Modeling and Forecasting the Onset and Duration of a Severe Dutch Fog Event

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1. Introduction and background

Low visibility due to fog and low stratus seriously affects airport and hub-and spoke operations, which has obviously direct economic consequences. In the long term, the fog frequency and predictability may even influence an airline's choice of home base. Lack of knowledge of the relevant atmospheric, hydrological and chemical fog processes inhibit successful fog forecasting. Also, an apparent feedback appears between fog occurrence and regional climate (Vautard et al. 2009). Climate projections and weather forecasts agencies use numerical weather prediction (NWP), for which fog remains a challenge. Model improvement is essential to reduce uncertainty in fog forecasting and in airport operations.

This exploratory study evaluates the performance of the WRF and HIRLAM mesoscale models for a case of thick radiation fog in the Netherlands. We aim to identify the importance of model formulation, parameterization choices and resolution in forecasting the onset and duration of fog and identify common model weaknesses. This evaluation is supported by simulations with a 1D model of HIRLAM and of Duynkerke (1991).

Studying fog onset and duration with NWP has a long history. Fisher and Caplan (1963) reported possibly the first feasibility study of using NWP for fog forecasting. Using 1D models, Brown and Roach (1976), Musson Genon (1987), Bott and Trautmann (2002) showed the need for inclusion of gravitational droplet settling, radiative cooling, turbulent transport, a vegetation scheme and detailed microphysics. Sensitivity tests with the COBEL model (Bergot and Guedalia, 1994) revealed the importance of dew deposition and the initial conditions. Despite the increased understanding of fog, the NWP modeling of fog remains challenging (Gultepe et al., 2007).

Fog studies with mesoscale models focussed on advection fog in coastal regions (e.g. Fu et al. 2006; Nakanishi and Niino 2006). Pagowski et al. (2004) addressed the sensitivity of model results to the initial and boundary conditions for a dense fog in Ontario, Canada.

2. Synoptic situation.

The synoptic situation on 24 and 25 Nov. 2004 was dominated by a high pressure system, with clear skies, light winds and subsidence, i.e. favorable conditions for radiation fog. Operations at Schiphol airport were reduced from 64 to barely 20 aircraft per hour and 107 flights were cancelled. The synoptic network, Cabauw tower observations, and AVHRR satellite products (Fig. 1) show that a 150 m deep fog layer developed in the west of the country in the early morning of 25 Nov, and which remained the full day. The fog layer was overlain by a very dry layer, and it was freezing several K close to the ground.

The innovative aspects of this study are the first WRF evaluation for fog; fog occurs for T< 0ºC, and the fog onset occurred relatively late at night and that the fog persisted during daytime.

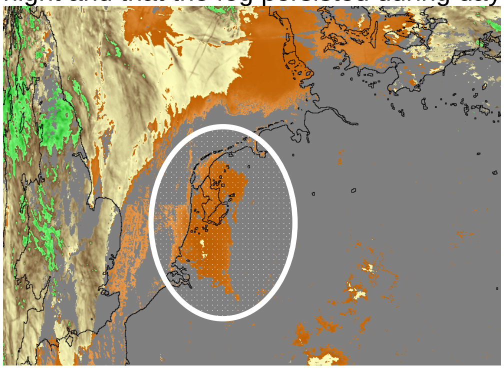

Fig.1: Observed cloud top temperature. Brown indicates low level clouds. The circle shows the fog under study. (http://wdc.dlr.de/apollo).

3. 3D model configuration and results

a). WRF

Using WRF/ARW 3.0.1 a domain was configured centered at Cabauw, on a horizontal grid of 33 x 33, 56 x 56 and 61 x 61 points with 30 , 6, 1.2 km resolution respectively. 35 terrain-following η levels, with the first level at η=0.998, and 9 layers below 240 m. WRF initial and boundary conditions have been taken from the NCEP final analysis. Impact of lateral boundaries is expected to be limited in this case because of low winds, i.e. large scale advection is small. Land use properties were provided by the USGS.

This study examines combinations of physics options to assess its impact on fog modeling. For microphysics we utilize Kessler, Eta-Ferrier, WSM3, and WSM6 (Hong et al. 2004). For the PBL schemes we tested the non-local 1st order YSU model (Hong et al. 2006), and the 1.5 order TKE closure model (MYJ, Janjic 2002), in which the minimum TKE was lowered 1.10^{-3}. The NOAH (Ek et al. 2003) and the 5 soil layer land surface scheme were both permutated in the simulations. One day spin up was applied.

b) HIRLAM

HIRLAM7.2 is a short range NWP model for operational use European meteorological institutes. The HIRLAM project focuses on a reference version with an optimal set of parameterizations. Al-

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ternative parameterizations are present, but for research purposes only. Lateral boundary conditions are provided by the ECMWF. Fog relevant physics contain the Savijärvi (1996) radiation scheme, the Rasch-Kristjànsson (1998) condensation scheme, the Cuxart et al. (2002) turbulence TKE scheme formulated in moist conserved variables and the ISBA land surface scheme (Noilhan and Mahfouf, 1996). Here, the model is run on a grid of 290 x 306 points with a spacing of 0.1º, centered at Cabauw and with 60 levels with the lowest level at 30 m. The model is run in a 6h assimilation cycle for 3 days prior to the fog experiment to allow the surface model to spin up.

c). Results

For WRF, only a few sets of parameterizations were actually able to create fog. This section presents WRF using WSM3-YSU-NOAH since it performed best based on incoming longwave ($L^{\downarrow}$), solar radiation ($S^{\downarrow}$), and 2m temperature (T2). On 24 Nov., the atmosphere is fog-free, since the observed $L^{\downarrow}$ is relatively low (Fig. 2), $S^{\downarrow}$ peaks at noon, and a substantial diurnal temperature cycle is present. On 25 Nov., $L^{\downarrow}$ clearly exposes the onset and duration of the fog event since it increases suddenly from 250 Wm^{-2} to 300 Wm^{-2} at ~0300 UTC. In WRF, the fog event of 25 Nov. is not represented, but fog occurs some hours before and thus corresponds with two $L^{\downarrow}$ peaks in the early morning and two $L^{\downarrow}$ peaks in the evening of 24 Nov. On the 2nd day, HIRLAM's $L^{\downarrow}$ increase agrees well with the observed fog onset. However, fog is limited to the lowest model level and suffers from early dispersal at 0900 UTC, as seen in the plunge in $L^{\downarrow}$ at sunrise. $S^{\downarrow}$ and T2 are reasonable well represented by both models on the 1st day. Before fog onset, T2 decreases from 7ºC at noon to -3ºC the next day. Only in HIRLAM the T2 decreases analogous with the observations. Clearly freezing occurs because of the late onset of fog. The fog onset may have been delayed by dewfall and hoarfrost as suggested by a small negative latent heat flux in HIRLAM in the hours prior to fog onset. The early fog onset in WRF in the evening of 24 Nov. prevents a further surface cooling to below freezing point. Apparently the coarser vertical resolution of HIRLAM does not inhibit fog formation, but may have influenced its growth to the mature stage. The extent of the fog area in HIRLAM is comparable to that in the AVHRR image, although fog over the Lake Ijssel and coastal waters is absent in HIRLAM. 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 T2, where in reality an ice day was recorded. On 26 Nov., the passage of a cold front can be recognized in the increased friction velocity (u_*). As the fog is cleared and replaced by low stratus, the $L^{\downarrow}$ in Cabauw increases again sharply to 320 Wm^{-2} and increased the rest of the day. The $L^{\downarrow}$ increase in WRF agrees very well with the observations, where as the frontal passage seems to be delayed in HIRLAM. The advection of low stratus is present in both models.

4. Column model configuration and results

a) HIRLAM

The HIRLAM column model (H-SCM) consists of the full physics of the 3D HIRLAM, with 47 levels below 2 km, starting at 4 m. Initial conditions for H-SCM are derived by interpolation from the +12 3D forecast at 1200 UTC 24 Nov. Temperature, wind and specific humidity are then replaced by values from the radiosonde of 1200 UTC at De Bilt. Below 1057 m the T and q profiles from D91 (see below), are substituted, while for levels between 1057 and 2000 m a linear transition is made between the D91 and sonde observations. A time dependent geostrophic wind ($\mathbf{V_g}$) as in D91 model was coded in the 1D dynamics.

b. Duynkerke model (D91)

This model consists of a 1st order turbulence model based on the moist conserved variable wet equivalent potential temperature, a greybody emissivity longwave radiation model, and includes droplet settling. The heat diffusion equation is solved for a 75 deep soil. Soil moisture freezing and thawing was introduced, which had substantial impact on the forecast near surface temperatures. Here, the Cabauw 200 m wind is used as $\mathbf{V_g}$. The initial profiles for T and q are obtained from closest radio sonde at EHDB at 1200 UTC 24 Nov. A subsidence of $-0.5 \cdot 10^{-3}$ ms^{-1} was applied. Based on a series of EHDB radio soundings, a 5 K hr^{-1} heating was induced above 250 m, which was linearly interpolated to zero towards the surface. D91 uses 40 logdistributed levels, between 0.3 m and 1.8 km.

c. Results

Column models allow for efficient experiments with physics options. D91 acts as a reference for subsequent sensitivity studies with HSCM. D91 is relatively successful in forecasting the fog onset and the following evolution, but is unable to forecast the fog dispersal. In practise, forecasting of fog decay and onset may be of equal importance. D91 estimates $L^{\downarrow}$ reasonably, although fog onset is slightly too early, due to somewhat overestimated surface cooling. However, in the mature fog stag, $L^{\downarrow}$ is ~10 Wm^{-2} overestimated, which indicates a slight overestimation of the fog liquid water content (LWC). The fog decay around 0000 UTC 26 Nov. is not captured by D91 although the wind speed increase is reasonably forecasted. Thus, the correctly forecasted $L^{\downarrow}$ after midnight is spurious because clouds were observed, while the model persists a fog layer. Both models estimate $S^{\downarrow}$ correctly, which is surprising for the last day considering the persistence of fog in D91. Apparently, the LWC of the modeled fog and the observed cloud do not differ substantially.

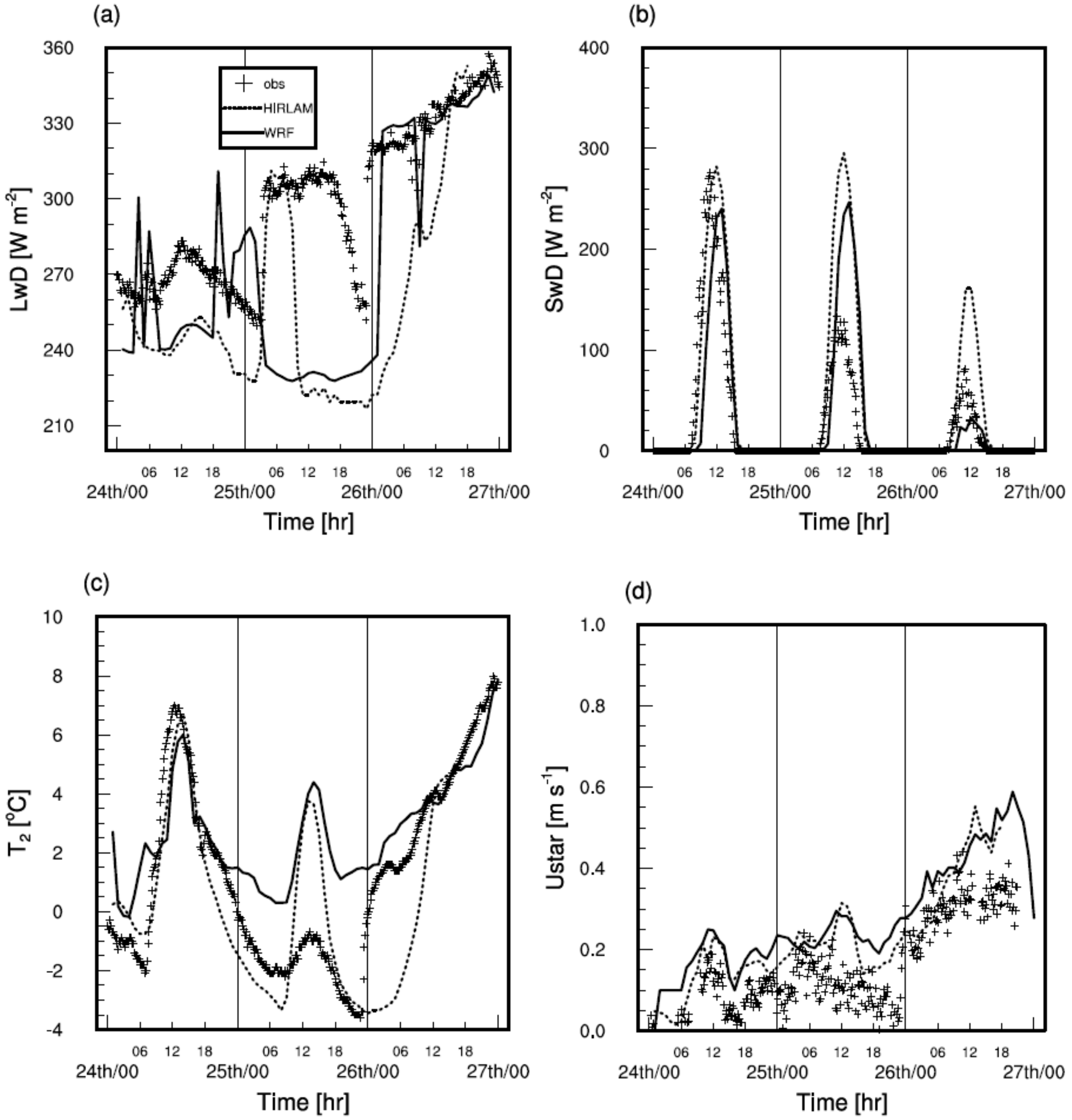

Fig 2: Modelled (3D models) and observed incoming longwave and solar radiation, 2 m temperature and friction velocity.

With D91, T2 shows a correct cooling in the afternoon of 24 Nov. The top soil layer starts to freeze at 1700 UTC, which hampers surface and screen level cooling for ~2 h. A similar cooling delay was observed. The minimum T2 of -3.5ºC is forecasted earlier than observed, again indicating that the model is ~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 T2 (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_*) between 1800 UTC and midnight on 25 Nov. After midnight, both 1D models provide enhanced turbulence compared to the observations. The D91 model gives the fog onset around 0200 UTC 25 Nov. 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 Nov., the near surface LWC shows a minimum, which would result in a visibility of 721 m (Kunkel 1984). A minimum visibility of 89 m was modeled, which is close to the reported observations. Note that the modeled visibility decreases more gradually in time than was observed. Finally, the model fails to remove the fog layer, even using substantial larger $\mathbf{V_g}$ speed as a forcing than has been observed. This occurs for different model settings 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 with 3D HIRLAM, H-SCM simulates the fog onset well. In the fog, the $L^{\downarrow}$ is close to the observations, which suggests the model LWC is comparable to reality. The modeled LWC is located at the PBL top and ascends with the PBL growth.

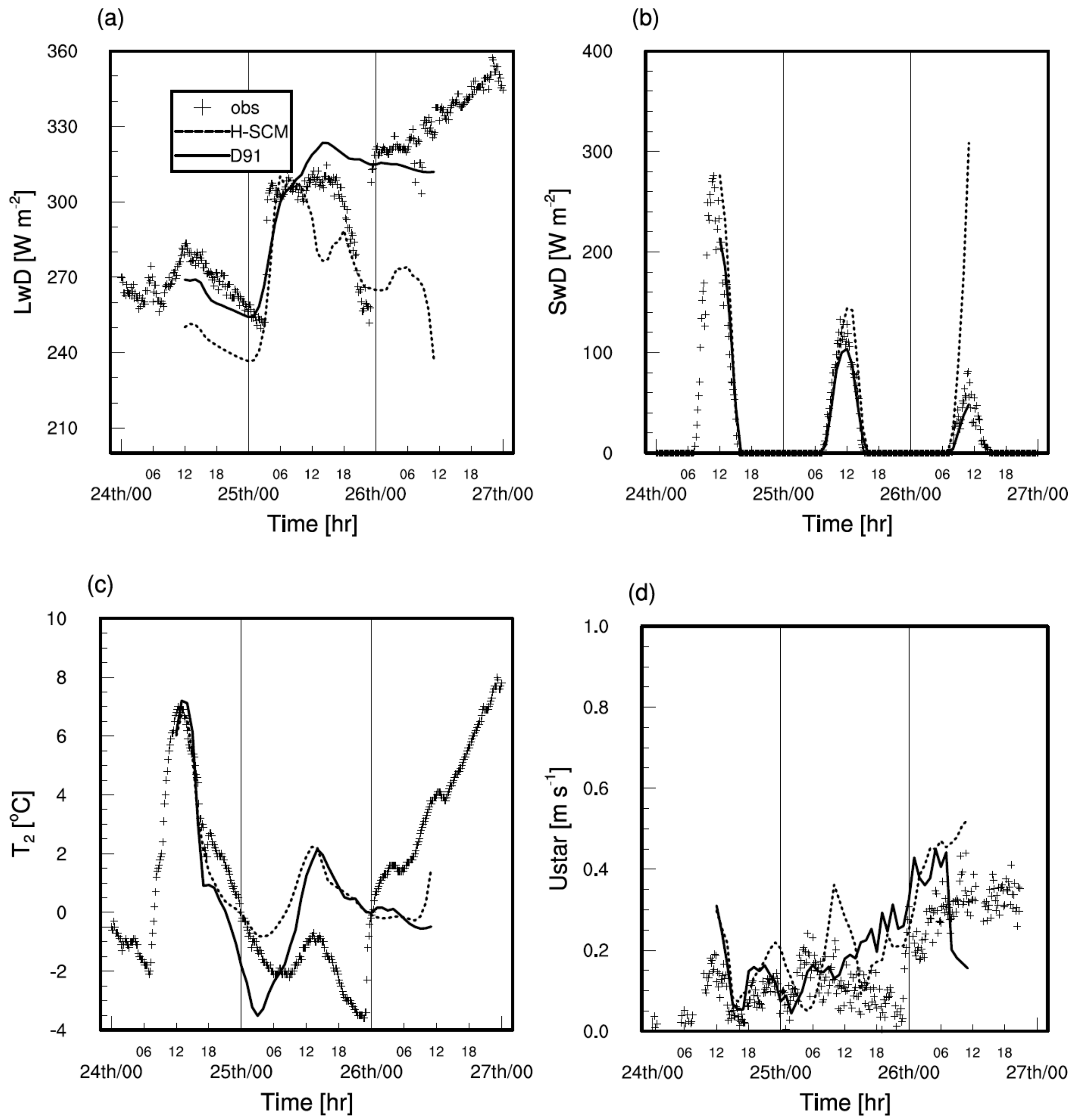

Fig. 3: Modelled (1D models) and observed incoming longwave and solar radiation, 2 m temperature and friction velocity.

H-SCM does not completely dissolve the fog, but forms a broken stratus deck. The cooling in H-SCM is not as strong as in the 3D model. At the end of the night the fog layer is ~150 m thick and well mixed. In H-SCM at this moment LWC is concentrated around the same level. This concentration of LWC near PBL top and the model temperature profile indicate that 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. H-SCM shows a small $S^{\downarrow}$ excess at noon, which is partly compensated by a negative bias in $L^{\downarrow}$. Hence, a warm bias occurs in addition to the warm bias in the preceding night.

To assess the effect of resolution sensitivity tests with a 60 and a 90-layer H-SCM were carried out. Both runs accurately predict the fog onset, but the initial fog layer growth was slower and the overestimation of $S^{\downarrow}$ increased with reduced resolution, suggesting a lower LWC and a resolution dependence of the condensation scheme. In addition, with the first model level at 30 m HSCM failed to produce fog. Thus high resolution near the surface is essential for the initialization of fog. As for the 3D model, resolution is also of the essence for further growth of the layer. Finally, when the fog lifts from the surface to form a stratus layer, resolution also becomes important at higher levels. The success of the 3D 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 of importance.

5. Discussion and conclusions

A case study of a widespread 150 m thick radiative fog over the Netherlands was presented as a benchmark for mesoscale model development, in particular for very high resolution forecasts for airport operations. Both WRF and HIRLAM have difficulties with the fog evolution. WRF only forecasts fog for a few permutations of the parameterizations, but the fog onset is offset in time and location, and the fog is particularly scattered. This is surprising since the mean variables are well captured. HIRLAM correctly forecasts the fog onset, but the fog layer remains at the lowest model layer. As a direct consequence, in both models fog does not persist, but is quickly dispersed.

Two column models performed well for the fog onset and its mature stage, although their results were sensitive to the initial and conditions and prescribed external forcings. High vertical resolution close to the surface is essential for fog modeling. Also, resolution at higher levels becomes important when the fog lifts to a stratus layer. In HIRLAM the fog and stratus LWC reduces with lower resolution. All models hamper during the daytime fog evolution: in D91 fog is too persistent, whereas fog in HSCM 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 understanding of the fog physics fog both mesoscale and column models are still not able to simulate all aspects of the fog evolution. Fog forecasting remains a challenging task.

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