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Fine-Scale Road Stretch Forecasting

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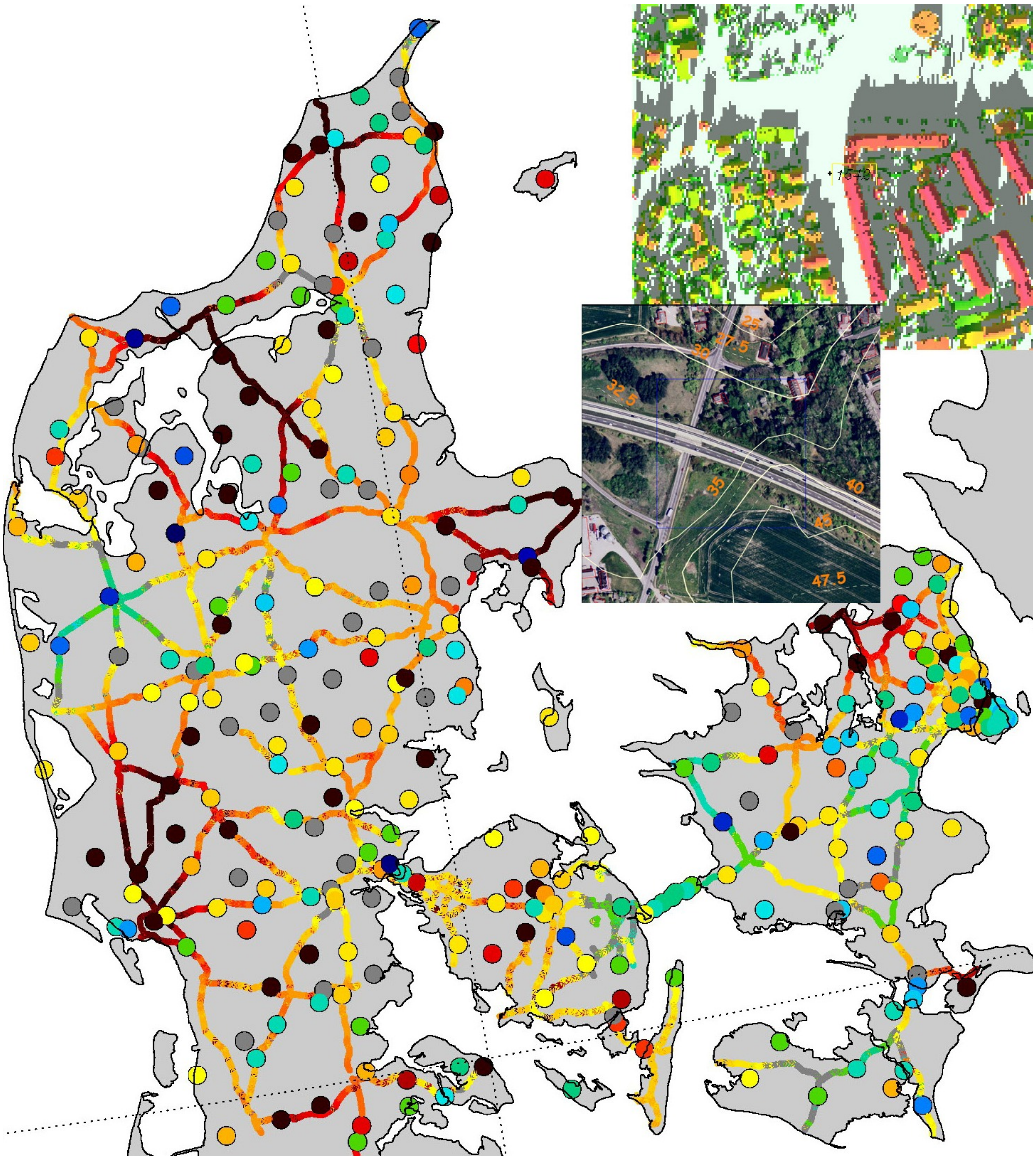

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Abstract

This report is intended as final report and documentation for the project entitled ‘Fine-Scale Road Stretch Forecasting’. The project has been running from 1. January 2009 to 31. December 2011. The project is a part of the efforts done to improve winter maintenance and safety of roads under winter conditions. This includes the economical and environmental benefits which can be obtained by only applying the needed dose of salt/chemicals to the road surface and do it with optimal timing. The outcome of the project is a system which delivers 24 hour forecasts 24 times each day of road surface conditions for 22800 road stretches in Denmark. This should be compared to the previous system where forecasts for about 400 road stations were calculated.

It has been a goal of the project that the quality of forecasts for all the road stretches should be comparable to the forecasts made for the road stations. However, at the road stations initial conditions of road surface temperature etc. are observed. Furthermore, accurate manual measurements of shadowing objects around each point are measured. This is not possible for the road stretches. Instead an automatic system to estimate the shadows from a height and surface database has been developed. Furthermore, a data-assimilation system has been implemented to get initial condition of road surface temperature, 2 m temperature and dew point. Knowing these quantities it is possible to use the same forecast model for the road stretches as for the road stations.

From test cases and a long term test the quality of the road stretch forecasts has been tested. These tests have shown good agreement between the quality of road stretch forecast and the road station forecasts. However, the verification showed problems with the observations of road surface temperature from moving vehicles. These observations were missing quality control or calibration, and this fact substantially reduced the number of useful observations. The uncertainties of the observations may be higher than 2 degree and thereby, may be larger than the forecast error. For this reason the long term test and comparison with these observations have high uncertainties.

Resumé

Denne rapport er dokumentation og afslutningsrapport for 'Højtopløselig vejstrækningsprognoser'. Projektet har løbet fra 1. januar 2009 til 31. december 2011. Projektet er en del af de bestræbelser der bliver gjort for at forbedre sikkerheden og vedligeholdelsen af veje under vinterlige forhold. Dette skal ses både med hensyn til de økonomiske og miljømæssige fordele der kan opnås ved kun at sprede den nødvendige mængde vejsalt eller andre kemiske midler mod glat føre og samtidig gøre det på det mest optimale tidspunkt.

Resultatet af projektet er et nyt system som leverer 24 timers prognose for vejforholdene 24 gange i døgnet for 22800 vejstrækninger i Danmark. Dette skal sammenlignes med det foregående system hvor der kun var prognoser for ca. 400 vejstationer.

Det har været et mål i dette projekt at prognoserne for alle vejstrækningerne skulle være af sammenligling kvalitet i forhold til prognoser for vejstationer. Imidlertid bliver de initiale betingelser målt ved vejstationerne ligesom skyggeforholdene manuelt er opmålt omkring vejstationerne. Dette er ikke muligt for vejstrækningerne. I stedet er der udviklet en metode der automatisk kan estimere skyggeforholdene ud fra en højde- og overfladedatabase. Et data-assimilerings modul er ligeledes blevet implementeret til at estimere startbetingelserne mht. vejtemperatur, 2 m temperatur og dugpunkt. Kender man disse betingelser og forhold er det muligt at bruge den samme prognosemodel som der anvendes til vejstationer.

Ud fra individuelle test af ulvalgte situationer og længere test kørsler er kvaliteten af vejstrækningsprognoserne blevet evalueret. Disse har vist god overensstemmelse mellem kvaliteten af prognoserne for vejstrækningerne og vejstationerne. Under verifikationen har der vist sig problemer med observationerne af vejtemperatur målt fra køretøjer. Disse observationer har vist sig at mangle tilstrækkelig kvalitetskontrol eller kallibrering hvilket reducerede mængden af brugbare observationer. Observationsfejlen er formentligt større end 2 grader og dermed større end prognosefejlen. Derfor er der en vis usikkerhed omkring verifikation af de længere testperioden når de sammenlignes med disse observationer.

Project background and vision

The Fine-Scale Road Stretch Forecasting (RSF; Jan 2009 – Dec 2011) project has been done as a TF project (50% - local financed, 50% - external financed) at the Danish Meteorological Institute (DMI). It has been externally funded by the Nordic VIKING project, which has received support from the EU Commission. This project is a new project, but is also a part of the efforts to develop a more intelligent forecasting system using advanced salt spreaders. The vision is to spread only the needed dose of salt on subsection of roads and at the most optimal time of the day in order to reduce the economical and environmental costs as much as possible. The main aim of this project is to replace the first version of the road stretch forecasting system with a more detailed and general method. In fact, the goal is that the quality of forecasts at road stretches should be comparable to forecasts at road stations of the Danish road network.

History

DMI and Danish Road Directorate (VD) have for many years developed a system to monitor and predict the road condition along the Danish road network. The road weather modelling (RWM) system consists of 3 main parts:

- Observations : about 400 road stations equipped with more than 500 road sensors;
- Road Weather Information System (RWIS);
- Road Condition Model (RCM).

Measurements from the road stations are done every 5 minutes and collected at DMI. These observations are visible to users through the RWIS system (http://vejvejr.dk, http://vintertrafik.dk) with a short delay. The observations are used in the RCM to get good initial conditions of road surface temperature, 2 m air temperature and dew point temperature.

During the last decade through various projects the RWM system has been step-by-step improved. New road stations have been placed along the road network, and new type of sensors have been placed at old and newly opened stations. New features have been added to the RWIS and RCM, and these have both been upgraded almost every year to solve problems and improve the forecast quality. This has to a high degree been driven by user feed back.

The main steps in the development of the model in the recent years are summarized in Table 1.1.

Table 1.1: *Steps in development of the road weather modeling system.*

Year	**Model change**
1992	1st version. Numerical model for road surface conditions (RCM) using numerical weather prediction (NWP) and road observation
1999	RCM integrated into NWP
2003	Improvement of cloud cover
2005	Use of satellite data to improve cloud cover
2008	First version of Road Stretch Forecast (RSF)
2011	Present version

The Nordic VIKING large-scale project has contributed to the development of both the RCM and RSF through several sub-projects. The present project benefits from these efforts. In the last years there have been the following projects:

- Jan 2001 – Dec 2003 – Development of New Generation of Cloud and Precipitation Analyses for the Automatic Road Weather Model (*Sass et al., 2002*);
- Jan 2004 – Dec 2005 – Improvement of Operational Danish Road Weather Forecasting using High Resolution Satellite Data (*Sass et al., 2006*);
- Jan 2006 – Dec 2008 – Road Stretches Forecasting (*Mahura et al., 2007*).

1. Introduction

It has been a goal to improve winter maintenance by using new technology. Vehicles equipped with GPS controlled sensors are becoming standard. In the first approach only information of the road size and locations of intersection etc. are feed to the control unit of the salt spreader so the doze can be adapted to the local conditions. This has both economical and environmental benefits. However the applied dose of salt to the road is the same every where along the salting route even though it is well known that variations from day to day and place to place are large.
For these reasons the project 'Road Segment Forecast' and 'Fine-Scale Road Stretch Forecasting' were initialized to provide more detailed information of the road conditions. These projects have as a goal to make accurate forecasts of the road conditions for all main roads in Denmark. In practice the resolution of the forecast is about 1 kilometre and the number of points is 22800. This should be compared with the approximately 400 road stations where the present system provides forecasts

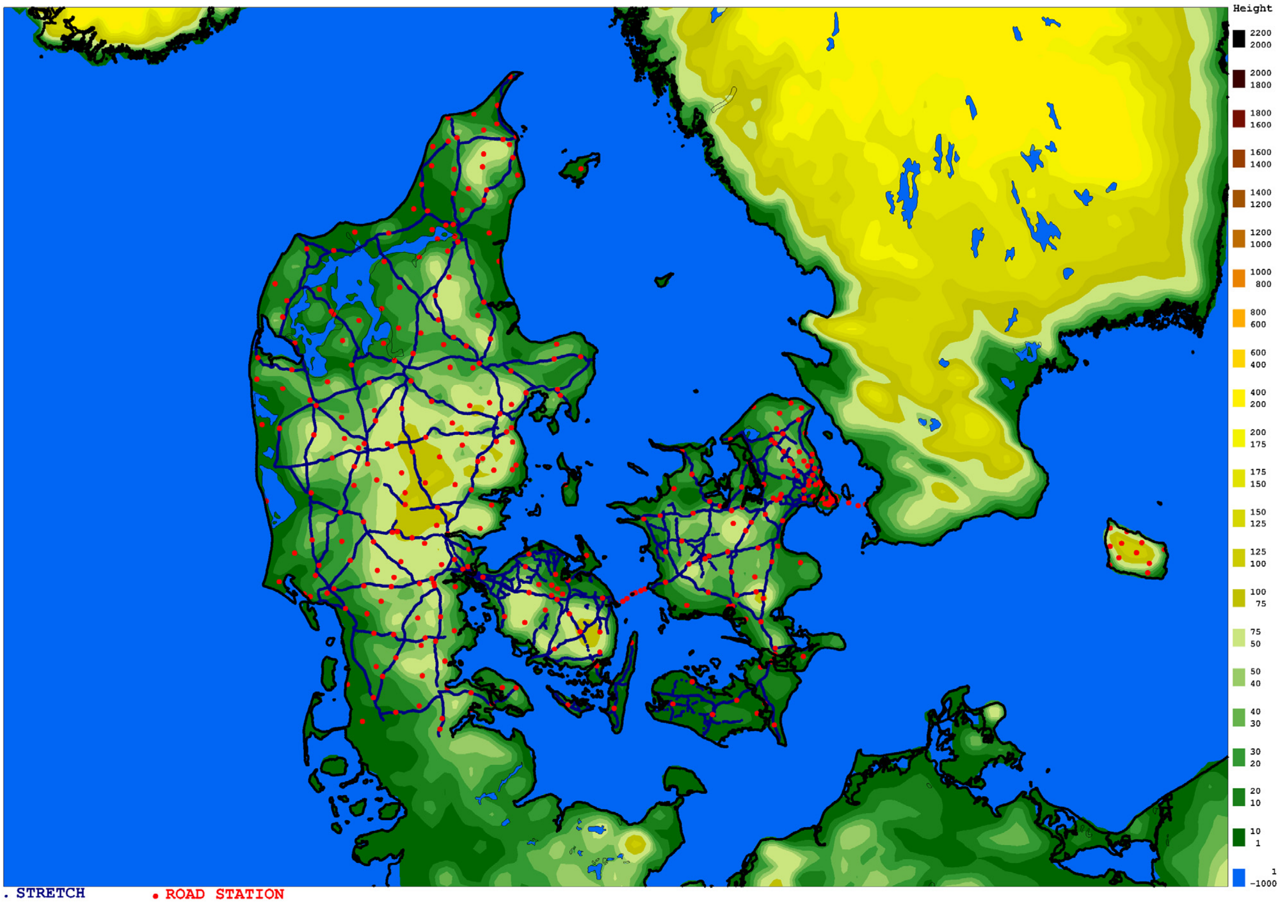


Figure 1.1: *Spatial distribution of road stations (red dots) and road stretches (blue lines consists of 22800 points) where forecasting of the slippery road conditions forecasts is done.*

Figure 1.1 shows positions of road stations and all 22800 road stretches of the Danish Road Network. As GPS controlled salt spreaders also are equipped with temperature sensors it is believed that these could be used to get information of local road conditions. These observations will be labelled as 'Thermal Mapping Data' in this document. These observations from salt spreaders have been used to verify the quality of the Road Stretch Forecasts (RSF). In the initial steps to construct a RSF system it was believed that using long term statistic of thermal mapping data these could get a 'fingerprint' of the variations in road surface temperature along a road and thereby it is only necessary to have forecast for 1 point along the road and then make forecasts for the rest of the road using the fingerprint signature. This approach unfortunately requires a very long time-series of thermal mapping data and will also depend of the weather such as cloud cover, wind speed and wind direction. The advantage of this technique is that it is computational cheap and can be calculated with very high spatial resolution. Due to lack of enough thermal mapping data and missing quality control of the data another approach was chosen. From a theoretical point of view it is also doubtful that it is possible to find a statistical method which will work for any conditions. Instead it was decided to apply exactly the same method to the RSF as with the forecasts at the road stations. The challenges are then to provide good initial conditions as well as detailed information of the shadow conditions for each road stretch.

2. Model

2.1. Numerical Weather Prediction (NWP) Model and Setup

The HIRLAM (HIgh Resolution Limited Area Model) is used as NWP model and interface to the RCM. HIRLAM consists of software to make data-assimilation for the free atmosphere as well as a data-assimilation module for the surface. Additionally, there has been added an extra module to assimilate cloud observations into the model. The data-assimilation is using observations from surface stations, weather balloons, satellites and aircrafts. The outcome of the data-assimilation is an analysis, which is used to initialize the model. Because the model is a limited area model, the boundary conditions to the model are applied from an outer model which is running on a larger size domain.

At the first time step, a digital filter is called to filter noise from unbalances in the initial conditions. Here, after the equations for the atmosphere are solved, and tendencies are calculated at each time step using a semi-Lagrangian time scheme. Besides 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.

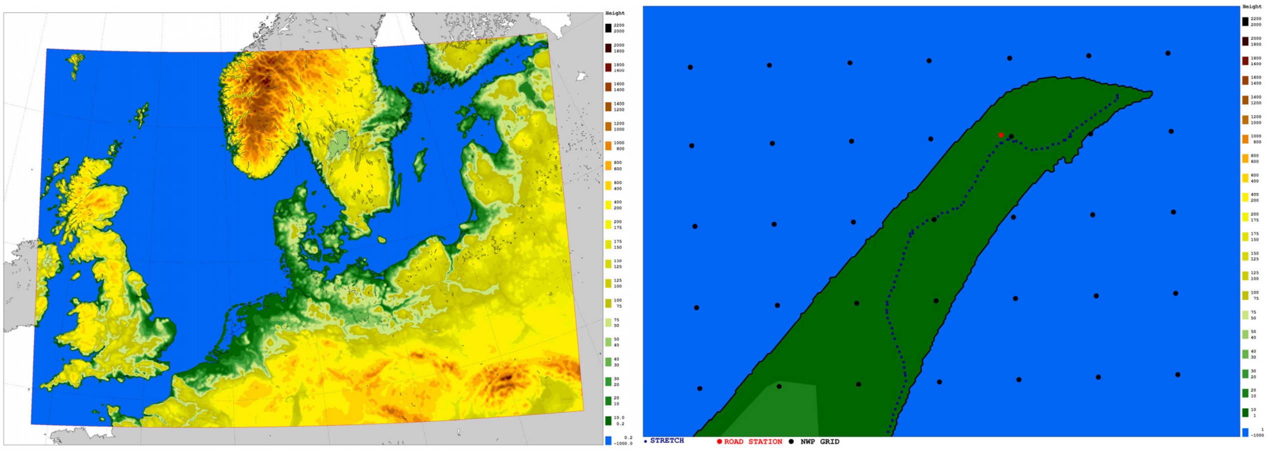


Figure 2.1: *(a) Boundaries and terrain for NWP modeling domain (with Denmark in the center of the domain); (b) An example of zooming-in the model domain(Northern tip of Denmark, Skagen) showing positions of model grids (in black), road stations (in red), and road stretches (in blue).*

Figure 2.1 shows the chosen NWP model domain. The area has been chosen in such a way that Denmark is in the centre of the domain. The size of domain has been chosen to ensure weather conditions likely to influence Danish area during the forecast period. The horizontal resolution is approximately 0.03 degree. The number of vertical levels is 40 and the time step is 120 seconds. The main features of the model domain and setup are summarized in Table 1.1.

The model is running 24 times each day making 25 hour forecasts and before each run data-assimilation is done accounting the latest observations. In order to have enough observations the model is starting with a delay of 1 hour and 20 minutes (e.g. forecast at 00 UTC is starting at 01.20 UTC). The RCM is accessed as a module from the NWP model every time step but first 1 hour in the NWP forecast (e.g. in the NWP forecast starting at 00 UTC the first call to the RCM is at 01 UTC and therefore, there is only 24 hour forecast for the RCM). This method ensures that the newest observations from the road stations can be used and also other observations arriving later than the start time of the NWP model.

Table 2.1: *Main characteristics of model domain and setup of the NWP model*

Model	Value (units)
X Gridpoints	650 points
Y Gridpoints	460 points
Dx(resolution in x direction)	0.03 degree
Dy(resolution in y direction)	0.03 degree
Number of vertical levels	40
Longitude Rotation of South Pole	3.0 degree
Latitude Rotation of South Pole	-40.0 degree
Forecast Length	25 hours
Frequency	24 each day
Time Step	120 seconds
Cut-off Time	80 minutes

2.2. Road Conditions Model (RCM)

The Road Conditions Model (RCM) is a so-called energy balance model developed at DMI (*Sass 1992, 1997*). It is a local model, which, in principle, means that the forecast for each horizontal point does not depend on other 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 from the corresponding energy balance model in the NWP model. The RCM has more layers (15) in the road and solves the heat equations for these layers, whereas the NWP model uses a simple 2 layer model. The RCM model has additionally been optimized to be used for asphalt surfaces which have characteristic much different from other types of surfaces.

The RCM is called every time step from the NWP model with the first call after 1 hour. As for the NWP model the RCM model is running 24 times each day making forecast 24 hour ahead. The RCM is running as a module inside the NWP model and receiving input every time step. Contrary to the NWP model, which is defined on a grid, the RCM makes forecasts for randomly distributed points (i.e. road stations and road stretches), and the input from the NWP is interpolated to these points.

At the first time step of the RCM, an analysis of the initial conditions is done. Observations of road surface temperature, 2 m temperature and dew point temperature from road stations or analysed equivalents from road stretches are used to run the 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 the RCM 3 hour ahead with observed road surface temperature as boundary condition. This provides an analysis of the temperature profile of all the road layers.

After the initial steps, a forecast of the road surface temperature, 2 m temperature and dew point temperature, accumulated water (rain water, dew) and ice (snow, rime, frozen water) on the road are calculated for each time step. In these calculations the following processes are considered:

- Short-wave heating of the road surface;

- Long-wave cooling/ heating of the road surface;
- Turbulence fluxes of temperature and moisture from/ to the surface;
- Evaporation, melting, freezing and sublimation of water and ice from the road surface.

In particular, both short- and long-wave radiation are affected of shadows and the so called 'sky-view' angle. Obstacles can shadow for incoming solar radiation and at the same time block for outgoing long-wave radiation. For consistency there is additionally a bias correction of the road surface temperature, 2 m air temperature and dew point temperature to ensure that the 0 hour forecast is identical to observations.

2.3. Road Stretch Forecasting (RSF)

For RSF the RCM is used as described in Chapter 2.2. The problem compared to perform the RCM at road stations is that the initial conditions and shadows at the points/ positions of road stretches are not known. If it is possible to estimate these quantities with the same accuracy as the road stations it must be assumed that the forecast quality will be comparable.

2.3.1. Shadow calculations

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'.

In the early phase of the project a method to calculate shadows from terrain and surface objects using high resolution databases was developed. The data used is from the topographic databases "Danish Terrain Model" (DTM) and the "Danish Surface Model" (DSM), which are often just referred to as the "Danish Height Model" (DHM). The method for calculation of shadowing effects was applied for almost 23 thousand points (road stretches) along the Danish road network. It is capable to replace manual measurements of shadows, which would be almost impossible task to do taking large amount of points into account. The calculations were done for each point by scanning into 32 directions (with a width equal to 11.25 degrees each) and finding within each sector the sector-mean angle of the horizon, as it would appear from the respective point when looking into the direction of that sector (Figure 2.2). In other words, the calculation results in 32 numbers for each point, where each number represents the angle to the most shadowing objects in the given direction, viewed with an eye that has a field of view of 11.25 degrees.

For selected road stations, the accuracy of the shadow calculation has been verified by comparing these with available surrounding photos as shown in Figure 2.3. It has been found that in some cases the calculated angles to the objects became unrealistically large in a certain direction. The cause for these errors could be found in the original DSM database, which represents the wood-side in form of a buffer zone. In a case of a narrow road with big trees along the edge this can result in the effect that these trees seem to cover the road completely, i.e. like a roof's coverage. In such a case the road surface would not receive diffuse radiation during the daytime, resulting in too low road surface temperatures during daytime. During night time the road would not be able to cool by long-wave radiation, and this would result in unrealistically high road surface temperatures at night time. The road would in fact be represented like a road passing through a tunnel. For such cases it is therefore, reasonable to set a limit for maximum possible angle of horizon.

The comparison of the horizon from the surrounding photos and the calculated shadowing horizon reveals some more insight into the possibilities, but also stressed limitations concerning the shadowing calculation using the DTM and DSM databases. In Figure 2.3 an example shows that the best performance of calculated angle to shadowing objects is best for large and tall obstacles. It should be noted that forests, bigger tree lines and solid objects are well captured, whereas individual trees and smaller objects may not be captured so well, and thus, their height and hence, influence may be underestimated. Nevertheless, the richness of details represented in the DSM database is still large.

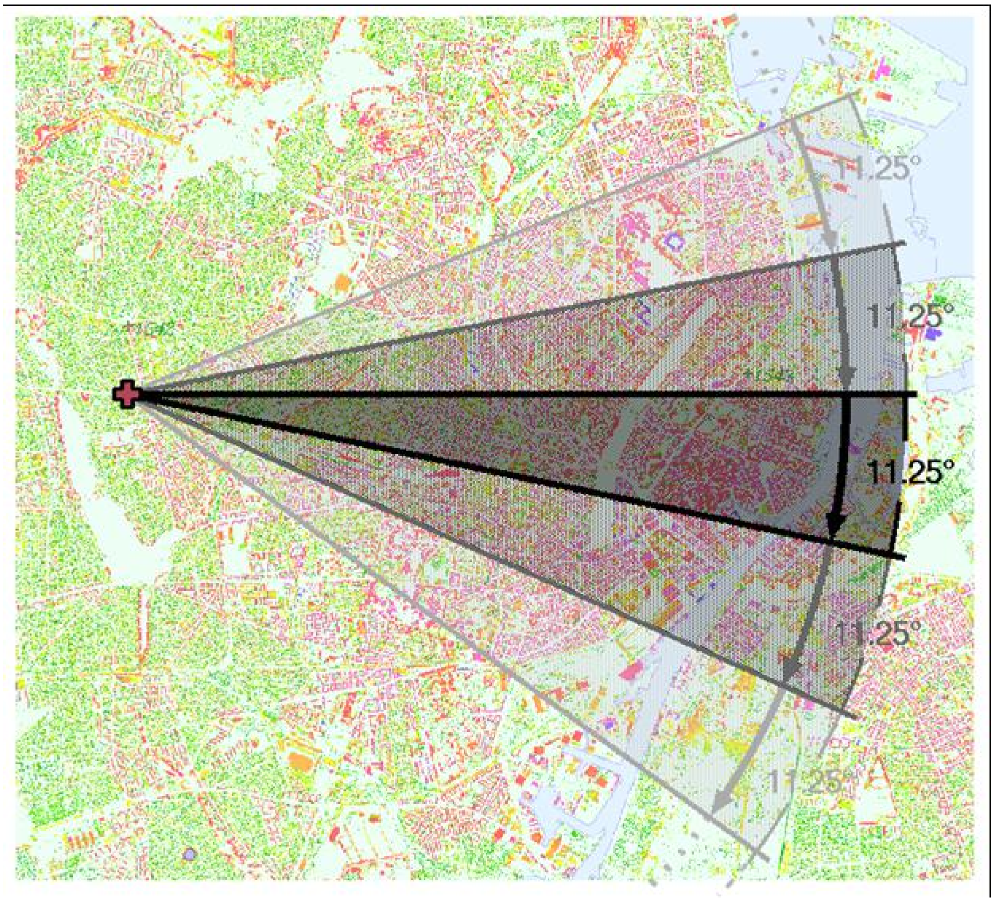


Figure 2.2*: Graphical representation of approach to calculation of shadowing effects due to terrain and obstacles situated at different distances from the point (road station or road stretch). The location is a road station in the Copenhagen metropolitan area.*

Figure 2.3: *Verification of the shadow calculations through comparison with road station surrounding photos. The red line is the calculated horizon calculated from the DHM (provided by VD)). The location is near the city center of Copenhagen.*

An example of the details of the shadow calculation is seen in Figure 2.4. The dark shaded colour in the figure illustrates how surrounding objects create shadows at a specific time of the day for each point in the area whereas the sun exposed areas are shown in bright colours. If the surrounding terrain is relatively flat, then the shadow casting obstacle is an object or a group of objects. If the surroundings are shaped by hills and valleys, then these natural obstacles may be the main reason to shadows. Shadowing objects may also be artificially created hills as often seen with large roads and multi-layer intersections with bridges over the land surface.

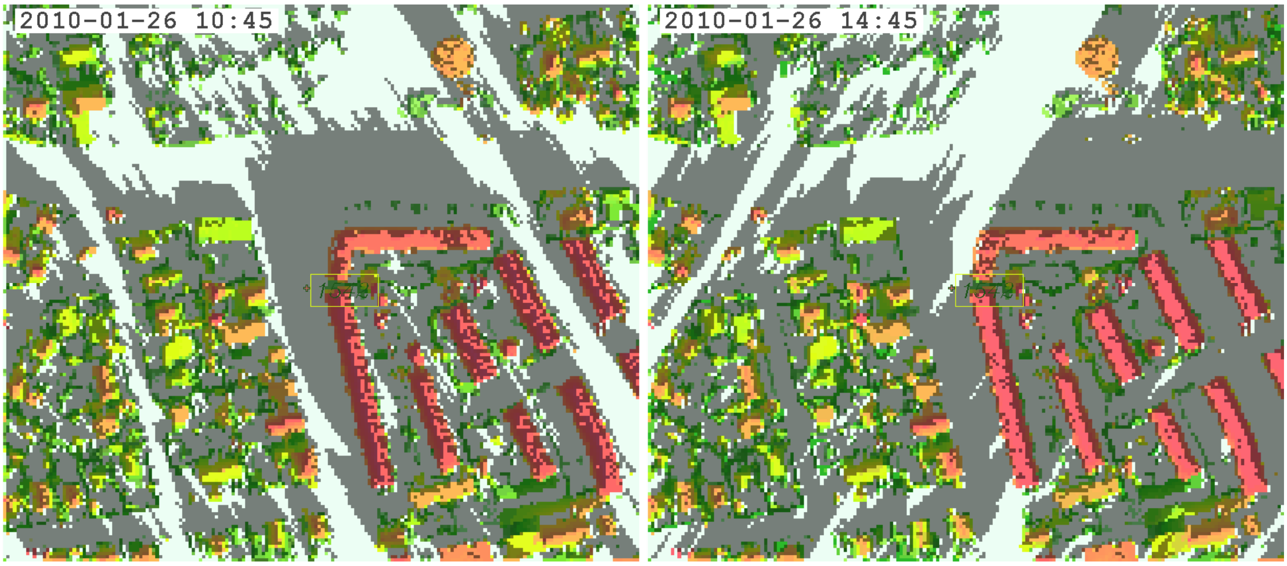


Figure 2.4: *Example of shadowing effects calculated from DSM/DTM high resolution databases at the selected road station in the Copenhagen metropolitan area late morning(left) and mid-day(right). The red colors are high objects, orange and yellow are medium high objects and green represents smaller objects*

2.3.2. Data-assimilation module

The main differences between making forecasts at road stations and an arbitrary point are the lack of information of initial conditions and shadows. As described above the latter were solved by using a high resolution topographic database, DHM. The road surface temperature, 2 m air temperature and 2 m dew point temperature are continuously changing as a function of a time. In meteorology it is a classical problem that observations are spread randomly comparing to the model grid. In the RSF system the problem is that there are approximately 400 randomly spread observational points (road stations) and almost 23000 spread "grid/road points" (road stretches).

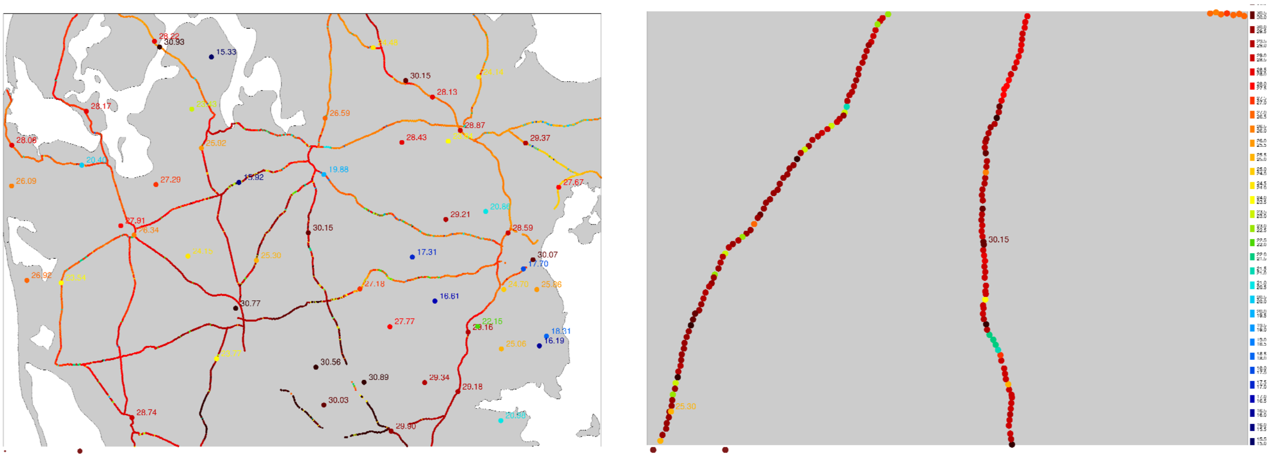
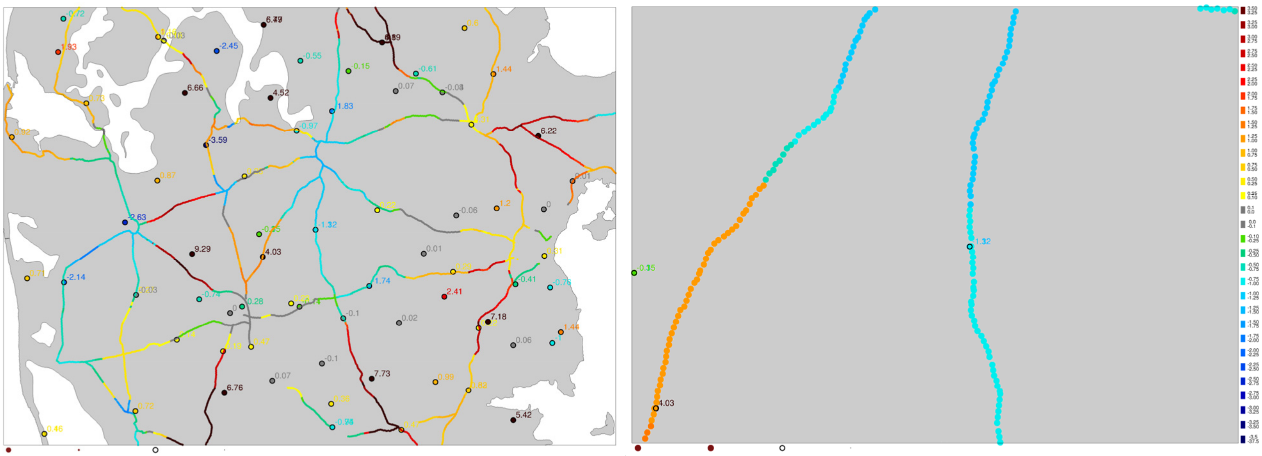
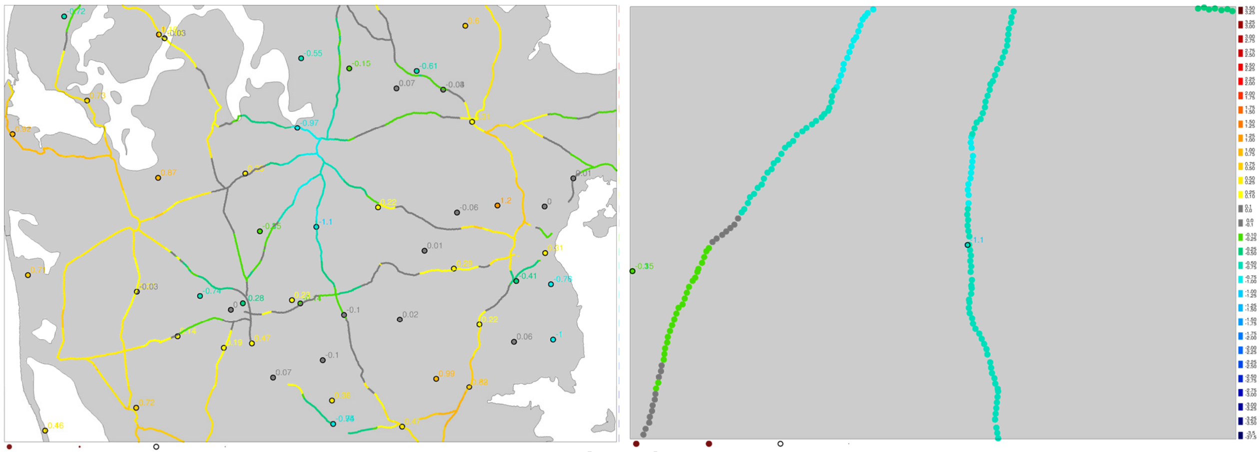


Figure 2.5: *RSF 1 hour forecast for the road surface temperature in a selected region of Denmark (central part of the Jutland Peninsula) /Figure to the right is zoomed-in for the central part of the figures to the left. Dark blue color is coldest temperature and dark red is hottest temperature/.*

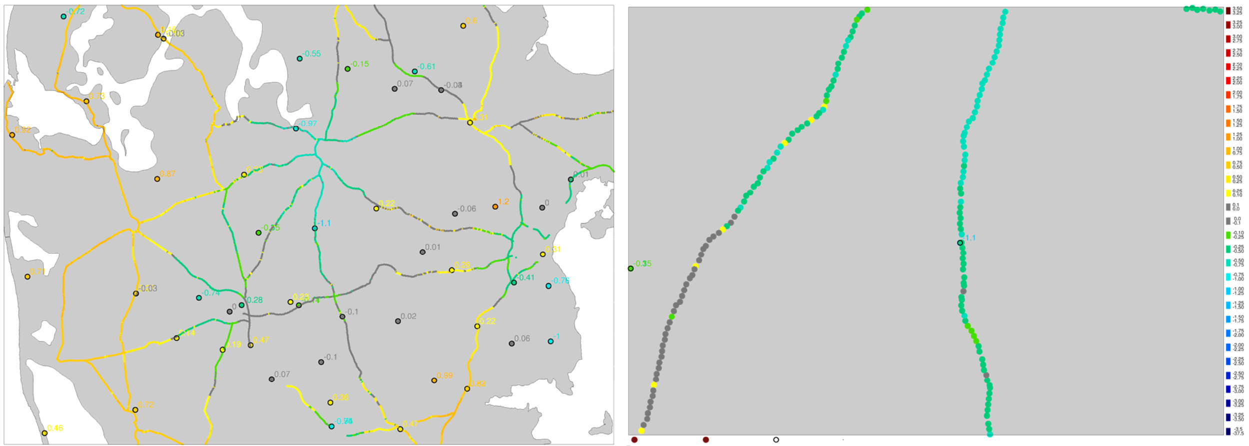
For both types of points the forecasts are calculated. In the analysis these forecasts (first guess, 1 hour forecast) are used in the 400 observations to calculate the difference between the observed value and the forecasted value of the road, air and dew point temperatures. These are the increments and input into the analysis which is calculated by using optimal interpolation method. In practice, the nearest 30 observation increments are weighted by distance and other factors, and thereafter, added to the first guess to obtain the analysis of the 3 mentioned parameters.



(a) **1st step** (b)



(c) **2nd to 4th step** (d)



(e) **5th step** (f)

Figure 2.6: *Road surface temperature increments in the observational points and the resulting increments at the road stretches. a and b is after rejection of the largest errors (step 1 in the text). b and c is after additional quality control (step 2 to step 4 in the text). e and f is after taken the ratio* T_2/T_s *into account. Figures to the right are zoomed-in for the central part of the figure to the left. Dark blue color is coldest and dark red is hottest temperature increment.*

On a sunny day the observed road surface temperature may be very different even though the distance between the two sensors is just a few meters. In this case a road station placed several kilometers away will fit better. In the correlation function a dependency of the difference (between 2 m air temperature and road surface temperature) has been added.

On a hot sunny day there will be a large difference in the difference on these 2 parameters all after if the sensor is sun-exposed or is in shadow. This also accounts for situations with variable cloud cover. The difference between the road surface temperature and 2 m air temperature will be the largest for cloud free area both in day and night times. It is also expected that the weight coefficients will depend on proximity of points to coastlines and topography, but these features have not been included in this version so far.
In the analysis of the road surface temperature some extreme observations will to some extend have a risk to be rejected in the quality control or have a lower weight compared to other observations. To illustrate the data-assimilation and quality control method an example from 1 October 2011 will be shown in details. This day was in fact the hottest October day ever recorded in Denmark. However, it is a useful case as it shows: how the data-assimilation will work in extreme situations. It was a situation with a light wind, few clouds and 2 m air temperature up to 23°C at analysis time.

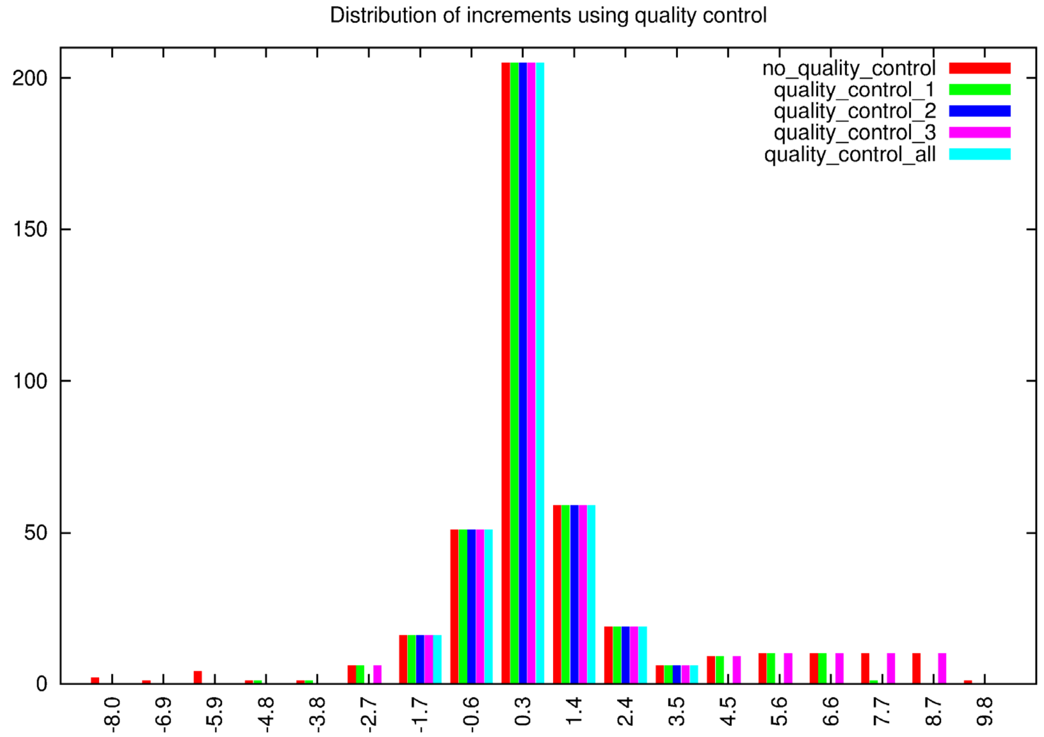


Figure 2.7*: Distribution of surface temperature observation increments. No quality control: All observations included. Quality control 1: minvalue + standard_deviation < increment < maxvalue-standard deviation. Quality control 2: Assume normal distribution and remove the outliers of the distribution. Quality control 3: Remove observations with low frequency. Quality control all: Reject all observations if just one of the methods result in rejection.*

Figure 2.5 shows a 1 hour forecast for the road stretches and road stations in a selected region of Denmark (central territories of the Jutland Peninsula). This forecast is used as input into the analysis. The high variability in road surface temperature (about 15 to 30°C) is a result of shadows from vegetation, terrain and construction objects. The first guess field shown in Figure 2.5 is compared with observations. At each observational point the difference between the first guess road surface temperature and observation is obtained. These are the increments which are used in the data-assimilation. Figure 2.6ab shows the increments in the observational points and the resulting increments at the road stretches after using optimal interpolation and quality control rejecting the largest increments.

It is clearly seen that it is simple interpolation depending only on a distance. However, quite a large fraction of the increments have large values indicating large errors in the first guess field. This is a result of errors or inaccuracies in the shadows calculated at the road station positions. It is assumed that the shadow calculation at the road stretches is correct. Therefore, it is necessary to have quality control of the observations or increments. Especially at daytime and under cloud free conditions large errors must be expected as a result of uncertainties in shadows. Three types of quality control have been used.

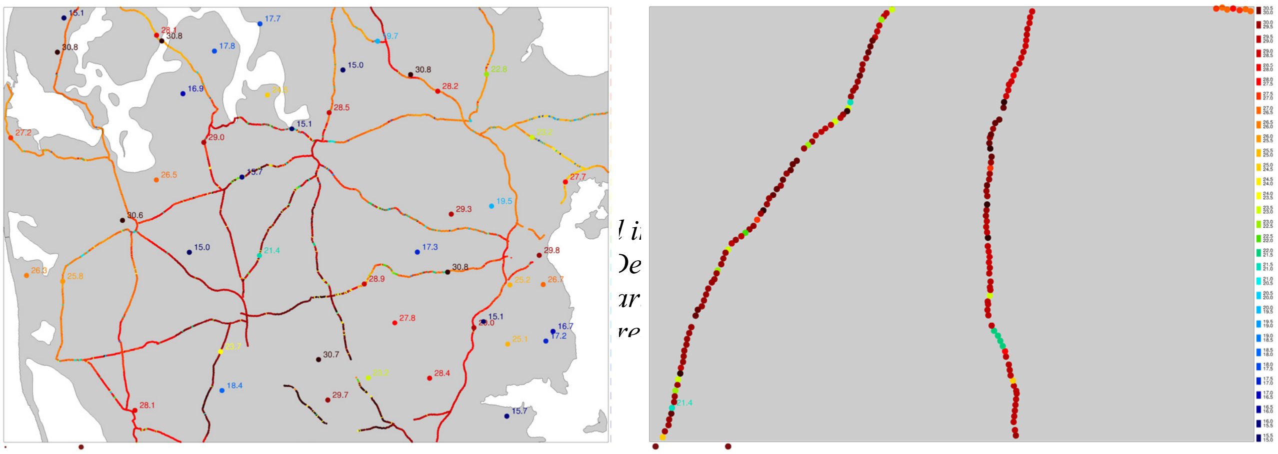


Figure 2.8: *Final analysis after adding analysis increments to the first guess. The figure to the right is zoomed-in for the central part of the figure to the left. Dark blue color is coldest and dark red is hottest temperature increment.*

At the first step, the increments with absolute error greater than a threshold value are rejected. These are the observations which are assumed to deviate so much from the first guess that these will damage the analysis. Using these observations would make the analysis biased or too depend of single observations. In this case the threshold has been set to 5 degree. At the second step, the extreme observations are also disregarded. These are defined as the following: inc > max value - standard deviation or inc < minvalue + standard deviation. Here, minimum and maximum values are defined as the extreme values of the increments after the first step; and the standard deviation is calculated from this subset of increments. At the third step, it is assumed that after removing extreme observations the error distribution for the remaining observations should follow a normal distribution. Using the mean value and variance of the observations a certain percentage of the outermost observations can be screened out. At the fourth step, the frequency of observations for each temperature interval is calculated. Observations with low frequency are removed. The result of the quality control can be seen in Figure 2.7. It should be underlined that the rejected observations may be correct and useful in the observational point itself where the correction can be applied. However, as the shadows presumably are incorrect at the observational point the forecast error will most likely increase rapidly. It should be noted that the quality control during night time and cloudy conditions in winter time can be less strict as shadow errors will have less importance.

After the quality control the increments at the observational points are interpolated to the road stretch points using optimal interpolation method. This interpolation depend mainly on a distance, but it also depends on T_2/T_s (where: T_2 is the 2 m air temperature and T_s is the road surface temperature) to reflect that the error increment will depend on the shadow conditions (step 5). If the road is sun-exposed this coefficient will be small and it will be large if the road is in shadow. The analysis, the result of the quality controls and the dependence of the T_2/T_s coefficient can be seen in Figure 2.6a-f. At the final step, the interpolated increments are added to the first guess field. The result is seen in Figure 2.8. The differences between the first guess field (Figure 2.5) and the final analysis (Figure 2.8) is the analysis increment shown in Figure 2.6ef. The analysis of the 2 m air temperature and 2 m dew point temperature is less difficult as the increments will not depend on shadows and therefore the quality control and interpolation is less complicated. In the used approach the interpolation does only depend on distance. However, it is planned also to take land sea mask and terrain height into account in next version. The quality control for these 2 parameters is set to a less strict level.

2.3.3. Implementation

The RSF system is an extension to the existing RCM. The existing system was constructed to make forecast for almost 400 points (road stations) whereas the RSF system makes forecasts for additional almost 23000 more points (road stretches). For this reason the existing system has been modified to use MPI (Message Passing Interface). This allows using more CPU's and reduces the required run time of the forecast model considerably. Both the existing point forecast at road stations and RSF are calculated at the same time-step using the same software. A pre-processing step makes the data-assimilation to the RSF before the model is operationally launched.

3. Thermal Mapping Data

The thermal mapping data has been provided by the Danish Road Directorate (DRD) through a database interface called VINTERMAN software package. The database contains detailed information about number of activities, measurements, and salting activities' parameters. The focus of this study is on observations of road surface temperature (*Ts*) and air temperature (*Ta*) (here refered to as thermal mapping data, ThMD) obtained from special instrumentally equipped vehicles. These measurements are mostly done during days when salt is spread along the roads to prevent icing conditions.

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. 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

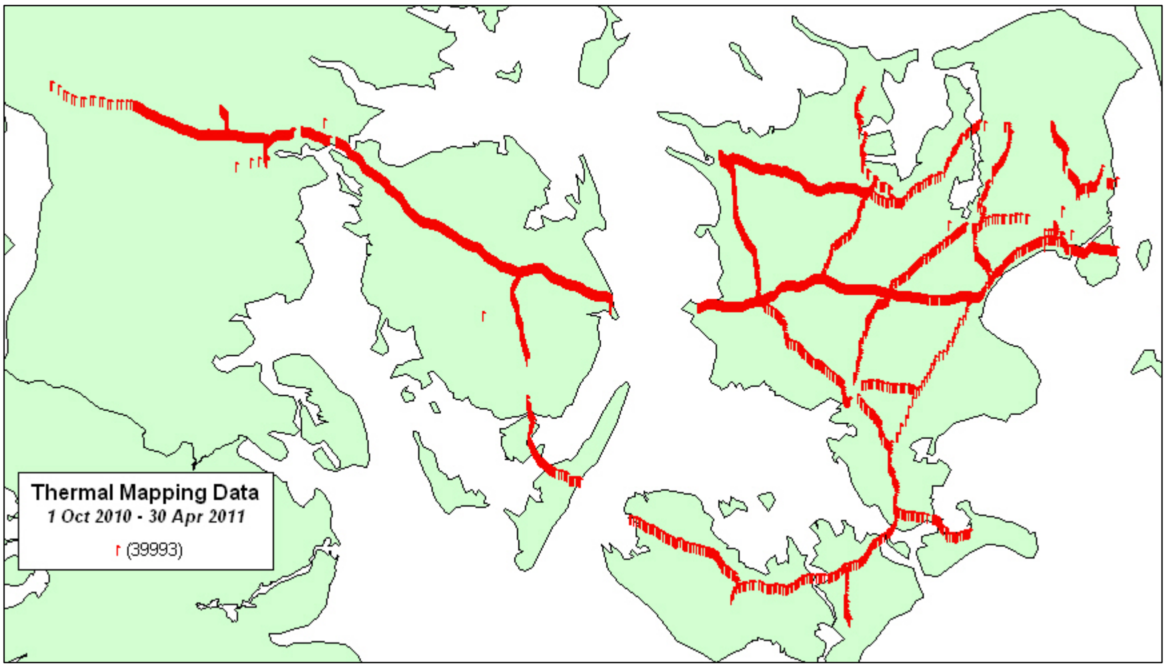
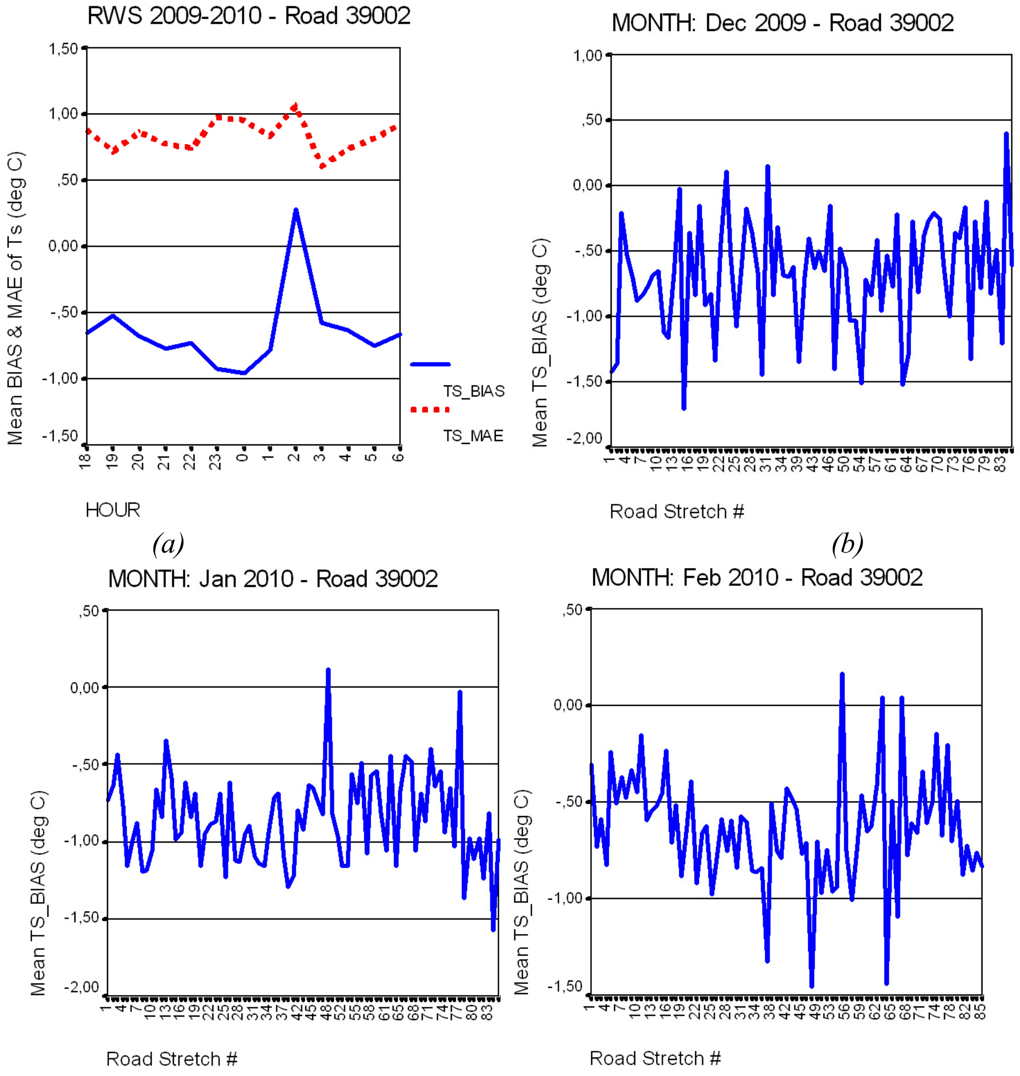


Figure 3.1: *Spatial distribution of thermal mapping data measurements (road surface temperature assigned to road stretches) for road weather season from Oct 2010 – 30 Apr 2011.*

(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 in night time (19-07 local time).

The ThMD measurements were thinned by choosing the observations closest to the road stretch requiring that the difference in forecast and observation time was less than 5 seconds. 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 250 to 1000 m); and (iii) the finest temporal resolution of the RCM forecasts is equal to 2 minute, and hence, ThMD need to be the closest to available forecasts' times. An example of the spatial distribution of ThMD measurements assigned to positions of road stretches for the road season 2010-2011 is shown in Figures 3.1.



(a) *(b)*

(c) *(d)*

Figure 3.2*: For the road stretches of road 39002: (a) Mean bias and mae of Ts (based on ThMD) during evening-nighttime hours; and (b,c,d) Mean bias of Ts (based on ThMD) at road stretches in (a) December 2009, (b) January 2010, and (c) February 2010 - for the road weather season 2009-2010.*

A summary on roads with largest time-series of ThMD measurements assigned to road stretches positions along the roads is given in Table 3.1.

From the previous project 'Road Stretch Forecasting' a simple approach to make RSF was developed(Mahura 2007). Forecasts using this approach were verified by using these observations to investigate the quality of the forecasts and observations.

Detailed analysis for one of the road (39002; located in the south-easter part of the Jutland Peninsula of Denmark) with the longest time series of measurements is given here as an example (road weather season 2009-2010). Results of comparison of the ThMD measurements vs. road conditions model forecasts are summarized. In total, 11653 averaged ThMD measurements (covering all Ts temperature ranges) of the road surface 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 ±3°C). Among these, the 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 to evening-nighttime period. A summary on a diurnal cycle for bias and mae is given in Figure 3.2a (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. Mean bias of Ts (based on ThMD) at 83 road stretches along the road 39002 for these 3 months is shown in Figure 3.2bcd.

Season	***2008-2009***			***2009-2010***			***2010-2011***		
#	**Road**	**N**	**%**	**Road**	**N**	**%**	**Road**	**N**	**%**
1	123001	2623	11,24	123001	14633	15,28	120001	6829	17,08
2	39002	2416	10,35	39002	11470	11,98	18003	6687	16,72
3	15001	2160	9,25	119003	9698	10,13	41001	5782	14,46
4	132001	1336	5,72	125001	9132	9,54	123001	4118	10,30
5	51001	1328	5,69	15001	6206	6,48	119003	3069	7,67
6	44001	1287	5,51	39001	4787	5,00	44001	2959	7,40
7	291001	1076	4,61	17001	3835	4,01	17001	2186	5,47
8	1002	1020	4,37	291002	3809	3,98	47001	1783	4,46
9	41001	930	3,98	4003	3624	3,79	15001	863	2,16
10	18003	916	3,92	291001	3230	3,37	234010	654	1,64
Σ 1-10		**15092**	**64,65**		**70424**	**73,56**		**34930**	**87,34**
Σ rest of roads		8253	35.35		25319	26.44		5063	12.66
Total		23345	100		95743	100		39993	100

Table 3.1: *Ten-top largest time-series of ThMD measurements for selected Danish roads /N – number of ThMD measurements assigned to positions of road stretches along the roads/.*

As previously mentioned it was found that the thermal mapping data or observations from moving vehicles were difficult to use in the verification due to irregularity and limited spatial and temporal distribution of measurements. All available data were carefully examined for the last road weather seasons and compared. It was found that a large number of the observations had a large negative bias in the road surface temperature. But very often the bias was as large as 10 degrees, which might be related to instrumental errors and calibration of measuring devices. Still these observations have 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. It is furthermore suggested to investigate the possibility to quality control the ThMD data or adjust the bias in the observations using observations from road stations.

4. Test and Verification

Standard verification of the RCM performance during the last 3 road weather seasons was done annually, at the end of each season. 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 ±1ºC was 80.00, 82.44, and 81.88% based on more than 519, 473, and 563 thousand corresponding forecasts (see details in *Petersen et al., 2009, 2010*). The overall seasonal averages of the bias and mean absolute error were -0.11, +0.02, and +0.09ºC and 0.76, 0.69, and 0.70ºC, 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 +0.18ºC and 0.78, 0.74, and 0.78ºC, respectively.

For verification of the new road stretches forecasting (RSF) system one month - December 2009 - was selected as a test month. This month was chosen due to the largest number of available thermal mapping data assigned to positions of road stretches. This month was dominated by much lower temperatures than normal and multiple snow fall events; and thereby many preventive salting actions from the road authorities.

However, as it was already mentioned quite a large number of the thermal mapping observations were of a poor quality. Some of the thermal mapping measurements were as much as 10 degree colder as described in section 3. These were relative easy to screen out in the verification. Worse are actually observations with a smaller bias, which can not be easily identified as erroneous. In this verification the thermal mapping data, which is a measure of road surface temperature, have been required to be reasonably fitting to traditional road station observations of surface temperature but still allowing extremes colder and warmer than observed at road stations. In practice, the maximum and minimum allowed temperature have been restricted to be in the same temperature interval as observed at the road stations +/- 2 degree.

Observations where a driving vehicle has measured the road surface temperature near a road stretch location within a range of ±5 seconds have been used. It is also required that the measurements have been done within ±2 minute interval compared to the forecast of the road surface temperature as the forecast model has a time step of 2 minutes.

The overall performance for the test month showed 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 when compared with the verification for the road stations for the last 3 seasons. 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 forecast, which is a smaller growth in error when compared to the road stations forecasts. The poor quality of the ThMD data makes it difficult to estimate the quality of the road stretch forecast as the observation error in most cases is larger than the forecast error. Analysis of individual cases has shown that the patterns in road surface temperature are similar to what is seen for road stations for forecasts longer than about 30 minutes.

5. Final Remarks

The new system to make road stretch forecasts (RSF) along the Danish roads has been developed, tested, verified and implemented. The method applied to make the forecasts for road stretches is identical to the method for making forecast for road stations. The framework for making the forecast includes a numerical weather prediction (NWP) 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 RSF system depends only on the quality of the input from the NWP model, the quality of the road conditions model (RCM) 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 of the system is improved, this will improve the overall forecast quality. Therefore, it is a good basic framework for further improvement.

There have been 4 main issues in the RSF project:

- Calculation of shadows or 'skyview' for all 22800 road stretches;
- Development of a method to get initial conditions for RSF;

- Test and verification of RSF using thermal mapping data;
- Elaboration and implementation of a generic framework for RSF and road stations forecasts.

A keystone in this project was the new high resolution dataset (Danish Height Model, DHM). The shadows were calculated from DHM taking into account both the terrain height and the height of obstacles surrounding the road. The method is generic and can be applied to any point in Denmark or any other places/ countries (which have similar height database). 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 of various constructions. At the moment it is unclear how often the DHM database will be updated. Up to now the detailed height database has only been used for shadow calculations. But the insight and know how obtained in this projects on how to use these data opens up for other use and methods to further improvement of RSF.

Optimal interpolation was used to get initial conditions for road stretches. This method is well documented and widely used in meteorology. The dense network of observations and relative small variations in topography will in most cases ensure a good analysis, in particular, for 2 m air and dew point temperatures. The largest challenges in the analysis are to screen out erroneous observations, shadow effects which especially in daytime can give large local differences in road surface temperature. There has been accounted for the shadow effect in the first version by using difference in 2 m air temperature and road surface temperature in the correlation function and data are checked through a strict quality control. However, it is likely that this function can be further improved taking into account other effects. The analysis ensures that forecast at road stretches will not drift away from observations and it does also take observational errors into account. For these reasons the RSF will be less sensitive to observational errors.

The new system has been tested for a selected month and for individual cases. The RSF performance was compared with thermal mapping data (ThMD) and by inspection of individual cases. It turned out that such data had a poor quality compared to observations at road stations. Even though the month (December 2009) was selected based on largest number of observations, quite many ThMD have been rejected in the verification procedure. Inspection of these data on individual days also clearly showed that even after removing the most obvious errors in road surface temperature the average observation error is still in the order of the forecast error. In terms of mean absolute error, the resulting forecast error for road stretches is larger than forecast error 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 the devices for measurements of ThMD and to perform scrutinized quality control of such data.

The design of the RSF system has been done to ease future development. Positions of new road stretches can be added or removed to/from the list with a small effort. To some extend the number of road stretches should be less 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 NWP grid points is 299000, whereas the number of road stretches is 22800. Thereby, there is a possibility to add more road stretches into a forecasting chain. There are no also limits on which domain the NWP and RSF model can be run.

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