In fact, work is currently under way at ECMWF to improve the erroneous representation of trade wind cumulus cloud cover identified here.

One of the most likely applications of a reanalysis is the use of its surface winds and fluxes to drive ocean models. Of major importance hereby are the radiative fluxes. Although cloud cover is not the only influence, its erroneous representation will contribute strongly to errors in surface radiation. This has been confirmed by Källberg (1997, personal communication) for the ERA, who found a strong underestimation of the solar radiation at the surface in the trade wind regions and an overestimation in the stratus areas, in line with the cloud cover errors found here. Furthermore the trend in cloud cover over continental Africa pointed out in section 4 has also been identified in the precipitation fields by Stendel and Arpe (1997). These are examples of studies for which this work can be of importance when interpreting the findings.

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Fig. 13. Time evolution of annual-mean cloud cover for ISCCP averaged over $0^\circ$–$10^\circ$N for the years 1984–90.

Fig. 14. Time evolution of annual-mean cloud cover for ERA averaged over $0^\circ$–$10^\circ$N for the years 1984–90.