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High Resolution Physiographic Data for Fine-Scale Road Weather Forecasting

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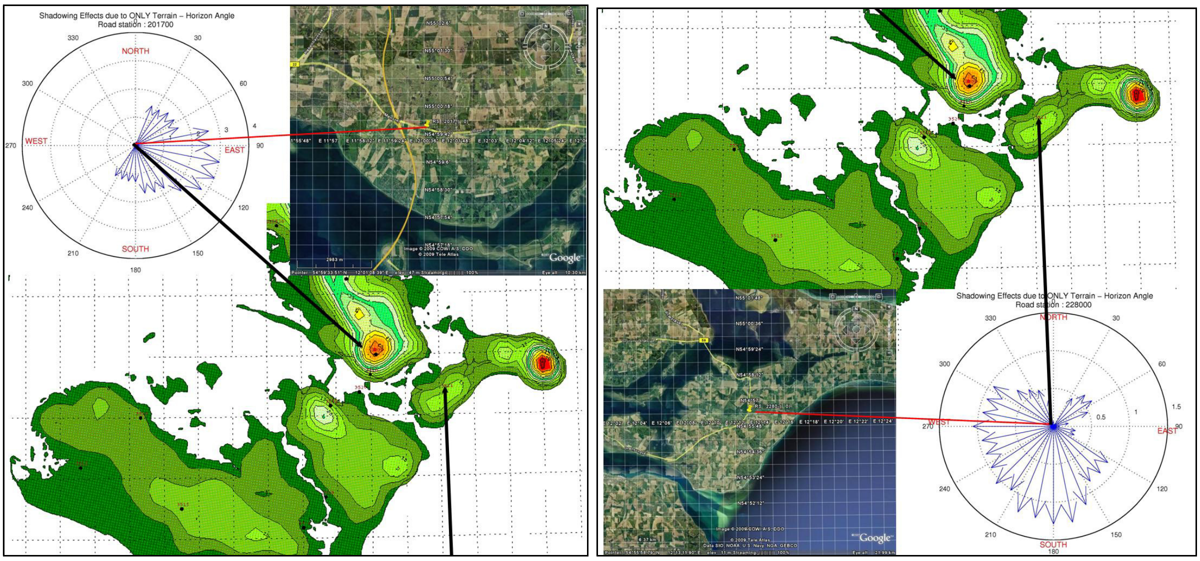

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Abstract

Forecasting of slippery road conditions is the important product delivered by the Danish Meteorological Institute in collaboration with the Danish Road Directorate. In order to avoid accident at slippery roads preventing salting must be taken. A balance on how much and where exactly this measure should be taken have become of critical importance for environmental and economical reasons. For these reasons, in addition to forecasts at road stations, recently practical use of the forecasts at road stretches along the driving lanes has been growing rapidly. The requirements to produce very accurate forecasts at specific points (depending on a distance between stretches, for example 0.25-1 km) are higher compared to standard numerical weather forecasts at fixed grid-cells (depending on a resolution of the model, for example 3-5 km). To satisfy requirements and capture local variations at road stretches it is necessary not only to have a high resolution model output (predicted road surface and air temperatures, humidity, speed and direction of wind, and water/ice accumulated on the road surface), but also detailed information about surroundings of the road stretch and road station.

In this study, the evaluation of the shadowing effects and skyview, proximity to the seashore and surrounding land-use are illustrated on examples. It is clear that due to a large number of road stretches (in particular, almost 23 thousand located at distances of about 250 meters from each other and covering 153 Danish roads), an extensive automatic post-processing of several databases had been applied in order to derive required local parameters. For that the high resolution databases such as Danish Height Model (DHM), Global Self-consistent Hierarchical High-resolution Shorelines (GSHHS), COoRdinate INformation on the Environment (CORINE) were selected and analysed. The Google-Earth has been actively used for visualization and analysis of derived parameters as well as clarification of geographical positions (road stations and road stretches) according to geographical positioning system.

Resumé

Forudsigelse af glatte veje er et vigtigt produkt, som udvikles af Danmarks Meteorologiske Institut i samarbejde med det danske Vejdirektorat. For at undgå ulykker på glatte veje er det praksis at foretage en præventiv saltning. Det er vigtigt at undgå unødig saltning , både af miljømæssige og af økonomiske grunde. Derfor er det i de seneste år blevet relevant at udvikle detaljerede og præcise prognoser langs vejstrækninger. Kravene til at producere meget præcise prognoser på specifikke punkter (afhængigt af afstand mellem strækninger, for eksempel 0,25-1 km) er højere i forhold til standard numeriske vejrudsigter på faste grid-celler . For at opfylde krav og forudsige lokale variationer på vejstrækninger, er det nødvendigt både at producere højere opløsning af model output (parametre for vejoverfladen, lufttemperaturer, luftfugtighed, hastighed og retning af vind), og at give detaljerede oplysninger om omgivelser (strækning / station)

I denne undersøgelse belyses forskellige forhold omkring beskrivelsen af topografi i forbindelse med glatføresystemet, bl.a. evaluering af de beskrevne skyggeeffekter , \`skyview´ og nærhed til kysten. Disse forhold illustreres med eksempler. Som følge af et stort antal vejstrækninger (næsten 23 tusinde placeret i en afstand af omkring 250 meter fra hinanden for 153 danske veje), er en omfattende automatisk efterbehandling af flere databaser blevet anvendt med henblik på at udlede de nødvendige lokale parametre. Følgende databaser er blevet anvendt og analyseret: \`Danish Height Model´ (DHM), Global Self-consistent Hierarchical High-resolution Shorelines (GSHHS), COoRdinate INformation on the Environment (CORINE). Google-Earth har været aktivt brugt til visualisering og analyse af afledte parametre samt afklaring af geografiske positioner (vej-stationer og vejstrækninger) i henhold til det geografiske positioneringssystem.

1. Introduction

For almost two decades the DMI has in collaboration with the Danish Road Directorate (DRD) used the Road Weather Modelling System (RWMS) to provide operational forecasts of the slippery road conditions at multiple points along the roads of the Danish road network. It is an important operational product produced by DMI. RWMS includes the dense network of road observations (almost 400 road stations equipped with more than 500 sensors measuring road surface, air and dew point temperatures), the Road Condition Model (RCM; *Sass, 1992; 1997*) and the numerical weather prediction (NWP) model - HIgh Resolution Limited Area Model, HIRLAM; *Yang et al., 2005*). RWMS is run to produce 24 hour forecasts every hour. The performance of the system is evaluated by estimating forecasts for key parameters such as mean absolute error and bias for the road surface temperature (*Ts*), 2 m air temperature (*Ta*) and 2 m dew point temperature (*Td*), as well as scores reflecting a frequency of good/poor quality forecasts. The verification of the road slippery conditions for the road weather seasons (duration from October through April) is carried out annually.

RWMS forecasts of other important meteorological parameters such as cloud cover and precipitations as well as radar and satellite images are also distributed to the users through the web-based interface vejvejr.dk and through DMI and DRD web-pages. Measurements from moving salt spreaders (so-called thermal mapping data) and from road stations have been used for verification and examination of the forecasts quality. During the road winter seasons of 2006-2008 the forecasts were performed for all Danish road stations and 16637 road stretches (located at distances of 1 km from each other) along 296 roads; and starting from 2009 – for 22840 stretches (located at variable distances of about 250 meters from each other) along 153 roads of the Danish road network. The forecasting at such fine spatial scale has underlined critical importance of detailed characteristics at positions of road stretches. During the road winter season, accurate information on spatial variation of road surface temperature is valuable and important for the road authorities who are making decisions on where and when to spread salt over the road surfaces. In other words: simply, if we want to make local forecasts in a specific point, we need to have all possible local information.

The overall aim of the “Fine-Scale Road Stretch Forecasting” Project (2009-2011) is to research, develop, and improve the quality of the road condition forecasts by refining, setting up, and running the fine-scale resolution NWP model with integration detailed information from high resolution databases. In particular, one of the key specific objectives is analysis and integration of detailed data and derived parameters at positions of road stations/ stretches into the RCM model based on available detailed Danish datasets on terrain, geographic positioning system (GPS) coordinates, land-use, and road properties.

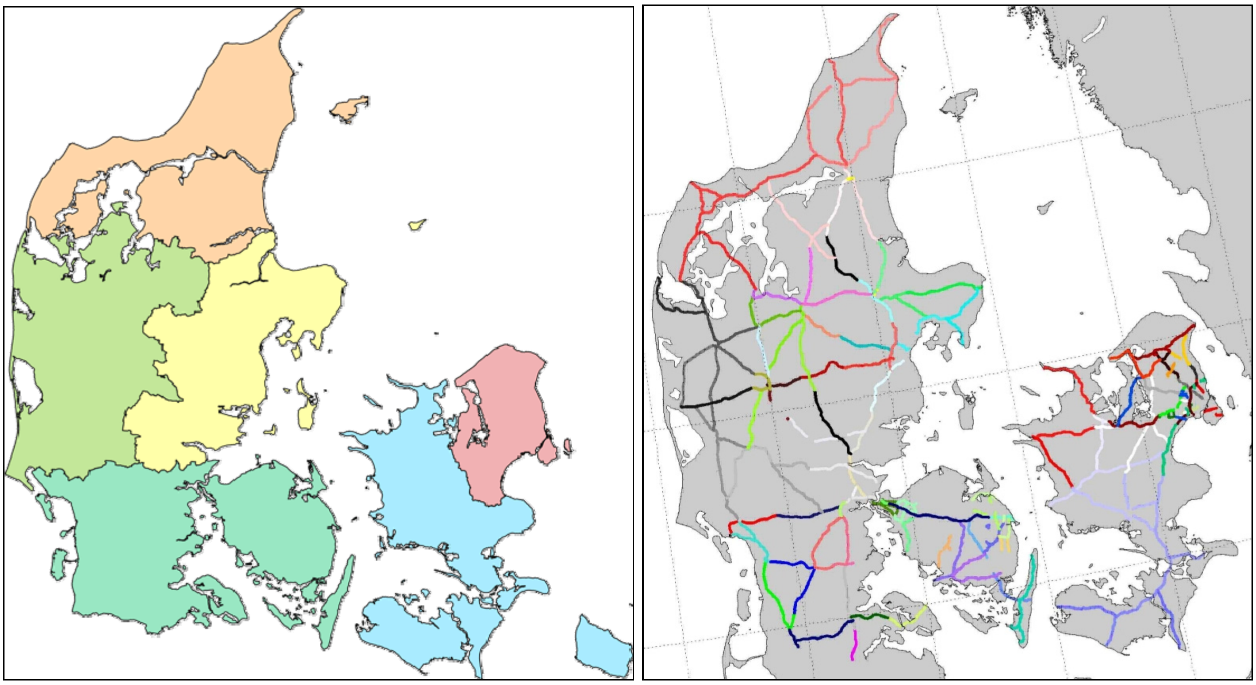
Although the area of Denmark is not so large compared with other countries, and the country has a relatively flat terrain, the distribution of occurrences (at road stations) of icing conditions within the Danish road network has shown a large spatial and temporal variability (*Mahura et al., 2008*). Developments in previous projects for the RWMS related to assimilation and routine usage of satellite data for cloud cover (*Sass et al., 2005)* and thermal mapping data for verification of the road stretches forecasts (*Mahura et al., 2007*) formed a base for further improvement of road weather conditions forecasting. The focus is shifted towards fine-scales, and in particular, to consider forecasting of road conditions at stretches from 1 km down to 250 meters.

In order to perform more detailed and improved forecasts of road conditions at such fine scales high resolution databases on Danish detailed land-use and fine resolution terrain datasets, geographical position system data and dataset on the roads' properties are important and crucial. Sets of detailed characteristics at every point (road station/ stretch) with a high accuracy need to be extracted and integrated into the RWMS system. These will include the estimation of shadowing effects, roughness, wind direction influences, characteristics of the road pavements with respect to thermal conductivity, emissivity, albedo, precise geographical positioning and location of the road stations/stretches, as well as their spatial placement with respect to water objects, slopes and tops of hills, valleys and their properties (width, depth, length, direction), etc. All these are important because such calculated parameters can be directly used to provide detailed local information to the road condition model (RCM) which is also receiving input from the fine-scale numerical weather prediction (NWP) model forecasting the future state of the atmosphere.

2. Methodology

2.1 Road network (stations and stretches)

The Danish road network is represented by a large number of the roads/driving lanes in various communes. There are more than 500 sensors (measuring continuously the road surface, air and dew point temperatures) at about 400 road stations. At some stations there are two or more sensors placed along the driving lanes or on the opposite side of the road not far from each other. Note, that positions of the road stations are not equally spatially distributed within the network, but the stations are placed along most of the roads to cover as much as possible the entire territory of Denmark. Roughly, it can be estimated that for a length of approximately 10 km there is one road station placed in the network. Beginning 2009, the network consists of several regions shown in Figure 1a (Nordjylland, Midt- og Vestjylland, Østjylland, Syddanmark, Sjælland, and Hovedstaden). Re-numbering and re-assignment of the road stations to these six regions was done.



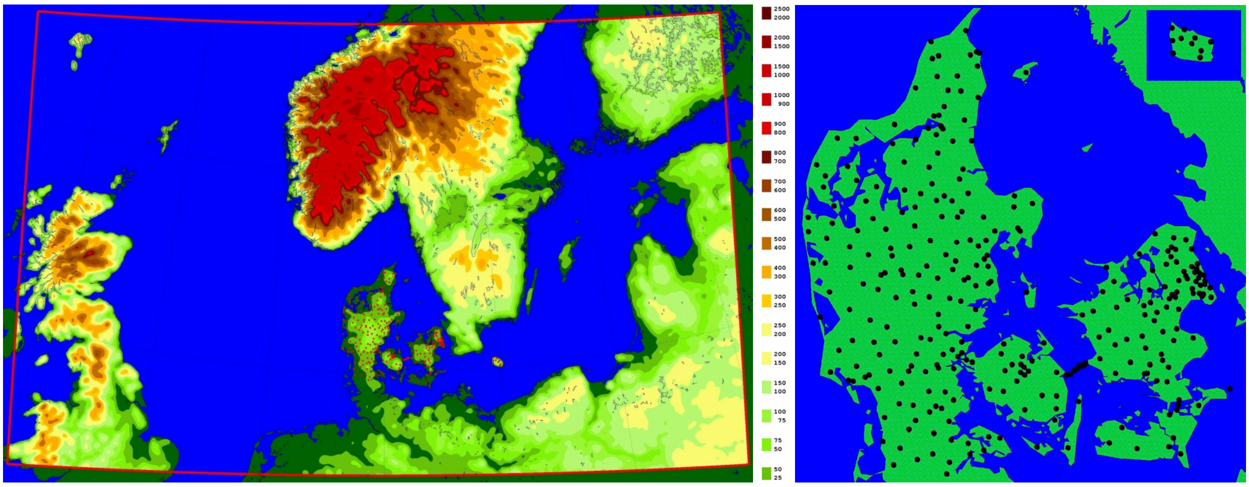
(a) *(b)*

Figure 1: *Division of the Danish road network into regions starting 2009 (Fig. 1a - source: see section Vejprojekter at http://www.vejdirektoratet.dk); (b) Danish main road network covering 153 roads with almost 23000 road stretches (2009-present).*

Before 2009, the forecasting of the road weather conditions at all road stations and at almost 16700 road stretches (located at distances of approximately 1 km from each other and covering 296 roads of the road network). Since 2009, the forecasting at road stretches includes the forecasts at almost 23000 stretches (located at shorter variable distances of 250 m from each other and covering 153 roads of the road network; Figure 1b). The geographical positions of these road stretches were identified based on detailed high-resolution GPS data (provided by the DRD) for the driving lanes of the road network. During road winter seasons, thermal mapping data (ThMD) measurements of the road surface temperature, air temperature and humidity are performed employing special devices mounted on salt-spread vehicles. Such measurements are done episodically and along selected roads.

2.2 Road weather modelling

During the last two decades the Danish Meteorological Institute (DMI) in cooperation with the Danish Road Directorate (DRD) has developed and used a Road Weather Model System (RWMS). This system provides monitoring and forecasting of road conditions at selected locations in Denmark. There are almost 400 stations and each station is equipped with different types of sensors with measurements of road surface temperature, air and dew point temperatures at 2 meters as the most important. These stations are not equally distributed within the road network. Forecasts of road conditions at these points are given every 30/60 minutes based on output from the DMI-HIRLAM RWM model (*Sass, 1992; 1997; Sass et al., 2002*).



(a) (b)

***Figure 2**: (a) Road weather modeling (RWM) system domain (-R05) having 5 km resolution (running from Fall 2007); and (b) road stations of the Danish network (black dots).*

The RWM system includes a web based user interface. The main idea is to use road observations from the Danish road stations as input into a numerical model which is designed to predict the road conditions. Essentially, this means the forecasting of the road surface temperature and the accumulated water/ice on the road surface. Data assimilation of road observations gives optimal initialization of the road surface temperature and temperature profile in the soil layer. The meteorological conditions are prescribed based on a 3D NWP model which is a version of the HIgh Resolution Limited Area Model (HIRLAM). The road conditions model is a 1D model, and it uses meteorological output from the NWP model. The NWP model domain (called DMI-HIRLAM-R model at 5 km resolution) and network of road stations are shown in Figure 2.

2.3 High resolution databases

Detailed spatial forecasts require additional information not only at the road stations but also at the positions of the road stretches. Until recent years the description of the physiographic conditions in the used RCM system was at a relatively low resolution. Since the high resolution models running at faster supercomputers as well as detailed physiographic datasets now are available, it provides possibility to improve the modelling and parameterization of significant physical processes influencing the formation of the slippery road conditions and their operational forecasting.
For a limited number of positions (such as road stations) the detailed information, in principle, can be obtained manually (although it is time consuming). When the number of points, where the forecast should be done, is rapidly increasing such as for road stretches, the detailed databases and automatic processing of such data are an essential requirement.

The following databases have been evaluated in this study:

- Danish Height Model (Danmarks HøjdeModel; DHM) database from the Danish *Kort & MatrikelStyrelsen (KMS)*. This database allows access to details of the topography of Denmark with a precision and high resolution much better than in previous datasets. It has detailed information on terrain / height and surroundings represented by different obstacles such as forest, trees, construction, fields, etc. It can be used to evaluate absolute height and horizon angle at local and remote scales for detalisation of shadowing effects and sky view factor.

- Global Self-consistent Hierarchical High-resolution Shorelines (GSHHS) database. It can be used to evaluate distance and direction to seashore in order to evaluate influence on atmospheric transport of cool/warm, most/dry air masses toward the positions of road stations/ stretches.

- COoRdinate INformation on the Environment (CORINE) database. Database has detailed land-cover and land-use characteristics. It can be used to classify road stations/ stretches and their surroundings at local and remote scales.

- DRD database on driving lanes characteristics. It can provide detailed information on albedo, density, heat conductivity, heat capacity, etc. and these can be used as direct input into RCM model.

2.4 Influence of local conditions on forecast

The road conditions depend strongly on the cloud cover, shadows, precipitation, wind speed, air temperature, and humidity. However, some of these quantities have a large local variability and the road conditions can be affected by changes in these parameters on very short temporal and spatial scales. Since existing model systems do not provide sufficient accuracy for these parameters, it is expected that detailed information on surroundings of the road stations/ stretches can give an insight on how to improve existing forecasts of the slippery road conditions at points along the roads.

In forecasting, the local conditions near the road station/ stretch are of great importance. In particular, a distance from the station/ stretch toward the seashore would be of importance for improvement of the road surface temperature forecast. For that reason the road stations (and stretches) could be classified into several groups depending on a number of various factors.
First, a location along a road with respect to the seashore is of importance.

- *coastal* – located near the seashore within a distance of less than 1.5 km – coastal station;
- *inland* – located away from the seashore at a distance of more than 5 km;

- *pre-coastal* – located within a distance of 1.5-5 km away from the seashore;

There are also stations/ stretches located on *bridges* connecting different territories of Denmark. Second, the spatial location in complex terrain and height at which the station is placed should be also considered, i.e.:

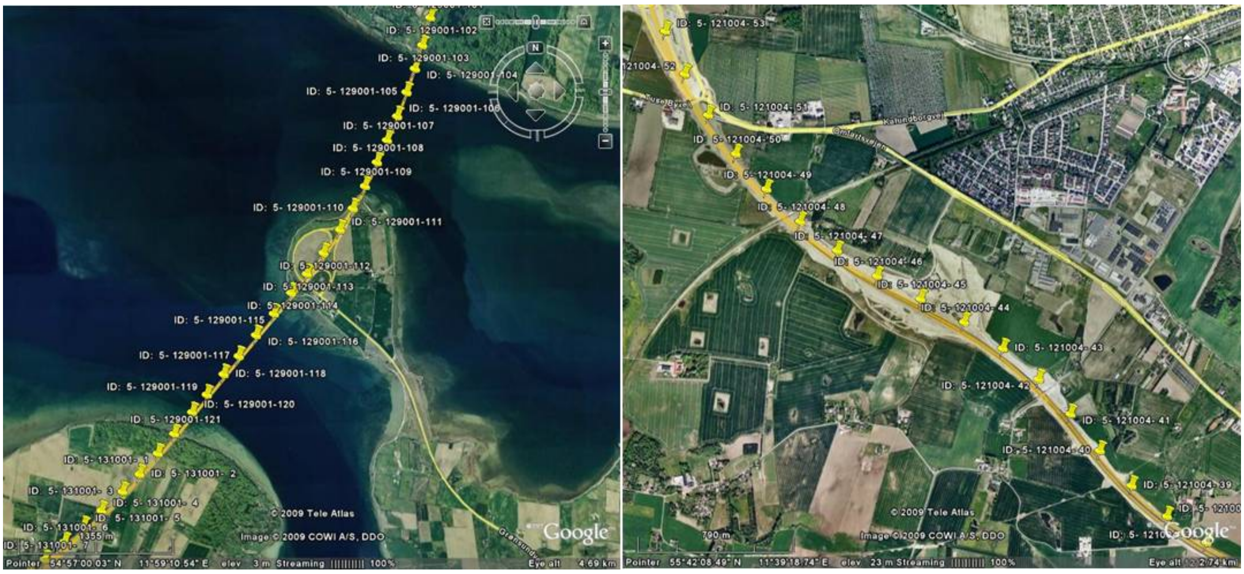
- on the *tops of hills* (or *bottoms of valleys*);
- on the *slopes of hills* (orientation of the slopes toward the N-E-S-W directions will show different exposure to sun radiation);
- in the *valleys* of different configuration, orientation, and sizes;

Third, the location of the station/ stretch depending on the land-use and land-cover surroundings, i.e.:

- where it is located – in *urban, suburban, or rural* environment;
- which surrounding type is dominated – *forest, agricultural fields, water objects, construction*, etc.

Fourth, the type of the road surface reflecting the material of the road, emissivity, and albedo characteristics also represents an important interest as well as the sky view factor for shadowing effects due to obstacles such as trees, housing, etc. An important factor can be also related to the temporal changing of traffic activities since it can also modify *Ts* due to heat from the car engines and friction heat dissipation from tiers and breaking.

The suggested classifications of road stations/ stretches can also give an insight on how the road stretches should be incorporated into the RWMS. Such classification can be also done in order to create a detailed database with a set of characteristics of the Danish road stations (and further road stretches), for example, employing GIS technology. Moreover, a substantially refined classification and following improved forecasts have an advantage. Improved road stretch forecasts can influence the decision making process and allow a driver, having operational on-line access to these forecasts, to optimize where and when exactly the salting activities should be performed and hence, reduce the amount of salt spread during the road weather seasons. Consequently, it will positively influence the environmental conditions of the surrounding area.



(a) (b)

***Figure 3**: Road stretches with specified GPS positioning with corresponding characteristics and land-use / land-cover identification (extracted from Google-Earth).*

Examples of the road stretches positions (defined using GPS positioning devices) along selected Danish roads are shown in Figure 3. As seen, each individual stretch has different characteristics of terrain and surrounding land-use and land-cover. In particular, as seen in Figure 3a, many stretches are placed along the road on the bridge, and hence, influence of the surrounding waters will have substantial impact on the road surface temperature. As seen in Figure 3b, the road is passing through relatively flat terrain and surrounded by agricultural fields.

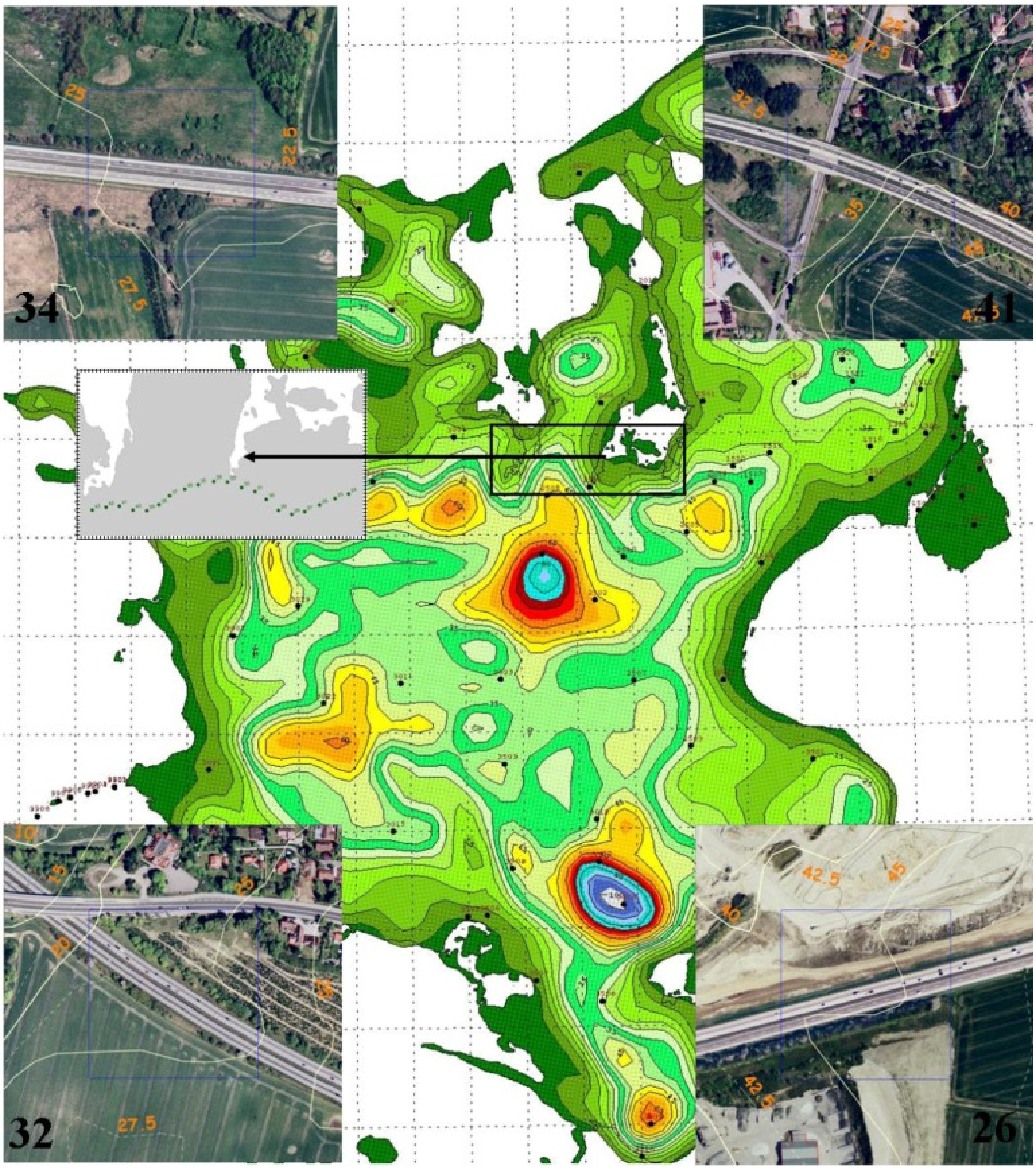
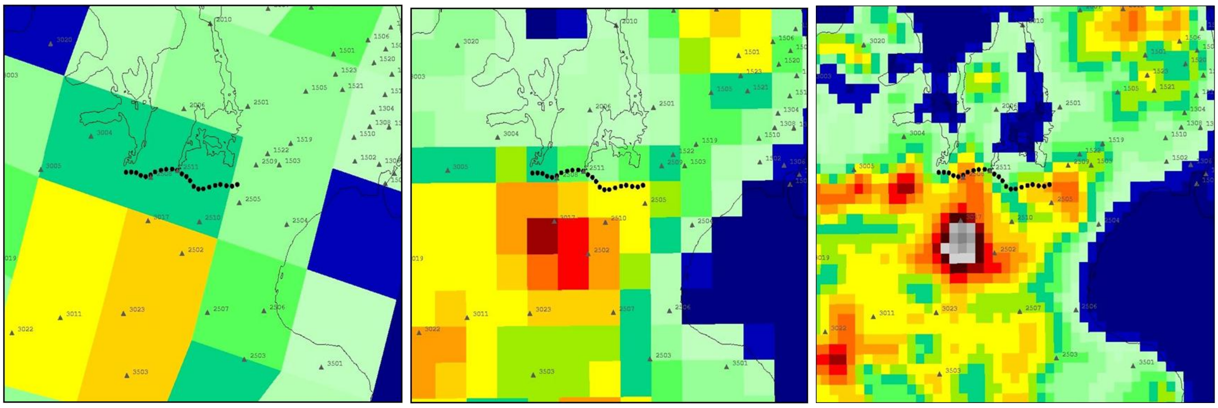


***Figure 4**: Detailed land-use and terrain data for the part of the road A-25 in the Roskilde Commune on the Island of Zealand /extracted from DRD database/.*

As an example, the local conditions at stretches of the road (A-25; national level road) located in the Roskilde Commune are presented for a part of the road in Figure 4. The main characteristics of this road are the following: route length is about 52 km, driving length is about 70 km, lane length – 96.64 km, and gritting area is about 387 thousand m^2; where it is an area where spreading of salt on the roads to prevent ice forming is done. The part of this road (extended in west-east direction) presented here is composed of multiple stretches placed at distances of approximately 1 km from each other. The road is passing through different types of surrounding land-use and terrain, at different distances to the seashore (in northern direction).



(a) (b) (c)

Figure 5*: Detalisation of the terrain height in the modelling domain with different horizontal resolution of NWP HIRLAM model (15 km, 5 km, and 1.5 km).*

In addition, the other important factor is the resolution of the operational NWP model, because smaller-scale features are visible at finer horizontal resolutions (Figure 5). As seen in Figure 5a, for a crude resolution it looks like practically the entire part of the A-25 road is situated at the same level (height) above the sea. By downscaling to fine scales (such as 5 and 3 km; Figure 5bc), a complexity of surrounding road terrain became more evident. In particular, there is larger variability in the height of the road above the sea level compared with Figure 5a. This road is passing through two small valleys and hills. Hence, some stretches along the road will be located at different heights, and therefore, exposure to sun and wind will be different. These will influence the local temperature, wind and humidity regimes.

3. Results and Discussions

3.1 Shadowing and skyview

Due to a new Danish database from the Kort og Matrikel Styrelsen (so-called Danish Height Model – Danmarks HøjdeModel, DHM) it is possible to access details of the terrain topography and surrounding obstacles with a much higher precision and resolution (i.e. at horizontal resolution – of 1.6 x 1.6 m, and vertical precision – 20 cm) compared with previously used datasets (see example of DHM output in Figure 6). DHM is composed of three subsets: DHM-Terrain, DHM-Surface, and DHM-Contour Lines. DHM-Terrain is a model of the terrain topography or the height above the sea level. It describes only terrain and excludes all other objects above the ground surface, e.g. trees, houses, etc. DHM-Surface is a digital model of the physical surface. This subset describes the height of buildings and vegetation above the sea level. DHM-Contour Lines is represented by isolines of the terrain topography. All data is stored in UTM Zone 32. All values are given in meters with an accuracy of 2 decimals. DHM data are stored as ASCII text files and divided into blocks of 10 x 10 km, and it is prepared for use in GIS environment.

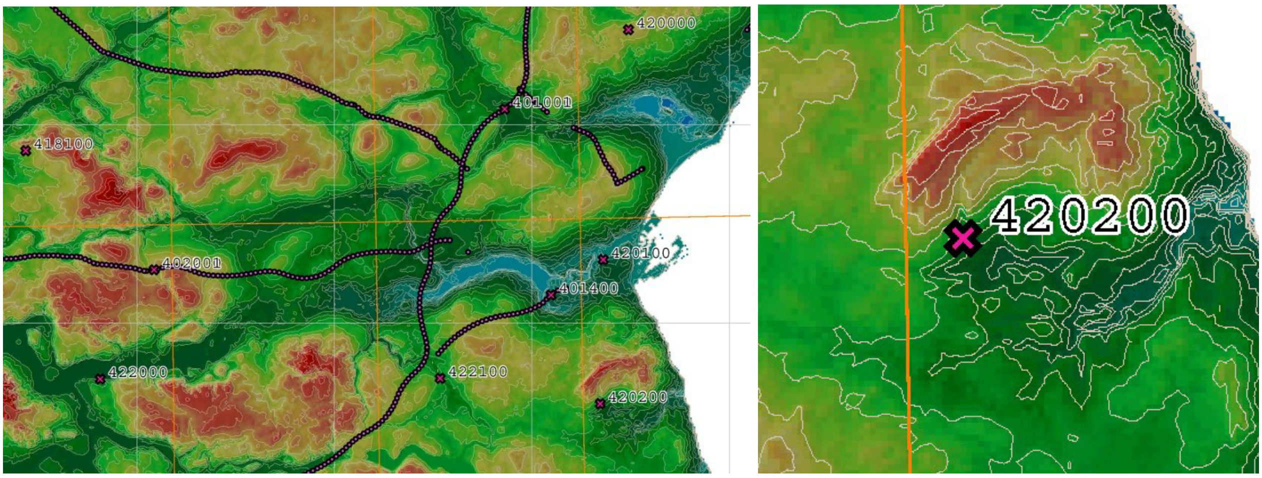


Figure 6*: Example of downscaled output generated from DHM data (Jutland Peninsula of Denmark) /circles – road stretches positions along the roads; crosses – road stations/.*

Such detailed data allows taking into account shadowing effects (without making manual observations at each point) when forecasting the road surface temperature. These effects were estimated by scanning the surroundings (terrain and obstacles) by sectors (32 sectors by 11.25 deg each) up to maximum distance of 10 km from the road station 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 and nearby obstacles (Figure 7). Compared with only terrain data use, the additional layers representing obstacles above the terrain level such as forest, trees, buildings, construction, etc. have improved accuracy and representativeness of shadowing for the roads.

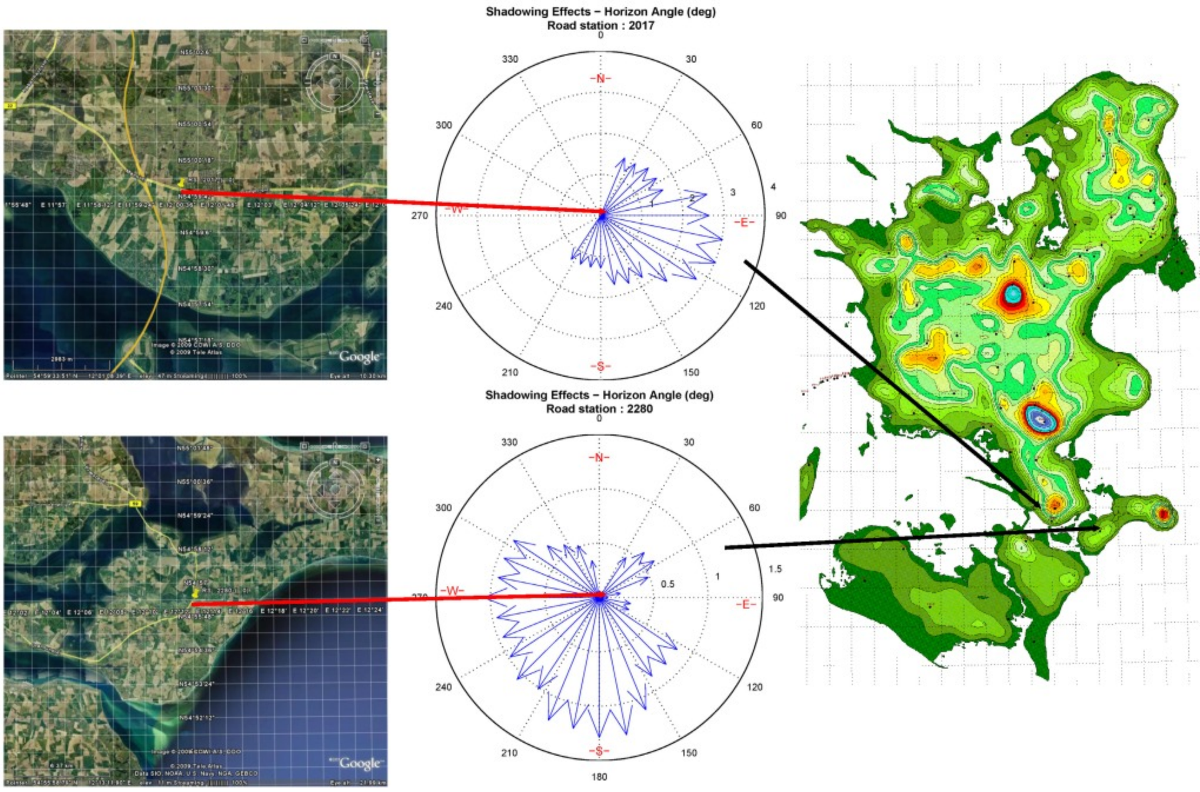
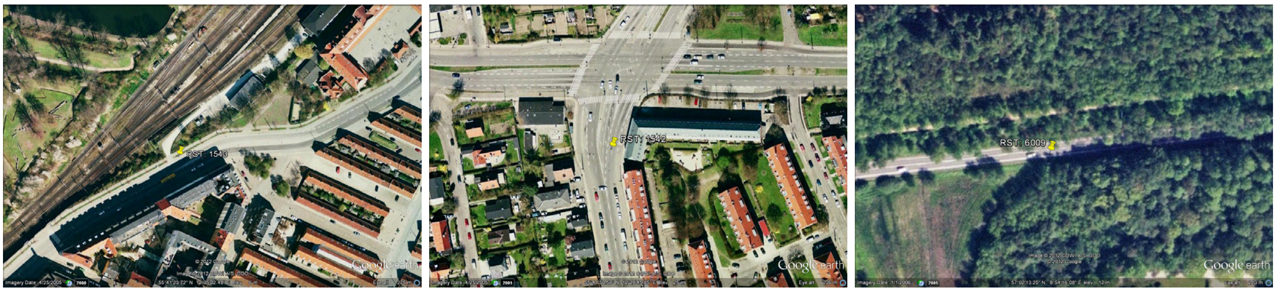


Figure 7*: Example of estimated shadowing effects — horizon angle due to terrain and surroundings for the Danish road stations N-2017 and N-2280 /left figures are extracted from Google-Earth/.*

Figure 8 shows surroundings (with obstacles – buildings, forest, etc.) near the urban station N-1543 (Figure 8a), suburban station N-1542 (Figure 8b) and rural station N-6009 station (Figure 8c). The differences between the urban and suburban stations are include first of all, the differences in heights of the surrounding buildings (lower height buildings are more often observed in the suburban areas) and more green areas with trees and bushes (due to a larger number of private houses) (Figure 8ab). The road stations in the rural areas mostly surrounded by forest (Figure 8c) or alley of trees along the sides of the roads or open agricultural fields.



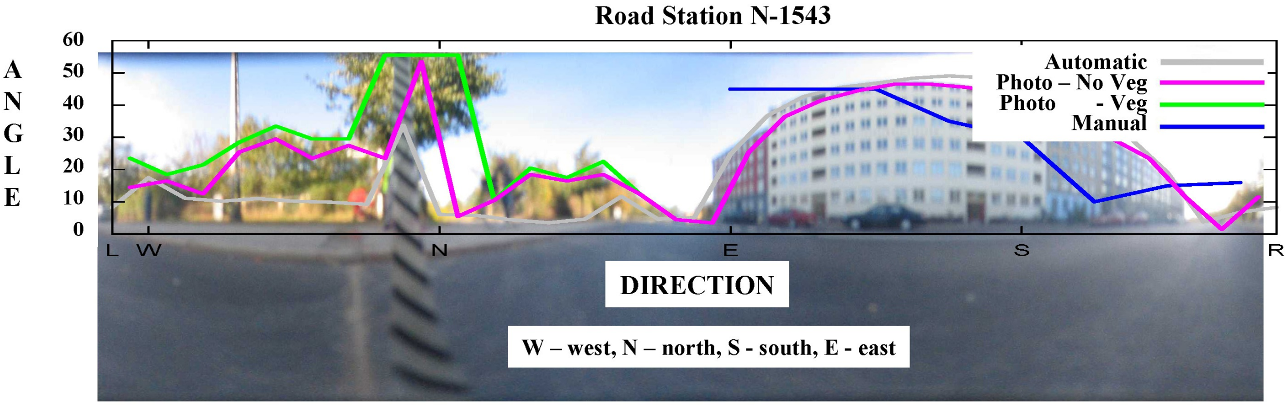
(a) (b) (c)

***Figure 8**: Surroundings (with obstacles – buildings, forest, etc.) of the urban N-1543, (b) suburban N-1542, and (c) rural N-6009 stations /extracted from Google-Earth/.*

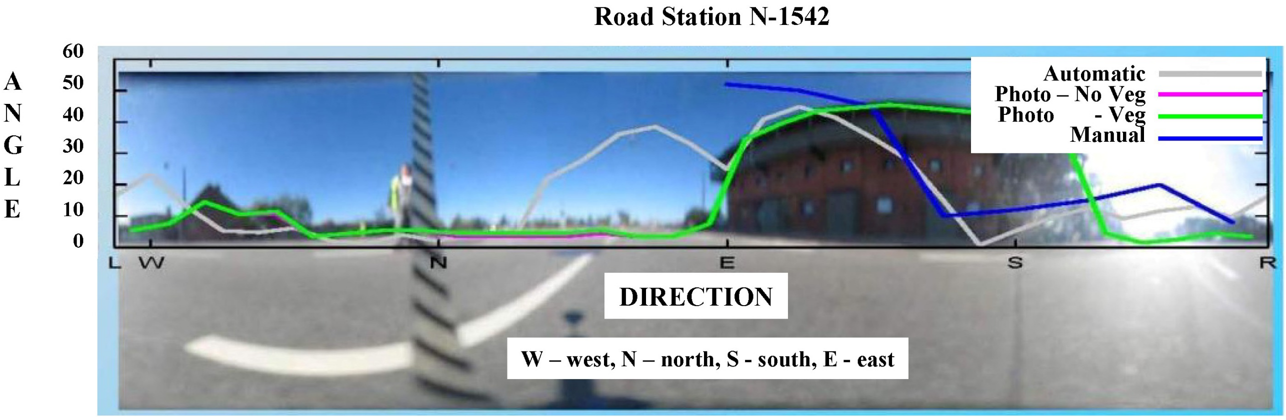
Figure 9 shows a 360 deg photo (panoramic view) from the road station N-1542 located in the metropolitan area of Copenhagen. As seen the main contribution to shadowing and skyview will be from surrounding high buildings and low vegetation (skyview angle is also seen in Figure 10b). Note that the sensor to measure the road surface temperature is placed on the surface (at some depth) of the road, but the station itself is located aside of the road. So, the shadow is calculated for the position of the sensor on the road.

***Figure 9**: Panoramic view of surroundings for the Danish road station N-1542 /extracted from Google-Earth/.*

Examples of obtaining the shadows and skyview angles are shown in Figure 10 for different types of road stations. As seen, there are substantial differences in accuracy of estimation depending on approach to obtain data – ranging from manual to automatic, and from vegetation with/without leaves coverage included. The two later depend on a time of the year, i.e. during growing season (spring-summer-fall) the crones of the trees and bushes are covered by leaves; and hence, it creates additional shadowing for the roads. The situation is opposite during late fall-winter-early spring time, when these are not covered by growing greening leaves, and hence, the trees become more transparent for sunlight, i.e. less shadowing should be accounted. In particular, it is less seen in the urban areas (Figure 10ab), but it is more pronounced in the country-side (Figure 10c), and especially near-by the roads surrounded by alleys of trees or forest. In main direction of the driving lanes such shadowing would be the minimal, but aside the driving lanes it will depend on the height of the surrounding trees. In some cases, shadowing might account for the dominating influence, especially when the trees will completely cover the road from the top and will compose a "shadowing tunnel" above the road. In Figure 10b a phase error is seen between "photo" and "automatic" approaches. This is a consequence of error in position of the camera, where north is shifted about 30 degrees away from the actual direction to north.



(a)



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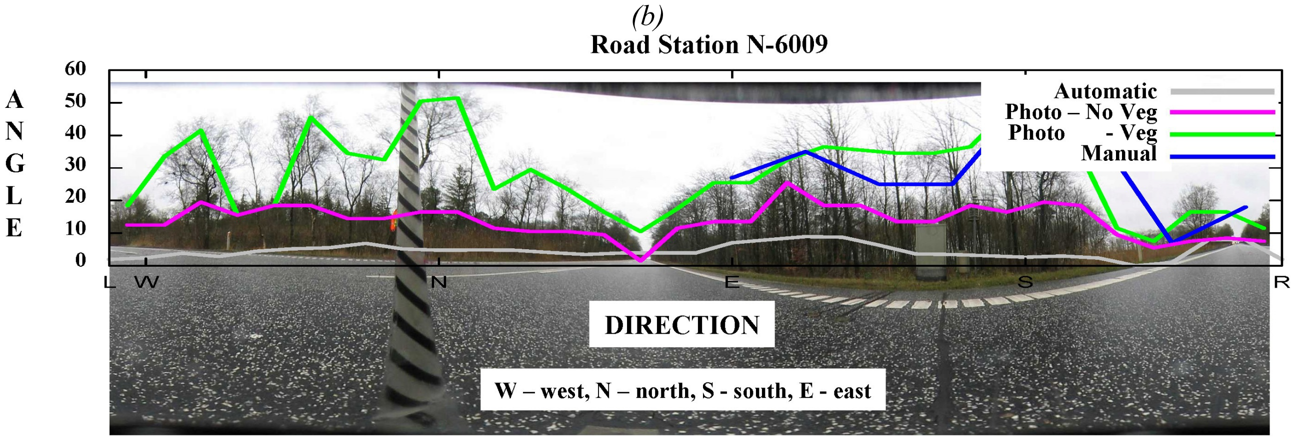


(c)

Figure 10*: Shadow and skyview angle obtained from panoramic view images using different approaches - manually, taking into account vegetation with leaves, vegetation without leaves, and automatically - for selected Danish road stations (N-1543 - urban, N-1542 - suburban, and N-6009 – rural).*

Figures 11-12 show temporal changes in shadowing effects due to surrounding road obstacles (buildings, trees, etc.) during selected dates on a diurnal cycle from the sunrise till sunset. Especially, it can be seen on the direct sunlight on the road surface (i.e. when a road will come in/out of the shadow zone). As seen, the taller buildings created the larger shadowing areas compared with shorter ones

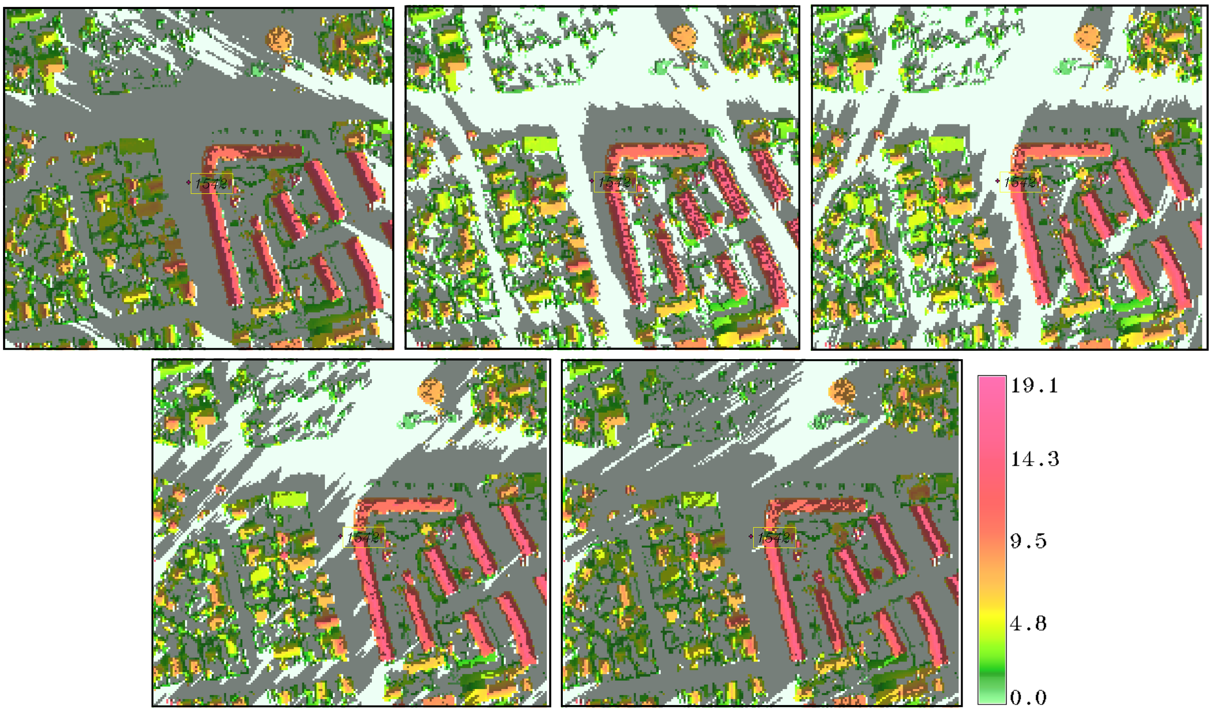


Figure 11*: Shadowing effects due to surroundings for the road station N-1542 during 13 Feb 2009 at 07:30, 09:30, 13:00, 14:30; and 15:30 UTC /scale—height of surroundings/.*

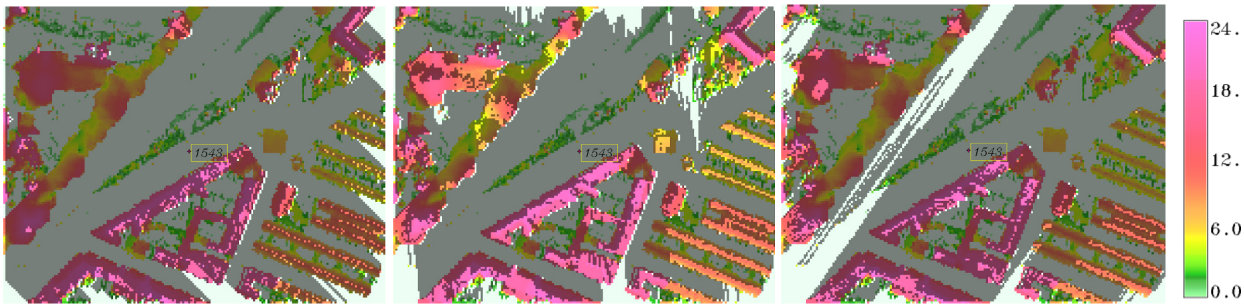
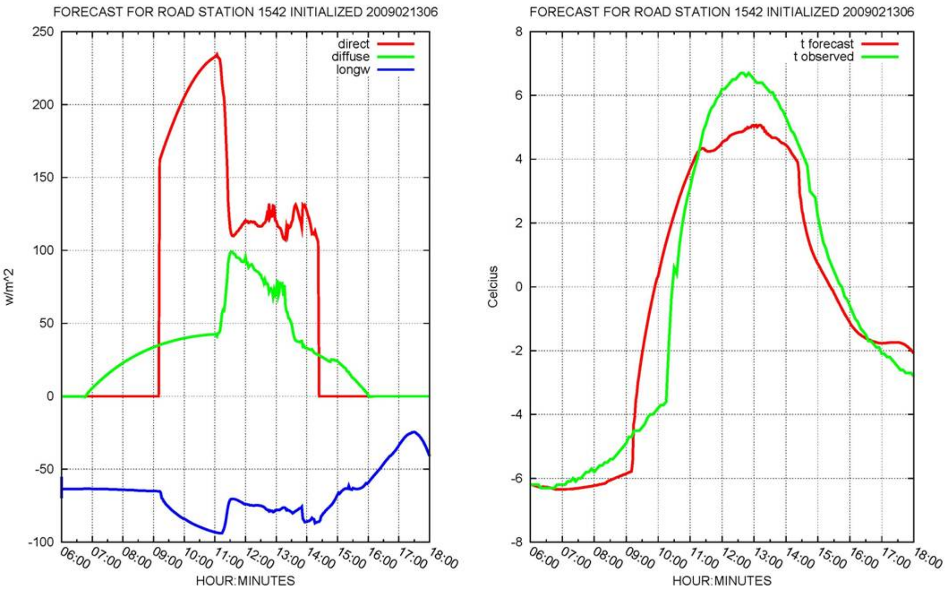


Figure 12*: Shadowing effects due to surroundings for the road station N-1543 during 22 Dec 2009 at 09:00, 12:00 and 15:00 UTC /scale—height of surroundings/.*

Figure 13 shows an example of 12 hour forecast on 13 Feb 2009 for the road station N-1542. In general, during winter months a period of sunlight during the day is shorter. The forecast of direct, diffused, and long-wave radiation is given (Figure 13a) on a part of diurnal cycle when the changes are the most recognizable. The skyview angle has also influence on reducing the incoming diffusive radiation and reducing the angle for incoming and outgoing long-wave radiation. The influence of shadowing effects becomes visible especially on the direct short-wave radiation. As seen it has increased sharply after 9 am reaching more than 150 W/m^2, i.e. once a part of the road became exposed to the sun. It rapidly continues to increase till 11 am reaching about 230 W/m^2. At about 11:30 am a shadow due to obstacles and increased cloud cover (also influenced the diffuse radiation) contributed to a rapid decrease of direct radiation by almost factor of 2.

After 14:30 pm (i.e. after sunset) the direct radiation is rapidly approaching zero value. The contribution of diffuse radiation begins at about 7 am, gradually rising through the day and reaching a maximum of about 100 W/m^2 at 11:30 am, and then gradually decreasing untill 16 pm (reaching zero value). The long-wave radiation is negative, and in general it is less than -50 W/m^2, although a positive tendency has been observed after 14 pm (i.e. when radiation increased to about -25 W/m^2 at 17:30 pm).

The forecast of the road surface temperature (vs. observations) at the road station is given in Figure 13b. In general, a diurnal cycle is well predicted by the RCM model, but there are some discrepancies in the morning hours, i.e. before the sunrise, In particular, there a shift in time (approximately 1.5 hour) when the sharp increase in the road surface temperature is observed. This reflects the error in the shadow calculation seen in Figure 10b.



(a) *(b)*

***Figure 13**: 12 hour forecast for the road station N-1542 — (a) direct, diffused, and long-wave radiation; and (b) forecasted and observed road surface temperature — during 13 Feb 2009.*

3.2 Proximity to seashore

Since Denmark is surrounded by the sea waters (the North and Baltic Seas on the west and east, and the Skagerrak and Kattegat passages on the north and east) the modeled conditions along the roads of the Danish road network are highly affected by proximity to the seashore line. Although in general the westerlies dominate in the atmospheric transport, sudden changes in wind direction can cause considerable variations in temperature and humidity regimes over inland territories. An air mass can be transported from an open water area toward inland territories of Denmark bringing a moist air or precipitation. These can change road conditions, and first of all, the road surface temperature. Hence, information – distances to seashore with corresponding azimuths - on a relation of road station (making continuous measurements) to surrounding open sea water became of importance for better quality forecasts.

To estimate distances to the seashore from the road station geographical position along radial directions as well as identify the shortest distance to the seashore with corresponding azimuth, the Global Self-consistent Hierarchical High-resolution Shorelines (GSHHS; *Wessel and Smith, 1996*) dataset output has been used. GSHHS is distributed under the GNU Public License. This dataset is based on two databases: the CIA world database WDBII and the World Vector Shoreline database. The shorelines are constructed from hierarchically arranged closed polygons. The original four-level hierarchy applied is the following: (i) seashore, (ii) lakes, (iii) islands within lakes, and (iv) ponds within islands within lakes. The GSHHS dataset can be downloaded and more details (also with respect to the latest releases) can be found at the NOAA National Geophysical Data Center - http://www.ngdc.noaa.gov/mgg/shorelines/data/gshhs.

In our study, from available global data, only data covering territory of Denmark (Jutland, Zealand, Fyn, Bornholm, and smaller size islands where the road stations are located) was extracted. In this new dataset, the distances between all close-by adjacent points along the line of shore were estimated, and two subsets with increment/ resolution of 0.0005 and 0.0001 degrees between any 2 adjacent points along the line of shore were created. For example, original shoreline data for Island of Bornholm included 523 pairs of latitude-longitude coordinates (points) in GSHHS. Post-processing or interpolation between points at different resolutions of 0.0005 (low) and 0.0001 (fine) had increased number of pairs/points up to 3190 for low and up to 13932 for fine resolution. Similarly, interpolation for Zealand increased original 9929 points to 58204 and 250077 at lower and finer resolutions, respectively, and for the overall Danish data (including all mentioned above territories) – from 26384 points to 157312 and 678104 points at lower and finer resolutions, respectively.

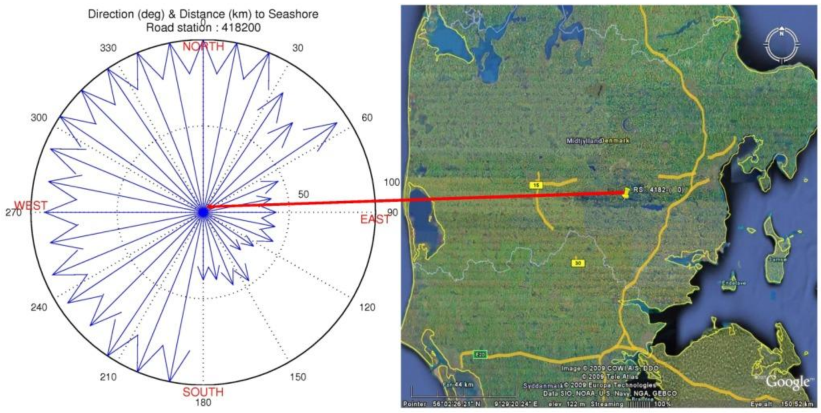
Both the geographical positions of shoreline points and road stations were taken at accuracy, at least, of 5 significant digits for further calculations. At first, the distance between two points was calculated in degrees, i.e. a length of the great circle connecting pairs (latitude and longitude) of points on the surface of a sphere. Such calculations might slowly degrade with increasing distance and have problems if both points are situated very close to the equator. For Denmark, such issues are not a problem due to smaller country size, proximity to sea water surroundings and faraway position with respect to the equator. At second, calculated distance was converted from degrees to kilometres (which is more appropriate to use in road modelling) as measured along a great circle on a sphere with the mean radius (6371 km) of the Earth.

In this study, for each geographical position of the road station within each sector (having interval of 11.25 degrees, in total 32 sectors) the distance (in km) was estimated at an intersection point of the sectoral line with the shoreline (defined by geographical coordinates). The distance was calculated taking into account geographical coordinates of both points: road station and intersection point. In order to estimate the shortest distance to seashore, the calculation of distances with a radial interval of 0.01 degree was done. Then, through screening of all calculated values of distances the absolute minimum value was chosen. It corresponds to the shortest distance to the seashore as well as it is assigned to corresponding azimuth angle.

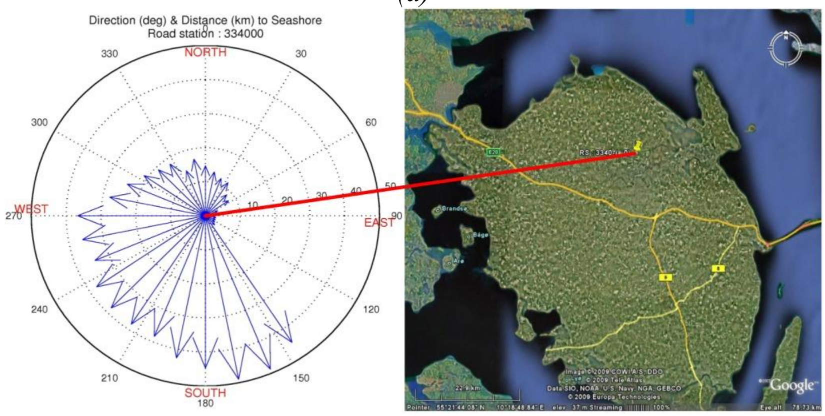
All road stations were classified according to the distance to the seashore: coastal, pre-coastal, and inland stations. Analysis showed that about 22% (including 13 stations near/at the very long bridge Storebæltbroen connecting Fyn and Zealand) of so-called *coastal* road stations are situated within a 1.5 km distance from a seashore line. About 24% of so-called *pre-coastal* stations are located between 1.5–5 km away from the seashore, and about 54% - *inland* stations are placed at distances more than 5 km.

Several examples are shown in Figure 14 for different types of Danish road stations (showing also surrounding station area extracted from Google-Earth). For the inland road station N-4182 the estimated minimum distance is 28.62 km, and it is the south-eastern direction (at 142.34°) from the location (see Figure 14a). For the pre-coastal station N-3340 the estimated minimum distance is 3.01 km in the eastern direction (at 89.49°) (see Figure 14b). For the coastal station N-2320 the estimated minimum distance is 0.93 km in the eastern direction (at 90.06°) (see Figure 14c).
If 13 road stations located near/at the Storebæltbroen bridge are excluded, than from the remaining 368 road stations analyzed, about 40% of these stations the shortest distance to the shoreline is associated with the eastern sector. I.e. a possible influence from an open sea on the road weather

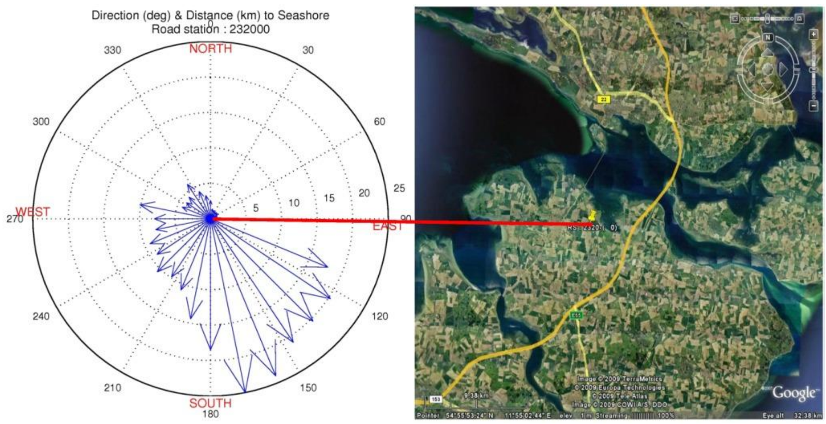
conditions near the station is linked with air mass transport from the eastern directions. About 25% (92 road stations) are linked with the western sector; and more than 17% each are associated with the northern and southern sectors.



(a)



(b)



(c)

Figure 14*: Example of estimated distance (in km) and direction (in deg) to the seashore line for the Danish road stations: (top) inland station N-4182 (minimum distance is 28.62 km at 142.34°), (middle) pre-coastal stationN-3340 (minimum distance is 3.01 km at 89.49°) and (bottom) coastal station N-2320 (minimum distance is 0.93 km at 90.06°) /extracted from Google-Earth/.*

3.3 Surrounding land-use

The surrounding terrain and land-use are very important characteristics for road weather modelling, and these are very dependent from the geographical location of the road station/ stretch. Examples of dominating land-use are shown in Figure 15.

***Figure 15**: Example of dominating land-use/cover for selected Danish road stations placed in surroundings of forest, agricultural fields, urban environment, and combined /extracted from Google-Earth/.*

It is known that cold air is more dense and heavier than warm air, and therefore, it will move down the slopes as well as it has a tendency to drain, so-called air pooling. That is reflected in influence of the local adjacent to roads terrain and land use on formation of the ice. In this case the valleys or bottoms of the hills tend to be cooler at night during calm and stable conditions compared with adjacent places of higher elevation. Moreover, the observed changes in temperature with height can be quite large. For example, in urban areas, the roads will be warmer during nighttimes due to pavement made of concrete/ asphalt which tends to accumulate during the daytime heat from the sun as well as heat from the buildings/constructions surrounding the roads. During the winter at nighttimes freezing will be less likely near large water objects, since the water surface is much warmer than the land surface. As variations in temperature due to almost unchangeable features of the local terrain are repeatable from night to night, these can be used for developing of suitable parameterizations which can lead to improving of forecasts at selected nearby locations. The influence of obstacles (such as trees, hills, and other objects) located near the roads is also very important. Shading of road surfaces by obstacles significantly influences the possibility of the ice formation. For example, during nighttime, the overhanging trees or other road covers will reduce such possibility due to decreasing of the infrared heat loss. Shading due to trees or hills can delay also melting at late morning hours and it will allow ice to remain for the rest of the day. Parts of the road, which are located in the shadow of the hills, can start to cool rapidly hours before sunset.

3.4 Road stations: catalog data

When the forecast of the road surface temperature is produced for the road station, on occasion, there might be noticed significant differences compared with observations. In order to identify possible reasons for such deviations the analyses of both the NWP model forecast and information about local peculiarities and conditions at the location of the forecast might be necessary. For that, the cataloguing of individual characteristics of each road station was carried out. Information in such catalogue includes the following:

- Position of the road station using geographic position system (GPS) data (which has been originally provided by DRD and re-verified through Google-Earth with respect to roads);
- Altitude at which the road station is located;
- Sectoral distribution (every 12.5 deg) of the horizon angle in order to reflect the shadowing effects due to surrounding terrain and obstacles (such as forest, construction, trees, etc.);
- Sectoral distribution (every 12.5 deg) of the distance to the seashore with corresponding azimuth (or direction toward the shoreline);
- Minimum distance to the seashore with corresponding azimuth;
- Classification into coastal (less than 1.5 km), pre-coastal (1.5-5 km), and inland (more than 5 km) stations depending on a distance from the position of the road station to the seashore line;
- Surrounding detailed land-use and land-cover types, especially with respect to forest, open agricultural fields, urban/ suburban/ rural areas, closest water bodies (sea, river, lake, etc.);

(a) (b) (c)

(d) (e) (f)

***Figure 16**: Example of road stations located at bridges (a) constructed over other crossing roads, (b) located over the ground surface, (c) tunnels under the ground surface, (d) passing over rivers, (e) passing over channels, (f) passing over sea /extracted from Google-Earth/.*

When the road station is located at bridges a specification is needed. For example, it could be bridges constructed over other crossing roads (Figure 16a); bridges located over the ground surface

(Figure 16b); tunnels under the ground surface (Figure 16c); bridges passing over the lakes, ponds, rivers (Figure 16d), channels (Figure 16e), sea (Figure 16f).

Examples of road stations catalogues are shown in Figures 17-18. As seen in Figure 17, the road station N-2017 is located in the region of Zealand in the suburban area. It is placed in a closer proximity to the seashore within the southern (S) sector compared with others. And it is the largest NW-N sector (more than 50 km in distance to the seashore). The minimum distance is about 3.1 km at an azimuth of approximately 208 degrees (i.e. in SSW direction). Based on estimated distance, the station is classified as pre-coastal. Because this station is located on a relatively steep western slope of the hill, the shadowing effects due to terrain and obstacles are zero within the SSW-NNE (210->030 degrees) sector. But the shadowing becomes more significant in the opposite direction reaching a maximum value (about 3 degrees) of the horizon angle in the E-EES (090->120) sector from the site. Within a few hundred meters around the road station, the surroundings are dominated by a large forest in the W-S-E sector. The suburban/ residential area with small size buildings/ constructions is situated in the W-N-E sector, although a large agricultural field could have more influence and be more dominant in the N-W sector from the site.

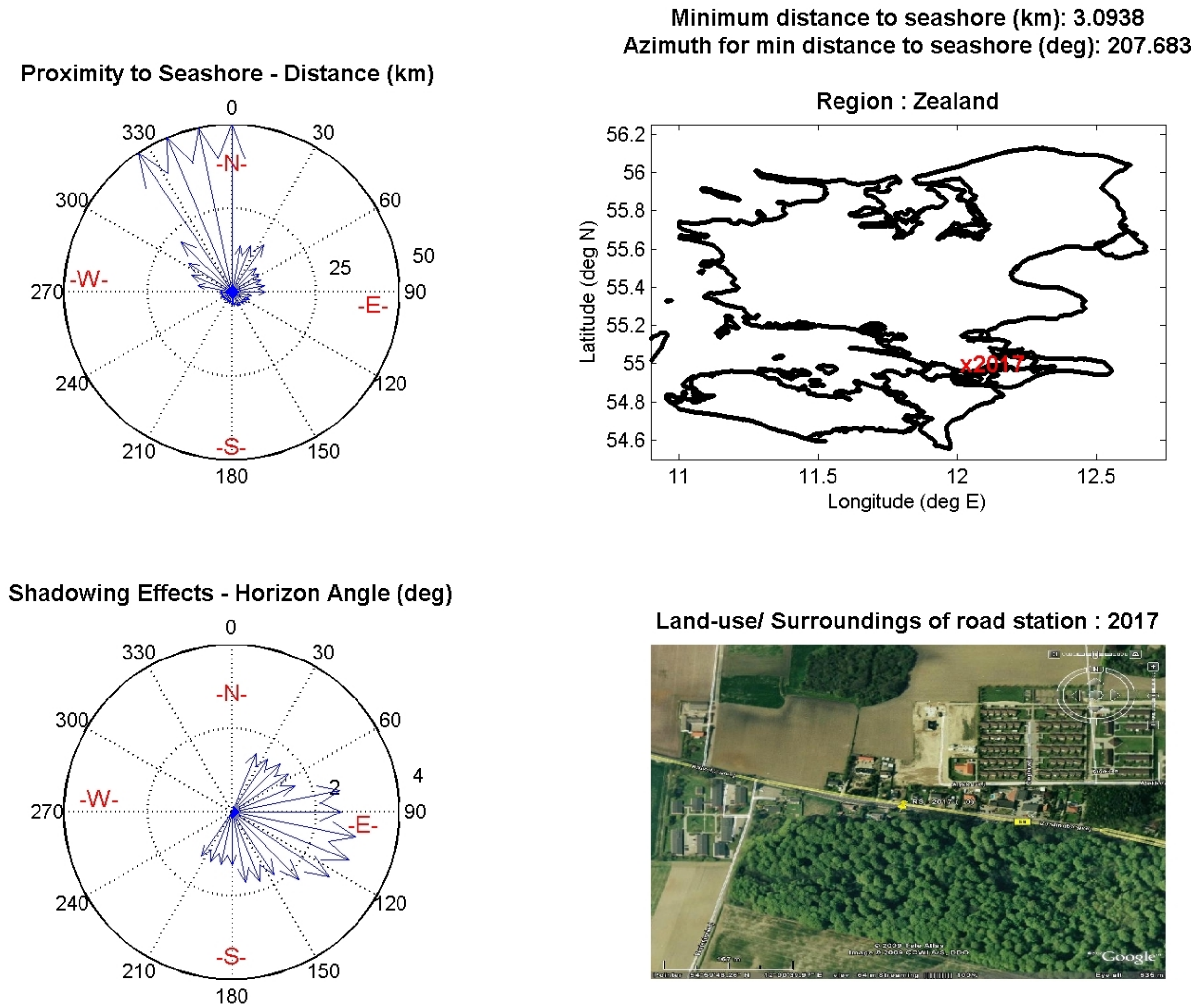


Figure 17: *Example of catalogued data for the Danish road station N-2017 (remark: consisted of direction and distance to the seashore, shadowing effects due to terrain and surrounding obstacles, minimum distance to the seashore at corresponding azimuth, geographical placement in the Danish area, land-use and environmental surroundings).*

As seen in Figure 18, the road station N-3015 is located in the region of South Jutland in the rural area. It is placed far from the seashore, and the closest proximity is within the western (W) sector compared with others. The minimum distance is about 16.8 km at an azimuth of approximately 288 degrees (i.e. in W direction). Based on estimated distance, the station is classified as inland station. Because this station is located on a relatively flat terrain, the shadowing effects due to terrain are minimal, and obstacles (in particular, the forest surrounding the road) contribute most. The shadowing became more significant within the E-S-WWS sector from the site, reaching a maximum (about 8 degrees) of the horizon angle in the SSW (180->210) sector. Within a few hundred meters around the road station, the surroundings are dominated by a large deep forest in the western directions and by the agricultural fields in the eastern directions, except to the east from the site, where there is an alley of older (taller) trees as well as a section of young (smaller size) planted trees, which could also have influence on the forecast of the road surface temperature.

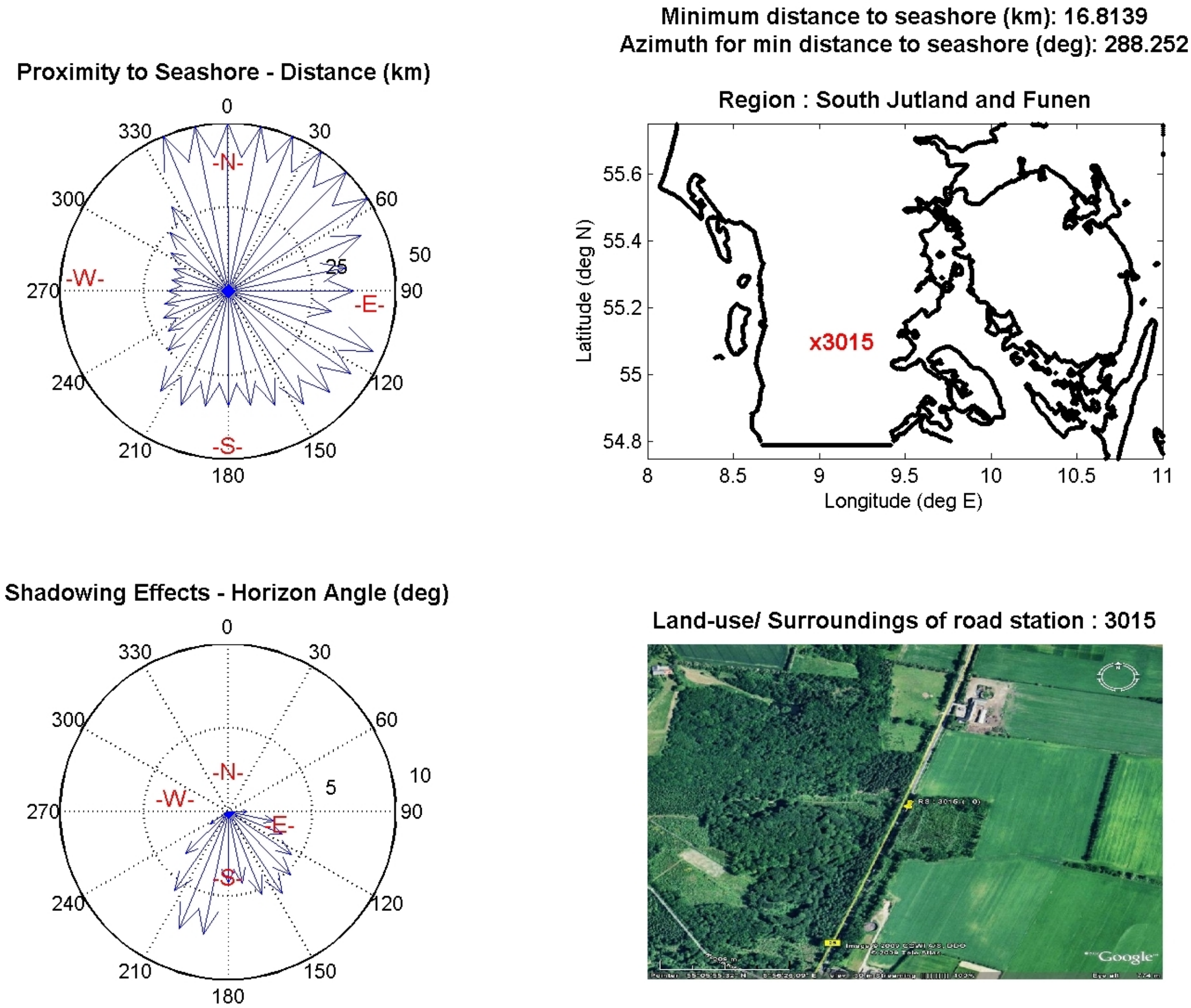


__Figure 18__: Example of catalogued data for the Danish road station N-3015 (see for explanation the remark in Figure 17).

Note, that similar cataloguing for the road stretches positions along the roads (where, at least, the salting activities are taken place during the road winter seasons) would be also important; and in particular, it could be used for additional evaluation of the verification of the road stretches forecasts compared with thermal mapping measurements (which are taken every road winter season at selected roads of the Danish road network).

4. Conclusions

Forecasting of slippery road conditions is the important product delivered by DMI in collaboration with DRD. In order to avoid accidents on slippery roads the preventing salting must be taken. A balance on how much and where exactly this measure should be taken became of critical importance for environmental and economical reasons. For these reasons, in addition to forecasts at road stations, recently the practical use of the forecasts at road stretches along the driving lanes has been growing rapidly. There are about 400 road stations within the Danish road network, but the number of road stretches is about 23000 and these are located at short distances down to 250 meters from each other and cover 153 Danish roads.

Already now it is possible to take the effects of skyview and shadows into account in the RCM model (in particular, in the radiation scheme). Note, that on sunny days, the direct effect whether the road surface is sun exposed or not is large. Surrounding road obstacles (such as, for example, trees and buildings) can often cause the shadow. Hence, it is necessary to measure the position of the location with very high accuracy using GPS. Otherwise, an error of a few meters could lead to large changes in shadowing. Due to large skyview, the emitted long-wave radiation could be of less important compared to effects of cold air pooling and reduced sensible heating of the road. The two later caused by terrain geometry and roughness. Distance to the seashore is important for forecasting in the coastal areas, where the dominating wind direction and speed are important to take into account.

Requirements to produce accurate forecasts at specific points, in particular, at road stretches located at distances of about 0.25-1 km between each other are higher compared to standard numerical weather forecasts at fixed grid-cells which depend on a resolution of the NWP model. In order to follow requirements and capture local variations and peculiarities at/near the road stretches it is necessary to have:
(i) higher (finer than 5 km) horizontal and vertical (more layers within the atmospheric boundary layer) resolution of NWP model including predicted road surface temperature, air temperature, relative humidity, wind speed and direction, and water/ice accumulated on the road surface;
(ii) detailed information about surroundings of the road stretch/ station which includes shadowing effects and skyview due to terrain and obstacles; proximity of the location to the seashore; types and domination of surrounding land-use; height of the location above the sea level; etc.

In principle, for a limited number of road stations it is possible to extract detailed information manually, but for tens of thousands of points several methods were developed for automatic post-processing of available high resolution databases and deriving local parameters at both road stations and road stretches. These high resolution databases include the following.

Danish Height Model (DHM) which is composed of 3 subsets so called DHM-Terrain, DHM-Surface, and DHM-Contour Levels. It has detailed information on terrain, obstacles and height contours above sea level. It has been used to calculate shadowing effects (horizon angle and skyview) in different directions from positions of road stations/ stretches, and height of the site.

Global Self-consistent Hierarchical High-resolution Shorelines (GSHHS), which has detailed information on geographical positions of the coastline. It has been used to calculate in radial directions a distance to seashore. It can be used to evaluate influence on atmospheric transport of cool/warm, most/dry air masses toward the positions of road stations/ stretches.

COoRdinate INformation on the Environment (CORINE) has detailed information on spatial distribution of different land-use/ land-cover classes and their characteristics. It has been used to identify the land-use/ land-cover surrounding the road stations/ stretches at local and remote scales and to clarify shadowing effects.

For clarity and convenience the Google-Earth has been actively used for visualization and analysis of derived parameters as well as clarification of geographical positions (both road stations and road stretches) according to geographical positioning system (GPS).

Moreover, the Danish Road Directorate database about detailed characteristics of the roads has been also analysed. As for roads the natural wearing is continuously taking place due to traffic, exposure to sunlight and various precipitations. The continuous from time-to-time repairment and replacements of the parts or segments of the roads by patches with new asphalt (or any other material) are changing specific characteristics of the road surface at exact locations. These are more difficult to incorporate as temporally and spatially variable parameters into the RCM model compared with almost unchangeable shadowing effects due to terrain, distance to seashore, height above sea level, and less variable shadowing effects due to obstacles and land-use/land-cover. Therefore, as for now, the averaged characteristics for albedo, density, heat conductivity, heat capacity, etc. are used in the model.

The applicability of results related to the improved quality of detailed forecasts at road stations and road stretches will:

- Facilitate the use of data from the road stretch forecasting to automatic adjustment of control of the dosage spread by salting spreaders, i.e. for optimization of the amount of salt spread over the road surface to prevent the icing/freezing as well as better timing of schedule for such operations by the road authorities;
- Lead to improvement of the overall safety of the road traffic in winter weather;
- Contribute to further development and improvement of the visualization tools for the road stretches forecasting; and
- Reduce the environmental impact in the road surroundings due to an optimized spreading of the salt.

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The Google-Earth (http://earth.google.com) has been used to visualize information for road stations/ stretches.

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