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Improvement of Operational Danish Road Weather Forecasting using High Resolution Satellite Data

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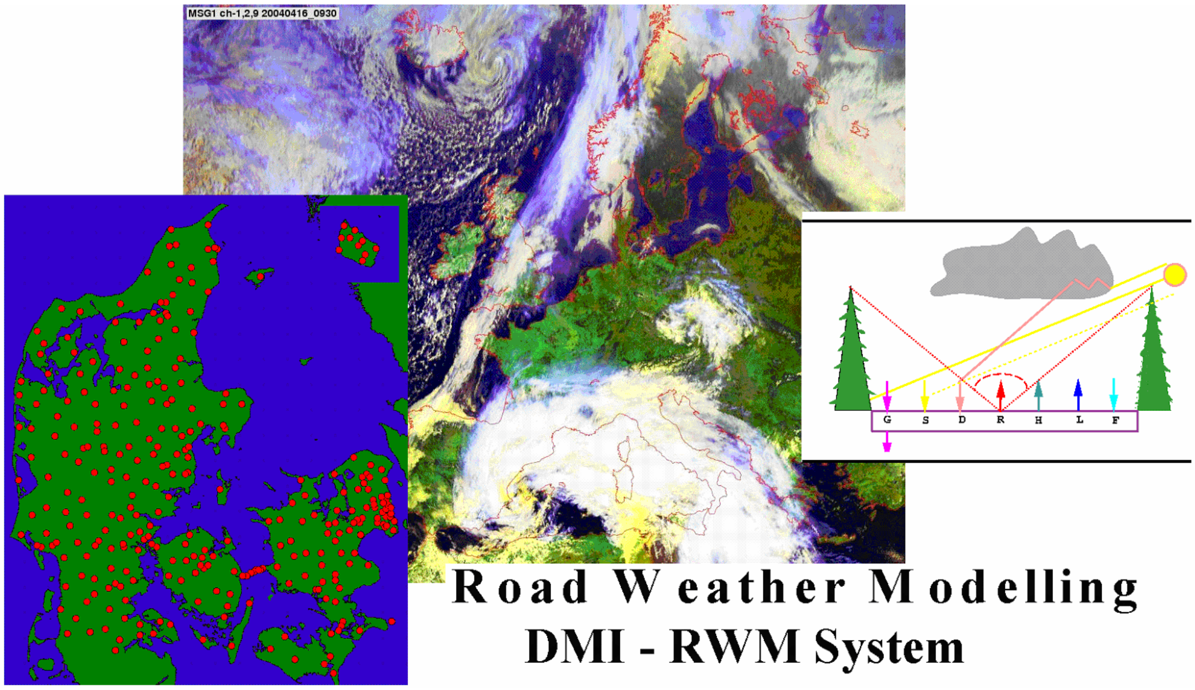

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Abstract

The Road Weather Modelling system developed at the DMI in cooperation with the Road Authorities (Vejdirektoratet) during a 3 year long project has been further developed to improve the forecast of the road surface temperature. It has been realized that this mainly could be achieved by improving the forecast quality of cloud cover and precipitation which traditionally are difficult to predict with a high accuracy in numerical weather prediction (NWP) models. Therefore, the main issue has been to improve forecasting of cloud cover by using satellite observations to analyze the initial 3 dimensional cloud structure and assimilate the analyzed cloud structure into the NWP model used at DMI. It has been necessary to develop and refine a method to analyze and assimilate these data. In this project the satellite data from the NOAA and MSG1 satellites have been utilized and a brief verification study of the quality of the data compared to conventional observations has been conducted. Test and verification of the new Road Weather Modelling system has been done successfully and this system has become operational since October 2005.

Resumé

DMI's vejmodel er udviklet i samarbejde med Vejdirektoratet og er i løbet af et 3-årigt projekt blevet yderligere udviklet for at forbedre prognosekvaliteten af vejtemperaturen. Studier har gjort det klart at dette primært kunne opnås ved at forbedre prognosekvaliteten af skydække og nedbøren som traditionelt er vanskelige at forudsige med høj kvalitet i numeriske vejrprognosemodeller. Derfor har hovedsigtet med projektet været at forbedre prognosekvaliteten af skydækket ved at anvende satellitdata til at analysere den initiale 3 dimensionale skystruktur og assimilere denne ind i DMI's numeriske prognosemodel. I den forbindelse har det været nødvendigt at videreudvikle en metode til at analyse og assimilere disse data. De anvendte satellitdata er hentet fra NOAA og MSG1/METEOSAT-8 satellitterne og en mindre undersøgelse af kvaliteten sammenlignet med konventionelle observationer er blevet udført. Test og verifikation af den nye vejmodel blev gennemført med succes, og systemet har siden oktober 2005 kørt som den operationelle vejmodel.

1 Introduction

Both the cloud cover and precipitation, including variations in cloud cover and cloud thickness, are among the most important topics of research and key parameters for the road weather warning. For years it has been known that inaccurate forecasting of cloud cover and precipitation has been an important issue for most of complex road weather situations. To solve this problem, the Road Authorities of Denmark and the Danish Meteorological Institute (DMI) in 2003 initiated within the frameworks of the "*VIKING* " Programme the 3 year project entitled "*Development of a New Generation of Cloud and Precipitation Analyses for the Automatic Road Weather Model*". The main objective is focused on improvement of forecasts for slippery roads by developing a revised road weather model.

Note, that during the last 15 years DMI in cooperation with the Danish Road Authorities (*Vejdirektoratet*) has developed the Road Weather Modelling (RWM) system based on road forecasts and observations. This also includes a web based user friendly interface with additional facilities. The main idea was to use road observations along the Danish roads as input to a numerical model which is designed to predict the road conditions (*Sass & Pedersen, 2002a*). Verification and evaluation of RWM system capabilities were done for slippery road conditions for several seasons and for specific cases (*Kmit & Sass, 1999; Sass & Petersen, 2000; Petersen & Nielsen, 2000; 2003*).

Some preliminary estimates of short-range atmospheric forecasts using a nudging procedure to combine analyses of cloud and precipitation with a numerical forecast model were done by *Sass & Petersen (2002b*); *Sass et al. (2002b)*. Further, analyses and short range forecasts of cloud cover were investigated by *Sass & Petersen (2002c)*. Improvement of short-range forecasting of the clouds based on analyses of cloud cover at road stations derived from conventional observations and numerical weather prediction models was investigated and implemented into the RWM system. Essentially, the short-range forecasting of cloud cover in the system was evaluated by combining NWP forecasts and analyses of cloud cover with exponentially decaying coefficients depending of time and initial error in cloud cover (*Sass & Petersen, 2002c*). Further, the analysis of cloud cover was extended for the NWP model area, and a nudging technique was developed to assimilate conventional SYNOP and SHIP observations of clouds into the NWP model. This model then provides improved cloud forecast for road stations and eliminates the empirical methods with decaying coefficients (*Sass & Petersen, 2002b; Sass et al., 2002b*).

For the current project, during the first year (2003), the focus was on study: how satellite data (cloud and precipitation information in high dimensional resolution) from the American NOAA-17 and European Meteosat Second Generation (MSG-1) satellites could be made available and used in the analysis module of the DMI-RWM forecast system (*Sass & Petersen, 2004*). Initially, the NOAA-17 data on the cloud mask, cloud top temperature and height, and cloud type, as derived by the Satellite Application Facility (SAF, www.eumetsat.com), has been monitored and quality controlled. Methods for utilizing (data reading and transforming into the model grid) such satellite data for RWM have been developed. The satellite data of high resolution (1 km) has been averaged to the coarser model grid. A method has been developed to combine the cloud mask information and cloud top height from satellite with other data including the model cloud profile of RWM, to produce an updated analysis profile. It became evident that the satellite data impacts significantly the cloud cover over the ocean, where synoptic cloud cover observations are absent or very sparse. The quality of the satellite derived data is generally considered good during daytime, whereas the cloud information in the case of low clouds at night is considered more uncertain. However, the SAF tools have been recently updated and improved to a much higher quality in the cloud products including the low clouds during night time. By the end of 2003 the cloud analysis module was prepared for tests in real forecast conditions during the following winter 2003-2004.

During the second year (2004), the focus was on testing and implementation of the NOAA satellite data for cloud mask data as well as cloud top temperature into the RWM system (*Petersen & Sass, 2005a*). These allow modification of the initial 3D cloud cover structure of the numerical weather prediction (NWP) model. Note, that additional parameters from the NWP model such as air temperature and dew point at 2 meters also benefit from the improved cloud cover. The prototype for semi-operational use including the cloud mask and cloud top temperature was developed and tested by fall of 2004.

During the third year (2005), the focus was on continuation of testing and implementation of both the NOAA and MSG-1 satellite data into the RWM system (*Petersen & Sass, 2005b; Petersen & Sass, 2005c; Petersen et al., 2006*). The tuning of the RWM system was done over the first two weeks of March 2005 (dominated by relatively cold winter weather with a large variation in the road conditions, i.e. a challenge for the RWM system prediction). A statistical analysis and comparison of the NOAA satellite data vs. ground observations for cloud cover was also done for the long-term series for the Danish stations located in different climatic regimes. In fall 2005, the modified road weather model with implemented assimilation of the MSG-1 satellite data became the operational model for the slippery road season of 2005-2006. The summary of research activities on the project and preparation of documentation and publications were done. During the same period the pilot study entitled "*Vej-Stræknings-Vejr : Road-Stretch-Weather"* was initiated to demonstrate possibilities for further development of the DMI-RWM system.

2 Methodology

Observations of high resolution satellite unconventional data such as cloud cover, cloud top temperature, precipitation, and other non-standard data are only used to a limited extend in present NWP models. In most cases, the data assimilation system associated with the NWP model is limited to use conventional data such as SYNOP, SHIP, TEMP, AIREP, BOUY, and processed data from satellites providing the analysis of temperature, humidity, and wind profiles primarily from the upper atmospheric levels and only for limited areas. Analyses of cloud cover, cloud water, and precipitation are neglected in most models, and there exists no standard method to adopt these data in NWP models. A common feature for these data is that they are available with high resolution in time and space. Moreover, these data is mostly used for short-range forecasting and nowcasting in a subjective manner directly by the weather service.

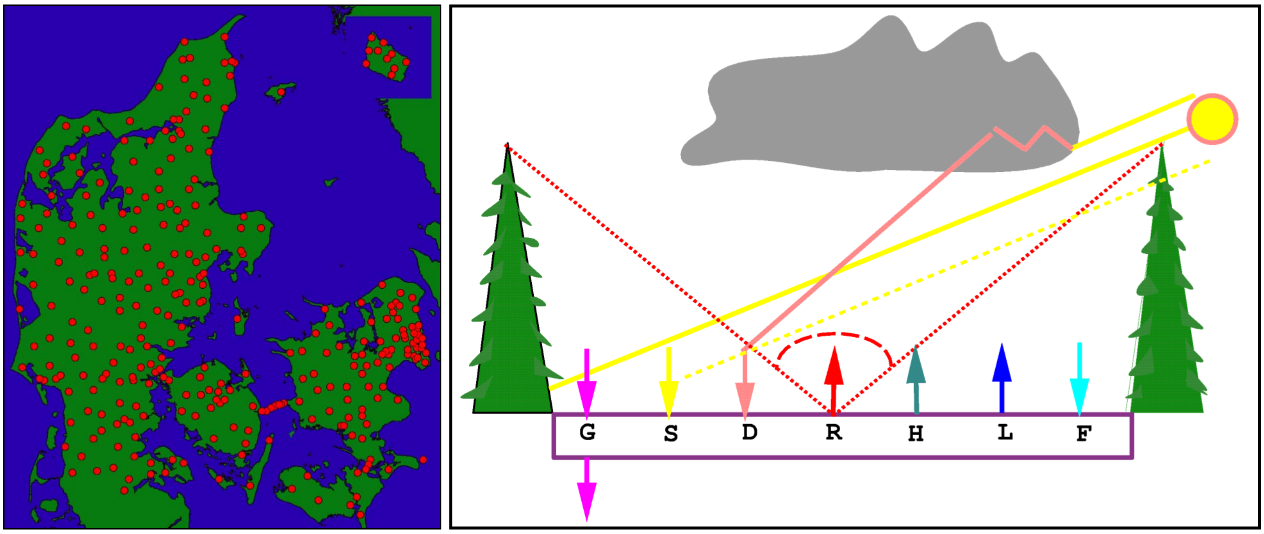
Recently, it has become standard at DMI to have the surface analysis as a part of the forecasting system. In contrary to the upper air analysis the amount of surface data tends to be available with higher frequency and of higher resolution. For the Danish area, the surface observations from road stations and conventional meteorological data have an average distance of about 10 km between each observational point. This can provide the NWP model with a very detailed surface analysis of both the temperature and dew point temperature at 2 m. However, these quantities depend on the actual weather such as precipitation and cloud cover. In many cases inconsistency between analyzed conditions in the atmosphere and at the surface can decrease the benefit of detailed surface analysis and give a high growth in the error statistics of the surface quantities. For short-range forecasting this can have the consequence that a simple bias correction of the surface quantities can be superior to more physical correct surface analysis. The latter will very fast drift away from its initial condition and adjust to a state, which is in balance with the atmosphere. For road forecasting it has been recognized that poorly predicted cloud cover and precipitation in most cases are responsible for large errors in prediction of road surface temperature. Shadow from the surroundings is another factor. During daytime it can contribute to a large error in the error growth of the road surface temperature. This type of error can be minimized by careful measurements of the shadowing objects at the observational points.

In this report it will be shown how the DMI-RWM system uses cloud cover observations to improve the prediction of surface quantities. Instead of using advanced data assimilation methods a more simple nudging technique is applied (see Chapter 2.3).

At the same time, the high resolution data of surface quantities are used in the surface analysis to obtain initial surface conditions. The improved cloud cover prediction will ensure that the surface analysis is more consistent with the atmospheric state which shows that the NWP model provides the DMI-RWM system with improved data for the future state of the atmosphere.

2.1 DMI Road Weather Modelling System

The DMI's road weather model was originally a 1D model which predicted the meteorological and road conditions at selected locations along Danish roads (*Sass, 1992; 1997)*. At these locations measurements of meteorological parameters and specific measurements of the road conditions are used to initialize the surface and soil conditions of the road in the model. Fig.2.1.1a shows the locations of the Danish road stations. The 1D model calculates all fluxes at the road surface and solves the heat equation for the soil which is divided into 16 layers. Furthermore, freezing and melting of water/ice on the road as well as deposition of frost and dew are all considered. The model includes a data assimilation of road surface temperature. Observations for the last 3 hours are used to initialize the temperature in the soil layers. In this mode the model runs with observations as upper boundary conditions, and the first guess field is obtained from previous forecast. For the last 20 minutes of this period the model runs with forcing from the atmosphere, and a flux correction (marked as "F" in Fig. 2.1.1b) is estimated. The flux represents all uncertainties in the model, but in practice it will compensate for incorrect cloud cover or shadow measurements. It is assumed that the flux correction decays to 0 as a function of time and change in short-wave radiation. In most cases, during daytime the flux correction is the largest. The details are summarized in Fig. 2.1.1b.



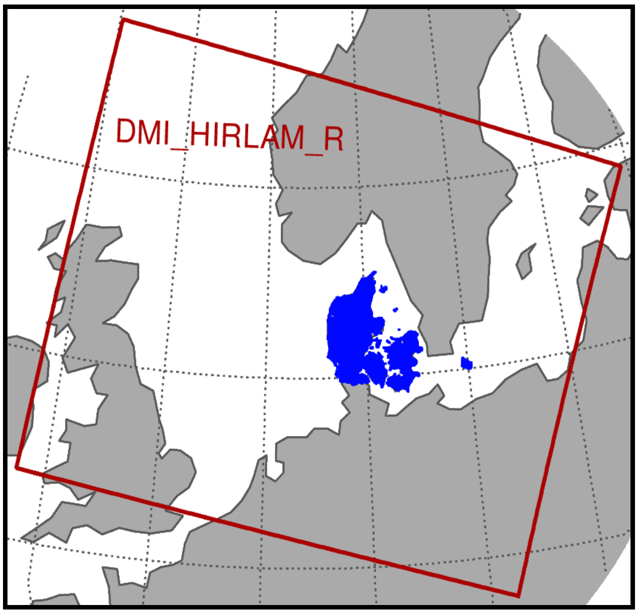
(a) (b)

Figure 2.1.1. (a) Geographical locations of the Danish road stations (in the right top corner of this figure the Island of Bornholm is presented), and (b) Schematic view over fluxes in the one dimensional road model, where : G - ground heat flux, S - direct insolation, D - diffuse insolation, R - infrared radiation, H - sensible heat flux, L - latent heat flux, and F - flux correction.

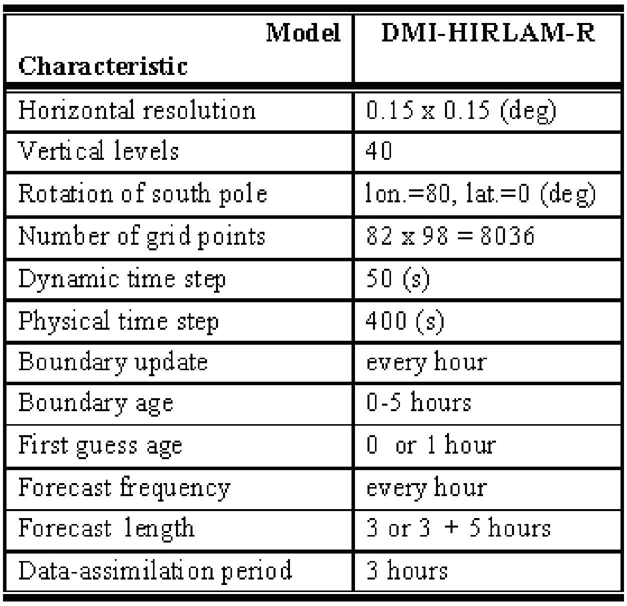
The state of the atmosphere is passed to the DMI-RWM system at every time step. In the original 1D model, bias corrections of temperature and dew point temperature at 2 m and cloud cover ensured that large errors in the observed values compared to the derived values from the NWP model at initial time, only were allowed to slowly approach the predicted values from the NWP model, depending on the initial error and empirically determined decay coefficients. It has been recognized that in order to improve short-range forecasting of the road conditions and especially to capture its fast changes, it is necessary that the NWP model can predict weather specific parameters with a high precision. These are primarily the temperature and humidity at 2 m, precipitation and cloud cover. The first step was to integrate the NWP model into the RWM system and to use road and cloud cover observations, and to ensure that the NWP model's initial state is consistent with the observed conditions at the road stations.

2.2 Numerical Weather Prediction Model for Road Weather Forecasting

The NWP model associated with the DMI-RWM system is a modified version of the HIgh Resolution Limited Area Model (HIRLAM). It is a hydrostatic model including a 3D variational (3D-var) data assimilation system and a surface analysis module. Currently the NWP model used in connection with the DMI-RWM system deviates from the latest release of HIRLAM. It is an earlier version of HIRLAM which was modified at DMI and where new features from the HIRLAM project were implemented. This model is still used for the road forecasting. Moreover, it was the operational NWP model at DMI until June 2004 and has been named DMI-HIRLAM-R. It used the first guess fields and boundary condition files from the DMI-HIRLAM-E model. The details of this model are also described in *Sass et al., (2002ab).* From the beginning of summer 2004 the new version of DMI-HIRLAM-T15 became operational, and now these first guess fields as well as boundary condition files are used for the RWM system purposes. Main characteristics and domain boundaries of the DMI-HIRLAM-R model are shown in Fig. 2.2.1.



(a)



Model Characteristic	DMI-HIRLAM-R
Horizontal resolution	0.15 x 0.15 (deg)
Vertical levels	40
Rotation of south pole	lon.=80, lat.=0 (deg)
Number of grid points	82 x 98 = 8036
Dynamic time step	50 (s)
Physical time step	400 (s)
Boundary update	every hour
Boundary age	0-5 hours
First guess age	0 or 1 hour
Forecast frequency	every hour
Forecast length	3 or 3 + 5 hours
Data-assimilation period	3 hours

(b)

Figure 2.2.1. DMI-HIRLAM-R model (a) domain and (b) characteristics for the RWM system.

Boundaries and large scale analysis are supplied through a nested system of models to the DMI-RWM. The main DMI-HIRLAM operational model is running 4 times every day with 2 additional data re-assimilations cycles and is supplied with boundaries from the ECMWF global model. The host models cover the North America and Europe, North Atlantic Ocean and Mediterranean Sea. Both the horizontal and vertical resolutions of the host model are identical to DMI-RWM. On the contrary to RWM, the outermost model in the nested system is based on the release of HIRLAM as described by *Unden et al., (2002).*

Note, for the short-term reference forecast the forecast length is 3 hours. For the long-term forecast the data assimilation cycle is 3 hours, and it continues with an additional 5 hours forecast. In order to improve the RWM short-range forecasting additional modules were developed to assimilate both the cloud and road observations into the NWP model. Primarily the modules make analyses of 3D cloud structure, temperature and dew point temperature at 2 m by using observations and model data (which are obtained from the first guess fields). Originally, this was developed for 1D DMI-RWM, where analysis of cloud cover was used to predict cloud cover at the road stations (*Sass & Petersen, 2002b*). It was assumed that at initial time the analyzed cloud structure is decayed towards the predicted cloud structure obtained from the NWP model as a function of time and an empirically determined decaying coefficient. In DMI-RWM, a similar approach for temperature and dew point temperature at 2 m was also used. In order to eliminate this empirical method which tends to fail in cases with large initial errors and fast changes in weather conditions, *Sass & Petersen (2002c)* have extended the data analysis of cloud cover and surface quantities to cover the entire NWP model domain. The analyzed parameters are assimilated into the model using a nudging technique (see Chapter 2.3). This will force the NWP model towards the analyzed value.

2.3 Approaches Used

2.3.1 Data Assimilation

Worldwide different data assimilation techniques are used and combined. Most of the large scale NWP models have different data assimilation modules. Recently 3D and 4D variational (4D-var) data assimilation have replaced the traditionally used optimal interpolation (OI) analysis. However, these techniques are based on some tight constraints which primarily are linked to dynamics of equations. With 4D-var the parameterized part of the equations such as convection is beginning to be considered, although only in very simplified linear versions. Note, that especially 4D-var is computationally extremely expensive. To keep these costs at low level a nudging technique was tested and applied.

The nudging technique is not widely used in NWP models, but in situations where traditionally assimilation schemes are too complicated, the nudging technique can be used. For example, *Stauffer & Nelson (1990; 1991)* used such an approach to assimilate data into a NWP model. Essentially, they used the technique with traditional data such as rawinsonde data (TEMP). The basic initial conditions (background fields) were interpolated into the grid from a host model. It was shown that by the nudging of rawinsonde data into the model, the results were improved even though it must be assumed that these data already was used in the data assimilation in the host model. Modern assimilation systems can now assimilate these data types very well. However, some data such as wind at 10 m and radar data are not used. Data may even be thinned to fit the resolution of the analysis or reduce the computational costs. Typically, the analysis is done at a lower resolution. This is the case with DMI-HIRLAM where the resolution of the analysis is 0.5 degree, whereas the model is running at a resolution of 0.15 degree. The large scale waves of the analysis are blended with the smaller scales from the first guess fields. Compared to the nudging technique this gives a better control of the noise level in the initialization of the model, and resources have been used to improve the technique (now theory and mathematical concept is well documented and tested). Nevertheless, nudging seems to provide a method to assimilate high resolution data and inadequate model parameters for limited area models on a small domain, where 3D- or 4D-var is not suitable. Cloud cover, precipitation, and humidity have a much higher variability than traditionally analyzed parameters such as mean sea level pressure, upper air temperature, and wind. This means that prediction of the small scale variability solely depends on the model’s capability to simulate the smaller scales. The surface quantities are typically analyzed with a higher resolution in areas with a dense network of observations.

Already now, both 3D- and 4D-var are used for the upper air analysis, but at the same time it is accepted and customary to use OI analysis for the surface quantities. This combination of methods can be justified if the processes, which are responsible for the large variation in the surface parameters, are caused by the parameterized part of the equations rather than as a consequence of advection. However, certain surface parameters such as the surface temperature and surface wetness are very dependent on the evolution of cloud cover and weather. The lack of smaller scales in the upper air analysis will rapidly destroy the small scale features of the surface analysis, because of inconsistency between two different analysis systems. Even though the detailed surface analysis will improve the prediction of the surface parameters for short-range forecasts, it is not guarantied that it would be better than a simple bias correction for short-range forecasts. *Bayler et al., (2000)* used satellite data to initialize the cloud structure in the NWP model. The cloud water and relative humidity were adjusted following some rules, where the background fields and derived parameters from satellite data were used to initialize the cloud water and humidity. In general the best results were obtained with satellite data, but they noted that a large part of the improvement was a consequence of changes in the condensation scheme. It was also clear that nudging data gradually into the model during data assimilation gave better results compared with simulations, where the moist variables only were adjusted at the initial time of the forecast. *Yucel et al., (2003)* assimilated satellite data into a version of the MM5 model in a similar fashion. In this case the model domain was smaller, but with higher horizontal resolution. Although adjustment of the moist variables was only done at the initialization step, this gave a better prediction of cloud cover and precipitation. The benefit of the satellite data use was shown to be significant only for very short forecast ranges.

2.3.2 Satellite Data Types

The Satellite Application Facilities (SAF; http://www.eumetsat.com) project has provided easy access to high resolution satellite data. At the present stage, the SAF derived data from the American National Oceanic and Atmospheric Administration (NOAA-16 and NOAA-17) and the European Meteosat Second Generation (MSG-1) weather satellites are operationally available at DMI. Gridded data are processed and can be easily interpolated into the NWP model domain. The high horizontal resolution of cloud cover in these data is used to calculate fractional cloud cover. The SAF module derives many fields such as cloud cover, cloud top temperature, cloud type, and precipitation intensity. Altogether this does not provide total 3D structure of the cloud cover. However, it gives some constraints about the cloud structure. Conventional ground based observations for cloud cover and height of cloud base are also included in the available data types. Even though the frequency and area coverage of such data are much smaller than of satellite data, in most cases they are of higher reliability. Especially during nighttime, surface observations are particularly important over land area since it is difficult to distinguish cold surfaces from low thin clouds in satellite data. The information about height of cloud base also gives additional constrains to 3D cloud structure. The NWP model will provide a first guess field to 3D cloud structures.

2.3.3 Nudging Technique

In most cases the NWP model will simulate the cloud structure very well in situations with large scale precipitation bearing weather systems with large-scale dynamic forcing. However, NWP models often have problems to simulate the extension of the cloudy area associated with these large systems. Non-precipitating clouds can appear too soon or too late in the NWP model. These cloudy areas are not necessary dominated by strong dynamic forcing, and it is possible to adjust the moisture and cloud water field applying a nudging technique and force the model towards the observed cloud cover. It is clear that in cases, where large errors in the wind field or surface pressure causes large errors in the cloud cover, it will be difficult to correct the NWP model cloud cover towards observations, and in such condition correction by nudging may only have a limited effect. The used nudging technique allows some freedom for the model to adjust those layers of the model which most easily can be forced towards the observed cloud cover within some limits. This ensures that only rather small corrections of the moisture and cloud water field are necessary.

The nudging technique can have some difficulties in situations with strong convection. It is possible to suppress convection during the data assimilation and to correct the amount of precipitation. At the present stage, there is no difference in the treatment of stratiform or convective clouds in the nudging module. Suppressed or enhanced precipitation may reappear/disappear in the model after the nudging module has been switched off depending on the strength of the dynamic forcing.

The convection problem is not of major concern for the DMI-RWM system since the model output is only used in winter time where convection only contributes a little to the observed cloud cover and accumulated precipitation. The RWM's purpose is to predict the road surface temperature and deposition of frost on the road. In critical situations it is crucial to predict the cloud cover and temporal clearances. During winter, the dominating clouds are low clouds or a massive layer of stratus clouds which can cover a large area. The precipitation form is mostly of a stratiform type. For prediction of the road surface temperature it is also important to know correctly the height of the cloud base as well as cloud thickness. Especially, the short-term clearances are important to predict, for example, clearance after a cold front passage during the nighttime (which in many cases leaves a wet road with a potential risk for slippery conditions). In these cases, the nudging technique can be effective to force the NWP model cloud cover towards the observed cloud cover (if the timing of the system is well predicted).

Technically, the nudging module adds tendencies of specific water vapor and specific cloud water contents. During the data assimilation, the nudging module is called as a part of the physical package of the NWP model (just after the vertical diffusion scheme and before the condensation scheme). The equations are the following:

$$\left(\frac{\partial q}{\partial t}\right)_{nud} = \left(\frac{\partial q}{\partial t}\right)_{*} + K_{q1} \cdot q \cdot \left(f_a - f_p\right), \tag{1}$$

$$\left(\frac{\partial w}{\partial t}\right)_{nud} = \left(\frac{\partial w}{\partial t}\right)_{*} + K_{w1} \cdot w \cdot \left(f_a - f_p\right), \tag{2}$$

where q is specific water vapor and w is specific cloud water. The first term on the right hand side of the equations represents the preliminary tendencies from other physical processes, e.g. vertical diffusion and tendencies from the dynamics. For both equations, the additional tendencies from the nudging depend on the differences in analyzed cloud cover at the individual model levels (f_a) and the predicted value of the cloud fraction at each level from previous time step (f_p). The empirical coefficients - K_{q1} and K_{w1} – have to be determined by experiments (*Sass & Petersen, 2002b*). Compared to the equations as described in *Sass & Petersen (2002c)*, only the most significant parts of the nudging terms are given here. Additional constraints have been added to avoid spurious precipitation and very large tendencies (see details in *Sass & Petersen, 2002c*).

Note, the final state of w and q parameters after nudging depends on the actual formulation of the condensation scheme. Moreover, changing the condensation scheme would most likely lead to another result for these two parameters, but the resulting cloud cover should converge towards the same structure. Similar nudging equations are developed for predicting the temperature and dew point temperature at 2 m. Tendencies for soil water, surface temperature, temperature, and humidity of the lowest model level are calculated. The analyzed temperature and dew point temperature at 2 m are used in the equations instead of analyzed cloud cover.

2.3.4 Setup

The DMI-RWM system has been run for tests and verification for the first two weeks of March 2005. First, the model runs a 3 hour forecast using the 1 hour forecast from the previous run as a first guess input. Afterwards, it runs a forecast with the same initial start date with the nudging module switched on for the first 3 hours and continues to produce forecasts for additional 5 hours. This means that the maximum forecast length is 5 hours. This two step procedure allows using the newest data as well as having a reference run. The latter is used as NWP model data in the cloud cover and surface analysis modules. The model output for this run is also used in the analysis of precipitation intensity and ensures that the cloud cover nudging is switched off if the precipitation intensity is increased beyond a certain limit (as a consequence of the nudging terms). In the precipitation analysis only SYNOP and SHIP observations of present weather and accumulated precipitation are used. The specific road model is only called in the last 5 hours after the nudging module has been switched off.

Several model versions and setups were tested for the period. Here, as an illustration, output of three different runs is compared. First, it is the reference run where all nudging modules are switched off. Second, it is the run where only cloud nudging is switched on. And third, it is the run with both the cloud nudging and surface nudging switched on. All these three setups call the road condition model and produce 5 hour forecasts. Note, all features of the road model are switched on for every model run. This includes a bias correction of temperature and dew point temperature at 2 m as well as flux correction in the road surface energy budget.

3 Improving of Road Weather Forecasting Using High Resolution Satellite Data

3.1 Testing

The first two weeks of March (1-14 March) 2005 were colder than normal, and moreover, several events of snowfall occurred during this period. Note, it is also relatively difficult to predict the road surface temperature during this month. This is because the daily variability is higher than in other months. Fig. 3.1.1 presents the day-to-day variation in the mean absolute error (MAE) for 3 hour forecasts averaged over all Danish road stations (i.e. 384 sites) and the corresponding variation in bias (BIAS) (definition of both MAE and BIAS is given in Chapter 3.2). The variations were estimated for three parameters: 1) road surface temperature (*Ts*), 2) temperature (*T2m*) at 2 m, and 3) dew point temperature (*Td2m*) at 2 m (example is shown for the road surface temperature in Fig. 3.1.1). Three runs were performed: 1) reference run, 2) only cloud nudging is switched on, and 3) both cloud and surface nudging are switched on. The largest difference between these three experiments was observed during 3-5 March 2005. The signal was most pronounced in *T2m* and *Td2m*, whereas only small differences in both MAE and BIAS were seen for *Ts*. Such daily variation for *Ts* is a consequence of larger uncertainties in the radiation budget and shadows during daytime in situations which are dominated by clear weather.

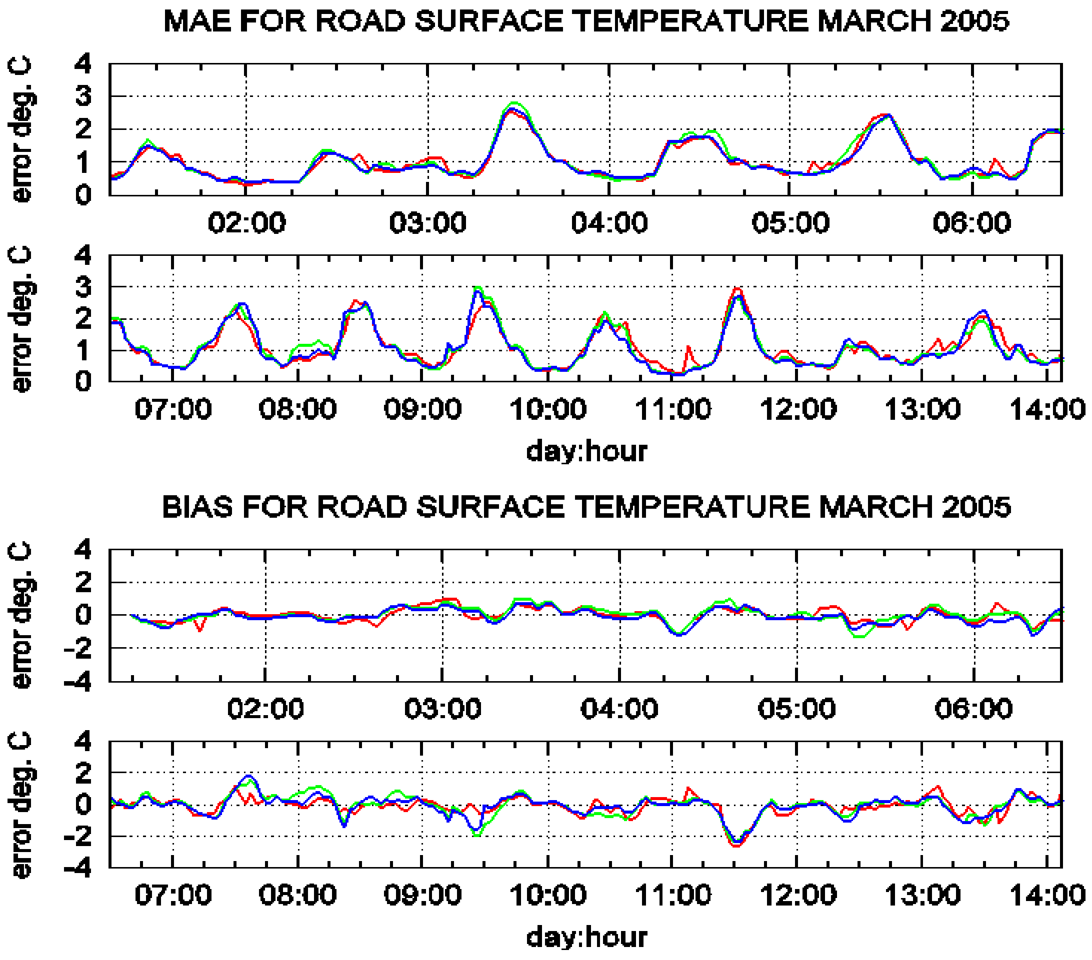


Figure 3.1.1. Mean absolute error (MAE) and bias (BIAS) for 3 hour forecasts for the road surface temperature during 1-14 March 2005 (Runs: reference (red), only cloud nudging switched on (green), and both cloud and surface nudging switched on (blue); the time indicated is valid time for the forecast).

During 3-5 March, a relatively clear weather and low temperatures were dominating. The large error in MAE during nighttime is a result of weak wind due to decaying turbulence as a result of the fast cooling over the snow covered areas. The reduced MAE for *T2m* is mainly achieved when the surface nudging module is switched on (not shown). However, when only cloud nudging is switched on, the performance is slightly better compared with the reference run. Figs. 3.1.2ab illustrate an example of difference in the cloud cover, i.e. an evolution of the total cloud cover during 3 hour interval (from 3rd March 2005, 22 UTC to 4th March 2005, 01 UTC) as viewed from the MSG-1 satellite. Figs. 3.1.2cd illustrate evaluation for the same terms, but for the run where both the cloud and surface nudging are switched on and using the same satellite data (from Fig. 3.1.2a) in the data assimilation. It is clear that the initial conditions more closely resemble the observed cloud cover in such a run and the impact is still seen 3 hours later. The clouds are all none or light precipitating. For the Danish area, the clouds are formed over a relatively warm sea surface. Moreover, from the reference run it is clear that the physics and dynamics of the model itself are able to simulate these processes rather detailed.

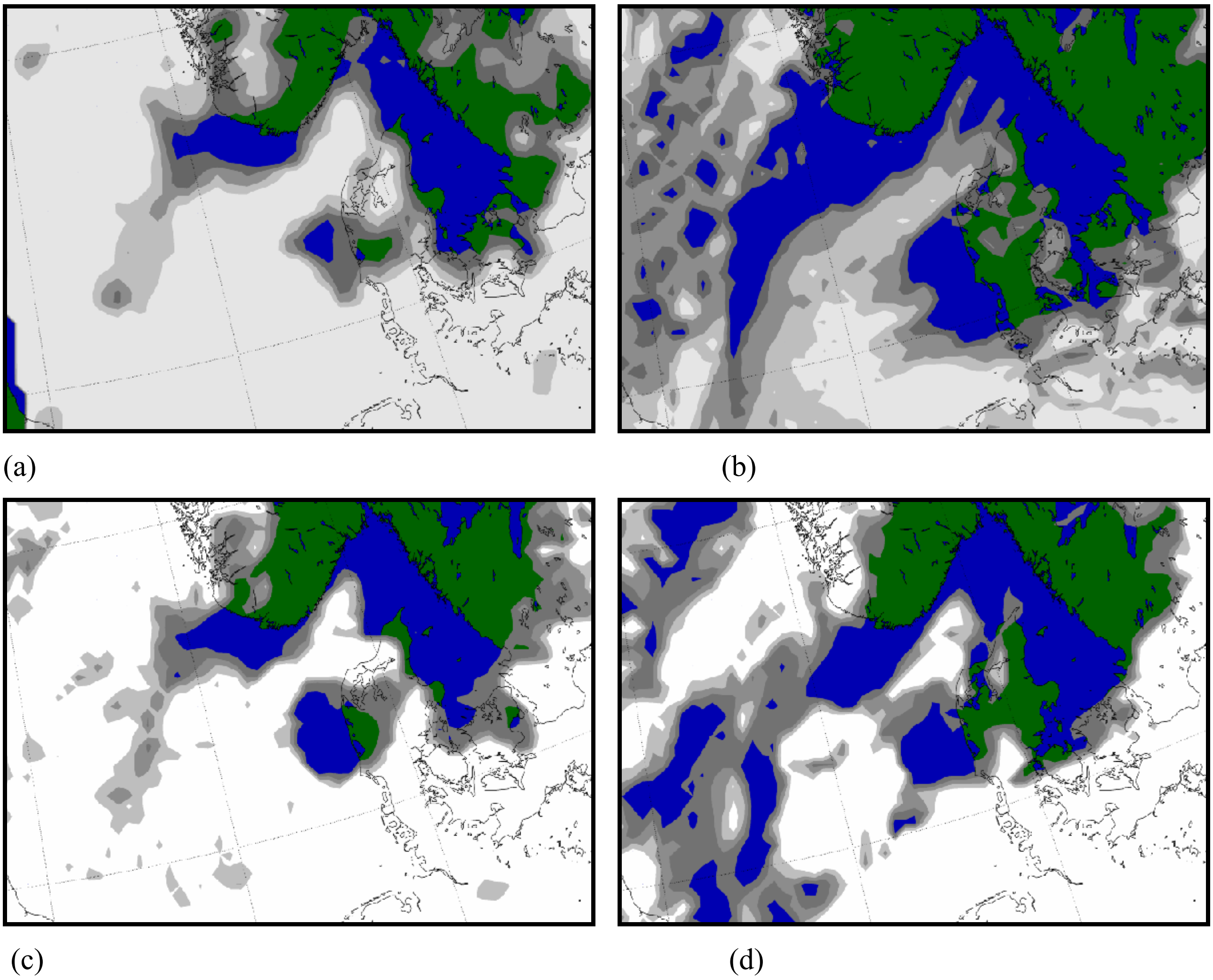

(a) (b)
(c) (d)

Figure 3.1.2. Total cloud cover: the observed cloud cover at (a) 3 March 2005, 22 UTC and (b) 4 March 2005, 01 UTC; (c) initial conditions for both surface and cloud cover nudging are switched on; (d) forecasted cloud cover 3 hour later (Note, cloud fractions are given in the intervals: 0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1).

3.2 Verification

Verification can be done in many ways. For road forecasting it is of particular importance to predict relatively rare events such as, for example, heavy snow storms. At the same time the system must be robust and stable as well as capable to predict more typical situations and avoid a large number of false alarms. Here, the RWM system performance, as compared in terms of mean absolute error (MAE) and bias (BIAS), is defined by the following equations:

$$MAE = \frac{1}{N}\sum_{i=1,N}\left|T_{f_i} - T_{o_i}\right|, \tag{3}$$

$$BIAS = \frac{1}{N}\sum_{i=1,N}\left(T_{f_i} - T_{o_i}\right), \tag{4}$$

where: N is the number of road stations or total number of observations, i denotes the i^{th} observation, T_f and T_o are the forecasted and observed values, respectively.

In terms of MAE and BIAS (both averaged over all road stations and all forecasts) the overall *Ts, T2m,* and *Td2m* verification scores for March 2005 were good. The benefit of the additional data assimilation of the cloud cover and surface analysis affected *T2m* and *Td2m* to a higher degree than *Ts*. It was found that in some days the daily variation in MAE for *Td2m* showed significant improvement during daytime. The reason of a little impact on *Ts* is most likely a consequence of high uncertainties in shadows from surroundings and the existing flux correction. At initial time the flux correction will be totally compensated from *Ts* errors. The biggest impact was seen for *Td2m*. The processes which control *Td2m* depend on the specific water vapor which is affected by advection, mixing of air masses, and evaporation of water vapor from the surface. This is in contrast to *T2m*, which also depends on radiation. The larger improvement in *Td2m* is most likely a result of a little ventilation of the surface layer in the model during daytime. In these cases the nudging within the surface layer is effectively reducing the error.

An additional verification was also made for approximately 50 Danish SYNOP stations for both the reference run and the run with all nudgings switched on. The forecasts for these stations are not bias corrected and are interpolated from the NWP model output to the SYNOP stations' locations. Fig. 3.2.1 shows MAE and BIAS for the cloud cover. The first 3 hour forecasts were not verified since the data assimilation takes place during this period and since the forecast first will be available after this time interval. The verification results (not shown) were quite similar to the results for the road stations. The most significant improvements were seen in *Td2m*. There was also a clear signal in the cloud cover verification, but the improvement declined faster than for *Td2m*. This corresponds to a spin up time of the model, where the dynamics will remove inconsistency between the mass field and nudged cloud cover. This is also observed after the conventional data assimilation, where it is often seen that there is an underestimation of precipitation in the first hours of the forecast. For the HIRLAM model, the spin up time is typical up to 6 hours, but it is reduced with increased horizontal resolution.

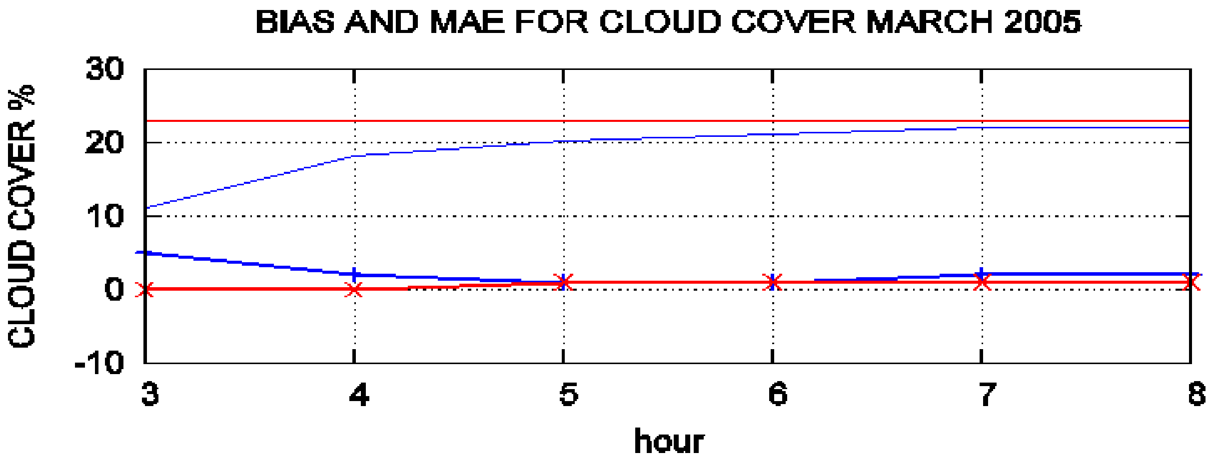


Figure 3.2.1. Evolution of BIAS (thick lines) and MAE (thin lines) of the cloud cover for the forecast range of up to 5 hours averaged for all SYNOP stations and all forecasts for runs – 1) reference run (red) and 2) both cloud and surface nudging switched on (blue) - during 1-14 March 2005 (Time indicated is valid time for the forecast).

3.3 Comparison of Long-Term Meteorological Ground vs. Satellite Observations of Cloud Cover for Improvements of Road Weather Forecasting

3.3.1 Approaches to Data Analysis

In order to estimate the potential impact of satellite data a verification of ground vs satellite observations was done for cloud cover. The NOAA satellite data (resolution of 1 km) and ground observations for cloud cover were evaluated and intercompared for the September 2004 – May 2005 (i.e. 9 month) period. Note, the satellite data was not available at each UTC term, and due to difference in the time and space span of the NOAA satellite, these are not given every hour and often do not cover the entire selected DMI-RWM system domain. The cloud cover values were extracted at geographical locations of the stations (including land, coastal, and sea located sites) in the domain and re-recorded separately for each available UTC term as time series. To unify data and analysis the cloud cover from both the satellite and ground observations were reevaluated from scales of fractions (0 to 1) and points (0 to 8) to a scale ranging from 0 to 100%. Then both types of data – satellite and ground meteorological observations (conventional observations) – were combined into one dataset and re-arranged as time series records including: year, month, day, hour (UTC term), cloud cover (in %), type of observations (satellite vs. ground), station type, station's identification number. Analyses of cloud cover were performed on a basis of: a) data type analyzed, i.e. satellite vs. ground meteorological (conventional) observations; 2) separation into Danish land vs. coastal stations; 3) month-to-month variability; and 4) diurnal cycle variability.

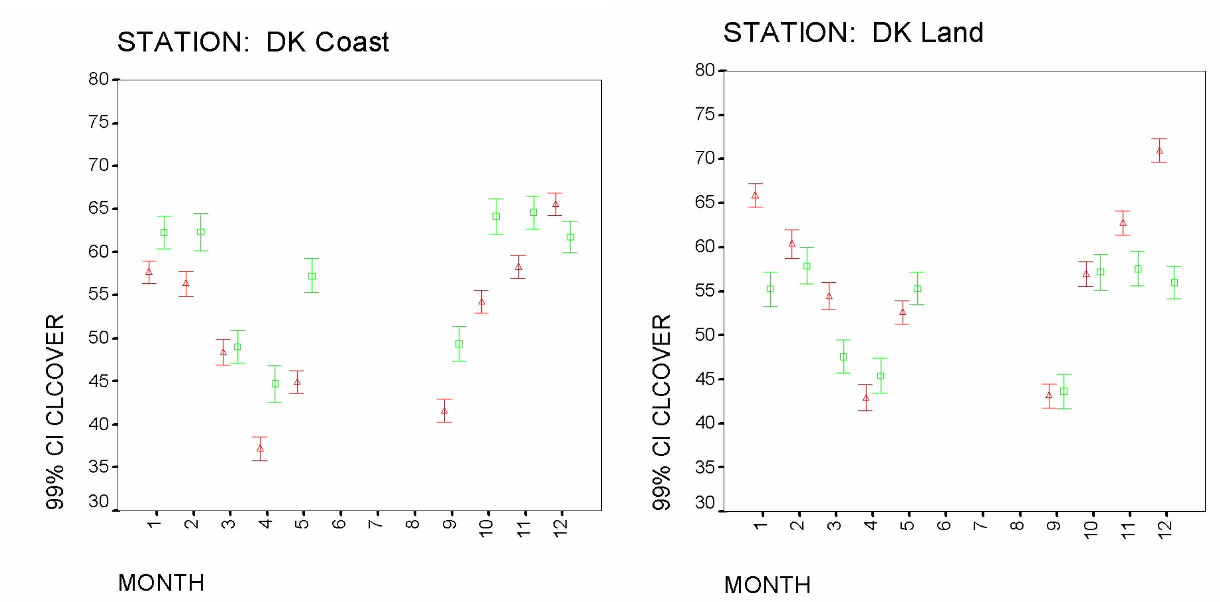
3.3.2 Monthly Variability

The monthly variability of the cloud cover observed from the ground vs. satellite observations for two groups of stations is shown in Fig. 3.3.2.1. Note, throughout the year the cloud cover from the ground observations on average is higher by 3.8% compared with the satellite, but the monthly variability is significantly larger. For the Danish coastal stations, the satellite cloud cover is about 5.7% higher compared with the ground observations. During May this difference is the highest (12.3%). Only in December the ground observations are higher (by 3.8%) compared with satellite ones. For the Danish land stations the situation is more complex. During November-March, satellite observations showed the lower (maximum of 15% in December) values compared with the ground observations. In other months it is an opposite situation (but difference does not exceed 2.7%).

3.3.3 Diurnal Variability

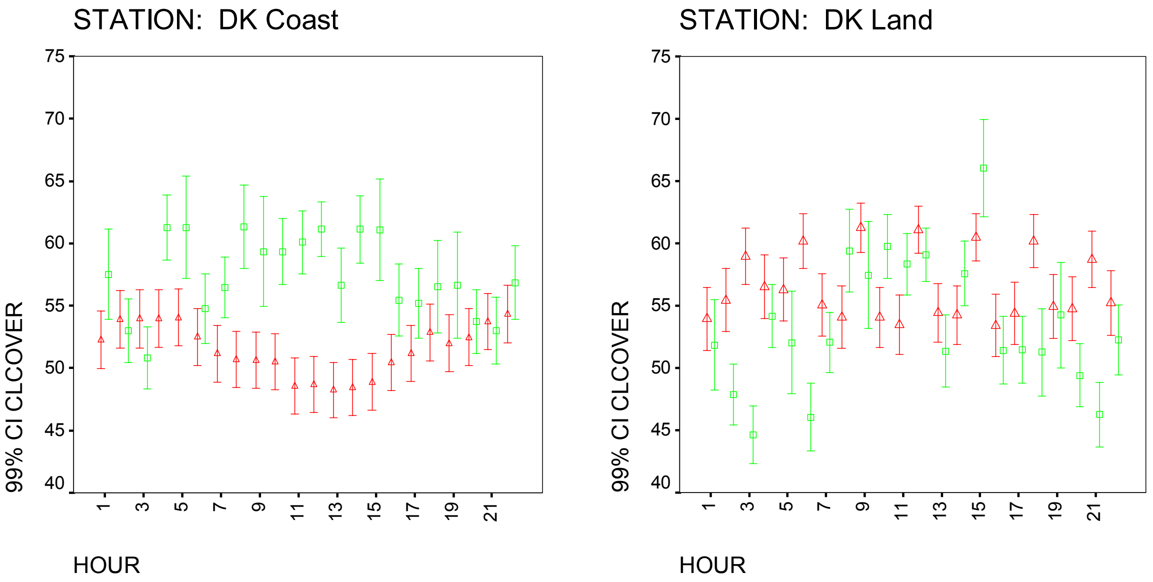
The diurnal variability of the cloud cover observed from the ground vs. satellite observations for two groups of stations is shown in Fig. 3.3.3.1. On an annual average diurnal cycle, in general the ground observations showed higher values compared with the satellite observations (if all stations are considered). The difference is higher during 16-08 UTCs with a maximum of 21.4% at 03 UTC. During other time (09-15 UTCs) the difference is significantly lower – less than twice and even more compared with other hours. For the Danish land stations, the difference is small, except during nighttime (with a maximum of 14.3% at 03 UTC). For the Danish coastal stations, the difference in cloud cover is more visible and underlined, especially between 07-16 UTCs (with a maximum of 12.7% at 14 UTC), and moreover, mostly satellite observations showed higher values compared with ground observations.

Detailed analysis of monthly diurnal cycles showed that for the Danish coastal stations, during all months (except September and March), the values of satellite observations are mostly higher than those of the ground observations. The highest number of UTC terms (i.e. 15 terms), when the difference is more than 1 point (12.5%), was observed in January, and then followed (10 terms) in May. On a diurnal cycle, the highest difference is observed during May (-21.3% at 15 UTC). For the Danish land stations, throughout the day during all months, except March, the ground observation's values are higher compared with satellite. Note, during February and March, between 10-14 UTCs this difference is negative. On a diurnal cycle, the highest number of UTC terms (i.e. 13 terms), when the difference is more than 12.5%, was observed in April; and then followed (12 terms) in December and January. Moreover, the difference became larger than 25% during September-October and December-January at 14-16 UTCs as well as during some nighttime hours, especially in September. The absolute maximum of 41.3% was observed at 15 UTC in September too.



(a) (b)

Figure 3.3.2.1. Summary of monthly variability (at UTC terms) of cloud cover (in %) at 99% of confidence level for two types of observations (red triangles – for metobs – ground meteorological observations, and green squares – for satobs – NOAA satellite observations) for two groups of stations: (a) DK Coast – coastal Danish stations, (b) DK Land – land Danish stations. (Note: June-July-August months are excluded since these did not have full months of satellite data).

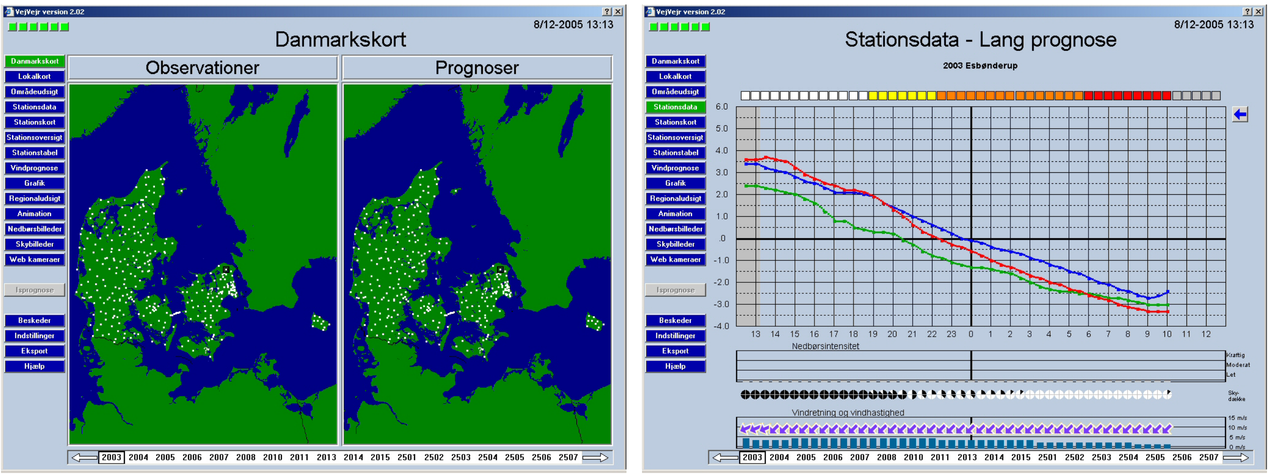


(a) (b)

Figure 3.3.3.1. Summary of diurnal variability (at UTC terms) of cloud cover (in %) at 99% of confidence level for two types of observations (red triangles – for metobs – ground meteorological observations, and green squares – for satobs – NOAA satellite observations) for two groups of stations: (a) DK Coast – coastal Danish stations, (b) DK Land – land Danish stations. (Note: 00 and 23 UTC were excluded since no satellite data were available for analysis from Danish stations).

3.4 DMI Visualization of Road Weather Forecasting for End-Users

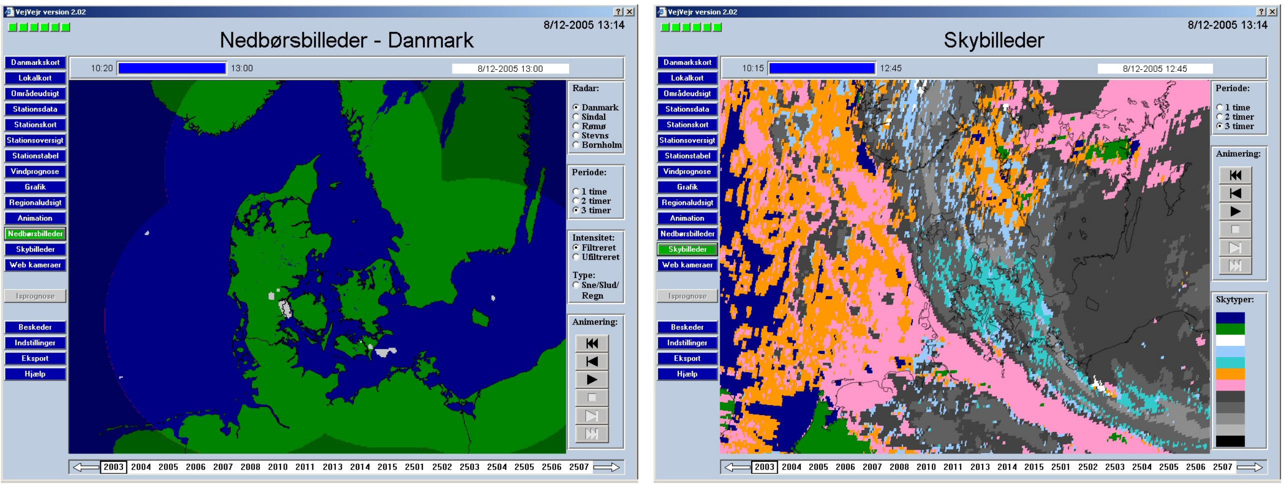
The RWM system has been developed as a user application which helps the road authorities to make decisions whether it is necessary to perform preventive actions against the slippery conditions at the roads. The RWM users do not have meteorological education, but have some basic introduction and skill lessons on how to use the RWM system. In order to access observations, forecasts, and other meteorological data a graphical user interface was developed (*GlatTerm, 2004;* user guide for RWM system users – for DMI internal and RWM official users). In the latest release this is essentially a web based application which can access online as well as historical data from a DMI database and display data in various graphical ways. Figure 3.4.1a shows the login screen and the left panel shows the options in the application. The application is developed for the Danish users (interface is in Danish language). The core in the system is the capability to display forecasts and observed values of the road surface temperature, temperature and dew point temperature at 2 m. This is done by showing on maps where the locations of the road stations are indicated by a square (as marked in Fig. 3.4.1a). The screen is split into two windows: left panel shows the actual status; right panel shows the forecasted status. The squares have colors after the road condition. Red color indicates that there is a risk of slippery road, whereas a yellow color indicates that the road surface temperature is close or below 0 degree. By clicking on the squares it is possible to see the precise forecasts or observations at the selected points.



(a) (b)

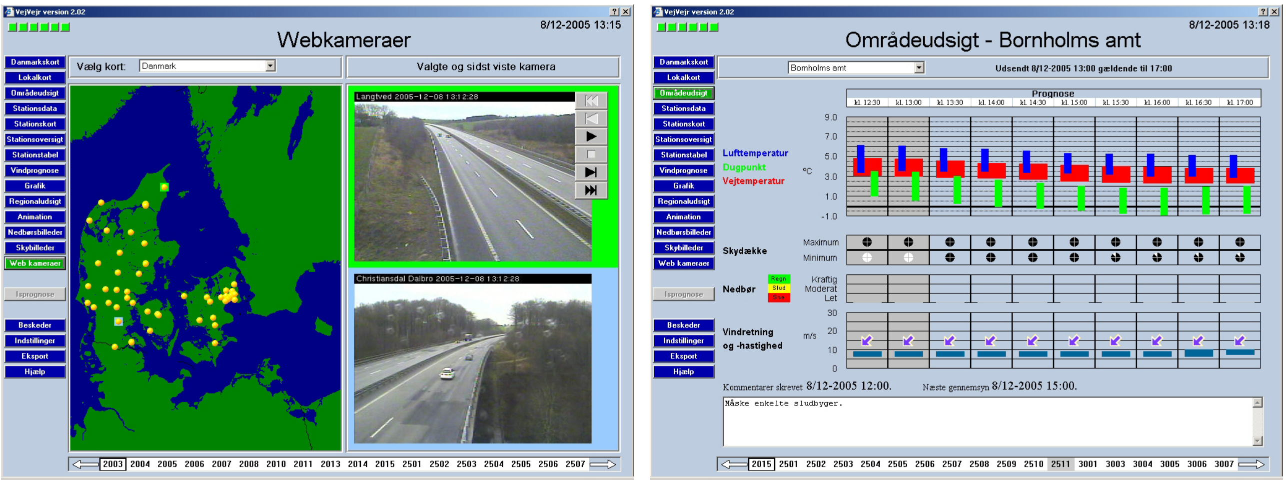
Figure 3.4.1. (a) Login screen with map of Denmark where the locations of Danish road stations are displayed (options can be selected in the left panel); (b) Clicking on a station and choosing 'stationdata' the forecasts for selected parameters are displayed (the shown curves are for the road surface temperature, temperature, and dew point temperature at 2 m).

Figure 3.4.1b shows an example of a 24 hour forecast for a selected point. Note, two types of forecasts are delivered by the system. First, a 5 hour forecast is delivered immediately when it is processed to secure that the road authorities receives a new forecast as soon as possible based on the newest observations. Second, a 24 hour forecast is delivered with a delay of about 20 minutes and it is a continuation of the short forecasts. The short forecasts secure that the road authorities have a longer time to take a necessary action in situations where there are fast changes in the road conditions. Figure 3.4.3b shows an example of a road forecast as in Fig. 3.4.1b. However, here the forecasts are for an area and it is possible in an easy way to show the variations of the meteorological parameters within an area. As seen from Figs. 3.4.1b and 3.4.3b other meteorological variables are displayed too. These shown are 10 m wind, cloud cover, and precipitation intensity. Additional nowcasting utilities have been added to the application. It is possible to view animations of radar images and satellite images (as shown in Figs. 3.4.2ab) and it is also possible to view the actual weather and road conditions from web cameras placed at the road stations (as shown in Fig. 3.4.3a).



(a) (b)

Figure 3.4.2. (a) Radar images and animations can be displayed for the last 3 hours; (b) Satellite data from the MSG1 satellite can be animated (data from the MSG1 satellite is received with 15 minute intervals, these data are also used in the RWM as initial conditions).



(a) (b)

Figure 3.4.3. (a) Web cameras placed along Danish road give valuable information about the actual weather and road conditions; (b) same information as in Fig. 3.4.1b, but shows the conditions for an area rather than for a specific road stations).

4 Conclusions

The DMI's road weather modelling (RWM) system, originally based on a 1D model for prediction of road conditions at selected locations (384 sites) along the Danish roads, is employed and run operationally at DMI. It uses the simulated outputs of the modified High Resolution Limited Area Model (HIRLAM) at DMI. The five hours' road weather forecasts are produced every hour for road stations and are available at an internal DMI web-server and to customers. Both archiving of data as well as verification of road forecasting conditions are done on short- and long-term periods with normal and slippery road conditions. The recent version of the DMI-RWM system now assimilates satellite data.

Verification for a period of two weeks in March 2005 showed that there was a reduction in mean absolute error for model runs when the data assimilation of cloud cover is used. The verification for the test period indicated clearly that the data assimilation of cloud cover is most important for short-range forecasting. A spin up time of the moist variables in NWP models is typically seen during the first 6 hours of the forecast. This corresponds approximately to the time range where improvement in the cloud cover is seen for the Danish SYNOP stations. This also emphasizes the importance of consistency between the wind and mass field and moist variables. In situations with large dynamic forcing, the data assimilation of moist variables into the model will have only limited effect and can even cause undesirable precipitation in the initial phase of the forecast.

From the reference runs it has been seen that the performance of the NWP model in general is good. When the nudging was used, the reference run can almost produce a forecast of the same quality for the road surface temperature, because the physics and dynamics of the model are able to produce the fine scale structure. At the same time the built in bias and flux correction is also able to correct larger errors except for the dew point temperature at 2 m.

Analysis of cloud cover from the ground vs. satellite observations, performed on month-to-month and diurnal scales for the Danish land and coastal stations, showed that although on average the annual difference is not high, for some months it might be more than 21%; and moreover, in some situations it can be even higher than 40%. It should be emphasized that the experience with the supplied satellite data is modest, and that verification for more individual cases and long-term periods is needed. Such kind of verification is important to improve current approaches in analysis and nudging technique.

Although the current output of the DMI-RWM system for the end-users is well designed and suitable providing detailed information about road weather conditions at Danish road stations, additional developments of end-user friendly products will be needed.

5 Recommendations

Currently the Danish Meteorological Institute (DMI) uses the Road Weather Modelling (RWM) system to provide forecasts of main road conditions at selected stations of the Danish road network. There are more than 300 stations, where forecasts of temperature of the road surface, air temperature and dew point at 2 meters are provided for the customers. These stations are not equally distributed along the road network. Forecasts of road conditions at these stations are given continuously (every 30/60 minutes) and simulations are based on output of the meteorological DMI High Resolution Limited Area Model (HIRLAM) with a horizontal resolution of approximately 15 km and 40 vertical levels.

Recently, the situation has been changed and some advancement became available and useful to be included in forecasting. There are several important issues which should be mentioned. First, the high resolution modeling (5 km and finer) became available in the numerical weather prediction (NWP) community. For example, DMI employs the HIRLAM model of 5 km resolution for the operational daily runs as well as a research version of this model with a resolution of 1.4 km (covering territory of Denmark and surroundings). Second, in Denmark, the road authorities started to use new equipment allowing getting additional information on road conditions, and which can be used also for forecasting purposes. Third, satellite data for cloud cover are now integrated and routinely used for the weather forecasting purposes, although additional verification over a longer time period is needed.

If detailed information on the road conditions along the road pathways points or road stretches (with distances between points of 5 km or less), and especially temperature related, can be provided for the road authorities, it can optimize the amount of salt spreaded over the road surface to prevent the icing/freezing as well as better timing of schedule for such operations by the road authorities. This is important for the safety of road traffic and environmental issues. Therefore, an unnecessary salting of roads and a possibility of forecasting of road conditions along the multiple and/or uniformly distributed stretches along the roads of the Danish road network will become possible to resolve and hence, it is needed to be implemented in the existing DMI-RWM system.

The findings and outcomes of the previous studies stimulated the further development and improvement of the DMI-RWM system capabilities and performance. These studies are the three year DMI project entitled "*Development of New Generation of Cloud and Precipitation Analyses for the Automatic Road Weather Model*" (Jan 2003-Dec 2005); pilot project "*Thermographic Forecasts of Road Surface*" (2005), and pilot study "*Road-Stretch-Weather*" (Fal 2005 – Win 2006).

The proposed further research and development (tasks are outlined in Table 1) of the DMI-RWM system include the following items focused on forecasting of the road surface, air and dew point temperatures along stretches of Danish roads. These include, at first, a detailed evaluation of the applicability and performance of several interpolation approaches and methods (such as based on geometrical nearness, statistical methods, and methods using basic functions) for the road weather forecasting along the road stretches. Second, the analyses and verification of the forecasting results based on the MSG1 satellite data for the cloud cover and precipitation will be performed over the long-term series records to investigate the month-to-month and diurnal cycle variabilities for further improvements of the RWM system performance. Third, the analyses and assimilation of available thermal mapping data with the subsequent RWM model modifications and improvements for forecasting along the road stretches will be conducted. Fourth, an analysis and overview of available precipitation intensity data obtained from measurements by radars and at the road stations and possibilities of their assimilation into the RWM system will be performed.

In order to improve the capabilities of the DMI-RWM system performance and improve the quality of road weather forecasts the following topics will be studied in more details. First, the contribution of other important factors such as the local climatic and location conditions (inland vs. coastal

Danish road stations and road stretches, shadow vs. sun exposed locations, height vs. distance of locations, wind characteristics dependence) will be evaluated. Second, the evaluation of satellite data for cloud cover, precipitation, and snow cover for the road conditions forecasting will be extended and verified over the long-term series of observational vs. forecasted data. Third, if the data will be available, the possibilities of use and assimilation of the road observations from the moving vehicles of the road authorities for optimization of quality of the road condition forecasts will be explored. Moreover, the evaluation and possibilities of assimilation of the road traffic data for estimation of contribution of anthropogenic heat fluxes into the DMI-HIRLAM land surface scheme, more detailed land-use classification of urban features, and especially with respect to artificial surfaces represented by the roads, pavements with and without vegetation/trees will be explored.

The important task of the operational setup of the modified RWM system, testing and verification will be done for the stretches along the Danish road network system. Moreover, the further development and improvement of the visualization tools for the road forecasting both at the Danish road stations and along the road stretches will be performed. For this, the needs and requirements/wishes of the end-users/ customers of the road conditions forecasts will be evaluated and maximally adapted in the RWM system.

In this new project/proposal, the RWM system operational runs and maintenance (including the operational items, standard quarterly verification of model performance, modifications of RWM source code, extension of porting of code between DMI-HIRLAM model and HIRLAM reference version, and estimation of computational stability, CPU usage, and RWM code performance) will be also routinely continued.

6 Acknowledgments

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