A coupled automatic road-weather forecasting system.

Bent H. Sass and Claus Petersen

Danish Meteorological Institute

1. Introduction

Automatic road-weather forecasting in Denmark started in the early 1990s with the development of a road weather model (RWM) as a joint project between the Danish Metorological Institute (DMI) and the road authorities in Denmark. This development has been justified from the rapidly growing work related to the manual road weather forecasting by duty meteorologists at DMI. The present report describes the latest developments of the automatic prediction system for the great number of road weather locations in Denmark.

Automatic forecasts of road weather conditions has become possible due to the rapid development of computers in recent years. The RWM forecast tool is a numerical computer model which determines the local energy and moisture fluxes at the road surface. The final forecast parameters are water and ice/snow on the road surface. In practice the evolution of road surface temperature, temperature and dew point at 2 m height, cloud cover and precipitation are also vital parameters in order to forecast whether ice can be formed or persist on the road surface. This is because these weather parameters control the energy conditions and moisture evolution on the road. The developed model has been documented (Sass 1992; Sass 1997).

The weather parameters including precitation, cloud cover, wind , temperature and humidity in the atmosphere are not forecasted by the RWM which computes the local road conditions. An atmospheric model at DMI, namely the operational numerical weather prediction model (DMI-HIRLAM) is used to predict the time evolution of atmospheric weather parameters which are transferred as input to the RWM. In this way the quality of the road weather forecasts depends on both the DMI-HIRLAM forecast and the RWM prediction.

Over the years it has become clear from operational experience (Kmit and Sass 1999; Sass and Petersen 2000) that the quality of the atmospheric weather input to the RWM is critically important. This feature is specifically addressed in the present report.

In the first years of operational road weather prediction the DMI-HIRLAM and the RWM were separate models. The RWM received new predicted values hourly from DMI-HIRLAM. In order to improve the exchange of data between the two models the RWM has recently been integrated into the framework of the atmospheric model. This allows in principle for a 2-way interaction between the two systems including use of observational data from the RWM system (e.g. temperature, dew point at 2m and precipitation from road weather stations). The new integrated forecasting system is quite unique in the sense that it is perhaps the first operational system of its kind worldwide.

A brief overview of the new coupled forecasting system is given in section 2. Also methods to assimilate new data for cloud cover and precipitation are mentioned in order to highlight the developments related to the use of new data of importance for predicting the road weather. The new forecasting system has become operational at DMI in October 2003. The potential of the system is illustrated in section 3 by a forecast example where the atmospheric transport processes are of vital importance for the prediction. Finally some concluding remarks are presented in section 4.

2. A coupled forecasting system

DMI-HIRLAM (Sass et al., 2002) is the operational atmospheric model for short range weather prediction at DMI. HIRLAM stands for HIgh Resolution Limited Area Model. This means that forecasts are made for a limited part of the globe. The new system combining DMI-HIRLAM and the RWM is called DMI-HIRLAM-R. Figure 1 shows the model area of the operational DMI-HIRLAM-R covering Denmark and surrounding areas. It turns out that an area of this size is needed if it is taken into account that the information from meteorological data may spread over a large distance during 6 hours or more relevant for road-weather forecasts. Currently the atmospheric prediction is carried out in a model grid with 40 vertical levels and 82*92 grid points in the horizontal directions, with a resolution of 0.15°. At the geographical boundaries DMI-HIRLAM-R receives the necessary time dependent atmospheric information from a host model which is another operational model (DMI-HIRLAM-E) using the same horizontal resolution, but operates on a larger model domain.

Technically, the coupling of DMI-HIRLAM and the RWM means that the RWM operates as a model component of DMI-HIRLAM. The coupling is active every time step of DMI-HIRLAM. The virtues of the atmospheric model is that it can transport (advect) heat and humidity from one location to another. This process is directly linked to 'changing weather' at a given place.

The challenge is to assimilate observational data into the atmospheric model in order to provide the best possible weather input to the RWM. The DMI-HIRLAM system is already having an advanced system for assimilating atmospheric observations (Sass et al. 2002), but efforts are being devoted to assimilate additional new information on cloud, precipitation and surface data prior to the time of the RWM prediction. The new observed data are not inserted directly into the atmospheric model at a given time because the data and the model state are most often not in a complete 'balance'. The observations sometimes represent local features which one cannot expect the atmospheric model to fully represent. Instead there is a risk that a direct insertion of information into the model leads to undesired unsteady behaviour ('noise') in the model. It turns out to be better to gradually force the model in the assimilation process towards an analysed state which is a combination of a previous model prediction at analysis time and available observations. This method of data-assimilation is known as 'analysis nudging'. It is adopted in DMI-HIRLAM-R to assimilate a cloud cover analysis, a precipitation intensity analysis and analyses of near surface temperature and humidity, using information from the many road stations (≈ 370) in Denmark.

The procedure for assimilation of new information is briefly outlined below. For a more detailed description the reader is referred to Sass and Petersen (2004).

2.1. The data assimilation

The assimilation and forecast is illustrated schematically in figures 2 and 3. Figure 2 illustrates the processes involved, each having a number betweem 1 and 5. The initial time of the road weather forecast is at 0h. The assimilation run ('3') starts 3 hours prior to the initial time of the RWM.

The DMI-HIRLAM-R is run every hour. The model starts from a combination of information from the larger scale operational model (DMI-HIRLAM-E) and the previous 1 hour old run with DMI-HIRLAM-R (step '1'). The temperature and humidity variables at the surface are taken from the DMI-HIRLAM-R model while other variables are taken from DMI-HIRLAM-E.

The assimilation process is illustrated by '3' in figure 2. At every model hour of the assimilation it is possible to analyse cloud cover, precipitation and surface variables 'an hour ahead', because observed data are known during the assimlation period from -3 h to 0 h. Analyses of all variables are determined from a combination of the preliminary value ('first guess') of a previous DMI-HIRLAM-R run and observed parameter values near to the analysis point (process '2'). The first guess is not modified if there are no observations nearby (see Sass and Petersen 2004). Currently, the observed information (cloud type, cloud height, cloud cover, precipitation information, temperature and dew point at 2 metres) are obtained from meteorological synoptic obervations including also the road-weather stations. It is planned to utilize also high resolution satellite information in the future. Analyses at all times of the assimilation period is obtained by time interpolation of the hourly analyses.

The analysis nudging operates by modifying the time tendencies of the humidity variables in the model ('cloud condensate' and 'specific water vapor') by terms which increase with growing differences between analysed cloud cover and precipitation intensity compared to the corresponding values in the model. Close to the surface, humidity and temperature tendencies are adjusted as a result of assimilating surface information. In this way the model gradually approaches the analysed state during the data assimilation period.

Figure 3 illustrates conceptually how the cloud cover assimilation operates. The coarse dashed line is an imagined cloud cover of DMI-HIRLAM-E. The finer dased line is the corresponding time evolution of cloud cover in DMI-HIRLAM-R. The finest dashed line is the cloud cover evolution during the forecast of the RWM from 0h and later on. The solid line displays the analysed cloud cover extended beyond 0h to illustrate how forecasts deviate from the observed (analysed) values. Figure 3 shows that the cloud cover of DMI-HIRLAM-R comes closer than DMI-HIRLAM-E to analysed cloud cover during the assimilation run. During the forecast the additional extra information is gradually lost and the cloud cover of DMI-HIRLAM-R usually approaches that of DMI-HIRLAM-E after some time. The figure shows that cloud cover of the RWM has a small advantage initially compared to DMI-HIRLAM-R, because it starts from the analysed cloud cover valid at the position of the road station site. Details of the cloud analysis and nudging procedure are given in Sass and Petersen (2002a, 2002b).

2.2. The forecast

At the start time (0h) of the forecast the RWM is initialized (process'4'). The purpose of the RWM is to produce site specific forecasts which should start from the the best possible local information. For 2 m temperature and dew point local observations are available and used. For cloud cover the same cloud cover analysis as mentioned above is used, but using the specific geographical location of the road weather station. This means that small differences exist between the DMI-HIRLAM-R simulated cloud cover from the assimilation and the cloud cover analysed at the road station site. The actual cloud cover (a vertical profile) used in the RWM during the forecast is a combination of the values transferred every time step from DMI-HIRLAM-R and the initial values analysed at the stations. In other words, the cloud cover of the RWM is described as the initial cloud cover plus a statistically based transition towards the values from the atmospheric model. The transition function is described by Sass and Petersen (2002b) A similar method is used for 2 m temperature and humidity. The input every time step from DMI-HIRLAM-R and the forecast procedure of the RWM (process '5') makes it possible to produce site specific forecasts for all road station sites in Denmark.

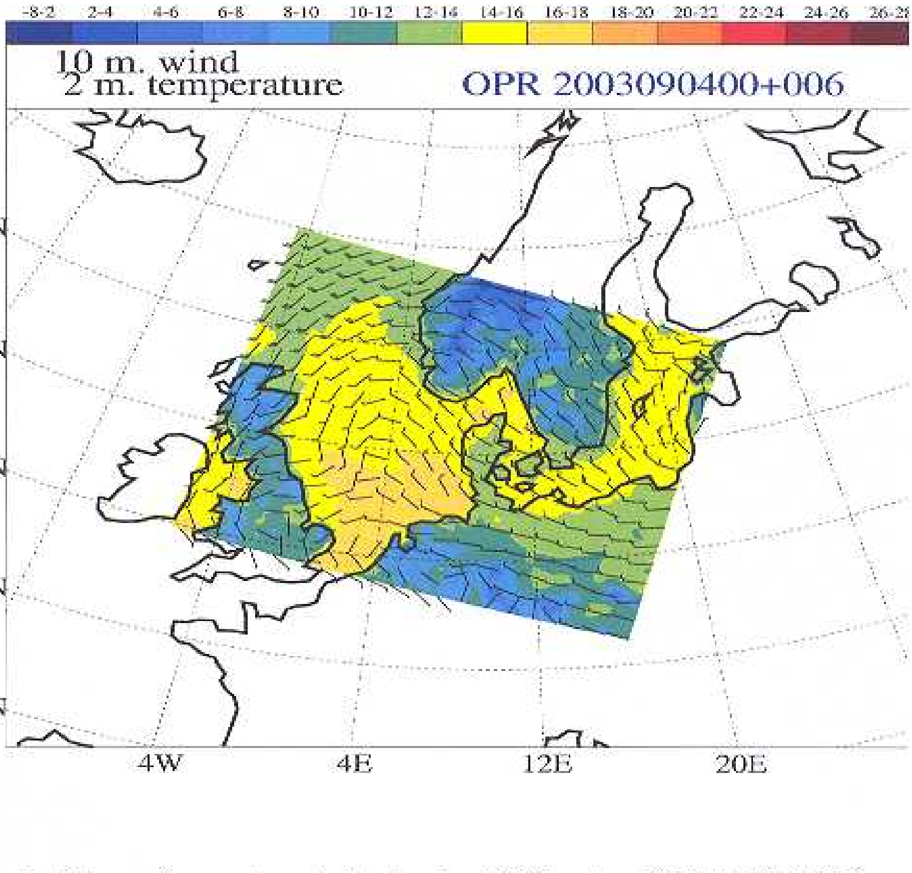

Figure 1: 6 hour forecast on 4 September 2003 using DMI-HIRLAM-R area with a presentation of 2 m temperature and 10m wind arrows

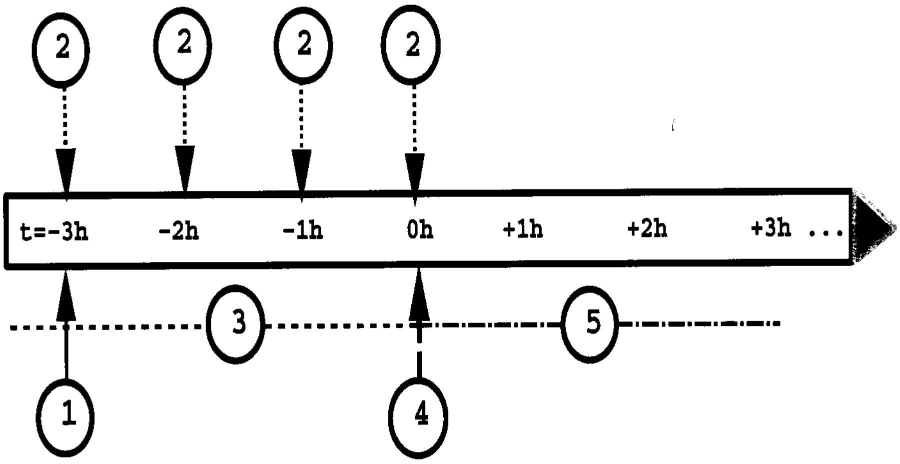

Figure 2: Processes (1-5) in the combined system DMI-HIRLAM-R (see text).

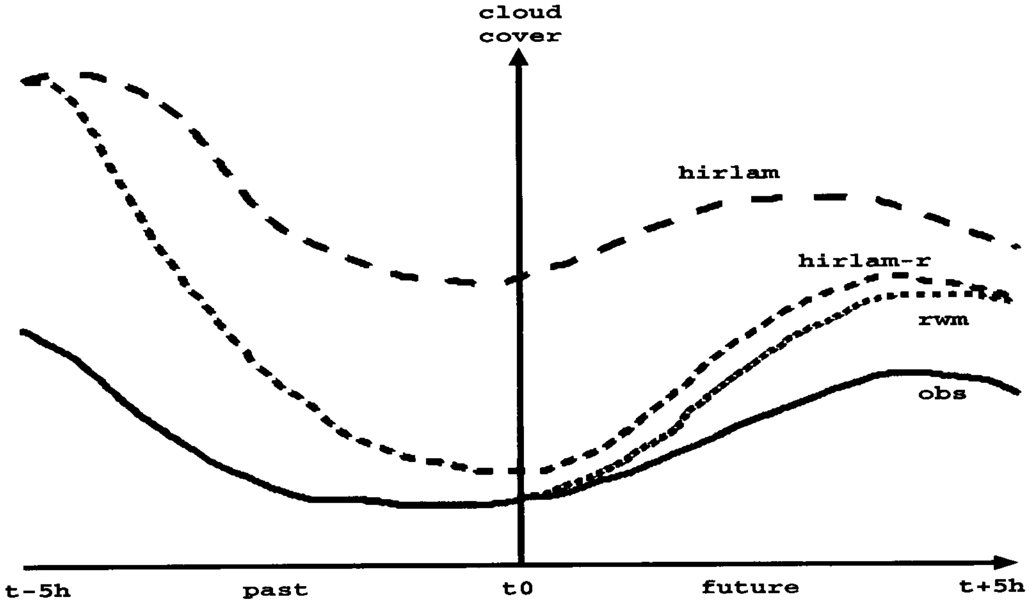

Figure 3: Illustration of the assimilation of cloud cover in the new model DMI-HIRLAM-R (fine dashed) compared to analysed values (obs) and the default forecast DMI-HIRLAM (dashed). The forecast of the RWM is given by the dotted line. For details see text.

3. A forecast example

The potential of the coupled forecasting system described above is illustrated by a forecast example from 8 December 2002. Rime occurred at some places in the morning hours due to road surface temperatures below 0°C and a supply of relatively moist air. It is a rather windy case with coastal winds between 10 m/s and 15m/s. The cloud cover varies across Denmark with almost cloud free conditions in the southwestern part of the country and mostly cloudy skies over the rest of Denmark. There is practically no precipitation reported during the period considered.

Fig.4 shows the results of a road surface temperature forecast for a model run based on assimilation of both cloud and surface information on temperature and dew point. The results apply to a station site on a bridge (55.5°N, 9.7°E) between the Island of Fyn and Jutland where almost cloud free conditions occurred. It is seen that the forecast manages to produce a higher dew point temperature ("$\mathrm{td}_{\mathrm{nud}}$") than road temperature ("$\mathrm{ts}_{\mathrm{nud}}$") for the last two hours of the prediction period. The observations of dew point temperature ("$\mathrm{td}_{\mathrm{obs}}$") also become larger than the observed road surface temperature ("$\mathrm{ts}_{\mathrm{obs}}$"). This means that conditions of rime formation are reproduced in the prediction. The duration of the period favorable for rime formation is almost one hour less in the forecast compared to observations. It is seen that a somewhat too high surface temperature and a lower dew point in the first part of the forecast contribute to the reduced period of rime formation. There are other four road station sites on the bridge. It turns out that 4 out of 5 has a period with dew point temperature in excess of the road surface temperature, which indicates a generation of some rime. The present run based on data assimilation with the new data sources can reproduce this feature that dew point exceeds road temperature for some period. A run without assimilating the extra data does only show dew point excess for 1 station (the one shown in Fig.4), for a period of less than an hour.

Fig.4b also illustrates the possibility of rime formation by showing dew point excess as a function of time for various model options. "$\mathrm{diff}_{\mathrm{noadv}}$" shows the results for an experiment where the humidity transfer by the model's dynamics, transporting humidity by the resolved scale motions, is switched off. The curve shows only small humidity change which are possible due to other processes in the model, e.g. transport due to turbulence in the vertical direction. The results are also shown for "$\mathrm{diff}_{\mathrm{hir}}$" and "$\mathrm{diff}_{\mathrm{nud}}$" representing runs with normal humidity transport and assimilation of new data switched off and on, respectively. Finally, "$\mathrm{diff}_{\mathrm{obs}}$" shows the observed difference at the same station. The important point here is that, with humidity transport switched off, the model completely fails to predict the developing rime formation. The best prediction is obtained with the assimilation of the new observational data.

Fig.5a and 5b show the total fractional cloud cover (%) at the initial time of the runs with and without assimilating extra data, respectively. The figures exhibit significant differences between the two options showing that 'nudging' of additional information leads to important differences in the initial state of cloud cover. Synoptic observations of total cloud cover during the night on 8 December 2003 (not shown) reveal that the run with cloud assimilation is quite realistic. This is consistent with the finding that the model during assimilation gets closer to the analysed cloud cover. The wide area of analytical model [7]. This model calculates the amount of ice that is present on the road at the end of the forecast period. It needs receiving the forecast values of the meteorological parameters by the forecast neural system described in the previous paragraph. Four modules make it up:

1st module: it [4,5,6] calculates water plus ice mass balance on the road.

2nd module: it [4,5,6] reckons water minus ice mass balance on the road. This modulus is used only when the road temperature is 0°C. In fact only in this case it's possible the water change phase. As far as this process is concerned it's very important the energy balance on the road.

3rd module: it calculates the snow heap and the snow melting on the road.

4th module: this module, according to the air – asphalt interface temperature, integrates opportunely the previous modules. On the starting integration instant we used the observed meteorological parameters whereas on the last instant we used that one forecast.

As we hadn't the interface temperature in the database, we calculated it with the following formula,

$$T(z) = T_0 + \left[\frac{T_{210} - T_0}{210 \cdot Rapp}\right] \cdot z \qquad (9)$$

where,

T_0 : road temperature (10 centimetres of depth)
T_{210} : air temperature (2 meter of altitude)

Putting z=10 in the formula, we get the interface temperature. The coefficient *Rapp* represents the ratio between asphalt and air thermal volumetric capacity. *Rapp* is necessary because we aren't in a homogeneous system. We tested the model on the period November (2001) – February (2002).

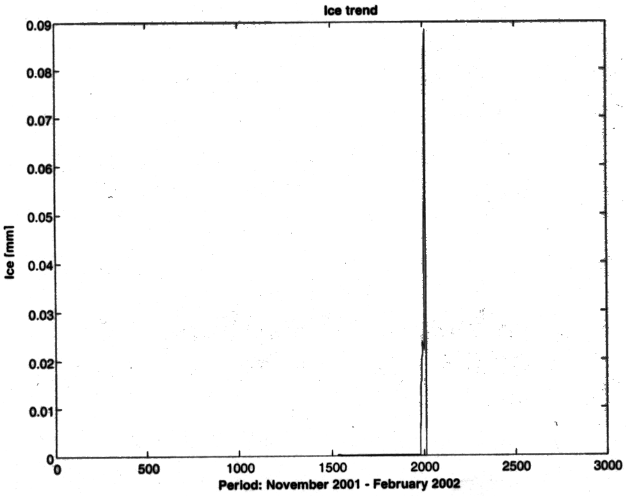

Figure 6: Ice trend

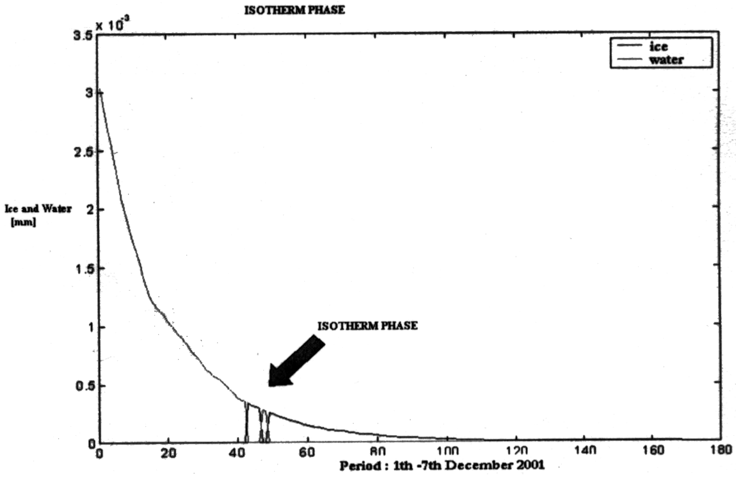

Figure 7: Isotherm phase (water and ice)

cloud cover, precipitation and near surface information of temperature and humidity. The data assimilation is still at a state of development where further improvements can be made, in particular with respect to the accuracy of the cloud analysis which is significantly limited by lack of high resolution data in space and time. The case study mentioned above is also affected by this limitation since only traditional synoptic observations have been used. A project has started to make use of high resolution satellite data through the EUMETSAT Satellite Application Facility (SAF) projects. This effort is likely to significantly enhance the quality of the cloud analyses used in the data assimilation. It is also very important to have a high quality surface analysis of temperature and humidity in the atmospheric model. The number of observations over land has now increased with the addition of data from road station sites. However, observations over sea areas are still sparse. Experience with the model system shows that it is also important for the Danish area to have a good knowledge of temperatures over sea. In the future the new satellites will also be able to supply good quality sea surface temperatures.

References

Kmit, M. and B. Sass (1999). 'Verification Report for the 1997-1998 Slippery Road Season'. DMI Tech. Rep. no. 99-1, Danish Meteorological Institute.

Sass, B. (1992). 'A Numerical Model for Prediction of Road Temperature and Ice'. J. Appl. Meteor., 31, pages 1499-1506.

Sass, B. and C. Petersen (2000). 'Verification Report for the 1998-1999 Slippery Road Season'. DMI Tech. Rep. no. 00-02, Danish Meteorological Institute.

Sass, B. (1997). 'A Numerical Forecasting System for the Prediction of Slippery Roads '. J. Appl. Meteor., 36, pages 801-817.

Sass, B. and C. Petersen (2002a). 'Short range atmospheric forecasts using a nudging procedure to combine analyses of cloud and precipitation with a numerical forecast model'. DMI Sci. Rep. no. 02-01, Danish Meteorological Institute.

Sass, B.H. and C. Petersen (2002b). 'Analyses and short range forecasts of cloud cover'. DMI Tech. Rep. no. 02-09, Danish Meteorological Institute.

Sass, B.H., Woetmann, N.W., Jørgensen, J.U., Amstrup, B., Kmit,M. and K.S. Mogensen (2002). 'The operational DMI-HIRLAM system 2002 - version'. DMI Tech. Rep. no. 02-05. Danish Meteorological Institute 2002.

Sass, B.H. and C. Petersen (2004). 'The coupled operational numerical road weather forecasting system at DMI'. DMI Tech. Rep. no. 04-01, Danish Meteorological Institute.