Modeling and Forecasting the Onset and Duration of Severe Radiation Fog under Frost Conditions

I. R. VAN DER VELDE AND G. J. STEENEVELD
Meteorology and Air Quality Section, Wageningen University, Wageningen, Netherlands

B. G. J. WICHERS SCHREUR
KNMI, Royal Netherlands Meteorological Institute, De Bilt, Netherlands

A. A. M. HOLTSLAG
Meteorology and Air Quality Section, Wageningen University, Wageningen, Netherlands

(Manuscript received and in final form 18 March 2010)

ABSTRACT

A case of a severe radiation fog during frost conditions is analyzed as a benchmark for the development of a very high-resolution NWP model. Results by the Weather Research and Forecasting model (WRF) and the High-Resolution Limited-Area Model (HIRLAM) are evaluated against detailed observations to determine the state-of-the-art in fog forecasting and to derive requirements for further research and development. For this particular difficult case, WRF is unable to correctly simulate the fog for any of the parameterizations and model configurations utilized. Contrary, HIRLAM does model the onset of fog, but is unable to represent it beyond the lowest model layer, which leads to an early dispersal of fog in the morning transition. The sensitivity of fog forecasts to model formulation is further analyzed with a high-resolution single-column version of HIRLAM, and with the Duynkerke single-column model as a reference. The single-column results are found to be sensitive to the proper specification of the external forcings. It is reconfirmed that high vertical resolution is essential for modeling the fog formation, the growth of the fog layer, and when the fog lifts for the maintenance of a stratus deck. The properly configured column models are able to accurately model the onset of fog and its maturation, but fail in the simulation of fog persistence and subsequent dispersal. Details of the turbulence parameterization appear to be important in this process. It is concluded that, despite all of the advances in numerical weather prediction, fog forecasting is still a major challenge.

1. Introduction and background

Despite the increased understanding of the relevant physical processes, and the progress in NWP in general, fog forecasting remains a big challenge (Gultepe et al. 2007). The faithful reproduction of fog depends critically on the horizontal and vertical model resolution, the initial conditions, the parameterizations of cloud microphysics, PBL turbulence, radiation, land surface feedback, and air quality (e.g., Holtslag et al. 1990; Bergot and Guedalia 1994; Clark and Hopwood 2001a,b; Fisak et al. 2006; Bergot et al. 2007).

Numerical modeling of fog onset and development has a long history. Fisher and Caplan (1963) were possibly first in examining the feasibility of constructing a numerical model for fog and low stratus forecasting. Single-column models have proven to be useful tools for the investigation of processes relevant to the life cycle of radiation fog. A seminal model was developed by Brown and Roach (1976), who included a parameterization for gravitational droplet settling. Their study led to the understanding that radiative cooling, turbulent transport, and the deposition of liquid water are the processes that enhance or impede the fog development. In addition, the column models by Musson-Genon (1987) and Duynkerke (1991, hereafter D91) were validated with detailed observations from the Cabauw experimental site. In the D91 model, the implementation of a vegetation scheme had a decisive influence on surface cooling and the subsequent fog
formation. Sensitivity tests with the Code de Brouillard à l’Echelle Locale (COBEL) column model (Bergot and Guedalia 1994; Bergot et al. 2005) revealed the importance of dew deposition and the initial conditions. Bott et al. (1990) developed the microphysical fog (MIFOG) and parameterized fog (PAFOG) (Bott and Trautmann 2002) models with a detailed description of the interaction of the radiative transfer, fog microphysics, and of the effect of low vegetation.

Fog simulation with column models presumes horizontal homogeneity in the external forcing and in the surface conditions. The surface fluxes of heat and moisture depend strongly on vegetation and soil properties, and the variability of these fluxes in heterogeneous terrain cannot be represented by column models (Terradellas and Bergot 2007). In contrast, mesoscale meteorological models do account for these horizontal heterogeneities at the scales resolved by their horizontal grids. However, in practice these models are limited by coarser vertical resolutions and simplified physics parameterizations as dictated by computational costs (Pagowski et al. 2004).

The study of fog with mesoscale models has been mainly concerned with advection fog over sea or in coastal regions (Ballard et al. 1991; Pagowski et al. 2004; Fu et al. 2006; Nakanishi and Niino 2006). The former two references showed a sensitive dependence of the fog evolution on initial conditions and on vertical resolution.

This paper summarizes an exploratory study on the performance of the Weather Research and Forecasting model (WRF) and the High-Resolution Limited-Area Model (HIRLAM) mesoscale NWP models for a case of thick and widespread radiation fog in the Netherlands during frost conditions. The purpose of the study is to evaluate the relative importance of model formulation, the parameterization choices, the resolution in forecasting the onset and duration of fog, and to identify weaknesses in the models. This evaluation is supported by simulations with single-column versions of HIRLAM and D91. This article aims also to establish this case study as a benchmark for the development of improved fog models.

For the selected case, the fog formed on the night of 25 November 2004 in a region of high pressure and covered a large part of the Netherlands. The fact that the fog persisted at several locations during daylight hours (e.g., at Amsterdam Airport Schiphol) made this event extra hazardous: the airport capacity was reduced from 64 to barely 20 aircraft per hour and 107 flights were cancelled.

This study has several innovative aspects as it is the first time (to our knowledge) that the forecast capabilities of WRF are investigated for a dense radiation fog event. In comparison to many previous studies, the circumstances of this fog event are also special in the sense that the recorded screen level temperature was \(<0^\circ\mathrm{C}\), that the fog onset occurred in the early morning (rather than in the evening), and last, that the fog persisted during daytime. Furthermore, comprehensive observations were available to investigate this event.

The paper has been organized as follows: section 2 describes the fog event in detail (i.e., its formation and development) and the available observations. To study the relevant physical mechanisms that are involved with the fog event, we explore the performance of the three-dimensional WRF and HIRLAM in section 3, while section 4 deals with the performance of the D91 and HIRLAM single-column models (H-SCM). Using comprehensive experimental observations at the Cabauw research tower site, we evaluate the forecasting skill, and we aim to identify important model shortcomings. Finally, section 5 covers the discussion and conclusions.

2. Synoptic situation and available observations

A high pressure system dominated the synoptic situation on 24 and 25 November 2004 (i.e., clear skies, imposed by large-scale subsidence and light winds, and favorable conditions for radiation fog; Croft 2003). The high progressed in southeastward direction between the Netherlands and Germany. Weak 10-m winds of 3 $\text{m s}^{-1}$ or less were recorded in the Netherlands. Maximum air temperature at Cabauw was about $7^\circ\mathrm{C}$ on 24 November 2004 and decreased to about $-2^\circ\mathrm{C}$ during the fog episode. Furthermore, 25 November 2004 was also significant in the sense that several synoptic stations recorded an ice day ($T_{\text{max}} < 0^\circ\mathrm{C}$).

The synergy between a network of 32 synoptic weather stations (Fig. 1) and the Advanced Very High Resolution Radiometer (AVHRR) cloud-top temperature satellite product, derived by the AVHRR Processing Scheme over Clouds, Land, and Ocean (apollos) analysis scheme (Fig. 2), provides information on the spatial extent of the fog event. In Figs. 2a,b the brown colors represent areas of relatively warm cloud tops of $-3^\circ\mathrm{C}$. Together with observed visibility from the synoptic weather stations information, these regions can be interpreted as low-level stratus or fog.

On 24 November 2004 (Fig. 2a, 2013 UTC) the Netherlands were still fog free. Routinely gathered visibility observations by the Royal Netherlands Meteorological Institute, interpolated by a spline method (Fig. 3) illustrate the spatial extent of the fog onset and its evolution during 25 November 2004. The fog covered the center, southern, and western parts of the Netherlands, and persisted throughout daylight hours. These observations correspond with the presence of relatively warm cloud tops in the satellite image of 1005 UTC (Fig. 2b).
micrometeorological observations, the temperature ($T_i$), the dewpoint ($T_{d,i}$), the wind speed, and the wind direction were observed at $i = 2, 10, 20, 40, 80, 140, \text{ and } 200 \text{ m}$. Unfortunately, visibility observations were not available for this case. In proximity of the tower, the landscape is flat and the land use is mainly agricultural.

The radiosonde observations (De Bilt) of 25 November 2004 indicated the presence of dry less opaque air above the fog layer, which promotes substantial radiative loss to space (not shown). Such conditions are excellent to instigate and maintain dense fog formation by radiative cooling. In addition, the recorded wind and temperature at Cabauw (Figs. 4a,b) were also typical for radiation fog characteristics (i.e., fog commenced under light winds of $1–3 \text{ m s}^{-1}$ and clear sky). After sunset, on 24 November 2004 a net radiation of $-49 \text{ W m}^{-2}$ caused continuous cooling in the atmosphere of about $0.4 \text{ K h}^{-1}$ near the ground. These conditions led to the development of a nocturnal inversion with a temperature difference of 4.2 K between 2 and 200 m (Fig. 4b and observed $T_i$ profiles in Fig. 5). Under the influence of radiative cooling and turbulent mixing the air became saturated at around 0300 UTC as the difference between $T_i$ and $T_{d,i}$ reached zero (Fig. 5) and specific humidity became well mixed (Fig. 6). Note that the observations with $T_i - T_{d,i} < 0$ are the result of the relatively large measurement uncertainty for nearly saturated conditions. Finally, the large wind increase on 26 November is thought to be related to a cold front passage (Fig. 4a).

The temperature profiles at Cabauw show that the initially shallow fog layer evolved into an optically thick layer (after 0300 UTC 25 November), with radiative cooling at the fog top (Fig. 5). As a result, the lowest 80 m quickly
destabilized (Fig. 4b). Consequently, vertical mixing increased the liquid water content (LWC) and transformed the fog into a more dense well-mixed layer. The large $T_{140}$ temperature decrease in the morning shows evidently that the fog top elevated upward to at least 140 m. Supposedly, due to large-scale subsidence later that day, the abrupt $T_{140}$ and $T_{80}$ increase indicate that these layers became again fog free. On 26 November the fog turned gradually into low stratus.

3. 3D model configuration and results

Next we present the experimental setup of the limited-area models WRF and HIRLAM, and model results are evaluated and compared with the Cabauw observations.

a. WRF model

Collaborated effort between different atmospheric research and operational-user communities led to the development of a next-generation mesoscale meteorological model: WRF. Since WRF offers a wide range of options regarding to the physical parameterizations, we tested different combinations of parameterization schemes. Here we particularly use the Advanced Research WRF core (ARW-WRF version 3.0.1). Three domains, all centered at Cabauw, are configured with a horizontal grid of $33 \times 33$, $56 \times 56$, and $61 \times 61$ points and a resolution of 30, 6, and 1.2 km, respectively. Two-way nesting has been applied for the two inner domains. The model uses 35 terrain-following hydrostatic-pressure $\sigma$ levels. Since fog is bounded in the vicinity of the earth’s surface we applied grid refinement in the PBL (10 layers below 240 m), with the first level at approximately 6 m (see Table 1).

WRF has been initialized with the NCEP final analysis. Information on vegetation, land-use type, terrain elevation, and albedo are made available by two-dimensional terrestrial data provided by the U.S. Geological Survey.
The physics in the ARW core are categorized in different modules, each with different options for the parameterization schemes (Skamarock et al. 2008). In this study, combinations of parameterization schemes are investigated to assess the impact on fog formation. Different options for the microphysics are utilized: Kessler, Eta Ferrier, and the WRF Single-Moment 3-, 5-, and 6-Class Microphysics Schemes (WSM3, WSM5, and WSM6, respectively). The latter is analogous to WSM5 (Hong et al. 2004) but includes graupel similarly to Lin et al. (1983). They mainly differ in the number of hydrometeor categories included and whether they include mixed-phase and ice-phase processes (Skamarock et al. 2008). Two PBL parameterization schemes have been selected: nonlocal first-order model by Yonsei University (YSU; Noh et al. 2003; Hong et al. 2006), and 1.5-order turbulent kinetic energy (TKE) closure model by Mellor–Yamada–Janjic (MYJ; e.g., Janjic 2002). The land surface module provides heat and moisture fluxes over the land/water surface grid and between the multiple soil layers. The two utilized schemes vary in the degree of complexity: the simple thermal diffusion model, which consists of 5 soil layers, and the more sophisticated Noah model, which consists of four soil layers and a vegetation layer on top (Ek et al. 2003).

b. HIRLAM model

HIRLAM is a short-range weather forecasting model for operational use by a group of European meteorological institutes participating in its development. The HIRLAM project is now in its seventh incarnation since its start in 1985 (see online at http://www.hirlam.org). Because of its objective of providing an operational forecasting suite, the research and development within the HIRLAM project is focused on a single reference
version of the model with an optimal combination of parameterizations. The code does contain alternative parameterizations, but for research purposes only. The 3D version of HIRLAM used in this research is the current reference model HIRLAM 7.2. It has a hydrostatic dynamical core and uses a hybrid vertical coordinate system and a two-time-level semi-Lagrangian advection scheme. Contrary to WRF, lateral boundary conditions are provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) global model using the Davies (1976) boundary relaxation scheme. However, the authors argue that the influence of the lateral boundary conditions is nevertheless small because our domain was dominated by a high pressure system (i.e., large-scale advection is small). Parameterizations used in the 7.2 reference are the Savijärvi (1990) radiation scheme, the Kain and Fritsch (1993) convection scheme combined with the Rasch and Kristjánsson (1998) condensation scheme, the Cuxart et al. (2000) turbulence scheme formulated in moist conserved variables, and the Interactions between Soil, Biosphere, and Atmosphere (ISBA) land surface scheme (Undén et al. 2002; Noilhan and Mahfouf 1996).

In this experiment, the model is run on a horizontal grid of 290 × 306 points with a spacing of 0.1° centered at Cabauw and with 60 vertical levels with the lowest level at 30 m (see Table 1). The model is run in a 6-h assimilation cycle for 3 days prior to the fog experiment to allow the surface model to spin up the observations used in HIRLAM. The HIRLAM 3D variational assimilation uses observations from the ECMWF Meteorological Archive and Retrieval System (MARS) archive. These observations include surface observations from synoptic stations, ships, and buoys and upper-air observations from the Aircraft Report (AIREPS) [including the Aircraft Meteorological Data Relay (AMDaR)], rawinsondes, and pilot balloons. In this situation with blocked flow over the western European continent, in particular the rawinsonde data is of importance in defining the vertical structure of the atmosphere. Nudging has not been applied for the forecast in this paper.

c. Results

The WRF and HIRLAM forecasts for the fog onset and duration are evaluated against observations at Cabauw. Since our aim is to understand model behavior, rather than to declare the best model, we do not provide further statistical evaluation. As for WRF, of the different evaluated compositions of parameterization modules, only a few were actually able to create fog during the selected days. This section presents the WRF simulation with permutations WSM3–YSU–Noah since it gave the overall best performance, regarding temperature, wind, specific humidity, RH, and downwelling longwave radiation. Note that the modeled temperature and humidity profile for 0000 UTC 25 November 2004 corresponds close to sounding observations below 800 m (not shown), and as such WRF provides correct starting profiles for the fog episode. For completeness, the fog onset and dispersal in four WRF permutations are listed in Table 2.

The observed downwelling longwave (L\text{\downarrow}) and short-wave radiation (S\text{'\downarrow}), the temperature at 2 m (T\text{'}) and friction velocity (u\text{'*}) are compared with the modeled values in Fig. 7. Moreover, profiles of T, T − T\text{'}, and specific humidity (q) are investigated, respectively, in Figs. 5 and 6. On 24 November 2004, conditions are generally fog free, since the observed L\text{\downarrow} (Fig. 7a) is relatively low at around 260 W m\text{−2}, which was confirmed from satellite observations. In addition, at noon, a clear peak is observed of S\text{'\downarrow} (Fig. 7b) and third, there is a substantial diurnal temperature cycle (Fig. 7c).

It was found that, at least for this study, a sudden increase of L\text{\downarrow} could be used as one of the indicators for fog detection (see the appendix). However, since the
increases suddenly from 250 to more than 300 W m\(^{-2}\) at around 0300 UTC. The increase of \(L\downarrow\) coincides with small values for \(T_d\) minus \(T_{2d}\) (also shown in Fig. 7a).

The modeled fog onset and duration deviates from the observations. In WRF the actual fog event of 25 November 2004 is not represented. On the contrary, the air reaches saturation on two other occasions as WRF’s RH progresses toward 100% (not shown), and thus corresponds with two \(L\downarrow\) peaks in the early morning, and two \(L\downarrow\) peaks in the evening of 24 November 2004. Those peaks coincide with the formation of liquid water in the lower model levels (Fig. 8). Both models underestimate \(L\downarrow\) by about 30 W m\(^{-2}\) during fog-free conditions on the first day. Although the observed \(L\downarrow\) has a positive bias of 10 W m\(^{-2}\) under clear-sky conditions (F. C. Bosveld 2008, personal communication), the differences between the model and Cabauw observations are still quite large but not uncommon (Steeneveld et al. 2008). The \(T - T_d\) profiles of WRF (Fig. 5) suggest that fog was already present at 0000 UTC 25 November up to a height of 60 m and at 0300 UTC up to 20 m, and was dissolved at 0600 and 0900 UTC. The modeled spatial extent of the fog at 0000 UTC 25 November is scattered and not widespread (Fig. 9).

HIRLAM’s \(L\downarrow\) corresponds well with the observations. The fog onset is perfectly simulated at 0300 UTC on 25 November 2004 as \(L\downarrow\) increases analogously with the observations. The \(T - T_d\) and \(q\) profiles show that the fog is limited to the lowest model layer and therefore it suffers from early dispersal at around 0900 UTC (Figs. 5 and 6). The dispersal of the fog is evident from the plunge in \(L\downarrow\) at sunrise.

The \(S\downarrow\) and \(T_2\) are reasonable well represented by both models on the first day. In the hours before the fog onset, \(T_2\) decreases from 7°C at noon to eventually around \(-3°C\) the next day. Only in HIRLAM the temperature decreases analogously with the observations. Clearly, freezing occurs because of the late onset of fog, and the fog onset may have been delayed by dewfall and hoarfrost for which there is evidence in a small negative latent heat flux in the HIRLAM forecast in the hours prior to the fog formation. Because WRF erroneously simulates fog in the evening of 24 November 2004, it forecasts an excess of \(L\downarrow\), which prevents a further temperature decrease to below freezing point. Apparently, the coarser vertical resolution of HIRLAM does not inhibit fog formation, but it may have played a role in its further development of being too shallow. The spatial extent of the fog in HIRLAM (Fig. 10) is comparable to that in the AVHRR image in Fig. 2b, although fog over the IJsselmeer and coastal waters is absent in the model. The absence of fog in the forecast of both models for the morning of the 25th, gives rise to an overestimation of \(S\downarrow\), and correspondingly a large rise in temperature, where in reality an ice day was recorded.

On 26 November, a cold front passage can be recognized in the increased friction velocity \(u_z\) (Fig. 7d). As the fog is cleared and replaced by low stratus, \(L\downarrow\) at Cabauw increases again sharply to 320 W m\(^{-2}\) and keeps growing the rest of that day. The advection of low stratus can be seen in both models. The sudden \(L\downarrow\) increase in WRF agrees very well with the observations, whereas the front passage seems to be delayed in HIRLAM. The late incursion of low stratus again leads to an overestimation of \(S\downarrow\) (Fig. 7b).

To learn about the robustness of the model results, additional permutations were implemented in WRF to circumvent possible limitations for the fog formation (e.g., disregarding the cumulus parameterization schemes, reducing the default minimum value of the TKE from 0.2 to 0.001 m\(^2\) s\(^{-2}\) in the MYJ scheme, and reducing turbulent transport and a large dew deposition by setting \(z_{0m} = 0.03\) m, and for MYJ specific \(z_{0m} = z_{0m}/10^5\), instead the default value of \(z_{0m} = z_{0m}\)). Even with the best combinations of available parameterization schemes, the WRF forecast remains incorrect. HIRLAM, however, predicts the fog onset very well but the fog layer is too shallow and its dissipation occurs too early. In addition, several tests were performed with WRF with either a larger outer domain of (i.e., 40 × 40 and up to 166 × 166 points),

<table>
<thead>
<tr>
<th>Vertical levels</th>
<th>WRF</th>
<th>HIRLAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>152</td>
</tr>
<tr>
<td>4</td>
<td>24</td>
<td>218</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>285</td>
</tr>
<tr>
<td>6</td>
<td>41</td>
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<td>55</td>
<td>424</td>
</tr>
<tr>
<td>8</td>
<td>70</td>
<td>498</td>
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</table>

<table>
<thead>
<tr>
<th>Models</th>
<th>Fog onset</th>
<th>Fog dispersal</th>
</tr>
</thead>
<tbody>
<tr>
<td>WSM3–YSU-Noah</td>
<td>1800 UTC 24 Nov</td>
<td>0300 UTC 25 Nov</td>
</tr>
<tr>
<td>WSM5–YSU-Noah</td>
<td>0300 UTC 24 Nov</td>
<td>1100 UTC 25 Nov</td>
</tr>
<tr>
<td>Ferrier–YSU-Noah</td>
<td>0600 UTC 24 Nov</td>
<td>1200 UTC 24 Nov</td>
</tr>
<tr>
<td>WSM3–MYJ-Noah</td>
<td>—</td>
<td>—</td>
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</tbody>
</table>
FIG. 7. Time series of modeled (WRF: solid line triangle; HIRLAM: solid line star) and observed (Cabauw tower, plus signs): (a) $L_1$, (b) $S_1$, (c) $T_2$, and (d) $u_0$. The fog event of 25 Nov 2004 is shown by the gray bar. Additionally, the observed $T - T_d$ (dashed line) is drawn in (a).
or more resolution in the inner domain (101 × 101 points),
or with ECMWF lateral boundary condition instead of
NCEP. All of these tests had no significant effect on the
forecasted fog onset or duration and therefore our WRF
model results seem to be consistent for this particular
difficult case.

Furthermore, it is important to stress that WRF’s
model domain configuration is not a limiting factor for
this case, as WRF does reproduce fog for a case study at
Cabauw (October 2005, not shown). However, the latter
case was less complex because of the absence of freezing
conditions. Therefore, we have to conclude that the WRF
results in the current case are due to the difficulties of the
particular meteorological conditions.

It is worthwhile to mention that the study by Liang et al.
(2008) shows that data assimilation experiments with
WRF had a positive effect on fog simulation. However,
our focus is on operational forecasting without using the
observations. Consequently, we do not investigate the use
of data assimilation in this paper.

In the next section, we investigate the underlying
physical mechanisms of the fog event by using two dif-
ferent high-resolution single-column models.

4. Single-column model configuration and results

In a manner similar to the previous section, we present
in this section the experimental setup of two single-
column models: H-SCM and the model by Duynkerke
(D91). In section 4c, the results of these two models are
investigated and compared with the Cabauw observa-
tions. Additionally, sensitivity tests with both models are
discussed in section 4d.

a. HIRLAM single-column model

The H-SCM consists of the full physics package of the
HIRLAM reference system, with a one-dimensional dy-
namics shell that takes care of the initialization, time
stepping, case-specific dynamical forcing, and model
output. As frozen condensate in both schemes is pro-
duced only when the temperature drops below −8°C
they are identical for the purpose of this study. The
SCM simulations use a prognostic scheme for frozen
condensate, instead of the diagnostic scheme used by the
3D model.

As in the three-dimensional model, a hybrid verti-
cal coordinate system is used, but with a much higher
resolution especially near the surface. The model uses
150 levels between its top at 10 hPa and the surface, with
47 levels below 2000 m and the lowest level at 4 m. In
accordance with this change the near-surface diagnostic
scheme has been modified to allow for a proper diagnosis
of 10-m wind and $T_2$, even in the case where the lowest
model level lies below these levels.

The initial conditions for the 1D model are derived by
interpolation from the +12 forecast of the 3D forecast
valid at 1200 UTC 24 November 2004. This includes the
soil and vegetation parameters, turbulence, and vertical
velocities. Temperature, wind, and specific humidity are
then replaced by values from the radiosonde of 1200 UTC
at De Bilt, Netherlands. Below 1057 m, the temperature
and specific humidity profiles in Table 3 has been used,
which are idealizations of the radiosonde observations,
while for levels between 1057 and 2000 m a linear tran-
sition is made between the idealized profile and the ra-
diosonde observations. Following D91, the geostrophic
wind $V_g$ was time dependent, and taken from the 200-m

FIG. 8. Time series of $L_{\downarrow}$ (solid line triangle) and LWC (dashed line circle) for WRF. Peaks of $L_{\downarrow}$ coincide with the
formation of LWC.
wind at Cabauw. The $z_{om}$ is derived from the 3D model climate and is dominated by the vegetation roughness $z_{oveg} = 0.25 \text{ m}$ at the Cabauw site where the orographic roughness is practically zero. The roughness lengths for heat and moisture are related to $z_{om}$ through the roughness Reynolds number $Re_z = z_{om} u^*/v$ and are therefore dynamic quantities (Garratt 1992). In this particular case, $z_{0h}$ varies between 0.05 and 0.10 m.

b. Duynkerke model

The other single-column model applied in this study originates from D91, with extensions as in Steeneveld et al. (2006). The model consists of a first-order turbulence closure model based on the wet equivalent potential temperature (Pointin 1984), which is a moist conserved variable, and consists of a graybody emissivity approach for longwave radiation (Garratt and Brost 1981) is employed. The land surface scheme consists of a 75-cm soil for which the diffusion equation for heat is solved, assuming horizontal and vertical homogeneity in the soil. Since temperatures are around the freezing point in the selected case study, soil moisture freezing and thawing was introduced, which had substantial impact on the forecast near-surface temperatures (Viterbo et al. 1999, not shown). The soil moisture content for this simulation is set to 0.5, as was estimated from Cabauw observations. On top of the soil mineral material a vegetation layer is placed, which has been connected with the first mineral soil layer by a conductance law. This aims to represent the stagnant air layer with a small heat capacity within the grass layer. The $z_{om}$ is set to 0.03 m and $z_{0h} = z_{om}/10$ (as in Garratt and Hicks 1973). The innovative aspect of the D91 model is the use of a droplet settling parameterization, with a droplet number concentration of $100 \text{ cm}^{-3}$. The D91 model uses 40 logarithmically distributed vertical layers, with the first model level at 0.3 m, and the model top at 1800 m.

The geostrophic wind and initial profiles are similar as in H-SCM, except for soil temperature, which were taken at the Wageningen (Netherlands) weather station (Jacobs et al. 2006; see Fig. 1) and are shown in Table 4.

Inspired by the series of radio soundings in De Bilt, a vertical wind of $-0.5 \times 10^{-3} \text{ m s}^{-1}$ was imposed to mimic the subsidence under the high pressure area, and
for the first 12 h, a 5 K h\(^{-1}\) heating was induced above 250 m, which was linearly interpolated to zero toward the surface. At the model top \(L_\downarrow\) was specified at 250 W m\(^{-2}\) following the climatology of Cerni and Parish (1984).

Both 1D models ran from 1200 UTC 24 November 2004 to +48 h. Note that the operational forecast skill of 1D models is normally limited to a time period of \(\sim 12\) h, but we extended the simulation to investigate the model skill for the dissipation phase of the fog. Therefore, this is more an academic exercise rather than for operational use. It is interesting to note the wide range of \(z_{0m}\) applied in the different models. Since all values of \(z_{0m}\) have been determined from the literature, it is clear that the parameterization of \(z_{0m}\) is still an open issue, even for a relatively homogeneous site as Cabauw.

c. Results

The framework of single-column models allows for efficient experimentation with physics parameterizations. A successful comparison of single-column models with observations depends critically on the application of the correct initialization and dynamical forcing. In the present study the large-scale subsidence confines humidity to the lowest 300 m of the atmosphere, the evolution of \(V_g\) influences turbulence intensity and eventually the frontal passage clears the fog and brings in low stratus. Sensitivity experiments with HIRLAM confirmed that all these factors influence the evolution of the fog layer (see below), even if the predominant process behind radiation fog is radiative cooling. The clouds advected with the front, however, are not included in the forcing and the column models are not able to model their effect.

The D91 model is used as a reference for subsequent sensitivity studies with H-SCM. The D91 model appears to be relatively successful in forecasting fog onset and evolution, but is unable to forecast the fog dispersal. For practical applications, however, the forecasting of fog dispersal may be as important as the prediction of the timing of fog onset.

The modeled \(L_\downarrow\) (Fig. 11a), usually a difficult quantity to forecast (Niemala et al. 2001; Guichard et al. 2003), is reasonably estimated by the relatively simple gray-body scheme employed in the D91 model. The modeled fog onset (increase in \(L_\downarrow\)) is slightly ahead of the observations, due to slightly overestimated surface cooling. However, during the mature stage of the fog, D91 slightly overestimates \(L_\downarrow\), which suggest a slight overestimation of
LWC. The fog decay around 0000 UTC 26 November is not captured by the model, although the wind speed increase is reasonably forecasted. Thus, the correctly forecasted $L_\downarrow$ after midnight is spurious because clouds were observed, while the fog layer is persistent in the model.

The $S_\downarrow$ (Fig. 11b) is correctly modeled for all daytime periods, which is surprising for the last day considering the persistence of fog in the model. This suggests the LWC of the modeled fog and the observed cloud do not differ substantially.

Screen level temperature $T_2$ (Fig. 11c) is a difficult quantity to forecast during fog episodes. The D91 model shows correct cooling in the afternoon of 24 November. Around 1700 UTC the top soil layer starts to freeze, which hampers the surface and screen level cooling for approximately 2 h. A similar temperature behavior is seen in the observations, although $T_2$ remains at a higher level (~1.5 K warmer) than modeled by D91. It should be noted that the onset and amount of soil moisture freezing depends on the available soil moisture, which is very locally determined. However, soil moisture observations that are representative for the grid scale are virtually impossible, and as such, the model might be forced with a slightly offset soil moisture. Therefore, the modeled temperature offset should not be seen as a surprise.

The modeled minimum $T_2$ of ~3.5°C is forecasted earlier than observed, again indicating that the model is approximately 1–2 h ahead of the observed fog onset. This overestimated cooling might be attributed by an underestimated vegetation heat capacity, which is a challenge to retrieve from field observations. At noon, H-SCM and D91 forecast the same maximum $T_2$ (correctly timed) about 3 K too warm and the consequent cooling is substantially underestimated. This might be a result of the overestimated turbulence intensity (e.g., $u_*$ in Fig. 11d) between 1800 and 2400 UTC on 25 November. Also after midnight, both 1D models provide enhanced turbulence compared to the observations. Note that the Wageningen weather station reported a maximum temperature of 1.8°C, which is close to the model forecast.

Although not shown here, it is informative to discuss the model performance on micrometeorological variables. The modeled sensible heat flux correctly follows the observations during the fog episode, but for 1200 UTC 25 November 2004, 50 W m$^{-2}$ is modeled while 30 W m$^{-2}$ has been observed. Also, after midnight on 26 November 2004, the observed sensible heat flux is negative while a positive flux is modeled because incoming clouds are not captured by the 1D model. Latent heat flux is correctly modeled before fog onset, but after fog onset observations are lacking. Also the modeled net radiation corresponds with the observed net radiation, although its increase at fog onset is more gradual in the model than was observed. Before the frontal passage ~40 W m$^{-2}$ was recorded although 0 W m$^{-2}$ was modeled.

From the modeled LWC in the D91 (see Fig. 12) the fog onset occurs around 0200 UTC 25 November 2004 and the layer gradually grows to 100 m at 0600 UTC and 180 m at 1200 UTC, and even reaches (obviously erroneously) 260 m at the end of the model simulation. At 1345 UTC 25 November 2004, the near-surface LWC shows a minimum, which if converted to visibility (Kunkel 1984) and assuming droplet number concentration of $N = 100$ cm$^{-3}$ (D91), would result in a visibility of 721 m. A minimum visibility of 89 m was modeled, which is close to the reported observations (Fig. 3). Note that the modeled visibility decreases more gradually in time than was observed. This might have disadvantages for practical applications. It should be noticed that the D91 results are relatively sensitive to the advection rate. Without heat advection, the maximum LWC = 0.72 g kg$^{-1}$, while this is 0.54 g kg$^{-1}$ (for the reference case (5 K h$^{-1}$)). In addition, without heat advection the fog onset starts 1 h earlier.

Finally, the model fails to remove the fog layer, even using substantial larger $V_g$ as a forcing than has been observed. This occurs for different model settings (not shown), and is thus a particular persistent feature. This indicates that the physical processes that control the fog dissipation are not well represented in the model physics, and further research to improve this aspect of the forecast is warranted.

As was the case with the 3D HIRLAM, the fog onset is correctly simulated by the 150-layer H-SCM. During the clear-sky conditions, preceding the fog formation, $L_\downarrow$ shows a similar negative bias in the column model as in the 3D model. When fog has formed the modeled $L_\downarrow$ equals the observed value. In the model the LWC is

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**Table 3. Initial profiles for temperature and humidity.**

| $z$ < 1057 m | $T(z) = 279.15 - 0.006055z$ (K) |
| $z \geq 1057$ m | $T(z) = 272.6 - 0.002979z$ (K) |

**Table 4. Initial profiles for soil temperatures.**

| $z_s$ < 0.05 m | $T_s(z_s) = 7.2 - [(7.2 - 5.0)0.05z_s] + 273.15$ (K) |
| $z_s \geq 0.05$ m | $T_s(z_s) = 10.7z_s^{0.2572} + 273.15$ (K) |
concentrated near the PBL top and moves up as the PBL grows (see Fig. 12). At the day transition there is again a sharp reduction in $L_\downarrow$. However, in the column model, $L_\downarrow$ does not return to a clear-sky value. The fog does not completely dissolve. In fact, the LWC in Fig. 12 is lifted from the surface and forms a broken stratus deck at the top of the humid layer at a height of around 300 m.
The cooling in H-SCM is not as strong as it is in the 3D model. This may be due to some temperature advection missing in the forcing. A reduction of dewfall at this elevated temperature may have had a compensating effect, so that this has not caused a delay in the formation of fog. In the early morning the observed temperature and humidity profiles are almost constant with height (see Figs. 5 and 6) and indicate that the fog layer is about 140 m thick and well-mixed. However, at the same moment in H-SCM, the LWC is concentrated near the top of developing PBL (see Fig. 12), hence, the fog layer in the model is far from well mixed. This may point to a deficiency in the parameterization of turbulent mixing under stable conditions.

As Fig. 11b shows, $S_y$ in H-SCM is quite similar to that observed. The maximum value of 150 W m$^{-2}$ is about 10% higher than observed. This small excess in afternoon $S_y$ is in part compensated by the negative bias in $L_y$. It leads to a warm bias in addition to the overestimation in temperature that is due to a lack of cooling in the preceding night. The relative agreement in $S_y$ might be related to an agreement in the LWC of the observed fog layer and of the modeled stratus, which may be a function of the bulk humidity of the layer confined below the subsidence inversion. Furthermore, it shows that the relatively simple radiation schemes of the column models are adequate for this case.

d. Sensitivity tests

1) RESOLUTION

To assess the effect of vertical resolution, sensitivity tests with a 60-layer and a 90-layer version of H-SCM were carried out. Both models had a lowest level around 10 m. Again with these lower-resolution models the onset of fog was accurately predicted, the level of $L_y$ was as observed, and the fog lifted at sunrise to form a broken stratus deck. However, with reduced resolution, the initial fog layer growth was slower and the overestimation of $S_y$ increased with reduced resolution, suggesting a lower LWC and a resolution dependence of the condensation scheme. In addition, another experiment was conducted with a 60-layer model, but now with the level definition used in the 3D HIRLAM and with a lowest model level at 30 m. This column model failed to produce fog altogether. Also, we have rerun the D91 model with 24 and 16 model levels (instead of 40). With the 16-levels run, the fog onset was delayed nearly 3 h, and the maximum LWC reduced with 16% relative to the 40-layer runs. The 24-layer run provided a correct timing of the fog onset, but the LWC was also 16% lower than in the reference run.

It is concluded that a high resolution near the surface is essential for the initialization of fog and also confirms in general the findings of Tardif (2007). As was argued for the 3D model, resolution is also of the essence for further growth of the layer. The success of the 3D HIRLAM model in producing fog with the same resolution must be attributed to the larger cooling rate in this model. Accurate forcing of the column model is clearly also important.

2) TURBULENT MIXING

The major deficiency in modeling fog of both the single-column and 3D versions of HIRLAM appears to be the quick dissipation of fog during the daytime. To study the possible contribution of the turbulent diffusion in this process, a sensitivity experiment was conducted with an earlier version of the TKE scheme. This earlier scheme, dry CBR, had not yet been formulated in moist conserved variables. With the new scheme the fog forms 2 h earlier than with the original scheme. This fog was then maintained during the day and was only partially dispersed as the wind increased after passage of the front. From the fact that the value of the modeled $S_y$ was only half that observed, it can be inferred that the model-predicted LWC of the fog was exaggerated. While this simulation again fails to faithfully represent the life cycle of fog, it clearly shows the role turbulent diffusion and its formulation in the model context play in this process.

5. Discussion and conclusions

In this study a case of widespread, thick radiative fog over the Netherlands during frost conditions was presented as a benchmark for mesoscale model development,
in particular for very high-resolution forecasts. A comprehensive set of observations, including satellite imagery, tower observations, routine radiosonde, and synoptic observations was collected and analyzed. The development of the fog layer was influenced by frost and a strong capping inversion caused by large-scale subsidence. At Cabauw it grew to 150 m and persisted throughout the day.

Two state-of-the-art mesoscale models, WRF and HIRLAM, were evaluated for this situation, with an aim to assess strengths and weaknesses in the mesoscale modeling of fog and from this determine directions for future research and development. Both models have difficulties in simulating important aspects of this particularly difficult fog under freezing conditions. WRF only forecasts fog for a few permutations of the available parameterization schemes, but the fog onset is particularly offset in time and location. This is surprising since the mean variables are well captured. HIRLAM correctly forecasts the onset of fog, but is unable to model the growth of the fog layer beyond the lowest model layer. As a direct consequence, in both models fog does not persist, but is quickly dispersed.

The sensitivity of HIRLAM to its model formulation was further evaluated in a single-column version and benchmarked against the Duynkerke (1991) single-column model, which has proven successful for similar cases of radiation fog. Both models performed well for the onset and the mature stage of the fog. Given the synoptic situation and the extent of the fog area it was likely that large-scale conditions were uniform. The forcings for this case could thus be derived with confidence from the comprehensive observations available. This will not be true in general and the sensitivity of column models to proper forcings will be a challenge for their use in operational forecasting.

A high vertical resolution close to the surface proved to be essential for the formation and growth of the fog layer. Additionally, resolution at higher levels becomes important when the fog lifts to form a layer of stratus. In the HIRLAM model, the liquid water content in the fog and low stratus reduces with a lower resolution.

The column models have similar problems as the mesoscale models in modeling the daytime evolution of the fog layer. The fog layer in the Duynkerke model is too persistent, whereas the fog in the HIRLAM single-column model again dissipates too quickly. A sensitivity experiment indicated that the turbulence scheme plays an important role in this process. Given the importance...
of the early morning dispersal of fog for an airport’s operation this is probably the main area of research in
the development of a high-resolution fog model.

This study has shown that despite advances in the un-
derstanding of the physics of fog both mesoscale and
column models have major shortcomings. Thus, fog fore-
casting remains a challenging task and much more re-
search on the relevant physical processes and model
aspects is needed. This holds in particular for the frost
conditions examined in this study.

Acknowledgments. The authors would like to ac-
knowledge the Royal Netherlands Meteorological In-
stitute, in particular F. C. Bosveld for providing the
Cabauw observations and personnel communications as
well as S. Tijm for providing H-SCM and insightful
discussion. We also would like to thank the ICSU/WMO
World Data Center for Remote Sensing of the Atmo-
sphere for making the APOLLO satellite products avail-
able. G. J. Steeneveld acknowledges financial support
from the BSIK-ME2 research programme (Climate
Changes Spatial Planning), from the Royal Netherlands
Academy of Science (Casimir-Ziegler Stipendium), and
from the Knowledge for Climate research program
(HSMS03).

APPENDIX

LWC–$L \downarrow$ Relationship

In this study a sudden change of $L \downarrow$ is used for fog
detection. However, we realize that factors as temper-
ature, humidity, and cloud cover limit the formulation of
a general threshold $L \downarrow$ value for fog detection. To show
that for this case study $L \downarrow$ is a useful fog onset indicator,
Fig. A1 shows the mean LWC over the lowest 100 m
versus the modeled $L \downarrow$ (WRF). For $L \downarrow < 250$ W m$^{-2}$
LWC equals 0, but for $L \downarrow > 250$ W m$^{-2}$ an approxi-
mately linear relation between LWC and $L \downarrow$ is found.
Hence, at least for this case, the relation between LWC
and $L \downarrow$ is evident from the model point of view. Note
that Vehil et al. (1989) reports a similar relationship
between optical thickness and $L \downarrow$. Also, Fig. 7a supports
a strong relationship between the dewpoint depression
$T_2 - T_{2d}$ and $L \downarrow$.

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