Simulation of fog with the ECMWF prognostic cloud scheme

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SUMMARY

A prognostic cloud scheme has been operational at the European Centre for Medium-Range Weather Forecasts (ECMWF) since 1995. In this paper the performance of the cloud scheme in simulating fog is assessed. A case-study is performed with the one-column version of the ECMWF model in order to analyse how the model reproduces the main mechanisms of fog generation and dissipation. A climatology of the model's fog is produced using data from the ECMWF Re-Analysis and compared with climatological data. High resolution (T21L31) operational forecasts with the prognostic cloud scheme are compared with synoptic reports of visibility for Europe. In this context the relation between fog and temperature, on the one hand, and fog and wind speed, on the other, is explored in some detail.

The comparison between the simulated and the observed visibility, in the one-column model case-study, shows that the evolution of fog is properly simulated. The analysis of the behaviour of the different parametrized physical processes suggests that the subtle balance between the various processes, fundamental for a realistic fog simulation, is achieved. This study also shows that in radiation fog a cooling process like radiation, that only changes the temperature without changing the moisture, is rather essential in order to reach saturation. The comparison between the model's fog climatology and the climatological data shows that the model is able to reproduce most of the major fog areas, particularly over the ocean.

The analysis of the results from high-resolution fog forecasts for Europe and the comparison with synoptic observations of visibility shows that the model simulates realistically some of the fog over Europe, particularly at 00 and 06 UTC. At 12 UTC the fog in the model is usually underestimated. In general, the number of situations where the visibility is between 2 km and 11 km is underestimated by the model. It is shown that the model is always slightly closer to saturation than the observations and this might be helping the model in producing fog. The model reproduces the observed behaviour of fog as a function of temperature and wind speed rather realistically.

KEYWORDS: Fog climatology Fog forecasting Global model Prognostic cloud scheme

1. INTRODUCTION

Fog is a common meteorological phenomenon and fog forecasting is an important and challenging task. The World Meteorological Organization (WMO) (1966) defines fog as a suspension of very small water droplets (sometimes ice crystals) in the atmosphere, reducing the horizontal visibility at the earth's surface to less than 1 km (if the visibility is above 1 km it is called mist). According to Cotton and Anthes (1989) fog typically has a lifetime of 2 to 6 hours and a liquid water content from 0.05 to 0.2 g kg$^{-1}$.

A simple and instructive way of thinking about the fog-generation mechanisms is by representing the thermodynamic state of an air parcel in a Clausius–Clapeyron diagram, where the water vapour pressure (or specific humidity) is plotted against temperature. Taylor's (1917) analysis of this diagram, still widely used (e.g. Cotton and Anthes 1989; Stull 1995), shows that fog generation can be conceptually reduced to three main processes: cooling (e.g. radiative cooling) by which the temperature is reduced without changing the moisture; moistening (e.g. evaporation of warm precipitation falling through cooler air) by which the moisture content is increased without changing the temperature; and mixing of air parcels (of which at least one might be unsaturated) that may lead to saturation due to the nonlinearity of the Clausius–Clapeyron saturation curve.

In the real atmosphere all these processes may occur at the same time, although one mechanism might be dominant. Mixing is always present and plays an important role in the

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formation and dissipation of most fog events. However, without some additional cooling and/or moistening, fog seldomly forms by mixing alone. Oliver et al. (1978) conclude that radiation plays a significant role in most surface fogs deeper than a few metres.

In a global numerical weather-prediction (NWP) model, the most relevant aspect of fog is probably its intimate relation with the existence of low stratus: the lifting of fog from the ground in the morning is typical during radiation-fog dissipation, and stratus-lowering fog is a common event, for example in coastal California (e.g. Pilie et al. 1979). Fog is also considered to be related to the generation of Arctic stratus (Houze 1993), while the possibility of marine stratus being formed as fog is referred to by Moeng (1993).

The evolution of fog in an NWP model depends on several parametrized physical processes: turbulent mixing, radiation, clouds, condensation and interaction with the surface. A successful forecast of a fog event suggests that a suitable and delicate balance has been achieved between all these different parametrized physical mechanisms.

The first numerical studies of fog used one- and two-dimensional (1-D) and (2-D) boundary-layer models with a rather simplified physics (e.g. Fisher and Caplan 1963; Zdunkowski and Barr 1972; Brown and Roach 1976). More recent studies (e.g. Musson-Genon 1987, hereafter M87; Turton and Brown 1987) have focused on the interaction with the vegetation (Duynkerke 1991) or on the interaction between radiative transfer and fog microphysics (Bott et al. 1990). Some recent studies used three-dimensional (3-D) mesoscale models (e.g. Ballard et al. 1991; Golding 1993). A recent introduction to numerical studies of fog can be found in Bergot and Guedalia (1994).

Until quite recently, forecasting fog was made, and still is, by means of empirical rules or statistical methods (see Tremant (1989) for a review). However, in the last few years some numerical models have been developed that are able to forecast fog operationally. The existing models can be divided into the two groups already mentioned: 3-D mesoscale models and 1-D boundary-layer models (sometimes coupled with horizontal advection schemes). A detailed review of operational models for fog forecasting can be found by Reiff (1987).

In some diagnostic cloud schemes used in global NWP models (e.g. Slingo 1987; Campana 1990) no clouds are allowed in the lowest model level (i.e. fog). The main reason is that the existence of fog in the model is detrimental to the forecast due to a positive feedback with the long-wave radiative cooling.

Recently, a prognostic cloud scheme was developed at the European Centre for Medium-Range Weather Forecasts (ECMWF), in which cloud processes are treated in a more complete and consistent way (Tiedtke 1993). In the first studies of the performance of the new cloud scheme (Tiedtke 1993; Kvamsto 1993) clouds were still not allowed in the lowest model level. In more recent versions of the scheme clouds are allowed to develop at any model level. So in principle the model is capable of producing fog, and it is therefore important to make an assessment of the capabilities of the new cloud scheme in simulating fog and low stratus. Another reason for such work is the fact that studies of fog with global atmospheric (NWP or climate) models are virtually non-existent.

The purpose of this paper is to assess the performance of the prognostic cloud scheme in simulating fog. In section 2 the prognostic cloud scheme is briefly presented. A detailed analysis of how the model simulates the main mechanisms of fog generation and dissipation in radiation fog is presented in section 3, where the results of a case-study with the one-column (1-C) version of the ECMWF model are shown. A climatology of the model's fog was produced using the ECMWF Re-Analysis (ERA). These results are compared in section 4 with climatological data. In section 5 high-resolution (T213L31) forecasts with the prognostic cloud scheme are compared with synoptic reports of visibility for Europe. In this context maps and time series are produced and the relation between fog amount and
temperature, on the one hand, and fog amount and wind speed, on the other, is explored. Finally, in section 6, some conclusions are presented.

2. THE ECMWF PROGNOSTIC CLOUD SCHEME

Prognostic cloud schemes started to be implemented in global atmospheric models only very recently. Most of them treat cloud fraction by means of diagnostic relations (e.g. Sundqvist 1988; Smith 1990). Tiedtke (1993) presents a scheme with prognostic equations for cloud fraction and liquid/ice water content. This scheme improved the simulation of clouds considerably in the ECMWF model compared with the diagnostic cloud scheme that was used before (Tiedtke 1993; Kramsto 1993; Jakob 1995; Miller et al. 1995).

The prognostic cloud scheme is described in detail by Tiedtke (1993). It consists of two prognostic equations, one for liquid/ice water, \( l \), and one for cloud fraction, \( a \):

\[
\frac{\partial l}{\partial t} = A_l + CV_l + BL_l + C - E - P - ENT
\]

\[
\frac{\partial a}{\partial t} = A_a + CV_a + BL_a + C_a - D
\]

where, respectively, \( A_l \) and \( A_a \) represent the advection of liquid/ice water and cloud fraction, \( CV_l \) and \( CV_a \) represent the sources of liquid/ice water and cloud fraction from the moist convection processes, \( BL_l \) and \( BL_a \) represent the source terms of liquid/ice water and cloud fraction due to boundary-layer turbulence, \( C \) is the condensation rate, \( E \) is the evaporation rate, \( P \) is the precipitation rate, \( ENT \) is the destruction of liquid/ice water due to cloud-top entrainment, \( C_a \) is the generation of cloud fraction by stratiform condensation and \( D \) is the dissipation of cloud fraction by turbulent erosion. The prognostic cloud scheme allows ice and liquid water to co-exist (mixed phase) based on a simple quadratic temperature dependence between 0 °C and -23 °C (see Jakob 1995).

It will be assumed that fog exists in the model when the liquid/ice water content at the lowest model level (roughly 30 m above the surface) is above a certain value. At this level the dominant sources and sinks for the cloud scheme are the stratiform condensation and evaporation terms, that are based on the computation of \( dq_s / dt \) where \( q_s \) is the saturation specific humidity and \( t \) is time. In the stratiform part of the scheme another process that dissipates the clouds is horizontal turbulent mixing of cloudy air with environmental air. Cloud-top entrainment also contributes as a sink term for the liquid/ice water. In the cloud it is assumed that the liquid water is homogeneously distributed. While the liquid/ice water evaporates the cloud fraction remains unchanged, dropping to zero only when the liquid/ice water is totally gone. The only sink term for cloud fraction is the one due to mixing between cloudy and environmental air. For a detailed description of the cloud scheme see Tiedtke (1993).

3. A ONE-COLUMN MODEL SIMULATION OF RADIATION FOG

In order to study in more detail how the ECMWF model handles the physical mechanisms responsible for fog, a fog event that occurred at Cabauw, the Netherlands, 3 August 1977, was simulated. This particular fog situation has already been studied using 1-D boundary-layer models developed by Grandin (1983) and M87 among others. The data used in this study were taken from M87.

The 1-C version of the ECMWF model is based on the global NWP model and integrates a set of six prognostic equations (wind components \( u \) and \( v \), temperature \( T \),
specific humidity $q$, $a$ and $l$) for a column of the atmosphere. In the soil there are evolution equations for the temperature and wetness of the different soil layers plus an evolution equation for the skin temperature and the skin water content. The 1-C model can be used with prescribed external forcing: the zonal and meridional components of the geostrophic wind, the vertical velocity and the horizontal advection of the atmospheric variables. The surface pressure is kept constant and the vertical advection is computed using a semi-Lagrangian scheme. The model has 31 levels in the vertical and the heights of the five lowest model levels are roughly 30 m, 150 m, 360 m, 640 m and 990 m.

The following set of physical parametrizations are in the version of the ECMWF Integrated Forecasting System (IFS) used here. The radiation parametrization is based on a band emissivity scheme for the long-wave parametrization and a delta Eddington scheme for the short-wave parametrization (Morcrette 1990). The cloud scheme is the one described briefly in section 2 and presented in detail by Tiedtke (1993). The moist convection is parametrized by using a mass-flux scheme and is described by Tiedtke (1989). The vertical diffusion parametrization is based on a K-diffusion approach with a K-profile closure (Beljaars and Betts 1993) for the unstable boundary layer, a Richardson number dependent diffusion coefficient for stable situations above the surface layer (Louis et al. 1982), and a Monin-Obukhov type closure in the surface layer (Beljaars and Holtslag 1991). The subgrid-scale orographic scheme is described by Lott and Miller (1997).

The soil/surface scheme includes prognostic equations for snow mass and for temperature and moisture in four soil layers. An interception layer collects water from precipitation and dewfall. The evaporative fluxes consider separately the fractional contributions from snow cover, wet and dry vegetation and bare soil. The canopy resistance and the emissivity are global constants. The roughness-length coefficients for momentum, heat and moisture, $z_{0m}$, $z_{0h}$ and $z_{0q}$, are geographically dependent and $z_{0m}$ is at least one order of magnitude larger than $z_{0h} = z_{0q}$. The soil-levels thicknesses are 7 cm, 21 cm, 72 cm and 189 cm. The soil/surface scheme is described in detail by Viterbo and Beljaars (1995).

The data used to initialize the 1-C model is described by M87, and consists of vertical profiles of the mean variables at 00 UTC 3 August 1977, and constant values of the geostrophic wind and temperature advection in the layer from 0 to 200 m. Advection of heat and moisture are not known accurately for this situation. M87 made an estimate for temperature advection of about $-0.18 \, \text{K day}^{-1}$ in the layer up to 200 m. Moisture advection is assumed to be negligible. In the current simulations the estimates for advection are as in M87.

(a) A simulation with the standard version of the model

To compare model results (liquid/ice water content) with the observed visibility the following empirical relation between visibility and liquid water is used (Kunkel 1984):

$$\text{VIS} = -\frac{\ln(0.02)}{\beta}$$

where VIS is the model derived visibility and $\beta = 144.7 \, (\rho l)^{0.88}$, with $l$ being the lowest model level liquid/ice water and $\rho$ the atmospheric density.

The time evolution of the simulated visibility at the lowest model level is presented in Fig. 1 together with the visibility observations at the 30 m level from the Cabauw tower. The model results are good: the onset of fog is only half an hour late, the lowest values of visibility are close to the observations and the dissipation stage is also properly forecast.

To understand better the time evolution of this fog situation, Fig. 2 shows the Clausius–Clapeyron diagram for the model's lowest model level, where the values of $q$ and $q_s$ are
Figure 1. The time evolution of the simulated visibility at the lowest model level together with the visibility observations at the 30 m level from the Cabauw tower.

Figure 2. The Clausius–Clapeyron diagram for the model’s lowest model level, with specific humidity, $q$, and saturated specific humidity, $q_s$, as functions of temperature, $T$. The dots and the numbers represent the hours of simulation (in UTC).
plotted versus $T$. Three different periods of the fog's evolution can be distinguished: (i) during the first period, from 00 until 04 UTC, the values of $T$ and $q$ are located on a mixing line that represents the way in which the model is evolving towards saturation; (ii) when saturation is reached a second stage starts, until 06 UTC, in which the fog is intensifying, more liquid water is being produced and $T$ and $q$ keep decreasing but remain on the saturation line, and (iii) after 06 UTC, until roughly 0730 UTC, a third period starts in which the fog is dissipating, the liquid water is decreasing and $T$ and $q$ are increasing but still on the saturation line.

In order to assess the role of the different parametrized physical processes on the fog's evolution, Fig. 3(a) shows the lowest model-level temperature tendencies and Fig. 3(b) the lowest model-level specific humidity tendencies, produced by each one of the parametrizations, during the simulation period. Figure 3(a) shows the temperature tendencies from the radiation parametrization (RAD) (both long-wave and short-wave), the vertical diffusion parametrization (VDIF), the cloud parametrization (CLOUD), the total tendency (TOTAL) and also the horizontal advection tendency (ADV) (constant during the simulation and equal to $-0.18$ K day$^{-1}$). Figure 3(b) shows the corresponding tendencies for specific humidity.

The three different periods can be distinguished from these figures. From 00 UTC until the onset of fog the cooling tendencies from radiation and vertical mixing are almost constant in time and with similar values, the vertical mixing being a bit higher than the radiation tendency. During this period the total tendency is nearly constant and around $-0.75$ K day$^{-1}$. In terms of specific humidity during this period the vertical diffusion is generating an almost constant negative tendency of around $-0.2$ g kg$^{-1}$ day$^{-1}$.

Around 04 UTC (about half an hour after the onset of fog) the liquid water starts to increase substantially and reaches values that are radiatively important. The long-wave cooling increases and reaches a stationary peak of around $-2.5$ K day$^{-1}$ between 05 and 07 UTC. The condensation heating produced by the cloud scheme becomes relevant, reaching a peak value of around 1.5 K day$^{-1}$ at 05 UTC, decreasing then to negative values between 07 and 0730 UTC. After the onset of fog the cloud scheme produces negative tendencies of moisture that dominate the total tendency. At 05 UTC they reach a value of around $-0.6$ g kg$^{-1}$ day$^{-1}$.

After sunrise the skin temperature increases and around 05 UTC it becomes higher than the temperature at the lowest model level. As a consequence the vertical diffusion tendency changes sign and increases until it reaches a peak value of around 5 K day$^{-1}$ for temperature and 1.5 g kg$^{-1}$ day$^{-1}$ for moisture at 07 UTC. Mainly due to this effect the total tendency changes sign and begins to warm and moisten the lowest model level just before 06 UTC, reaching a peak value of 3 K day$^{-1}$ for temperature and 1.6 g kg$^{-1}$ day$^{-1}$ for moisture around 0730 UTC which is the time the fog has dissipated.

(b) A sensitivity study of the impact of the radiative cooling of the lower atmosphere

The notion that radiative cooling of the surface has a fundamental role on the development of radiation fog is an established idea, at least since Taylor (1917). However, it was only comparatively recently shown (Brown and Roach 1976) that for a good numerical simulation of radiation fog, the long-wave cooling of the lower atmosphere should be included in the model.

To study the impact of the long-wave atmospheric cooling in radiation fog the same case was simulated but with the atmospheric radiation tendencies set to zero. In this simulation the lowest model level did not get close enough to saturation and, as a consequence, the model did not produce fog, as can be seen in the Clausius–Clapeyron diagram shown in Fig. 4. The cooling and drying associated with the mixing between 00 and 05 UTC is not
Figure 3. The lowest model-level tendencies produced by the different physical processes (see text) for (a) temperature and (b) specific humidity.
enough to saturate the lowest model level. What can be seen from analysing Figs. 2 and 4 is that the thermodynamic state of the lowest model layer always evolves along a mixing line during the first hours of the simulation or until the onset of fog. However, the model needs a cooling process like radiation, that only changes $T$ without changing $q$, in order to reach saturation.

The simulation of this radiation-fog event by the ECMWF 1-C model can be seen as a good example of a combination of the simple cooling and mixing mechanisms referred to in the introduction as the primary processes that are responsible for fog generation.

4. Simulated Climatology of Fog

A climatology of the model’s fog was produced using the ERA. The ERA project has produced a new 15-year dataset of assimilated data for the period from 1979 to 1993 and was produced using the ECMWF IFS that contains the model and the analysis part of the data-assimilation system. For details about the ERA see Gibson et al. (1997). The main model features are that it is a T106 global spectral model with an equivalent Gaussian grid of 1.125° resolution and has 31 vertical levels. The advection scheme is semi-Lagrangian. For details about the dynamics see Ritchie et al. (1995). The physical parametrizations were briefly described in section 3.

To produce the fog climatology, 5 years of data were analysed, from 1985 to 1989. The daily 6, 12, 18 and 24-hour forecasts were used to calculate the frequency of occurrence of fog in the model. This is estimated by computing the frequency of occurrence of liquid/ice water, in the lowest model level, higher than 0.016 g kg$^{-1}$. This value roughly corresponds to a horizontal visibility of 1 km (Kunkel 1984). The frequency of occurrence of fog in
the model is halved in order to make the model climatology more compatible with the Warren et al. (1986, 1988) climatology. Warren et al. (1988) suggest that the frequency of fog at a distance and fog within the past hours (which is not included in the observational climatology but is part of the model's climatology) is roughly of the same magnitude as the frequency of 'sky obscured' due to fog.

The observed frequency of occurrence of sky obscured due to fog is taken from the cloud climatology of Warren et al. (1986, 1988). This climatology is based exclusively on surface observations, either ships or land stations. The climatology results represent averages of 30 years (1951–81) of data for the oceans and 10 years (1971–81) for the land areas.

(a) December–January–February

Figure 5(a) shows the frequency of occurrence of fog in the model, for the December–January–February (DJF) period. Figure 5(b) shows the observed frequency of occurrence of sky obscured due to fog for the same period.

Comparing both figures, it can be seen that the simulation of fog over the ocean is good. The model reproduces the major fog areas over the Southern Ocean. This maximum of fog frequency during the austral summer could be associated with a maximum of stability in the lower troposphere for that time of the year (Klein and Hartmann 1993). The model is also able to reproduce approximately the regions where fog frequency around Antarctica reaches maximum and minimum values. Some fog over the ocean is also produced by the model in observed fog areas like close to the east coast of Greenland, the Bering Strait, the coast of Newfoundland and in some parts of the north-east Pacific.

The model simulates reasonably well some of the main areas of fog in Europe, except for some parts of the Iberian peninsula where there is a lack of fog. The fog in areas along the north Mediterranean coast and close to the Black Sea and Caspian Sea is well reproduced. Fog in Scandinavia, particularly around the Baltic Sea, and fog in eastern China are also reasonably well captured by the model.

As it can be seen in Fig. 5(b), winter fogs can be frequent along the coast of the Gulf of Mexico. According to Petterssen (1969), the drainage into the Gulf of cold, fresh water from the rivers, coastal bays and estuaries causes fog to form when there is a warm and moist flow from the south. The model reproduces some of the fog in this region. Fog frequency is underestimated by the model for the west coast of the United States.

In mountain areas, such as part of Canada, north-west United States, Mexico, New-Guinea and, particularly, the Andes, the model is producing too much fog when compared with climatology. According to Barry (1981), fog is a prominent feature of most mountain areas and depends very much on local orography. Therefore model and observations are difficult to compare in mountainous areas. The model does not have the resolution to represent the details of the topography, and the density of observations tends to be low in these areas.

(b) June–July–August

In Fig. 6(a) the values of frequency of occurrence of fog in the model, for the June–July–August (JJA) period, are presented. Figure 6(b) shows the observed frequency of occurrence of sky obscured due to fog for the same period.

Comparing both figures it can be seen that again over the ocean the model performs well. In fact, the model is able to capture the areas over the ocean where fog is most frequent during the northern hemisphere (NH) summer, particularly in the western parts of the Pacific and the Atlantic Ocean. Close to Newfoundland the model is performing very
Figure 5. The climatology of the frequency of occurrence of fog, for the December–January–February period, for (a) the model and (b) the observations. The first contour is at 2% and the contour interval is 5%. See text for further explanation.

well. However, over the western Pacific the peak values of fog frequency are underestimated by the model.

The fog that occurs during the NH summer over the Arctic Ocean and neighbouring coastal regions is also well simulated, with some of the peak regions, like the ocean areas north of Iceland, being reasonably well captured. In some areas, however, the model underestimates the fog frequency. Fog is produced by the model in some areas of the Southern Ocean even during the southern hemisphere (SH) winter. However, the number of observations in that area, especially during this time of year, is very small, which makes the validation of model results virtually impossible.
During the NH summer, the areas over land where fog is most frequently observed are coastal regions (Newfoundland, north-east Asia or the coastal areas of the Arctic Ocean) that are associated with ocean areas with a high frequency of fog. As seen before, the model seems to simulate well the fog in these regions. Close to the east coast of continents, the high fog frequency is associated with large-scale advection of warm and moist air, over ocean regions with large gradients of sea surface temperature. The success of the fog forecast in these areas is mainly related to the ability of the model to simulate realistically the low-level flow and the large-scale advection of temperature and moisture over these ocean areas. As in the DJF season, the model misses some of the fog observed at the west
coast of continents, on the margins of the oceanic subtropical highs. The reasons for this problem will be explored in section 4(c).

From Figs. 5(b) and 6(b) it can be seen that in some areas of the tropical rain forests, particularly in the Congo basin, fog is expected to exist. Radiation fog, formed at dawn, frequently occurs over the tropical forests (e.g. Ratisbona 1976) due to the high moisture content of the air. As in the DJF season, the model is reasonably successful in simulating fog over the tropical forests of Africa.

Finally, the model reproduces the climatological observation that more fog occurs in the summer hemisphere over the ocean and more fog occurs in the winter hemisphere over the land.

(c) Fog near the west coast of continents

There are areas at the west coast of continents, on the margins of the oceanic subtropical highs, where the model does not generate fog as observed. These regions include the west coasts of the United States, South America and southern Africa. Since on many occasions the evolution of fog is coupled with the evolution of low-stratus clouds, the model performance in simulating stratus is analysed.

The global distribution of low-cloud cover produced by the ERA for the period JJA 1985–89 is presented in Fig. 7(a). As for fog, the daily 6, 12, 18 and 24-hour forecasts were used. In comparing Fig. 7(a) with climatological data for low-stratus distribution (Warren et al. 1986, 1988) for the same JJA period (Fig. 7(b)), it can be seen that the model produces a reasonable distribution of low clouds. A similar conclusion was drawn by Tiedtke (1993): a comparison with ISCCP* data for July 1987 shows that the model produces realistic low- and middle-level clouds. In Fig. 7(b) there are few contours south of around 40°S because there are not enough observations to develop a statistically significant climatology.

Returning to the problem of why the model misses fog at the west coast of continents and comparing Figs. 7(a) and 7(b), it can be seen that the model does not generate enough clouds in the stratocumulus areas and they are also shifted to the west. The relation between fog and stratus at the west coast of continents is reasonably well documented and stratus-lowering fog events are common, for example in coastal California (Oliver et al. 1978; Pilie et al. 1979). Taking this into account it is likely that the lack of fog at the west coasts is connected with this lack of stratocumulus and its westward shift. Apparently the model has difficulties in simulating fog events that are related to stratus since the physical processes that according to Pilie et al. (1979) and Oliver et al. (1978) dominate this stratus-lowering fog situations, like drizzle or turbulent mixing directly induced by cloud-top radiative cooling, are not very well represented in the model.

5. High-resolution fog forecasts over Europe

The prognostic cloud scheme was implemented operationally in the ECMWF model in April 1995. This version of the ECMWF model has already been described in the previous sections and the reader is referred to Miller et al. (1995) for a detailed account of the changes introduced operationally with this model version. The operational model has horizontal spectral resolution T213 which corresponds to a Gaussian grid with 60 km resolution. To initialize the cloud fields the first-guess results are supplied as cloud initial state (Jakob 1995).

The climatology of low-cloud cover, for the period June-July-August, produced by (a) the model and (b) the observations. The first contour is at 20% and the contour interval is 20%. See text for further explanation.

The observational data that are used to validate the quality of the high-resolution fog forecasts is composed by the SYNOP observations distributed by the WMO for the period from September 1995 to January 1996. The following observed quantities are used: wind speed at 10 m height, temperature and specific humidity at 2 m height, and visibility.

The relation between visibility and liquid-water content (Kunkel 1984) is used in order to compare the fog forecasts with the observations of visibility. For the fog-verification maps the model liquid/ice water content is converted to visibility and compared with the observed visibility. In the case of time-series plots or the computation of average values of fog amount, it is the observed visibility that is converted to liquid/ice water content and compared with the liquid/ice water content of the model.
(a) Fog-verification maps over Europe

Fog-verification plots for Europe were produced for 00 and 12 UTC. In these plots the 60 and 72-hour forecasts of liquid/ice water content at the lowest model level are shown, together with the visibility (if it is less than 6 km) reported by the synoptic stations for the same period.

Several of these plots have been analysed for the period from September 1995 to January 1996. Figures 8(a) and 8(b) (corresponding to verification at 00 and 12 UTC 13 October 1995 respectively) represent a particularly successful case of fog forecasting. It can be seen that most of the low-visibility (less than 1 km) stations in central and northern Europe at 00 UTC are covered by the liquid-water contours. The model produces more fog at 00 UTC than at 12 UTC. This also happens in nature, but not to such a degree. In fact, at 12 UTC, when the observed visibility in most of central Europe increases to values of 3 to 4 km, the liquid water in the model disappears almost completely.

In general, the model reproduces some of the major areas of fog and mist in Europe; however, it tends to underestimate the total amounts. Situations where the model visibility is between 2 and 6 km are extremely rare, whereas in nature this is very common. In order to see whether this is a model characteristic, the distribution of the number of fog events (observations and forecasts) for different values of liquid/ice water is plotted in Fig. 9.

Figure 9 shows that the number of events of liquid/ice water content less than 0.0005 g kg\(^{-1}\) in the model is around 80,000 whereas for the observations this number is much smaller, around 20,000. The number of events where the liquid/ice water is between 0.001 and 0.006 g kg\(^{-1}\) (which roughly corresponds to a visibility between 11 and 2 km) is largely underestimated by the model when compared with the observations. Above 0.007 g kg\(^{-1}\) the number of events produced by the model compares reasonably well with the observations.

Three possible reasons for the model underestimation of events in the visibility range between 2 km and 11 km are: (i) other physical factors like rain, drizzle, snow, dust or atmospheric pollutants can limit the horizontal visibility, (ii) the parametrization of fog still misses some generation or dissipation processes, and (iii) the empirical relation used to estimate the visibility from the liquid/ice water content was calibrated under very specific circumstances and its range of validity is exceeded.

(b) Time series for Europe for January 1996

Time series are produced for Europe (defined by the coordinates 35°N, 10°W, 65°N, 50°E) where a comparison between 30, 36, 42 and 48-hour forecasts and SYNOP observations is performed for January 1996. The total number of observations is around 100,000. The relation between visibility and liquid-water content (Kunkel 1984) is used to convert the observed visibility to liquid/ice water content.

In Fig. 10(a) the time series of liquid/ice water content (which will be often referred to as fog) for the observations and the forecasts (30, 36, 42 and 48-hour) for Europe is shown. The results can be considered good, particularly at 00 and 06 UTC when the forecasts are close to the observations. However, on some occasions the forecast values are higher than the observed ones. During the day (12 UTC) the fog in the model is usually underestimated, which confirms the results from section 5(a).

In Fig. 10(b) the equivalent time series for the 2 m temperature is shown. The most striking feature is the almost constant negative temperature bias of around \(-4\) degC. In theory these unrealistic cold temperatures could bring the model closer to saturation than in reality, which could then lead to more frequent fog in the model. It should be mentioned that the 2 m temperature cold-bias problem is much less serious in recent versions of the
Figure 8. The (a) 60-hour and (b) 72-hour forecasts of liquid/ice water content at the lowest model level, verifying respectively at 00 UTC and 12 UTC 13 October 1995, together with the visibility reported by the synoptic stations. Only the values from the stations that report visibility less than 6 km are shown. The number 0 means that the station is reporting values of visibility between 0 and 1 km and so on up to number 5. The liquid-water contours are 0.002, 0.007, 0.016 and 0.1 g kg$^{-1}$. These values correspond roughly to values of horizontal visibility of 6 km, 2 km, 1 km and 200 m respectively (Kunkel 1984).
Figure 9. The distribution of the number of fog events (observations and forecasts) for different values of liquid/ice water content. It uses the 30, 36, 42 and 48-hour forecasts and the synoptic observations for Europe for January 1996. The total number of events (including ‘fog’ and ‘no fog’ events) is around 100 000. The observed visibility is converted to liquid/ice water content. The number of events is distributed in intervals of 0.001 g kg\(^{-1}\) of liquid/ice water content, except for the first interval that is from 0 g kg\(^{-1}\) to 0.0005 g kg\(^{-1}\).

model due to changes in the surface and vertical diffusion schemes (Beljaars et al. 1996; Viterbo et al. 1998).

In order to verify if the model is actually closer to saturation than the observations, the average state of saturation of the surface layer for the model and the observations was analysed. In order to do that, the forecast and observed values of the 2 m temperature versus the 2 m specific humidity were plotted. The same dataset as for the time series is used. In Fig. 11 the following is shown: the average 2 m specific humidity as a function of 2 m temperature for both the model and observations, the saturation specific humidity (for liquid and ice water) for the standard atmospheric pressure of 101 325 Pa, and all the model forecasts. Some of the forecasts look like they are supersaturated because the saturation curve represented in Fig. 11 is calculated using the standard pressure and not the atmospheric pressure that corresponds to one particular dot.

It can be seen in Fig. 11 that the observations and the model have a lower relative humidity at higher temperatures than at lower temperatures. The model is always slightly closer to saturation than the observations. This is probably due to the cold bias of the model, which does not go along with a dry bias, and might enhance the model’s fog production.

However, the average forecast liquid/ice water content does not change significantly with the temperature bias (not shown). This is the case for biases that range from \(-20 \degree C\) to \(10 \degree C\) and shows that there is no direct correlation between the cold bias and the performance of the fog forecast.
Figure 10. The time evolution of (a) liquid/ice water content and (b) 2 m temperature, for the synoptic observations and 30, 36, 42 and 48-hour forecasts for Europe, January 1996. See text for further explanation.

From the analysis of time series for different areas it can be seen that both the model and the observations seem to produce less fog when the 2 m temperature decreases substantially below 0 °C. Also, it is when the 10 m wind speed reaches its lowest value that the amount of fog is the highest, and when the wind speed increases fog decreases considerably. These comparisons suggest a physical relation between the amount of fog and the wind speed and temperature, which will be explored in the next subsection.

(c) Fog versus temperature and wind speed

The statistical relation between the amount of fog and parameters like the 2 m temperature and 10 m wind speed, both in the model and in the observations, is analysed further by plotting liquid/ice water content versus 10 m wind speed and 2 m temperature, using all the data for Europe for the month of January 1996.

There is a low incidence of fog over snow or ice (Petterssen 1969). In fact, it is difficult for fog to develop over a snow surface, due to the difference between the saturation vapour pressure over ice and over water. As a consequence, condensation usually occurs directly onto the snow, before the air becomes saturated. According to Petterssen (1969) this effect is largest in the interval from −10 to −15 °C. For temperatures below −40 °C, fog amounts increase again and are frequent during such low-temperature conditions when fog is composed entirely of ice crystals.

The frequency of occurrence of fog formed of ice crystals is still a matter of discussion. According to Vowinckel and Orvig (1970), low-temperature fog only forms around settlements. On the other hand, Curry et al. (1990) claim that the presence of ice crystals in the lower troposphere is common in the Arctic polar night. These situations are associated
with low visibility in the horizontal but with a good visibility in the vertical that often leads to the designation of 'cloudless' ice-crystal precipitation. Since these events are more frequent during the polar night, they are difficult to observe, both from the surface or satellite. However, according to Curry et al. (1990, 1993), these lower-tropospheric ice crystals are quite opaque to long-wave radiation and might play a fundamental role in the radiative balance of the surface and the temperature profile of the lower troposphere during winter.

Since the prognostic cloud scheme permits mixed-phase clouds, it should be able to handle realistically the behaviour of fog over ice or snow when the air temperature is below 0 °C. To see how the mixed phase can reduce the frequency of fog, let us suppose that the temperature of the atmosphere at the lowest model level is −10 °C. In the prognostic cloud scheme the atmosphere would need a moisture content of 1.65 g kg⁻¹ to become saturated. However, if the cloud scheme had no mixed phase, it would only be necessary to have a moisture content of 1.59 g kg⁻¹ to saturate the atmosphere.

Even if the temperature of the surface is the same as in the lowest model level (which is unrealistic since surface inversions over snow are common in high latitudes in winter), the model's downward flux of moisture to the surface would prevent the model atmosphere from becoming saturated, leading to a moisture content of the lowest model level close to the saturation value over ice.

From the previous discussion it would be expected that the amount of fog should decrease with decreasing temperatures from 0 to −40 °C. Above 0 °C the amount of fog should also decrease with increasing temperatures. Petterssen (1969), in a plot, based on observations, of the probability of occurrence of fog versus temperature shows both of these behaviours and a maximum probability of occurrence of fog close to 0 °C.
In Fig. 12 the average liquid/ice water content versus the 2 m temperature is shown for the model and the observations. This average is performed by dividing the temperature in intervals of 2 degC and uses all the observations (around 100 000) over Europe for January 1996. Within the range of temperatures that were actually measured, the general behaviour of the observations is close to the one reported by Petterssen (1969). The behaviour of the model in the range from $-10$ to $10 \, ^{\circ}\mathrm{C}$ can be considered quite good when compared with the observations. The peak for both the observations and the forecasts is at $-2 \, ^{\circ}\mathrm{C}$ and has a remarkably similar value of around $0.015 \, \text{g kg}^{-1}$. Above $10 \, ^{\circ}\mathrm{C}$ the model values approach zero while the observations maintain an almost constant value between $0.0005 \, \text{g kg}^{-1}$ and $0.001 \, \text{g kg}^{-1}$. This value probably corresponds to bad visibility due to dust and pollution.

Below $-10 \, ^{\circ}\mathrm{C}$ the model produces more fog than is observed. However, the number of observations and model events below $-10 \, ^{\circ}\mathrm{C}$ is small, and the amount of ice starts to be the dominant component of fog, which makes the use of the relation proposed by Kunkel (1984) questionable. All this makes the results below $-10 \, ^{\circ}\mathrm{C}$ not very reliable.

It is known, at least since Taylor (1917), that light winds are conducive to fog formation over land (e.g. radiation fog) and there is a consensus that the frequency of occurrence of fog decreases with increasing wind speed. However, there is a certain degree of controversy about the role, in the development of fog, of the turbulent mixing at low wind speeds (e.g. Gerber 1981; Welch et al. 1986).

Some authors (e.g. Roach et al. 1976) believe that very low wind speeds contribute to fog generation, while others (e.g. Rodhe 1962; Gerber 1981; Welch et al. 1986) think that the role of turbulent mixing is fundamental for the development of fog, and that therefore very low wind speeds do not produce enough mixing for fog development.
Figure 13. As Fig. 12 but for the average liquid/ice water content versus the wind speed at 10 m.

In Fig. 13 the average liquid/ice water content versus the 10 m wind speed is shown. This average is performed by dividing the wind speed into intervals of 1 m s$^{-1}$ and uses all the observations over Europe for January 1996. A decrease of liquid/ice water with increasing wind can be clearly seen, both for the model and the observations. In that respect the model and the observations have a similar behaviour. Also the peak values of liquid/ice water both for the model and the observations are very similar at around 0.0105 g kg$^{-1}$.

However, while in the observations the two highest values for liquid/ice water are at 0 and 1 m s$^{-1}$, in the forecast these peak values correspond to wind speeds of 1 and 2 m s$^{-1}$. Actually in the model the peak value at 2 m s$^{-1}$ is followed by a decrease of the average liquid/ice water with decreasing wind speed. For the observations the liquid/ice water increases until it reaches its peak value at 0 m s$^{-1}$.

In this case the observations seem to favour the idea that very low wind speeds help fog to form while the forecasts seem to support the belief that very low wind speeds will decrease the amount of fog. However, both the observations and the model may be correct if the fact that the height of the observer is lower than the height of the lowest model level (around 30 m) is taken into account: very low wind speeds may be good for fog formation close to the surface but do not always produce enough mixing for fog to grow up to 30 m.

At wind speeds above 4 m s$^{-1}$ the results show that the model underestimates the amount of liquid/ice water. However, most of the fog events in the model are concentrated in the range between 0 and 4 m s$^{-1}$ while in the observations they are spread over a wider wind-speed range. These results are probably related to the model’s tendency to underestimate the wind speed in stable situations. Above 12 m s$^{-1}$ the amount of liquid/ice water in the model is negligible and its value is an imposed artificial minimum. In the
observations the amount of liquid/ice water is still significant, which means that there is a relatively low average horizontal visibility. At these wind speeds, low visibility is not due to fog but is probably associated with mid-latitude weather systems (e.g. precipitation).

6. Conclusions

The one-column version of the ECMWF model was used to simulate a well-documented case of radiation fog. A detailed analysis of how the model simulates the main mechanisms of fog generation and dissipation in radiation fog was presented. The comparison between the simulated and the observed visibility shows that the onset of fog, the lowest values of visibility and the dissipation stage are properly simulated.

From analysing the tendencies from the different parametrized physical processes it can be concluded that the subtle balances between the various processes, necessary to have a good fog forecast, are actually achieved. The analysis of the Clausius–Clapeyron diagram for the model's lowest model level provides a better understanding of the fog's evolution and shows the role of long-wave atmospheric cooling in radiation fog. This study shows that, although the thermodynamic state of the lowest model layer always evolves in time along a mixing line, during the first hours of the simulation or until the onset of fog, it needs radiative cooling to change $T$ without changing $q$ in order to reach saturation.

A climatology of the model's fog was produced using data from the ECMWF Re-Analysis. The comparison between these results and fog climatological data showed that the model is able to reproduce most of the major fog areas, particularly over the ocean. One exception is the lack of simulated fog at the west coast of continents. This seems to be related to a poor representation of stratocumulus and to difficulties of the model in parametrizing the processes that control the interaction between fog and low stratus.

High resolution (T213L31) 60 and 72-hour fog forecasts for Europe have been discussed for the period from September 1995 to January 1996. The forecasts were compared with synoptic observations of visibility and it could be seen that the model reproduces some of the major areas of fog and mist in Europe. The diurnal cycle is reproduced reasonably well by the model by producing more fog at 00 UTC than at 12 UTC, but the amount of fog at 12 UTC is too low when compared with the observations.

The number of situations where the visibility is between 2 km and 11 km is largely underestimated by the model when compared with the observations. This might be due to other physical factors like rain, drizzle, snow, dust or atmospheric pollutants that limit the horizontal visibility, and to problems that might still exist in the parametrization of fog.

Time series of liquid/ice water content from the observations and T213L31 forecasts (30, 36, 42 and 48-hour) were also analysed for all available surface stations in Europe. The results are good particularly at 00 and 06 UTC. During the day (12 UTC) the fog in the model is usually underestimated. The model is always slightly closer to saturation than the observations and this might help the model to produce fog. However, there is no direct correlation between the cold bias and the performance of the fog forecast.

A plot of the average liquid/ice water content versus the 2 m temperature showed that the model reproduces the observed behaviour of fog as a function of temperature. The amount of fog reached a peak value at around $-2 \, ^{\circ}C$ and decreased with increasing or decreasing temperatures. The behaviour of the model in the range from $-10 \, ^{\circ}C$ to $10 \, ^{\circ}C$ can be considered quite good. A plot of the average liquid/ice water content versus the wind speed at 10 m showed that the model reproduces the observations with a decrease of liquid/ice water with increasing wind speed.

As discussed in the introduction, the subtle balances between the various parametrized processes required for fog physics and also the results discussed here suggest that the
monitoring and study of fog in the model will provide impetus to improvements of the model parametrization schemes.

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