

Fine-Scale Road Stretch Forecasting: Applications of High Resolution Terrain and Thermal Mapping Data

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ABSTRACT

The system, which can provide operational forecasts of the road surface temperature, air temperature and dew point temperature for any road stretch in Denmark, has been developed, tested and verified. Detailed local characteristics influencing shadowing effects for road stretches were obtained from the high resolution Danish databases on terrain, obstacles, height, land-use, etc. The thermal mapping data taken during road winter seasons of 2008-2011 were used for verification. It was found that the forecast quality for the road stretches was comparable to the forecast quality for the road stations.

Keywords: road weather forecasting, road surface temperature, road station / road stretch, Danish Height Model, shadowing effect

1 INTRODUCTION

The DMI has in collaboration with the Danish Road Directorate (DRD) for almost two decades used a Road Weather Modelling (RWM) system (based on a dense road observations network, Condition Model (RCM), and numerical weather prediction (NWP) model - High Resolution Limited Area Model, HIRLAM) to provide operational forecasts of main road conditions at selected road stations of the Danish road network (see Figure 1a). As of 1 January 2012, there are almost 400 road stations equipped in total with more than 500 sensors, where measurements and forecasts of road surface temperature (T_s), air temperature (T_a) and dew point temperature (T_d) are conducted. Forecasts of other important meteorological parameters such as cloud cover and precipitation as well as radar and satellite images are also distributed to the users through the web-based interface and through DMI and DRD web-pages. For icing conditions, new technology has made it easy to vary the dose of salt, making it possible to spread salt only on the parts of the road network where it is needed.

The main aim of the "Fine-Scale Road Stretch Forecasting" (RSF, 2009-2011) project was to make a system which can provide forecasts for any road stretch in Denmark, and that the forecast quality for the road stretches should be comparable to the forecast quality for road stations (where measurements of road surface temperature, air temperature and dew point temperature are done every 5 minutes). This project has focussed on research, analysis, development, and improvement of the quality of the road condition forecasts by refining, detailisation, setting up, and running the fine-scale resolution NWP model with integration (from high resolution databases) of characteristics and derived parameters of surrounding roads the land-use, terrain, positioning and road properties at road stations and stretches. The objectives included, at first, the research and development of the existing RCM based on input from a fine-scale NWP modelling. At second, it included analysis and integration of detailed data and derived parameters at road stations and stretches into RCM based on detailed national high resolution databases. And at third, it focused on elaboration, testing, evaluation, and implementation of the methods and approaches suitable for RSF modelling and verification of the RWM system performance at fine-scales. See list of publications/ presentations related to the completed RSF project in the section 5 "References" [1-12].

2 METHODOLOGY

2.1 Numerical Weather Prediction (NWP) Model

The High Resolution Limited Area Model (HIRLAM) is used as NWP model and interface to the RCM model. HIRLAM includes modules to make data-assimilation for the free atmosphere as well as for the surface. An extra module has been added to assimilate cloud observations. The data-assimilation uses observations from surface, weather balloons, satellites and airplanes to produce an analysis used to initialize the model. Because HIRLAM is a limited area model, the boundary conditions are applied from an outer model (running on a larger size domain). At the first time step, a digital filter is called to remove noise from unbalances in the initial conditions. After the set of equations for the atmosphere is solved, the tendencies are calculated at each time step using a semi-Lagrangian scheme. Beside the dynamic tendencies, there are also calculated additional tendencies from physical processes such as radiation, turbulence, surface processes, transition between vapour-liquid-solid vapour in the atmosphere, rain and snow. For a more detailed description of the HIRLAM model see the website (<http://hirlam.org>) for further model documentation.

Figure 1c shows the chosen NWP model domain with Denmark in the centre. The model setup is the following: 650 x 460 grid points along longitude and latitude, respectively, 40 vertical levels, horizontal resolution - 0.03 deg in a rotated system of coordinates (south pole: longitude 3 deg, latitude -40 deg), 24 h forecast length, time step 120 sec, cut-off time - 90 minutes. Each day the model is running 24 times generating 25 hour forecasts. Before each run the data-assimilation is done accounting for the latest observations.

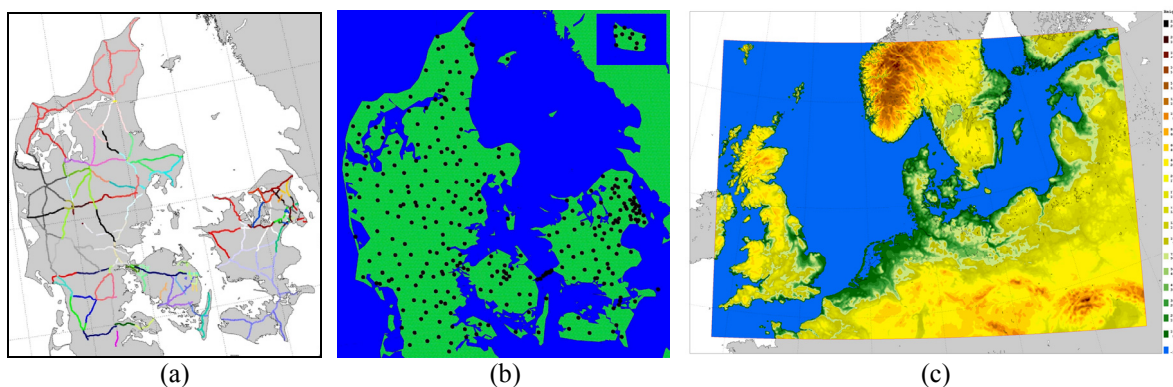


Figure 1. (a) Danish road network covering 153 roads with almost 23000 road stretches (from 2009-present); (b) Positions of road stations (black dots); (c) Boundaries and terrain for NWP modeling domain with Denmark in the center of domain.

2.2 Road Conditions Model (RCM)

The Road Conditions Model (RCM) is a so-called energy balance model originally developed at DMI [13-14]. It is a local model where forecast at each point does not depend on other surrounding points. All advection parts of atmospheric processes are done in the NWP model. Indirectly these processes are incorporated by obtaining the atmospheric state from the NWP model at each time step. The energy balance model in the RCM differs compared with the NWP model. The RCM model has 15 layers in the road and solves the heat equations for these layers, whereas the NWP model has simple 2 layer model. In addition, the RCM model has been optimized for asphalt surfaces, which have characteristic much different from other types of surfaces used in NWP.

The RCM is called every time step from the NWP model with the first call after 1 hour. Each day the RCM model is running 24 times generating 24 hour forecasts. It is running as a module inside NWP and receiving input at each time step. The RCM makes forecasts at “randomly” spatially distributed points (i.e. road stations/stretches) and the NWP output is interpolated to these points. At the first time step, an analysis of the initial conditions is done. Observations of T_s , T_a , and T_d from road stations (or analysed equivalents from road stretches) are used to run RCM in a forced mode. The equations of heat conduction for the road points are solved using the forecast from the last model run as initial conditions, and then run RCM 3 hour ahead with observed T_s as boundary condition. This provides an analysis of the temperature profile through the road depth. Then, the forecast of T_s , T_a , T_d , accumulated water (rain water, dew) and ice (snow, rime, frozen water) on the road is calculated for each time step taking into account (i) short-wave heating and long-wave cooling/ heating of the road surface (which are affected by shadowing and skyview); (ii) turbulence fluxes of temperature and moisture from/ to the road surface; and (iii) evaporation, melting, freezing and sublimation of water and ice from the road surface.

2.3 Road Stretch Forecasting (RSF)

For the road stretches forecasting (RSF), a new system to make road stretch forecasts has been developed, tested and implemented. The method to make forecasts at road stretches is similar to the method for making forecast at road stations. Such forecast is based on provided output from the NWP model and used as input into the RCM model. The strength of this method is that it has a generic interface, and it is based on a physical model. The performance of the system depends only on the quality of the input from NWP model, the quality of the RCM model and the initial and local conditions at the forecast points. There is no need for tuning and calibration of the system. If one of these components is improved then this will improve the overall quality of forecast. Hence, it is a good basic framework for further improvement.

The design of the RSF system has been done to ease future development of the system. With small efforts positions of new stretches can be added or removed from the list. Still the number of points (road stretches) should be lower than the number of grid points in the NWP model. It is because the computer resources to run this model are also used to calculate the RSF. At the moment the number of model grid points is 299000, whereas the number of road stretches is 22800, and thereby, there is a room to add more road stretches into forecasting chain. There are no limits on which domain the NWP and RSF model can be run.

Compared to forecasts at road stations, the forecasts at road stretches need initial conditions and shadows at the points/ positions of road stretches along the roads, and these are not known. Hence, if it is possible to estimate these quantities with the same accuracy as at the road stations, it could be assumed that the forecast quality at road stretches will be comparable. For that the thermal mapping measurements and high resolution physiographic data on terrain and surroundings along the roads are both needed as essential information.

2.4 Thermal Mapping Measurements

Thermal mapping is a process of measurement of spatial variation of road surface temperature under different weather conditions. It is done with infrared thermometers, temperature sensors which are used to measure the road surface temperature (T_s). The device is mounted on the vehicle in a way that sensor should have a clear sight to the road surface. The measurements are done continuously during the road salting activities. Mostly these measurements are performed during road winter seasons with a focus on nighttimes, since some cooling of the roads is most common during night. Differences in temperature along the roads can vary up to several degrees, and hence, some parts of the road can be near or below the icing/freezing point and others - may be not. For each road the energy balance is affected by complex interactions between various factors including: weather conditions; sky view factor or shadowing effects from trees, buildings, constructions, etc.; height of the road section; geographical location with respect to major water objects; effects of urban areas resulting in building up of so-called urban heat islands; road and traffic related peculiarities; etc. Combination of all these factors will create a unique “temperature finger-print” for each road.

For the RSF project, data have been provided by the Danish Road Directorate (DRD) through a database ftp-access. The database contains detailed information about road activities, time (year, month, day, hour, minute, second) of measurements, latitude and longitude of taken measurements applying GPS, and measured values of the road surface temperature (T_s , in deg C), air temperature (T_a , in deg C), and relative humidity (RH , in %). These are so-called the “thermal mapping data” (ThMD). Note that such measurements are mostly done during days when salt is spread along the roads to prevent icing conditions. Moreover, these data are irregularly measured depending on the road authority programmes, and the measurements are done at discrete time and space intervals. The measurements of T_s from road stations and salt spreaders have additionally been used to examine both road stations and road stretches forecasts along the main roads of the Danish road network (accounting almost 23 thousand points located at distances of 250 m). These results showed critical importance of availability of detailed characteristics of the roads surroundings.

2.5 High Resolution Physiographic Data

Previously, a description of physiographic conditions in RCM at a relatively low resolution was acceptable, but now such description should be done at finer scales and in more detail. To make local forecasts in a specific point all possible local detailed information is needed. Since high resolution models running at faster supercomputers as well as detailed physiographic datasets now are available, it is possible to improve the modelling and parameterization of significant physical processes influencing the formation of the slippery road conditions. For Denmark, first of all, it is based on a new dataset available from the Kort og Matrikel styrelsen (<http://www.kms.dk>), the so-called Danish Height Model (Danmarks HøjdeModel, DHM) which is a very detailed set of data with horizontal resolution of a few meters and fine height accuracy. It includes high resolution orography (Danish Terrain Model, DTM) and high resolution surface elevation (Danish Surface Model, DSM) databases.

Due to this new database it became possible to access details of topography with a much higher precision and resolution compared with previously used datasets. This allows taking into account shadowing effects when forecasting the road surface temperature. These effects were estimated by scanning the surrounding terrain (including natural and man-made obstacles/ objects such as forest, construction, trees, etc.) by sectors (32 sectors by 11.25 deg each) up to maximum distance of 10 km from the road station (and stretch) geographical position. The scanning was performed within 3 ranges of 0–100 m, –1 km, and –10 km with a horizontal step of 5, 10, and 20 m, respectively. For each sector, an average angle of the highest point was calculated as a horizon angle representing a shadowing effect due to terrain or obstacle. Such information can improve accuracy and representativeness of shadowing for the roads.

The method has proven to work well and includes many details. However, it is known that the height of obstacles might change over time such as height of trees, new vegetation, building and demolition various constructions. At the moment it is unclear how often the database will be updated. The method is generic and can be extended to any point in Denmark or elsewhere provided access to appropriate DTM/ DSM database.

Moreover, because Denmark is surrounded by the sea waters, the modeled road conditions are highly affected by proximity of roads to the seashore line. So, for each point the distances within each sector were calculated, as well as the shortest distance to seashore with a corresponding direction. In total, 20% are placed (within a 1.5 km distance from a seashore) at coastal stations and large bridges connecting the Danish islands; 23% at pre-coastal stations (between 1.5–5 km), and 57% - at inland stations (more than 5 km).

In addition, the cataloging of each road station individual characteristics was carried out. It includes the GPS positioning (re-verified routinely through Google-Earth with respect to roads); altitude of location; sectoral distribution of horizon angle, shortest distance to seashore with corresponding azimuth; minimum distance to seashore with corresponding classification into coastal, pre-coastal, and inland stations; surrounding detailed land use types, especially with respect to forest, open fields, urban/suburban areas, closest water bodies and types of bridges (over other roads, rivers, channels). A similar approach was applied for road stretches.

3 RESULTS AND DISCUSSIONS

3.1 Shadowing Effects

For the RCM model, the effects from shadowing and “skyview” have an important influence on the energy balance of the road surface. Shadows can reduce the direct short-wave radiation from the sun during daytime, and the skyview can reduce the long-wave radiation cooling of the surface or long-wave radiation heating from the “warmer clouds”. A method to calculate shadowing effects at points (positions of road stations and road stretches) was developed and described in Ch 2.5. The shadows were calculated from the DHM database taking into account both the terrain height and the height of obstacles surrounding the road. This method was applied for almost 23 thousand points (road stretches) along the Danish roads. An example of shadowing effects calculated from the DHM database at a selected road station in the Copenhagen metropolitan area is shown in Figure 2.



Figure 2. (a) Example of shadowing effects due to surroundings for the road station N-1542 /scale—height of surroundings/; (b) Station surroundings /extracted from Google-Earth; sensor is placed on the road surface/.

For road stations, the accuracy of the shadow calculation has been verified through comparison with available surrounding photos. It has been found that in some cases the calculated angles to obstacles became unrealistically large in some directions. Possible cause could be originated from the database. In a case of a narrow road with big trees it might look like a roof's coverage (i.e. road is completely covered by trees; like a road through a tunnel). Hence, during daytime the road surface would not receive direct short-wave and much diffuse radiation, and it will result in too low T_s . During nighttime the road would not be able to cool down by long-wave radiation, and it would result in unrealistically high T_s . Therefore, for such cases a limit for maximum possible angle of horizon due to shadow should be considered. The comparison with surrounding photos

revealed more insight into possibilities, but also stressed limitations concerning the shadowing calculation using available databases. In general, the most accurate calculation of shadows is for larger and taller obstacles (i.e. forests, bigger tree lines, and solid objects are well captured). But individual trees and smaller objects may not be captured so well, and thus, their contribution may be underestimated.

3.2 Thermal Mapping Data

During the recent road winter seasons (2008-2009, 2009-2010, and 2010-2011) the thermal mapping data (ThMD) measurements have been conducted along many Danish roads/ driving lanes. In total, the original raw data (time-series of measurements) obtained from the DRD database included 422697, 911277, and 562611 records for the three last seasons, respectively. During 2008-2009 season, the largest number of measurements (145003, or 34.3% of total) was obtained in March 2009, and the lowest (4050) - in October 2008. During 2009-2010 season, the largest number of measurements (476504, or 52.3% of total) was obtained in December 2009, and the lowest (601) - in November 2009. During 2010-2011 season, the largest number of measurements (139685, or 24.8% of total) was obtained in March 2011, and the lowest (15946) - in October 2010. Almost 77% (2008-2009), 64% (2009-2010), and 82.4% (2010-2011) of these measurements were observed during 18-06 UTCs time interval which corresponds to a higher likelihood of the icing conditions formation along the roads.

The ThMD measurements, which are closest to the minute within a range of ± 5 sec, were extracted and interpolated from the original raw ThMD data. It was done, because: (i) the thermal mapping measurements are done at a very short and non-equal discrete time intervals (due to different velocities of moving vehicles along different parts of the roads); (ii) the road stretches are located relatively close to each other (at variable distances of approximately 250 m); and (iii) the finest temporal resolution of the RCM forecasts is equal to 1 minute, and hence, ThMD need to be the closest to available forecasts' times. An example of the spatial distribution of measurements assigned to positions of road stretches for the road season 2010-2011 is shown in Figure 3a.

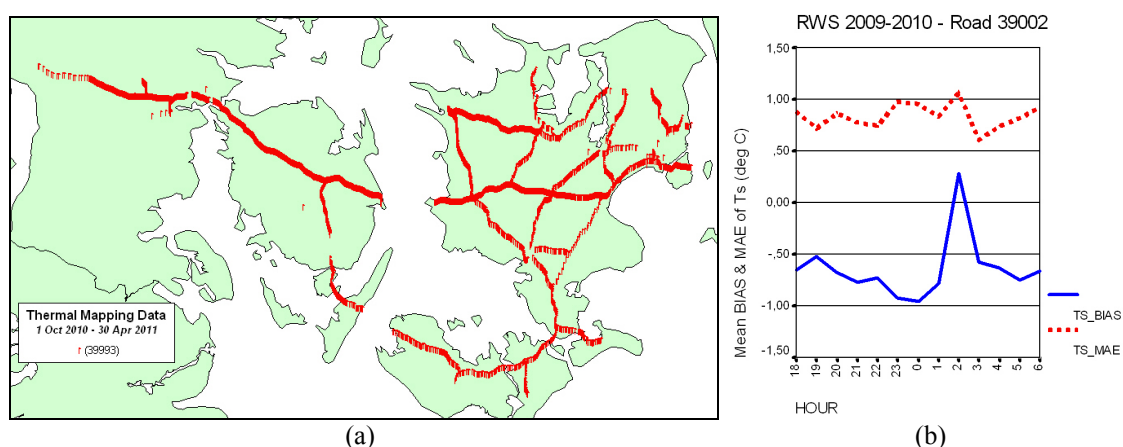


Figure 3. (a) Spatial distribution of thermal mapping data measurements (road surface temperature assigned to road stretches) for road weather season from Oct 2010 – 30 Apr 2011; and (b) Mean bias and mae of T_s (based on ThMD) during evening-nighttime hours for the road stretches of the road 39002 during the road weather season 2009-2010.

Analysis and verification of the RSF forecasts vs. ThMD for one of the Danish roads (39002; located in the south-eastern part of the Jutland Peninsula of Denmark) with the longest time series of measurements is given on example of winter months during road weather season 2009-2010. The RCM forecasts at road stretches were compared with ThMD measurements. In total, 11653 averaged ThMD measurements (covering all T_s temperature ranges) were assigned to road stretches positions of this road. For these, on average, the bias and mae were -0.57°C and 0.88°C , respectively. From these 11653, in total only 9809 ThMD were within a range of $\pm 3^\circ\text{C}$ (5094 are linked with 18-06 hour period and 4715 - from 06 till 18 h). On average, on a diurnal cycle, the bias (mae) was -0.68°C (0.89°C). For evening-nighttime hours the bias (mae) was -0.55°C (0.85°C); and for morning-daytime hours the bias and mae were larger (-0.82°C and 0.93°C , respectively) compared with evening-nighttime period. A summary on a diurnal cycle for bias and mae is given in Figure 3b (for the evening-nighttime hours). On a month-by-month basis, the bias (mae) were -0.65 (0.88), -0.88 (0.99), and -0.65°C (0.84°C) for December 2009, January and February 2010, respectively.

3.3 Verification at Road Stations

It should be noted that the standard verification of the RCM performance during the last 3 road weather seasons was done annually, at the end of each season (during spring – beginning summer). For the last three (2008-2009,

2009-2010, and 2010-2011) road seasons, the score for the 3 hour forecasts of the road surface temperature at road stations of the Danish road network with an error of less than $\pm 1^\circ\text{C}$ was 80, 82.44, and 81.88% based on more than 519, 473, and 563 thousand corresponding forecasts. The overall seasonal averages of the bias and mean absolute error were -0.11 , $+0.02$, and $+0.09^\circ\text{C}$ and 0.76 , 0.69 , and 0.70°C , respectively for the last three subsequent seasons. It showed a better performance of the road conditions model compared with the previous seasons 2005-2006, 2006-2007, and 2007-2008, where the biases and mean absolute errors were $+0.31$, $+0.22$, and $+0.18^\circ\text{C}$ and 0.78 , 0.74 , and 0.78°C , respectively.

3.4 Verification at Road Stretches

An example of verification of the new road stretches forecasting (RSF) system is shown for December 2009, selected as a test month. This month was chosen due to large number of available ThMD assigned to positions of road stretches, much lower temperatures than normal have dominated, and multiple snow fall have occurred; and thereby, also it required to take many preventive salting actions from the road authorities.

All available ThMD measurements from all Danish roads have been extracted and pre-processed for verification following Ch. 3.2. It should be noted that quite a large number of ThMD observations were of a poor quality, and even some measurements were as much as 10 degrees colder (which might be due to sensor calibration issues). Although these are relative easy to screen out, but worse are actually those with a smaller bias which can not be easily identified as erroneous. The ThMD have been required to be reasonably fitting to traditional road station observations of the road surface temperature (T_s), but still allowing extremes slightly colder and warmer than observed at road stations.

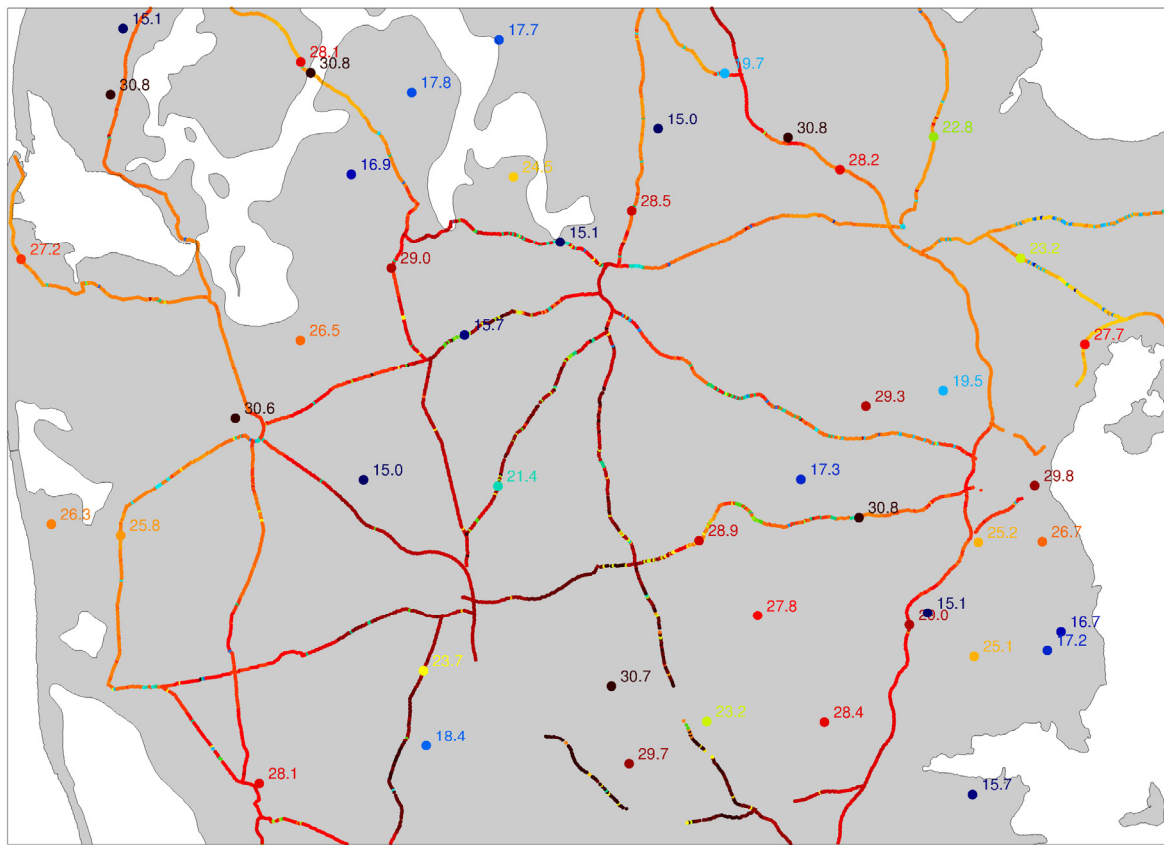


Figure 4. An example of forecasts of the road surface temperature at road stretches for the central part of the Northern Jutland Peninsula.

The RSF verification showed that overall performance to predict road surface temperature for the tested month had a mean absolute error of 1.34°C for 3 hour forecasts at road stretches. This is in the order of 0.5°C higher than would be expected for the forecast at road stations. However, it was also found that that an increase in mean absolute error only raised from 1.28°C (1 hour forecast) to 1.42°C (5 hour forecast) during the T_s forecast which is in a range or lower what would be expected for the road stations forecasts. An example of the RSF forecast is shown in Figure 4. Uncertainties in initial conditions or measurements of T_s are most likely to be expected to be

the reason. Analysis of individual cases has shown that the T_s patterns are similar to what is seen for road stations for forecasts longer than about 1 hour.

It was found that ThMD (or observations from moving vehicles) were difficult to use RSF operationally due to irregularity and limited spatial and temporal distribution of measurements. As all available data were carefully examined and compared. In RSF verification it was found that a large number of such observations have a large bias for the road surface temperature. Note, that mostly the bias was negative. The large bias might be related to instrumental errors and calibration of measuring devices. Still, these observations have important information about variation of the road surface temperature. For future application of such information the focus should be on how to use the variation in temperature rather than the absolute temperature measurements. However, it should be further examined from where such large measurement errors originate, how these measuring devices can be accurately and reliably calibrated and how already taken measurements should be quality controlled before practical use.

4 CONCLUSIONS

Within the frameworks of the “Fine-Scale Road Stretch Forecasting” (RSF) project, a new system has been tested for selected roads, cases, months and road weather seasons. The performance of the RSF was compared with thermal mapping data and by inspection of individual cases. It turned out that the thermal mapping data had a poor quality compared to observations at road stations. Even though the month was selected out from the maximum number of observations quite many observations have been rejected in the verification. Inspection of the thermal mapping data on individual days also makes it clear that still after removing the most obvious errors in road surface temperature the average error is still in the order of the forecast error. The resulting forecast error in term of mean absolute error is, therefore, larger than forecast for road stations. It is seen that the error growth in road surface temperature for RSF as a function of forecast length is small and comparable to road station forecasts. This indicates that either the observations are of poor quality or the RSF has large errors in the initial conditions. However, this is not supported by inspection of individual cases. Instead it seems clear that there is a need to develop a method to calibrate accurately sensors for making thermal mapping measurements and perform quality control of such data.

It should be noted, that although ThMD data showed that they are very useful for verification of the performance of the RWM system, these are less applicable and valuable for on-line assimilation into the system due to sparse and irregular measurements. But such ThMD can be used for possible correction of the road surface temperature forecasts by integration of these into a neural network based on long-term road surface temperature dataset over the Danish road network domain which needs to be further investigated. Analysis showed an importance of further investigation of the road surface temperature forecasts as a function of different road and environmental characteristics.

The results of this study are applicable for improvement of forecasts for road stations and stretches. This will facilitate the use of data from the road stretch forecasting to automatic adjustment of the dosage spread by salting spreaders (i.e. for optimization of the salt amount spread in order to prevent the icing/freezing and better timing of salting schedule). It will lead to improvement of the overall safety of the winter road traffic. It will contribute to further development and improvement of the visualization tools for the road stretches forecasting. And it may reduce the environmental impact in the road surroundings due to an optimized spreading of salt.

5 REFERENCES

- [1] Petersen C., Mahura A., B. Sass, (2009): Road Weather Modelling System: Verification for 2008-2009 Road Weather Season. *DMI Technical Report 09-10*, 20p., www.dmi.dk/dmi/tr09-10.pdf
- [2] Mahura A., C. Petersen, B. Sass, K. Sattler (2009): Fine-Scale Road Stretch Forecasting. *Proceedings of the International Symposium on Nowcasting and Very Short Range Forecasting, 30 Aug – 4 Sep 2009, Whistler, British Columbia, Canada, P1.10L*.
- [3] Petersen C., Kai S., Mahura A. (2009): Strækingsvejr – detaljer tæller. *Dansk Vejtidskrift journal*, Vol. 10, pp. 46-48 (in Danish).
- [4] Mahura A., C. Petersen, K. Sattler, B. Sass (2009): Fine-Scale Road Stretch Forecasting along Main Danish Roads. *Abstracts of the European Meteorological Society (EMS) Annual Meeting, 28 Sep - 2 Oct 2009, Toulouse, France, Vol. 6, EMS2009-71*.
- [5] Mahura A., K. Sattler, C. Petersen, B. Sass (2009): Improvement of Road Forecasting using Effects of Shadowing due to Terrain and Distance to Seashore. *Abstracts of the 9th European Meteorological Society (EMS) Annual Meeting, 28 Sep - 2 Oct 2009, Toulouse, France, Vol. 6, EMS2009-81*.

- [6] Pedersen T.S., Petersen C., Sattler K., Mahura A., Sass B.H., (2010): Physiographic Data for Road Stretch Forecasting. *Abstracts of the 15th International Road Weather Conference, SIRWEC, 5-7 Feb 2010, Quebec, Canada, T5.18, 5 p.*
- [7] Petersen C., Mahura A., B. Sass, (2010): Road Weather Modelling System: Verification for 2009-2010 Road Weather Season. *DMI Technical Report 10-12, 20 p.*, www.dmi.dk/dmi/tr10-12.pdf
- [8] Mahura A., Petersen C., Sattler K., Sass B.H., Pedersen T. (2010): High Resolution Physiographic Data for Fine-Scale Road Weather Forecasting, *DMI Sci. Report 10-05, ISBN: 978-87-7478-605-4, 30p*, www.dmi.dk/dmi/sr10-05.pdf
- [9] Mahura A., C. Petersen, K. Sattler, B.H. Sass (2011): Fine-Scale Road Stretch Forecasting: Improvements due to Applications of High Resolution Databases. *Abstracts of the International Conference on Computational Information Technologies for Environmental Sciences (CITES-2011), 3-13 Jul 2011, Tomsk, Russia, pp. 67-68*
- [10] Petersen C., Mahura A., B. Sass, (2011): Road Weather Modelling System: Verification for 2010-2011 Road Weather Season. *DMI Technical Report 11-19, 28p*; www.dmi.dk/dmi/tr11-19.pdf
- [11] Mahura A., Petersen C., Sass B.H., Holm P., Pedersen T.S. (2011): Thermal Mapping Data Measurements: Road Weather Seasons 2008-2011. *DMI Sci. Report 11-03, 49p, ISBN: 978-87-7478-602-3, www.dmi.dk/dmi/sr11-03.pdf*
- [12] Petersen C., Mahura A., Sattler K. (2012): Fine-Scale Road Stretch Forecasting, *DMI Sci. Report 12-02, 23p, ISBN: 978-87-7478-609-2, www.dmi.dk/dmi/sr12-02.pdf*
- [13] Sass B.H., (1992): A Numerical Model for Prediction of Road Temperature and Ice. *Journal of Applied Meteorology*, 31, pp. 1499-1506.
- [14] Sass B.H., (1997): A Numerical Forecasting System for the Prediction of Slippery Roads. *Journal of Applied Meteorology*, 36, pp. 801-817

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