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Road Icing Conditions in Denmark

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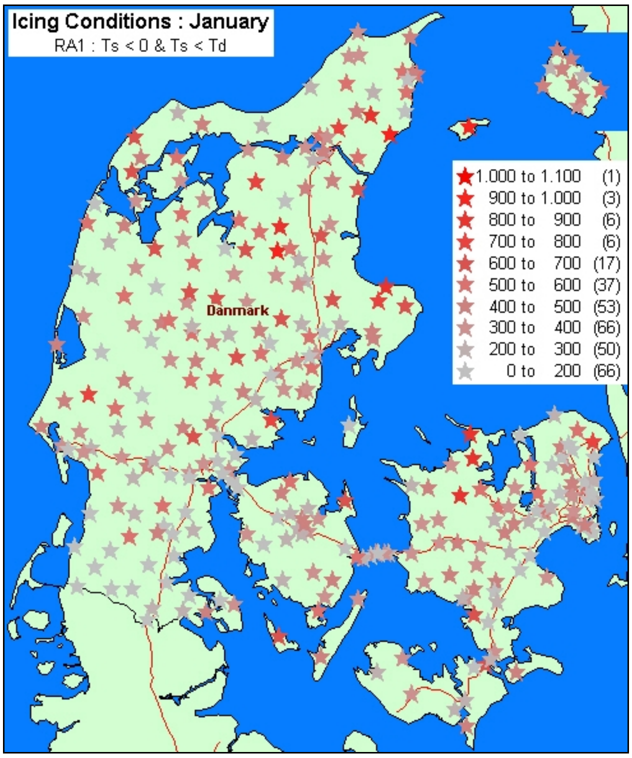

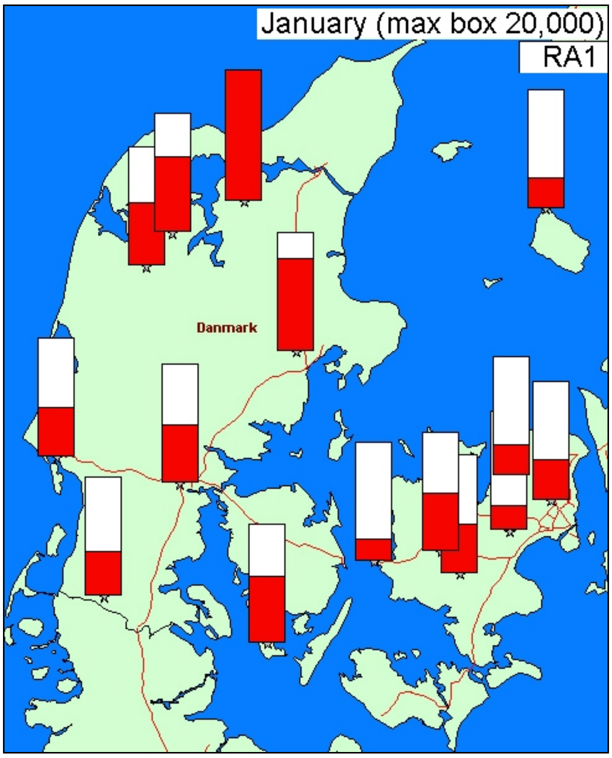

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Abstract

Evaluation of the road icing conditions in the Danish road network was conducted based on observational data (road surface, air and dew point temperatures) from 2003-2007 road weather seasons from the road stations. The red alert situations (representing the highest risk of icing conditions on the roads) and warning situations (representing a high likelihood of the ice and rime formation on the roads) were studied in more details. Analysis provided insight on a geographical spatial distribution of the situations leading to the icing condition and showed that during the road seasons the red alert situations might occur, on average, about 7%, and the warning situations (which might lead to formation of ice on roads) might account about 28%. The icing conditions are more pronounced at the inland stations compared with others, but contribution of other types of the stations is also significant. The “iciest” region of Denmark is NordJylland where the seashore, pre-coastal, and inland stations contribute around 13, 34, and 53%, respectively in observed icing conditions on the roads. The most sensitive areas were identified and hence, efforts to improve quality of the road forecasts in these areas should be done as well as additionally the thermal mapping measurements should be also carried out for improving quality and accuracy of the road stretch forecasting.

Resumé

Datamaterialet til beregning af is eller rim glatte veje for det danske vejnet er udarbejdet på grundlag af observationer(vejtemperatur, luft og dugpunktstemperatur) fra danske vejstationer for vintersæsonerne 2003-2007. 'Røde alarmer situationer' (is eller rim på vejen med meget stor sandsynlighed) og 'alarm situationer' (høj sandsynlighed for is eller rim på vejen) blev undersøgt i detaljer. Analyse gav indsigt i den geografiske fordeling af de situationer, der gav anledning til is/rim på vejbanen, og viste for den analyserede periode at 'røde alarmer' forekom i ca. 7 % af observationerne mens 'alarm situationerne' forkom i 28 % af observationerne. Is og rim situationer var mere udtalt for indlandsstationer sammenlignet med andre men bidrag fra andre typer af stationer var også signifikant. Flest rim og is situationer i danmark forekom i Nordjylland, hvor kyst, nærkyst områder og indlandsstationer bidrager med henholdsvis 13, 34 og 53 % af de situationer, hvor is på vejen forekom med meget stor sandsynlighed. De mest udsatte områder/vejstationer blev fundet og der lægges op til at disse områder/stationer undersøges i flere detaljer og evt. Undersøges gennem 'thermal mapping' målinger for at forbedre vejstrækningsprognoserne for disse særligt udsatte områder/stationer.

1. Introduction

1.1. Icing Conditions Formation

Ice on road surfaces is one of the most serious dangerous meteorological hazardous phenomenon, and it is well known that annually it causes serious injuries even deaths in road accidents, especially in the northerly located countries. It could be called the "silent death" since the weather often seems clear and calm. Although icing occurs under conditions which are generally well understood and often, with some degree of accuracy, possible to forecast, the reduction of the threat of the ice-related accidents still remain the key issue for the national road directorates. In order for ice to be formed on the road surface the following is required: temperatures near and below 0°C as well as presence of water (moisture) on the surface of the road. The formation of ice on the road surface can occur in different ways such as fog, frost, freezing of rain, freezing and refreezing of melted snow, or freezing of groundwater, with some of these icing mechanisms taking place also simultaneously.

Frost can occur during cold and clear nights at low wind conditions. When the road temperature and dew point temperature are above the freezing, then the water in a liquid phase will form on the surface. When the temperature is below freezing, then the frost accumulating slowly will form on the road instead. Such situation is more common for a moist atmosphere, and such conditions are more often seen after precipitation or near water objects. Frost is often observed in valleys and low areas which cool faster because of air pooling and low wind conditions.

Fog will form often during cold and clear nights when the temperature decreases to the dew point temperature. Since fog consisted of liquid water in large amounts, the passage over the driving lanes of the road, having a temperature of the surface below freezing, will lead to a relatively fast (even in a few minutes) formation of ice on the road surface.

Freezing of rain can occur when there is a layer of below-freezing air near the road surface with warmer air aloft. Rain will fall into the cold layer and it will be cooled to temperatures below freezing, and it will be remaining as a liquid. When the rain reaches the road surface, it will freeze almost immediately. It is often referred as "black ice" as the asphalt surface still looks black.

Freezing of melted snow is also dangerous situation for the road traffic. Such icing conditions frequently occur when the road surface temperature is above the freezing during the daytime, but it falls below freezing at the night. Even if the road surface is snow free, snow often can be found along the sides of the roads (in particular for roads that are actively plowed) with piles of snow adjacent to the open driving lanes. This snow melts during the day, especially in places nearby the relatively warm road, and the melted water runs over the road surface during the day, and then freezes at night when the sky is clear.

Freezing of groundwater can represent also a dangerous situation. In particular, it can take place when water drains over the road surface from a nearby water source. During the daytime this water will remain liquid on the road surface, but during the nighttime it will freeze. In addition, the wet roads often will freeze rapidly when the dry air will pass above the road. That is happen due to cooling from evaporation and it will result in localized icing (in general the low areas). So, it is important to identify such areas in advance for better maintenance of the roads.

Refreezing of melted snow on the road surface can occur at the beginning of the winter season or after the warm weather period. At these times the road surface is above the freezing. When the weather became cold and snow will start to fall, then initially it will be melted by the warmer road surface into a slush mixture. If the air temperature will continue to fall rapidly, then the warming from the road surface and the warm ground below is overwhelmed by the cold air above; and so, the mixture will become icy.

1.2. Influence of Surrounding Terrain and Land-Use

It is well 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, and moreover, the observed changes in temperature with height can be quite large. For example, in urban areas, the roads will be also warmer during night-times due to pavement made of concrete/ asphalt which tends to accumulate during the daytime a heat from the sun as well as a heat from the buildings/constructions surrounding the roads. Moreover, during the winter at nighttimes the freezing will be less likely near large water objects, since the water surface is much warmer than the land surface. Since 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 during the day before the sunset, and this can also result in icing conditions at evening hours.

A special attention should be paid to bridges (there are several relatively long bridges in Denmark, and especially one bridge which is connecting the Zealand and Fyn Islands) which often will ice first compared with surroundings and the land driving lanes. Since the temperature changes at the road surface will take days or even weeks to propagate into the ground at depth of several centimeters, the surface of the road is often cooler than the ground underneath during the nighttimes. The heat conducted from below the road surface will decrease the temperature fall at nighttime, and hence reduces possibility of the icing formation. Bridges have air, serving as a good insulator, underneath the driving lanes, and therefore, they will not accumulate the heat from the ground below. And thus, bridges will be more sensitive to icing conditions at nighttimes compared with the land driving lanes. Such situation, in particular, often can take place at the beginning of winter (i.e. when the ground surface is still relatively warm). Moreover, a dangerous situation can occur with the warm ground when the snow is falling and melting on the road surface, and then later it will be freezing as solid during a passage of the colder air above the driving lanes.

1.3. Road Weather Forecasting

The road weather forecasts with a focus on prediction of the slippery road conditions are performed by the Road Weather Modelling (RWM) system and it is an important operational product produced by DMI. In order to stimulate and continue further development of the existing system, the annual verification of its performance is conducted at the end of each road season. The performance of the Road Conditions Model (RCM; *Sass, 1992; 1997*) is evaluated by estimating forecasts for key parameters such as mean absolute error and bias for the road surface temperature (*Ts*), 2m air temperature (*Ta*) and 2 m dew point temperature (*Td*), as well as scores reflecting a frequency of good/poor quality forecasts. For the recent road weather seasons (i.e. during 2005-2008; duration from October through April) the verification reports are given by *Petersen et al. (2007, 2008).* In operational runs, the system uses the continuous observations from the synoptic weather stations and road stations (having now more than 440 sensors) of the Danish Road Network (DRN) along with the meteorological output from the DMI-HIRLAM (High Resolution Limited Area Model; *Sass et al., 2002; Yang et a., 2005*) numerical weather prediction (NWP) model as input to produce 24 hour forecasts every hour. The description of the RWM operational system/ product is given in the manual *GlatTerm (2004).*

Recently the road weather forecasting system extended its applicability with focus on detailed road stretch forecasting at distances of 1 km along the driving lanes (*Mahura et al., 2007*), the information about spatial variability of observed icing conditions on roads or situations leading to such danger became essential and needed. It is important to identify where local slippery road conditions occur, where complexities and failed predictions of road conditions in forecasting at short distances might be expected within the road network, and where the most research efforts should be invested to make forecasting with a higher accuracy. It is also important in order to continue further improvement of the overall slippery road forecasts at road stations (and in perspective, as well as at all road stretches). So, the geographical territories of Denmark, potentially sensitive to road icing conditions, should be identified and analysed in more details. For that, a statistical analysis of different situations (at first, with a focus on measurements of the road surface temperature, air and dew point temperatures) which can potentially lead to the formation of the icing conditions at the roads should be conducted. In our study, the focus will be on the so-called "red alert" and "warning" situations which are used to classify the frequency of the road icing conditions observed during the road weather seasons of 2003-2007.

2. Measurements of Road Conditions

2.1. Network of Danish Road Stations

For the studied period, the Danish Road Network was represented by almost 400 sensors (measuring continuously the road surface, air and dew point temperatures) at more than 300 road stations. At some stations there are two or more sensors placed along the driving lane or on the opposite side of the road not far from each other. Until recently, the network was divided into several road regions, as shown in Fig. 2.1.1. These road regions are the following. For the Zealand Island – regions of Copenhagen (N15), Frederiksborg (N20), Roskilde (N25), Vestsjelland (N30), and Storstrom (N35). For the Jutland Peninsula – regions of NordJylland (N80), Viborg (N76), Århus (N70), Ringkobing (N65), Vejle (N60), Ribe (N55), and SønderJylland (N50). There are also regions of the islands of Fyn (N42) and Bornholm (N40). It should be noted that there is also the region of Storebelt (N99) which is represented by the bridge connecting two islands of Zealand and Fyn. The positions of the road stations are not equally spatially distributed within the network, but the stations were placed along most of the roads to cover as much as possible the entire territory of Denmark as seen in Fig. 2.1.1. According to the RSF Project, in total almost 17,000 road stretches (located at distances of approximately 1 km from each other) were identified based on the detailed high-resolution GPS data (obtained from the DRD VINTERMAN database) for the driving lanes. Hence, it can be estimated that for a length of approximately 50 km there is one road station placed in the network.
The classification of the road stations (based on a number of the operational road stations – 312 (equipped with 393 sensors) – by the end of the road weather season 2006-2007) as a function of the distance from the seashore (*Mahura et al., 2008*) allowed to group all stations depending on influence of the local topography and typical local meteorology as well as influence of the water

objects, and in particular, the land-lake breeze circulation. The summary of this division is shown in Table 2.1.1. The seashore stations (CC) are situated within 1 km distance from the seashore. The inland stations (CL) are situated at distances more than 5 km from the seashore. And the all other stations were included into the class of the pre-coastal stations (CM). In total there are around 40 stations classified as the seashore stations, around 180 stations classified as the inland stations, and around 90 classified as pre-coastal stations.

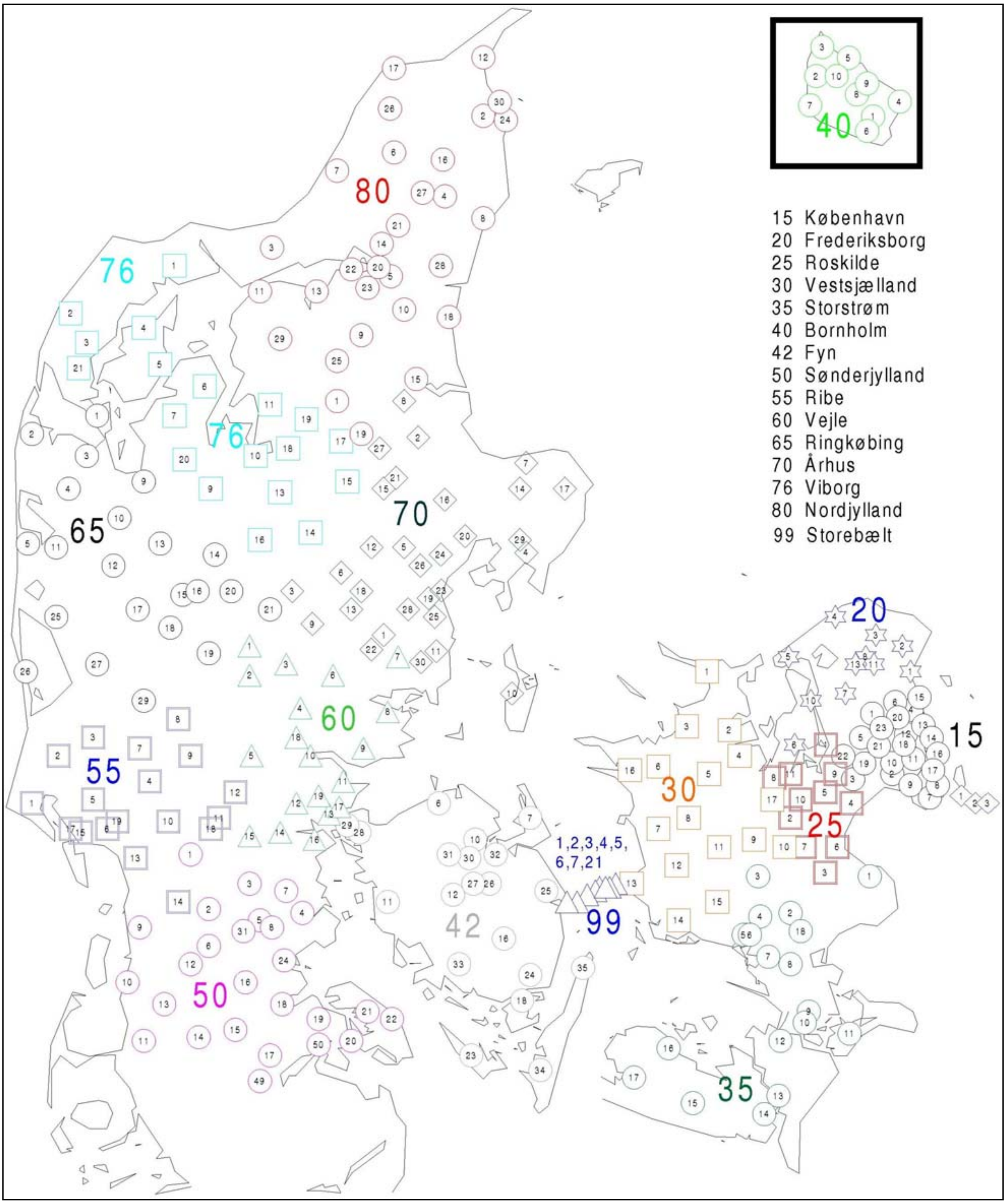


Figure 2.1.1 : Geographical distribution of the road stations within the Danish Road Network by specific road regions (numbered from 15 till 99; region 99 is represented by the bridge connecting the two islands of Zealand and Fyn).

The region of Storebælt is considered at specific view accounting for 8 road stations situated at the bridge (CB) and 2 road stations (assigned to the CC class) situated at the entrance/exit of this bridge. There is also a region (not included into the table) which is situated at the artificial island Amager (with the Copenhagen airport located there) with 13 sensors at 7 stations. At the beginning of the road weather season 2007-2008, the number of the road stations was increased up to 317 with 402 sensors in total. During 2008, in addition to placement of sensors near the roads around 20 sensors were also placed in the Copenhagen international airport area around the runways. At the beginning of 2008-2009 season, there are now more than 440 sensors located at 349 road stations within the Danish road network. Such rapid expansion of the measurement sites in the network will help to improve the quality of the road stretch forecasts as well.

Table 2.1.1 : Summary of the number of the road sensors, road stations, and classes/ types (and percentage in brackets) of the road stations for different road regions within the Danish road network (at the end of the road weather season 2006-2007).

Road Region	***Total N Sensors***	***Total N Stations***	***Road stations – Class/ Type***		
			Seashore CC	Pre-coastal CM	Inland CL
Copenhagen (N15)	26	20	2 (10)	9 (45)	9 (45)
Frederiksborg (N20)	14	13	2 (15.4)	3 (23.1)	8 (61.5)
Roskilde (N25)	13	11	1 (9)	5 (45.5)	5 (45.5)
Vestsjelland (N30)	19	17	1 (5.9)	4 (23.5)	12 (70.6)
Storstrom (N35)	26	20	5 (25)	9 (45)	6 (30)
Bornholm (N40)	10	10	3 (30)	4 (40)	3 (30)
Fyn (N42)	35	26	2 (7.7)	9 (34.6)	15 (57.7)
SønderJylland (N50)	33	26	3 (11.5)	6 (23.1)	17 (65.4)
Ribe (N55)	20	18	1 (5.6)	2 (11.1)	15 (83.3)
Vejle (N60)	25	22	2 (9.1)	4 (18.2)	16 (72.7)
Ringkobing (N65)	27	24	1 (4.2)	8 (33.3)	15 (62.5)
Århus (N70)	34	30	1 (3.3)	5 (16.7)	24 (80)
Viborg (N76)	30	21	2 (9.5)	7 (33.3)	12 (57.2)
NordJylland (N80)	56	37	5 (13.5)	14 (37.8)	18 (48.7)

2.2. Pre-Treatment of Original Data

In this study the observational data at road stations of DRN for the road surface, air and dew point temperatures have been extracted from the original datasets covering the road weather seasons during 2003-2007. To avoid a biasing due to measurements by several sensors (at one station) located closely to each other, the measurements only at one sensor were taken into account to more represent geographical spatial distribution. Following estimation for the flag of stated quality of the forecast, all cases with questionable measurements were also excluded. It should be noted that the measurements from the road stations located in the Copenhagen metropolitan area (Region N15) are conducted in the urbanized areas and should be considered with a caution due to presence and substantial influence of the urban heat island (UHI) on formation of icing road conditions. Moreover, in addition all cases where measurements of the dew point temperature were higher than air temperature were omitted. Also, cases, when differences between the dew point and air temperatures vs. road surface temperature were significantly different, were excluded. From the original large long-term dataset 7842997 validated records were extracted into an independent dataset as a time series for further analysis.

2.3. Time Series of Road Icing Conditions

In newly created dataset, representing a time series of temperatures' measurements of road conditions, each record consisted of the following information:

- road station identificator,
- sensor number (only one was finally used at each road station),
- region where the station is located,
- latitude and longitude of the station location,
- time (year, month, day, hour),
- road surface temperature,
- air temperature at 2 meters,
- dew point temperature at 2 meters,
- height of the station above sea level, and
- class/ type of the station.

The two latter parameters are of importance to include in order to study dependence of the road icing conditions as a function of the height and placement with respect to the Danish seashore. The height of the road stations was evaluated according to the specific individual geographical position and based on the estimates from the GPS Visualizer Utility (see at http://www.gpsvisualizer.com/elevation). For that, the so-called dataset SRTM3 (Shuttle Radar Topography Mission) was used which has a resolution of 90 meters for the geographical area located between 56°S – 60°N. The classification of the road stations included division into groups/classes depending on a distance from a seashore (see Ch. 2.1). The first class (CC) included sites located within a distance of less than 1 km from a seashore line, the second class (CM) included sites located within a distance of 1-5 km, and the third class (CL) included sites located farther than 5 km from seashore. In addition, the class of road stations located at bridges (CB, Region 99 in our study) was introduced due to completely different types of the surrounding land-use compared with the previous three classes. Moreover, the bridges might be subdivided into two categories: sea bridges and land bridges.

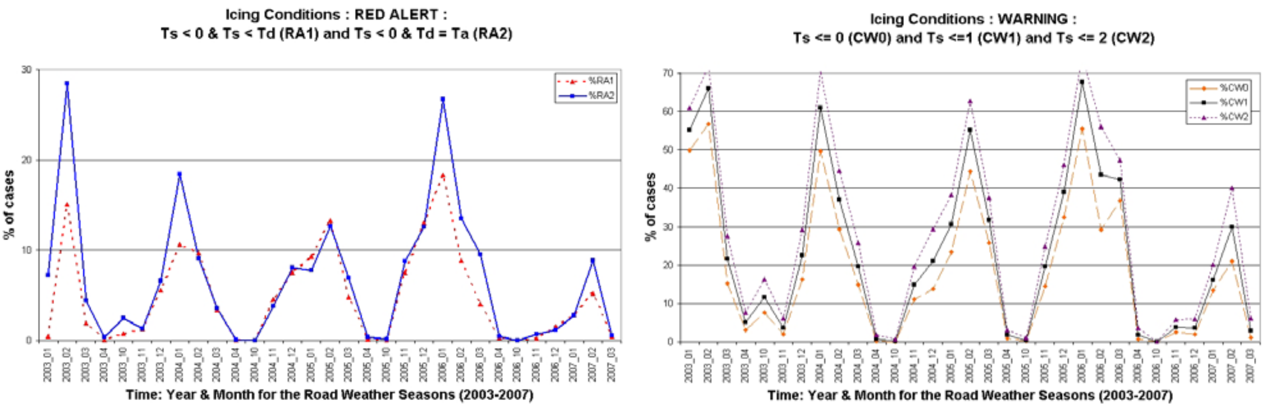
3. Results and Discussions

3.1. Overall Summary on Alert and Warning Situations

In this new dataset all cases with different conditions for *Ts, Ta,* and *Td* were evaluated. Cases with the road surface temperature, *Ts* of less than +2°C, +1°C and 0°C were assigned to the "warning" category. In total they accounted between 18 and 28% of the cases. Such situations do not necessarily result in formation of icing conditions on the roads, but these are the first sings of a potential likelihood that the icing formation can take place.
The most dangerous situations are represented by so-called "red alert" situations, when there is the highest probability of the icing formation. Two situations are considered. First, RA1, i.e. when the *Ts* is less than zero and at the same time it is comparable with the dew point temperature; and second, RA2, i.e. when the *Ts* is also less than zero and at the same time the air temperature and the dew point temperature are almost the same (with a difference of less than ±0.1°C). As seen from Table 3.1.1, from the total number of cases (7842997), the cases with such red alert situations account between 5-7%. The lowest number of such cases occurred in October (i.e., in beginning of the road season), and the highest - in January-February (Fig. 3.1.1) which is well seen from the inter-seasonal variability (in percentage of the cases) of the road icing conditions for different situations (RAs and CWs) based on long-term observations (2003-2007) of the road surface temperature in the DRN.

Table 3.1.1 : Summary on occurrence of potential conditions leading to development of icing on the Danish roads (based on road weather seasons 2003-2007).

Situation	Definition	Level	# cases	% cases
RA1	Ts < 0 & Ts ≈ Td	Red Alert	395866	5.1
RA2	Ts < 0 & Td ≈ Ta	Red Alert	525265	6.7
CW0	Ts ≤ 0	Warning	1385169	17.7
CW1	Ts ≤ 1	Warning	1780197	22.7
CW2	Ts ≤ 2	Pre-Warning	2170963	27.7



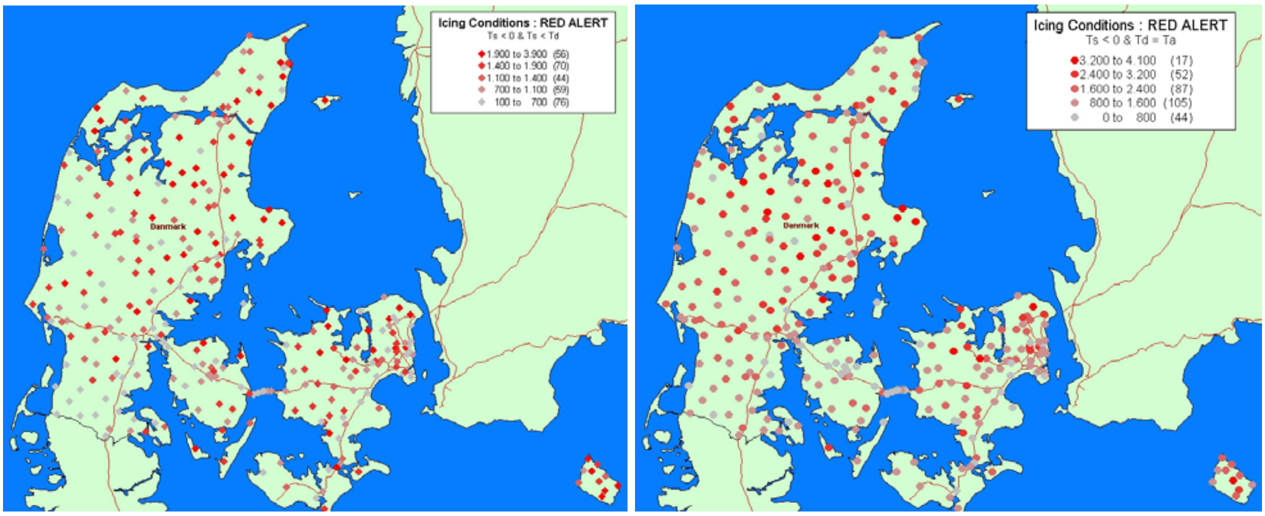
(a) (b)

Figure 3.1.1 : Percentage of the identified (a) road icing conditions for the red alert situations (RA1 and RA2) and (b) warnings to threshold temperatures leading to possibility of the road ice formation (CW0, CW1, and CW2) at the road stations with respect to observations during the road weather seasons of 2003-2007.

3.2. Spatial Distribution of Red Alert Situations

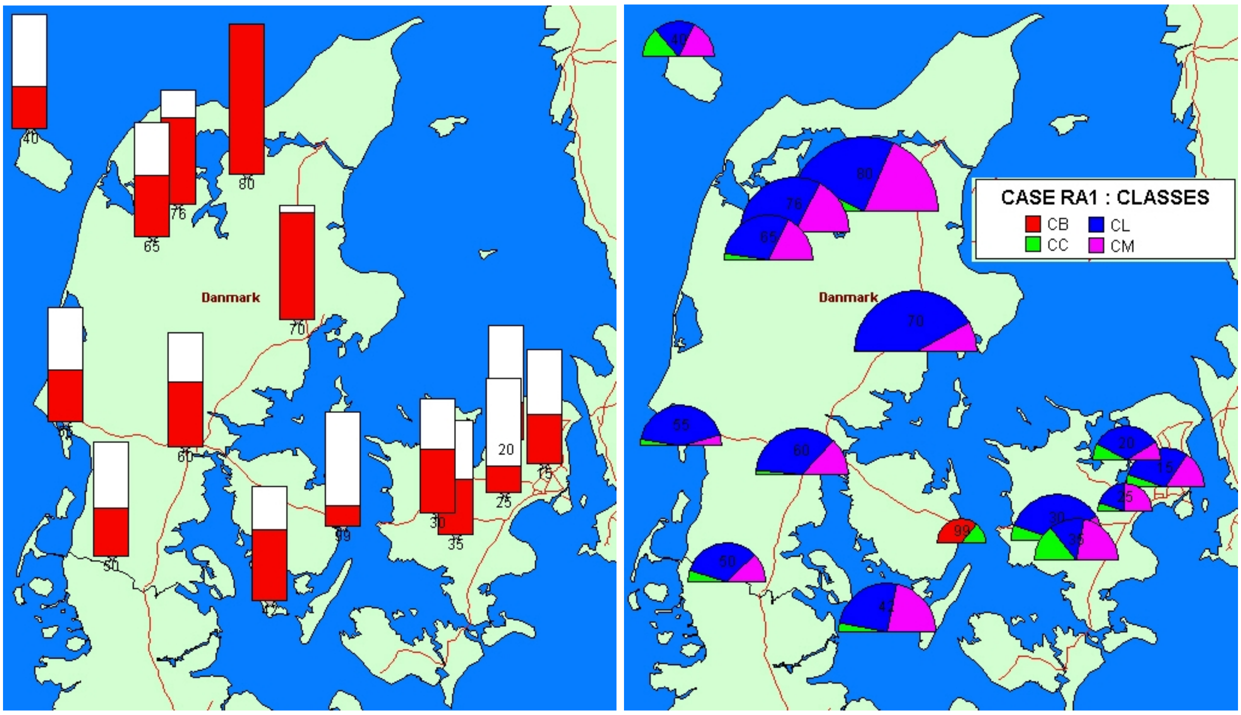
The spatial distribution of the red alert situations (RA1 and RA2) during the road weather season 2003-2007 is shown in Fig. 3.2.1 with a legend on a scaling of the number of stations having similar number of measurements corresponding to specified interval. As seen, there are some areas within the DRN where the road icing conditions are not observed frequently. For example, there are 76 road stations where the RA1 conditions observed at lesser degree compared with the rest of the stations, and there are 56 locations where such conditions have been observed very frequently compared with others (Fig. 3.2.1a). Similarly, there are 44 road stations where the RA2 conditions are observed at lesser degree compared with the rest of the stations, and there are also 17 locations where such conditions have been observed very frequently (Fig. 3.2.1b). Such representation of the spatial distribution is a very useful tool for preliminary identification of the territories and extended areas on a geographical map with the highest and lowest likelihoods in developing of the road icing conditions.

In a case of special division of the road network into specific regions (where boundaries can be defined as administrative boundaries of the national districts or regions), it is possible to identify and investigate the most sensitive areas subjected to building up icing conditions in both RAs situations (see Figs. 3.2.2-3.2.3). As seen in Fig. 3.2.2a, the regions of NordJylland (N80) followed by Århus (N70) are the most sensitive regions to icing on the roads. For these two regions, more than 62.7 thousand cases and almost 44.7 thousand cases, respectively, with icing conditions were identified. The lowest number (11.3 thousand) of such cases was found for the region of Roskilde (N25) compared with other regions. Similarly, since there are different types of road stations within the regions, it is possible to identify the distribution of icing conditions between the stations within the selected region as shown in Fig. 3.2.2b. For example, for the “iciest” region of NordJylland (N80), the seashore stations contributed approximately 14.4% (9052 cases), the land stations – 48.5% (30439), and the rest of the stations – 37.1% (23241) from all of the icing cases (62732) in this region. In Appendix 1, the month-to-month variability (from October till April) of the RA1 road icing conditions is presented for the DRN as a whole as well as by the road regions.



(a) (b)

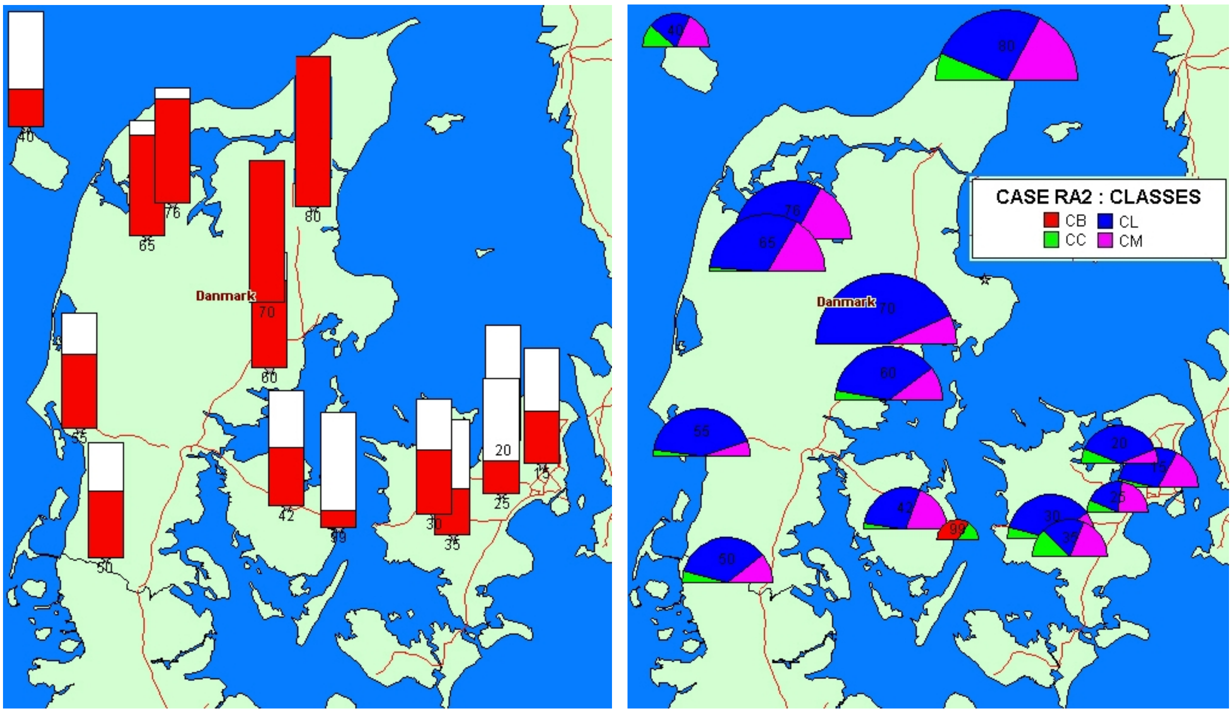
Figure 3.2.1 : Spatial distribution of occurrences (shown in number of cases) of the conditions leading to icing on the roads for the red alert situations (a) RA1 and (b) RA2 observed at the Danish road stations during the road weather seasons 2003-2007.



(a) (b)

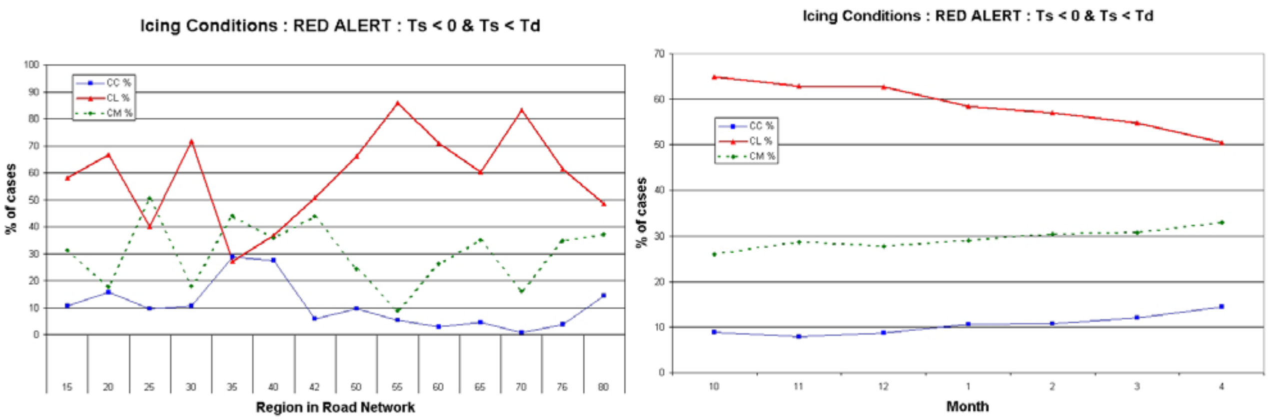
Figure 3.2.2 : Red Alert - RA1 - distribution of the number of the cases for the road surface temperature (a) by the Danish road regions (maximum height of the box is equal to 60,000 cases), and (b) by the road station classes (CB – bridges, CC – seashore, CM – pre-coastal, CL – land road stations) in the Danish road regions based on measurements from the road weather seasons of 2003-2007).

For some stations (as seen in Figs. of Appendix) the occurrence of icing conditions could the very high which depend on the location of the station with respect to the seashore and dominating surrounding terrain and land-use. Analysis of the surrounding land-use at these stations showed the possibility of influence of the shadowing effects local conditions, and in particular, it might be due to forest. As seen in Fig. 3.2.3a, the same regions of NordJylland (N80) and Århus (N70) are the most sensitive regions to icing on the roads. For these two regions, almost 70 thousand cases with icing conditions were identified. The lowest number (17.4 thousand) of such cases was found also for the region of Roskilde (N25) as for the RA1 situation. Similarly, distribution of icing conditions between the stations within the selected region as a function of the road station type is shown in Fig. 3.2.3b. For the same "iciest" region of NordJylland (N80), the seashore stations contributed approximately 12.7% (8828 cases), the land stations – 52.9% (36836), and the rest of the stations – 34.4% (24015) from all of the icing cases (69679) in this region.



(a) (b)

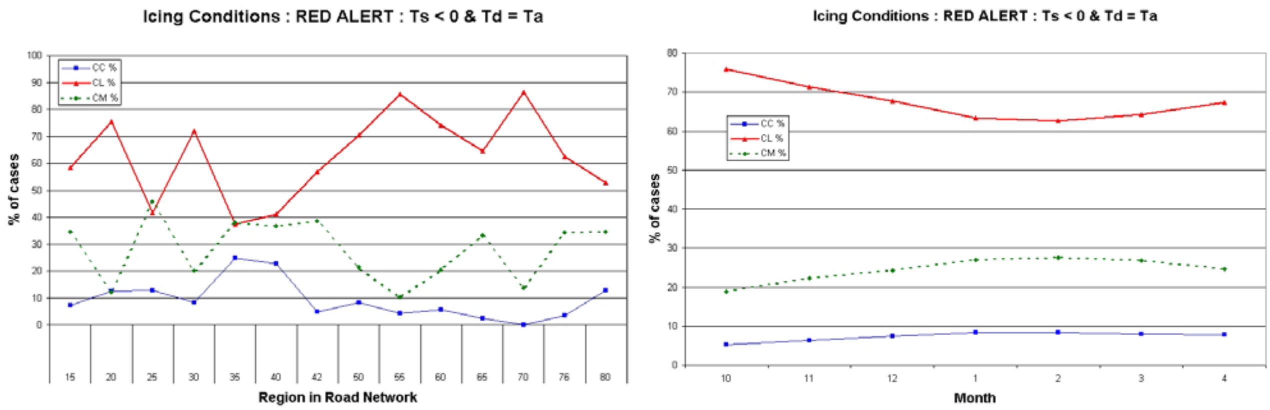
Figure 3.2.3 : Red Alert - RA2 - distribution of the number of the cases for the road surface temperature (a) by the Danish road regions (maximum height of the box is equal to 70,000 cases), and (b) by the road station classes (CB – bridges, CC – seashore, CM – pre-coastal, CL – land road stations) in the Danish road regions based on measurements from the road weather seasons of 2003-2007).



(a) (b)

Figure 3.2.4 : Percentage of the identified icing conditions for the red alert situation (**RA1**) observed at the road stations located near the seashore (CC), distantly inland (CL), and between (CM) as a function of (a) road region and (b) month of the road seasons (based on 2003-2007 period).

The variability in occurrence of the red alert situations at different road stations (inland - CL, seashore - CC, pre-coastal - CM) is also analyzed as a function of the road region (Figs 3.2.4a-3.2.5a) and a month (Figs 3.2.4b-3.2.5b). As seen, the largest number of such situations occurred at inland stations and the lowest at seashore stations. Within the entire DRN, for RA1, from total number of cases of 395866, the number of the road icing cases is accounted for approximately 10, 29, and 59% for the CC, CM, and CL types of the road stations, respectively; and the remaining of less than 2% corresponds to the bridge (CB) stations. For RA2, from total number of cases of 525265, the number of the road icing cases is accounted for approximately 8, 26, and 65% for the CC, CM, and CL types of the road stations, respectively; and the remaining of less than 1% corresponds to the bridge stations.



(a) (b)

Figure 3.2.5 : Percentage of the identified icing conditions for the red alert situation (**RA2**) observed at the road stations located near the seashore (CC), distantly inland (CL), and between (CM) as a function of (a) road region and (b) month of the road seasons (based on 2003-2007 period).

As seen in Figs. Figs 3.2.4a-3.2.5a, the regional variability is well underlined between the classified stations. Among the seashore stations, for the regions of Bornholm (N40) and Storstrom (N35) these are around 28 and 23% in both regions for RA1 and RA2 situations, respectively, compared with other regions. Among the inland stations, for regions of Århus (N70) and Ribe (N55) these numbers are almost 85% for both situations; and these are the highest compared with other regions. Among the pre-coastal stations, for the region of Roskilde (N25) these numbers are more than 45% for both situations.

As seen in Figs. Figs 3.2.4b-3.2.5b, the monthly variability is also well underlined between the classified stations. For RA1, the road icing cases account for more than 12% of the cases during March-April among the seashore stations, for more than 63% – during October-December among the inland stations, and for more than 30% – for the rest of the stations during February-April. For RA2, the road icing cases account for more than 8% of the cases during January-February among the seashore stations, for more than 71% – during October-November among the inland stations, and for more than 27% – for the rest of the stations during January-March.

As expected (Fig. 3.2.6), the curve and shape of the diurnal variability for the RA1 situation is similar to the RA2 situation. The highest occurrence is shown during nighttime, i.e. between 3-5 hours of local standard time; and it is up to 5 times lower during daytime. The amplitude of variability is more pronounced for the inland stations compared with seashore stations, where it has the lowest difference during the day.

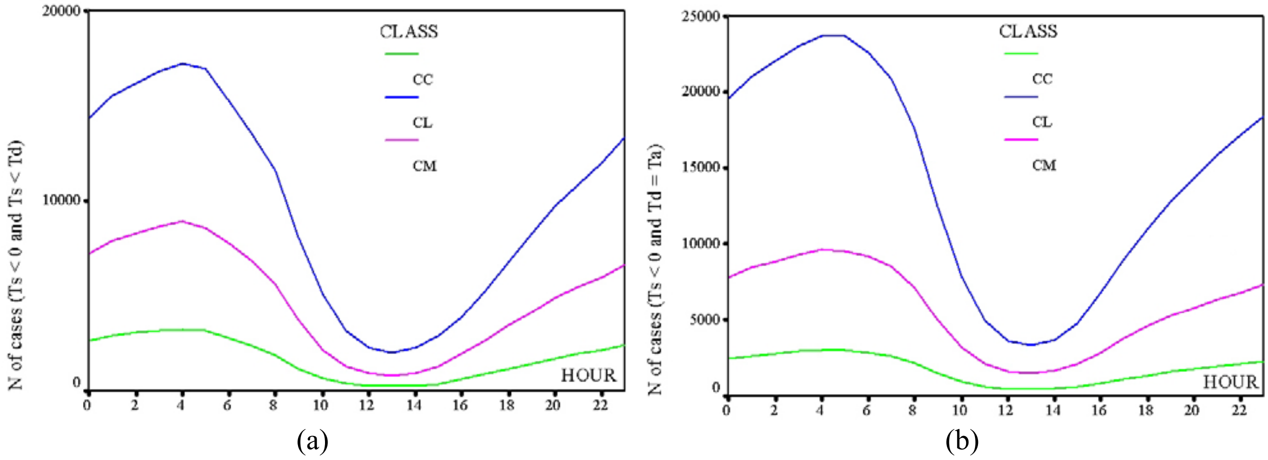


Figure 3.2.6 : Number of cases with identified icing conditions for the red alert situations (a) RA1 and (b) RA2 observed at the road stations located near the seashore (CC), distantly inland (CL), and between (CM) as a function of the diurnal cycle (based on 2003-2007 road weather seasons).

3.3. Spatial Distribution of Warning Situations

The spatial distribution of the warning situations (CW0) during the road weather season 2003-2007 is shown in Fig. 3.3.1 with a legend on a scaling of the number of stations having similar number of measurements corresponding to specified interval.

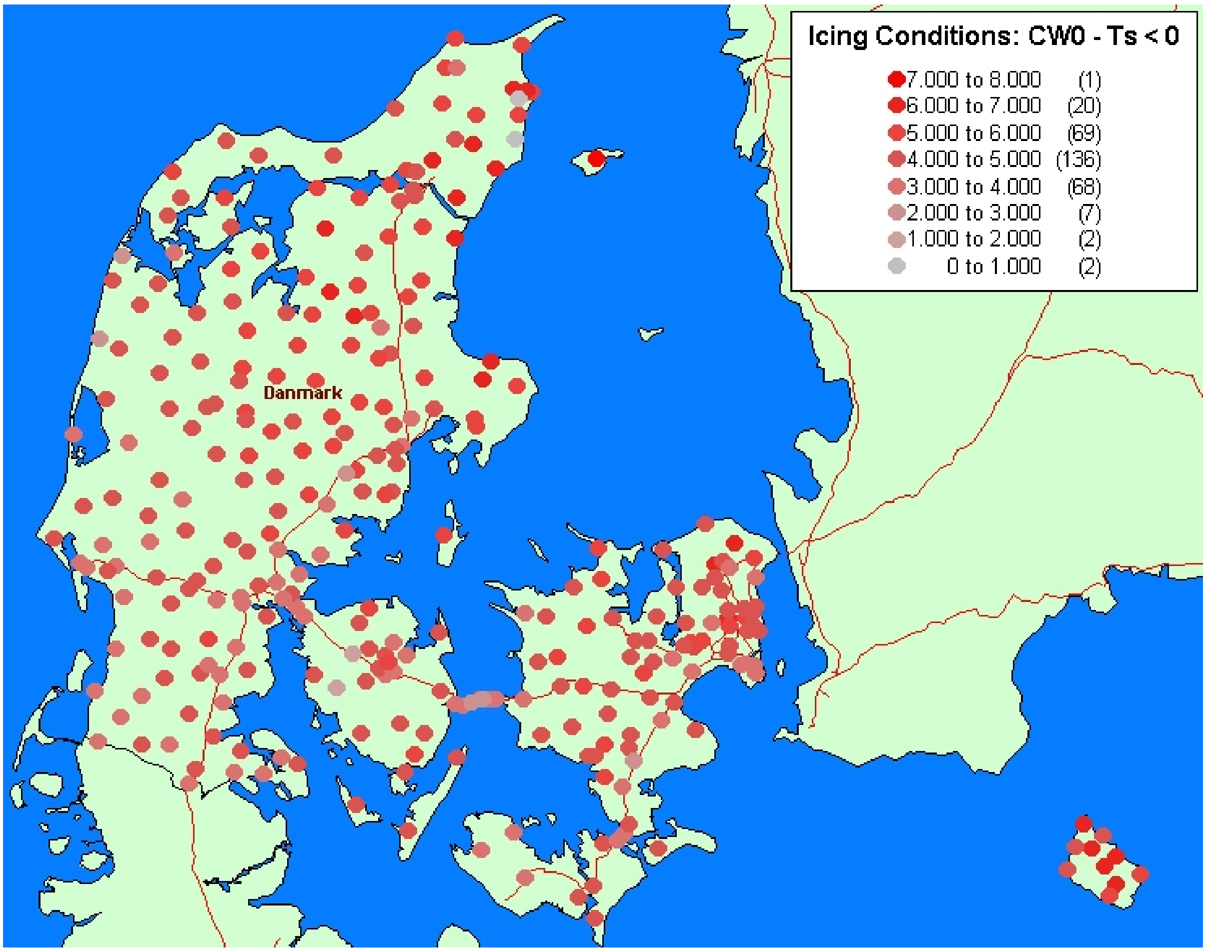
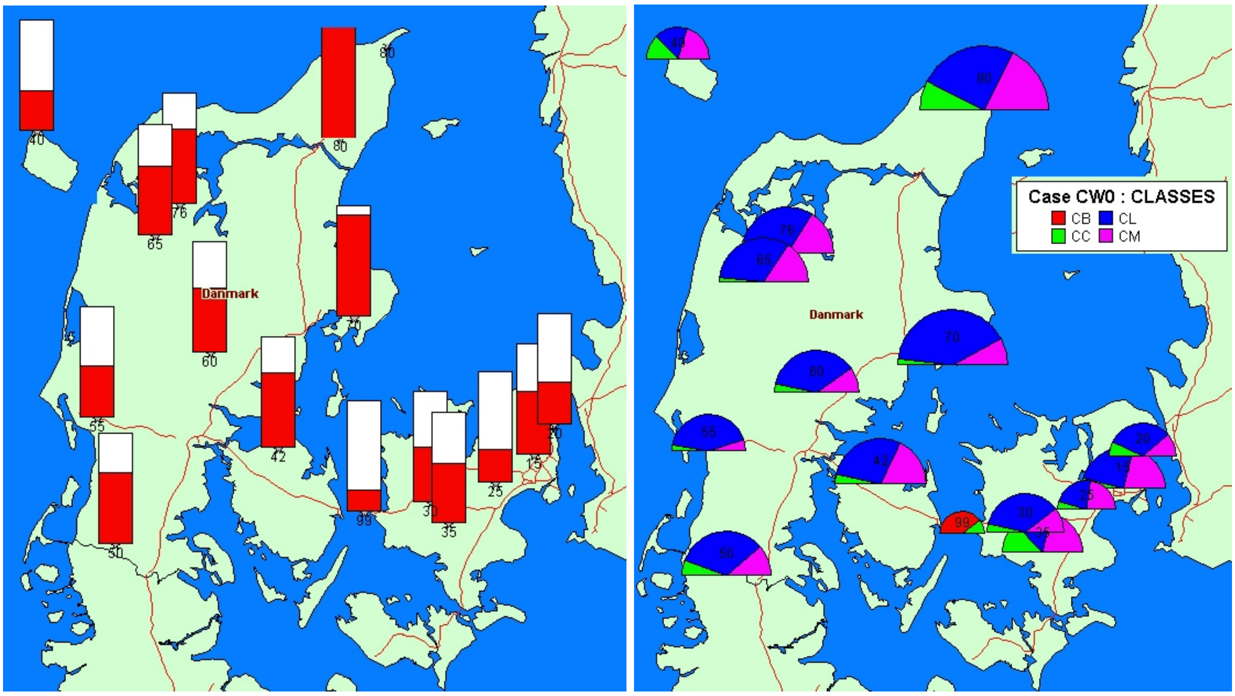


Figure 3.3.1 : Warning situation – CW0 – Spatial distribution of occurrence (shown in number of cases) of the conditions which can potentially lead to formation of icing conditions on the roads observed at the Danish road stations for the road weather seasons of 2003-2007.

As seen, practically in a whole DRN the road surface temperature might be reaching, on an occasion, 0°C, except a few locations where such situations are rare, and a few tens of the stations where such situations might occur very often compared with other stations. It should be noted, that for two other warning situation (with +1 and +2°C) the number of cases will increase by almost 30% and more than 55% compared with 0°C situation (i.e. assuming 100% accounted by 1385169 cases for the CW0 situation).

As seen in Fig. 3.3.2a, the regions of NordJylland (N80) followed by Århus (N70) are the most sensitive regions to icing on the roads. For these two regions, almost 194 thousand cases and almost 148 thousand cases, respectively, were identified for warnings, which can potentially lead to formation of the icing conditions. The lowest number (48.6 thousand) of such cases was found for the region of Roskilde (N25) compared with other regions. Similarly, since there are different types of road stations within the regions itself, it is possible to identify the distribution of icing conditions between the stations within the selected region as shown in Fig. 3.3.2b. For example, for the region of NordJylland (N80), the seashore stations contributed approximately 14.9% (28907 cases), the inland stations – 50% (96914), and the rest of the stations – 35.1% (68139) from all cases (193960) identified in this region.

The largest number of such situations occurred at the inland stations and the lowest at the seashore stations. Within the entire DRN, for CW0, from total number of cases of 1385169, the number of warning for possibility of the road icing formation is very similar to the red alert situations and it is accounted for approximately 10, 29, and 59% for the CC, CM, and CL types of the road stations, respectively; and the remaining of less than 2% corresponds to the stations situated at bridges.



(a) (b)

Figure 3.3.2 : Distribution of the number of the cases for the road surface temperature (a) by the Danish road regions (maximum height of the box is equal to 200,000 cases), and (b) by the road station classes (CB – bridges, CC – seashore, CM – pre-coastal, CL – inland road stations) in the Danish road regions based on measurements from the road weather seasons of 2003-2007).

As seen in Tab. 3.3.1, the regional variability is well identified between the stations divided into groups. Among the seashore stations (CC), for the regions of Bornholm (N40) and Storstrom (N35) these numbers are almost 25% in both regions compared with other regions. The lowest values of 3% are observed for both regions of Ringkobing (N65) and Århus (N70). Among the inland stations, for both regions of Århus (N70) and NordJylland (N80) these numbers are more than 81%, and these are the highest compared with other regions. The lowest value of 32% is for the region of Storstrom (N35). Among the pre-coastal stations, for the region of Roskilde (N25) these are more than 45%, and the lowest – 10% – for the region of Ribe (N50). The monthly variability is also well observed between the classified stations. The road icing cases account for more than 10% of the cases during January-March among the seashore stations, for more than 62% – during October-December and in April among the inland stations, and for more than 29% – for the rest of the stations during January-March.

Table 3.3.1 : Distribution of the number of the cases for the road surface temperature for CW0 by the Danish road regions and month-to-month variability as a function of the road station classes (CB – bridges, CC – seashore, CM – pre-coastal, CL – inland road stations) in the Danish road regions based on measurements from the road weather seasons of 2003-2007).

Road Regions Variability

	CB		CC		CM		CL		Total	
Region	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**
15	-	-	7534	8.3	38511	42.3	44961	49.4	**91006**	**100**
20	-	-	8665	14.0	13857	22.4	39344	63.6	**61866**	**100**
25	-	-	4417	9.1	22231	45.7	21967	45.2	**48615**	**100**
30	-	-	5587	7.0	16620	20.9	57442	72.1	**79649**	**100**
35	-	-	21817	25.6	36455	42.8	26910	*31.6*	**85182**	**100**
40	-	-	14012	24.6	23064	40.6	19790	34.8	**56866**	**100**
42	-	-	7415	6.9	38304	35.8	61271	57.3	**106990**	**100**
50	-	-	11659	11.3	23254	22.5	68377	66.2	**103290**	**100**
55	-	-	3840	5.2	7463	*10.0*	63191	84.8	**74494**	**100**
60	-	-	6271	6.7	18423	19.6	69230	73.7	**93924**	**100**
65	-	-	3088	*3.1*	31717	31.4	66063	65.5	**100868**	**100**
70	-	-	5200	*3.5*	23163	15.7	119584	80.8	**147947**	**100**
76	-	-	8827	8.2	34782	32.2	64480	59.7	**108089**	**100**
80	-	-	28907	14.9	68139	35.1	96914	50.0	**193960**	**100**
99	25648	79.1	6775	20.9	-	-	-	-	**32423**	**100**
Total	**25648**	**1.9**	**144014**	**10.4**	**395983**	**28.6**	**819524**	**59.2**	**1385169**	**100**

Month-to-Month Variability

	CB		CC		CL		CM		Total	
Month	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**
10	91	0.5	1389	8.3	4307	25.9	10852	65.2	**16639**	**100**
11	357	0.5	6981	8.9	21465	27.3	49925	63.4	**78728**	**100**
12	1960	1.1	16810	9.6	48007	27.4	108525	61.9	**175302**	**100**
1	8601	2.1	43192	10.7	116257	28.8	235499	58.4	**403549**	**100**
2	9079	2.0	47209	10.6	129293	29.2	257745	58.1	**443326**	**100**
3	5402	2.1	27291	10.7	73203	28.7	149201	58.5	**255097**	**100**
4	158	1.3	1142	9.1	3451	27.5	7777	62.1	**12528**	**100**
Total	**25648**	**1.9**	**144014**	**10.4**	**395983**	**28.6**	**819524**	**59.2**	**1385169**	**100**

4. Conclusion

In this study evaluation of the road icing conditions in the Danish road network was conducted based on observational data (road surface, air and dew point temperatures) from the road stations. The time series, consisting of measurements (in total more than 7.8 mln cases) conducted during 2003-2007 road weather seasons, was evaluated. Depending on variabilities between the observed temperatures, the red alert situations (representing the icing conditions on the roads) and warning situations (representing a high likelihood of the ice formation on the roads) were distinguished and analyzed in more details. Analysis showed that during the road seasons the red alert situations might occur, on average, up to 7%, although the warning situations (which might lead to formation of ice on roads) might account up to 28%. This analysis has provided also insight on geographical spatial distribution of the situations leading to the icing condition on the roads in Denmark.
The icing conditions are more pronounced at the inland stations compared with others, but contribution of other types of the stations is also significant. The "iciest" region of Denmark is NordJylland where the seashore, pre-coastal, and inland stations contribute around 13, 34, and 53%, respectively to observed icing conditions on the roads. The most sensitive areas were identified and hence, efforts to improve quality of the road forecasts in these areas should be done as well as additionally the thermal mapping measurements should be also carried out for improving quality and accuracy of the road stretch forecasting. The proposed visualization of these results is a very useful illustration, and it could be recommended to include it also into DMI's official annual reports (prepared at the end of each season) related to verification of the road conditions forecasts, as for the whole season as well as to show the month-to-month variability of the formation of the road icing conditions. Since some of the road stations showed very high probabilities for observing the icing conditions, these divided into different classes/ types of the stations (such as seashore, pre-coastal, and inland) could be also used as selected reference stations for revised verification (among the full list of stations available but only for stations having the longest time series of observations).

Acknowledgments

The computer facilities at DMI have been employed extensively. The Danish synoptical meteorological data from the DMI and Danish Road Directorate (DRD) archives have been used in this study. The authors are thankful for collaboration with DRD. The funding was provided within the frameworks of the joint DRD and DMI project entitled "*Road Segment Forecasts*" (2006-2008) within framework of the VIKING-6 Projects.

References

GlatTerm, **2004**: Brugervejledning til GlatTerm version 2.73. *Technical Documentation for the DMI Road Weather Modelling system*, 31p, September 2004.

Mahura A., C. Petersen, B.H. Sass, P. Holm, T.S. Pedersen, **2007**: Road Stretch Weather Forecasting: Thermal Mapping Data Applicability. *DMI Scientific Report, 07-06*, 33 p.

Mahura A., Petersen C., Sass B., **2008**: Road Weather Model Verification: Revised Approach and Formulations. *DMI Scientific Report*, *In Finalization.*

Petersen C., Mahura A., Sass B., Pedersen T., **2008**: Road Weather Modelling System: Verification for 2007-2008 Road Weather Season. *DMI Technical Report*, 08-09, 14 p.

Petersen C., Sass B., Mahura A., T.S. Pedersen, **2007**: Road Weather Model System : Verification for 2005-2007 Road Weather Seasons. *DMI Technical Report*, 07-11, 19 p.

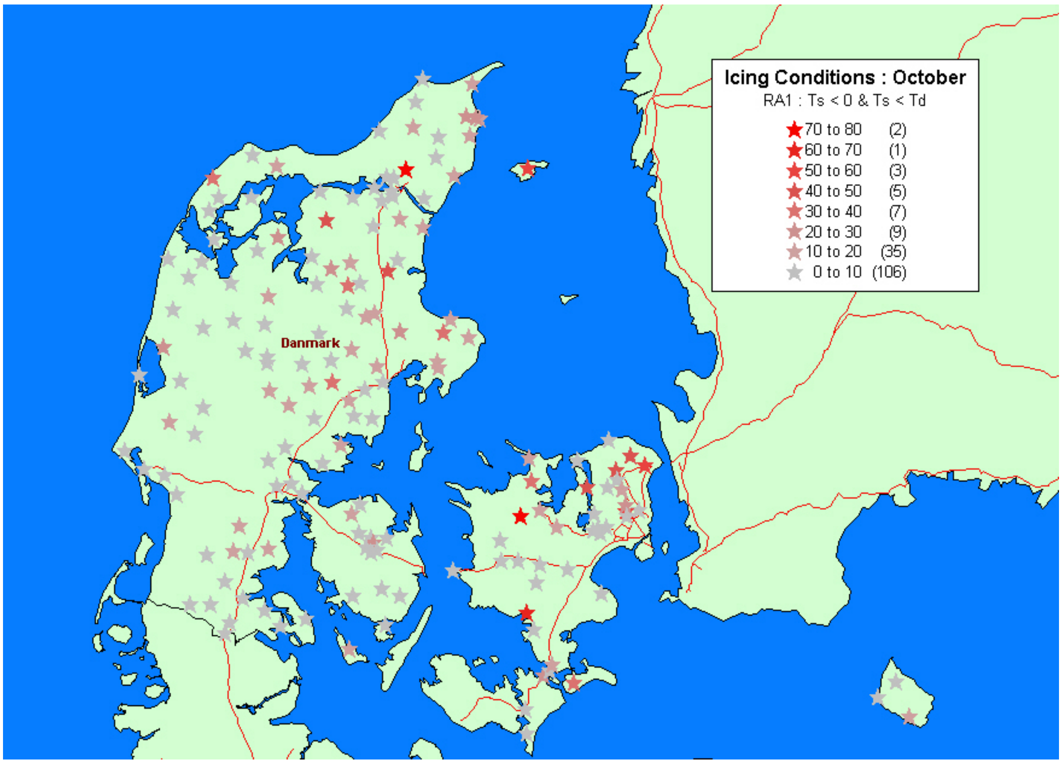
Sass B., **1992**: A Numerical Model for Prediction of Road Temperature and Ice. *Journal of Applied Meteorology,* 31, pp. 1499-1506.

Sass B., **1997**: A Numerical Forecasting System for the Prediction of Slippery Roads. *Journal of Applied Meteorology,* 36, pp. 801-817.

Sass B., Woetmann, N.W., Jorgensen, J.U., Amstrup, B., Kmit,M., K.S. Mogensen, **2002**: The operational DMI-HIRLAM system 2002 - version. *DMI Technical Report* N 02-05, 60 p.

Yang X., Petersen C., Amstrup B., Andersen B., Feddersen H., Kmit M., Korsholm U., Lindberg K., Mogensen K., Sass B., Sattler K., Nielsen W. **2005**: The DMI–HIRLAM upgrade in June 2004. *DMI Technical Report*, 05-09, 35 p.

Appendix 1. Monthly Variability of Road Icing Conditions in Denmark



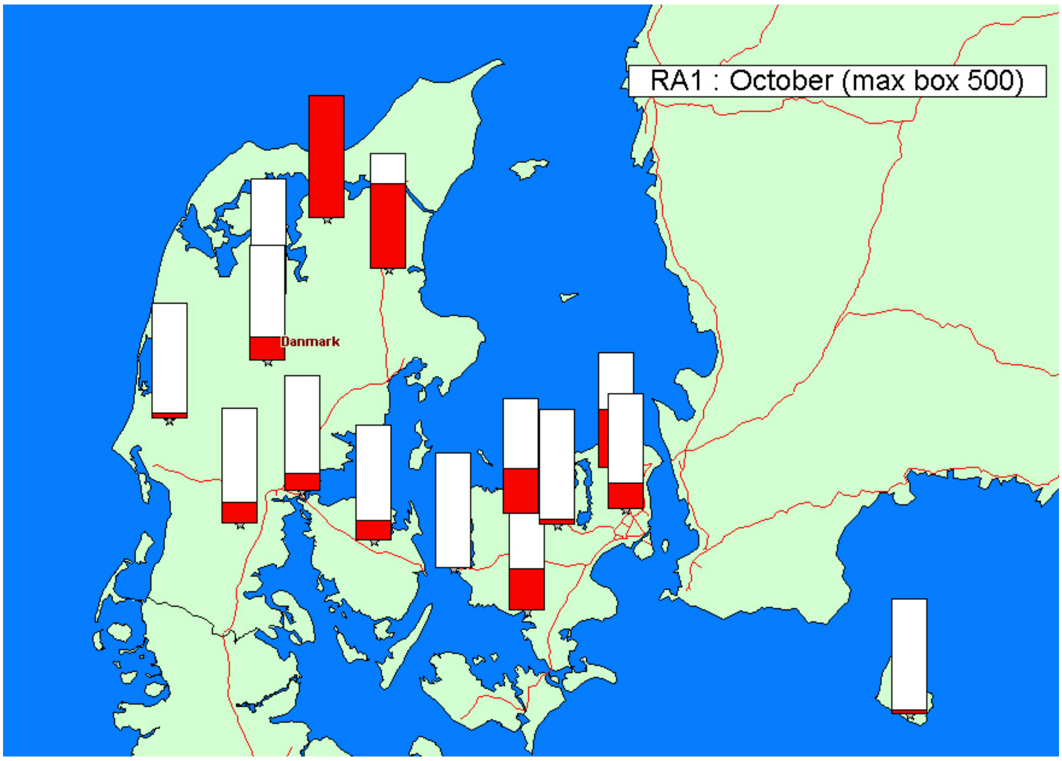


Figure A1 : (top) Distribution of icing conditions at road stations of the Danish road network during October (number in brackets corresponds to number of the road stations with similar conditions, and intensity of the colored symbol corresponds to higher likelihood of icing), and (bottom) Distribution of icing conditions by regions in January (maximum box height = 500 observations with icing conditions).

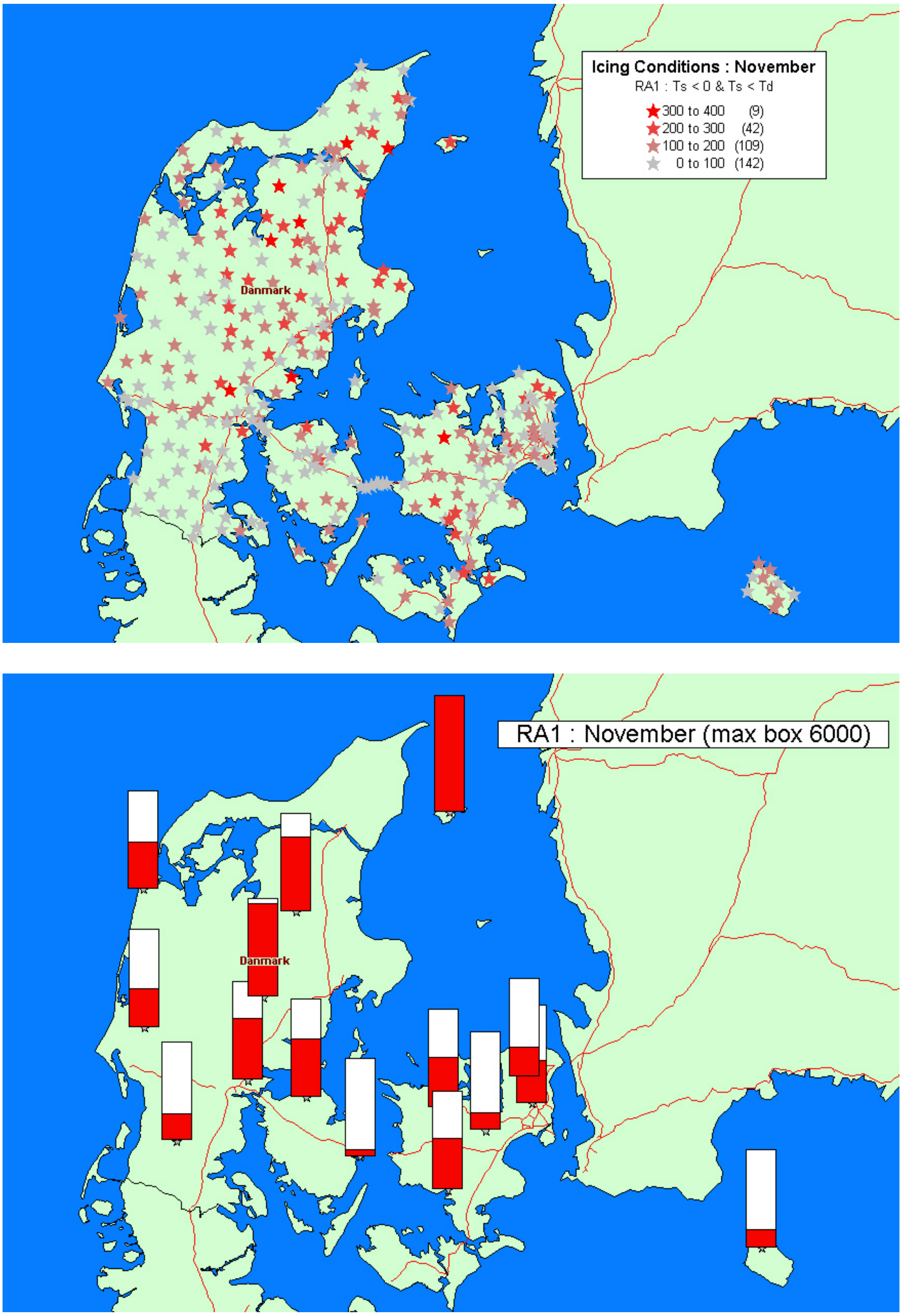
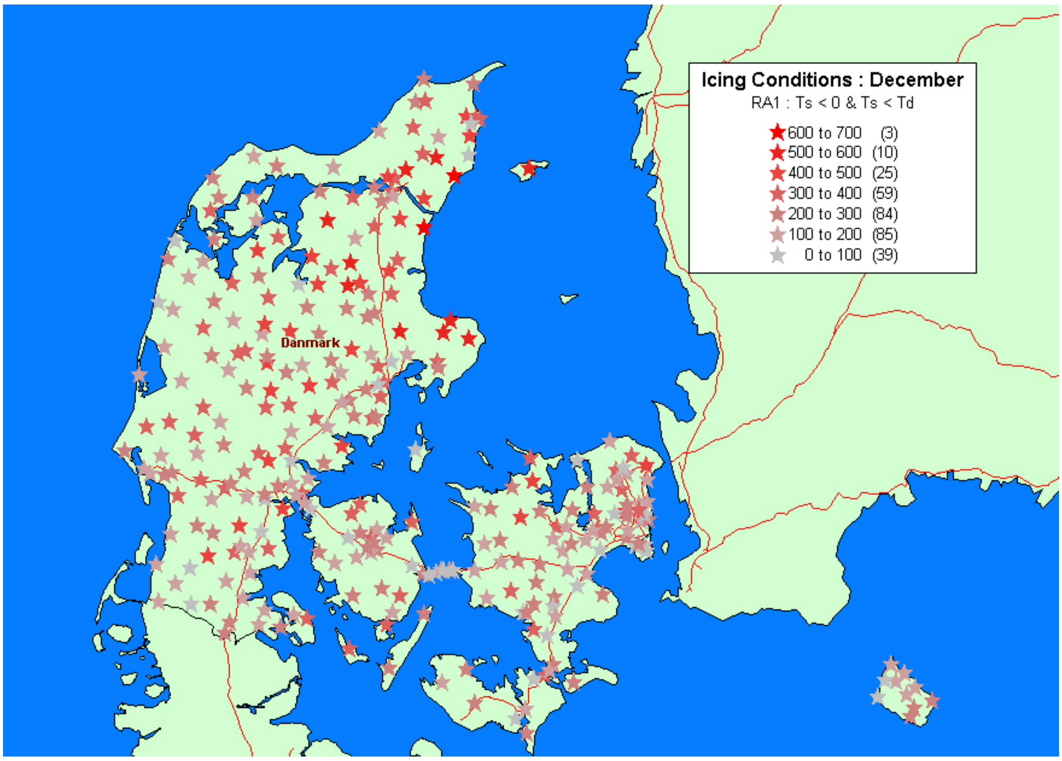


Figure A2 : (top) Distribution of icing conditions at road stations of the Danish road network during November (number in brackets corresponds to number of the road stations with similar conditions, and intensity of the colored symbol corresponds to higher likelihood of icing), and (bottom) Distribution of icing conditions by regions in January (maximum box height = 6,000 observations with icing conditions).



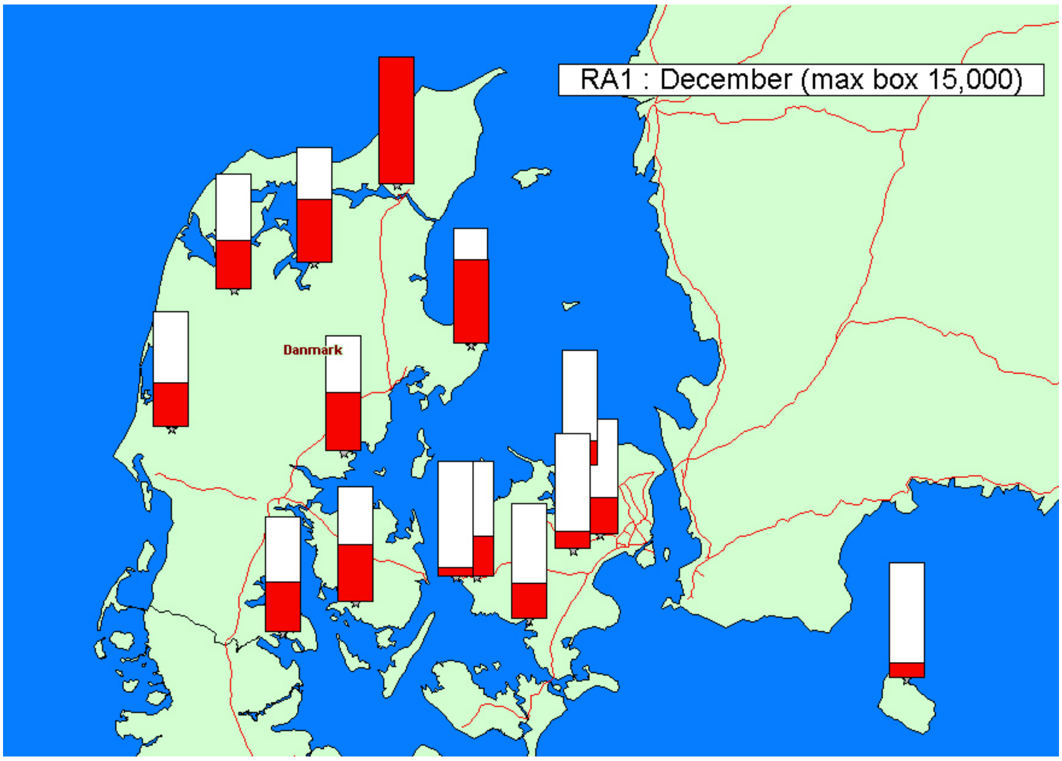


Figure A3 : (top) Distribution of icing conditions at road stations of the Danish road network during December (number in brackets corresponds to number of the road stations with similar conditions, and intensity of the colored symbol corresponds to higher likelihood of icing), and (bottom) Distribution of icing conditions by regions in January (maximum box height = 15,000 observations with icing conditions).

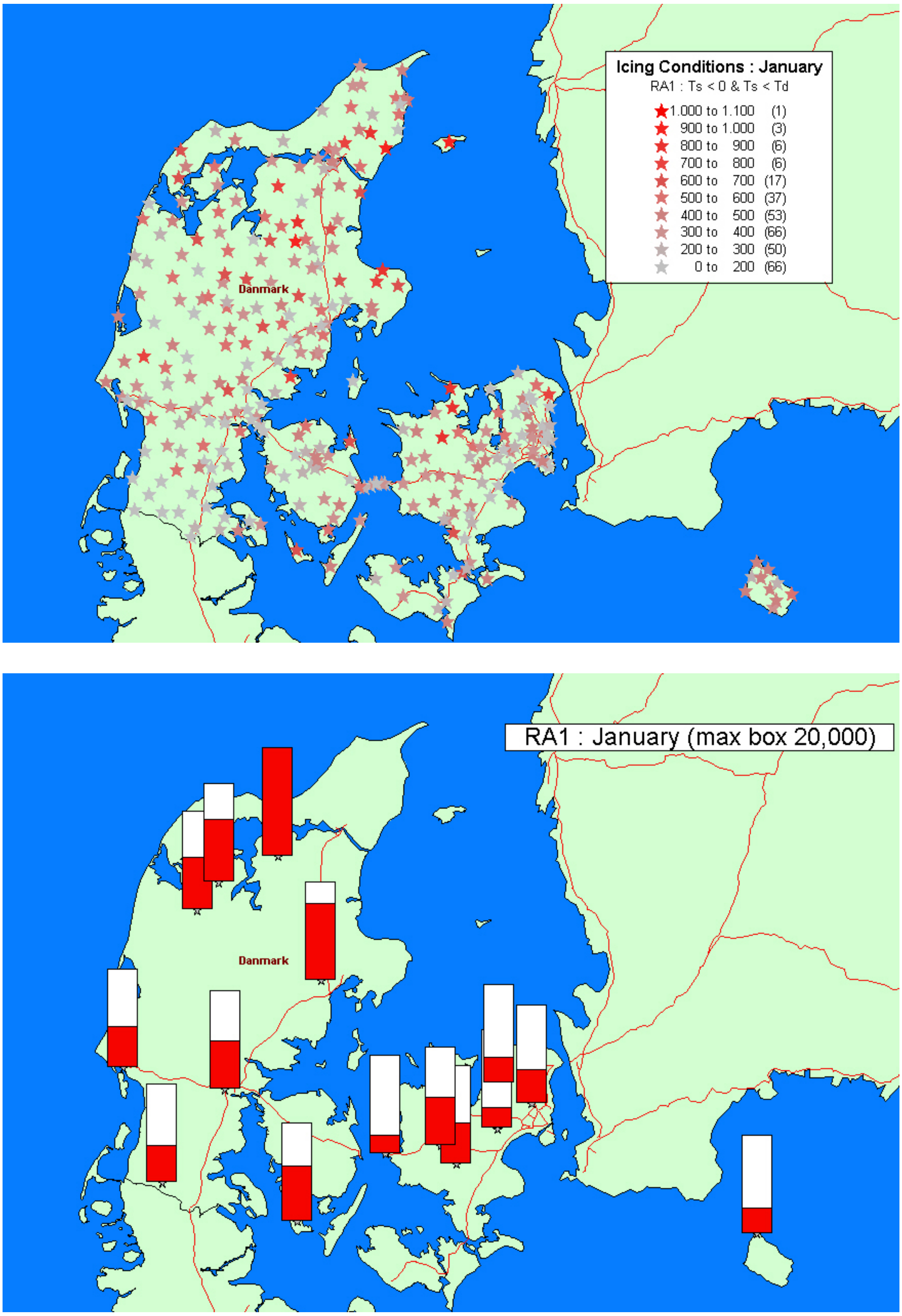
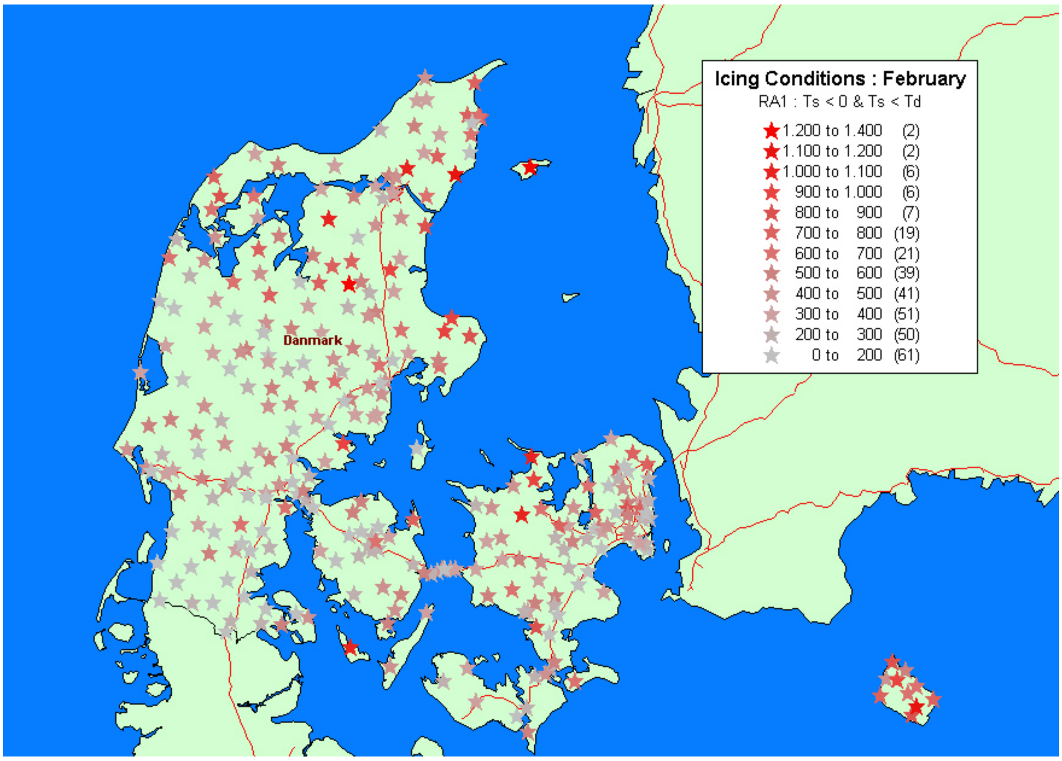


Figure A4 : (top) Distribution of icing conditions at road stations of the Danish road network during December (number in brackets corresponds to number of the road stations with similar conditions, and intensity of the colored symbol corresponds to higher likelihood of icing), and (bottom) Distribution of icing conditions by regions in January (maximum box height = 20,000 observations with icing conditions).



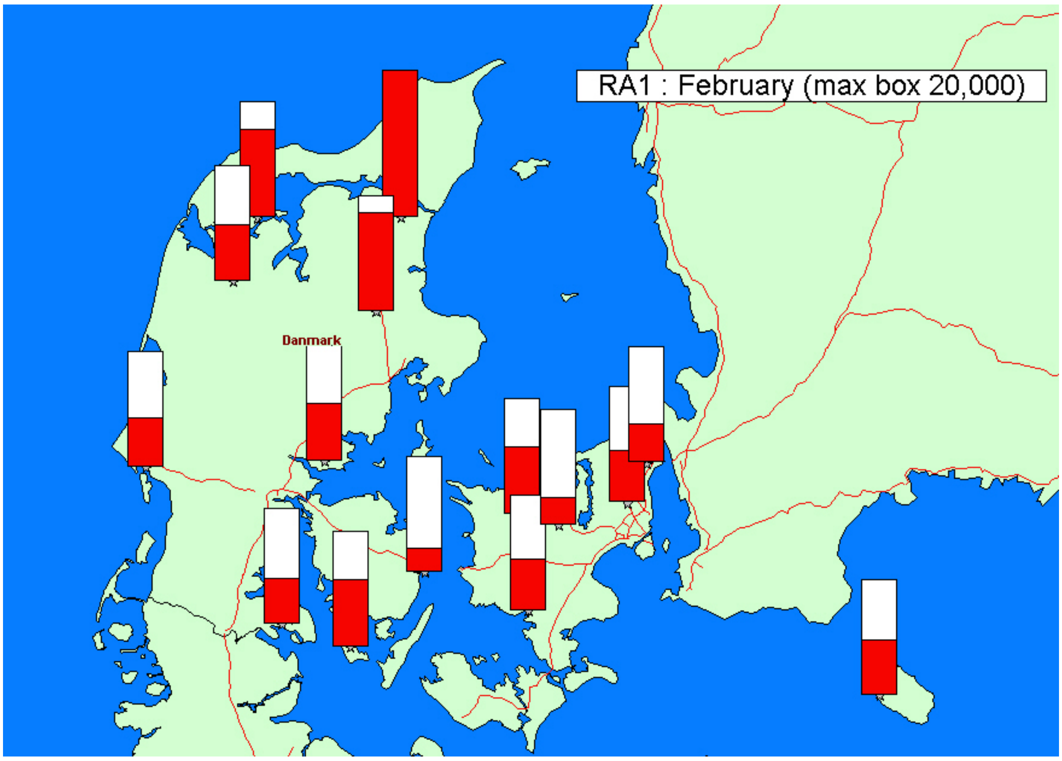
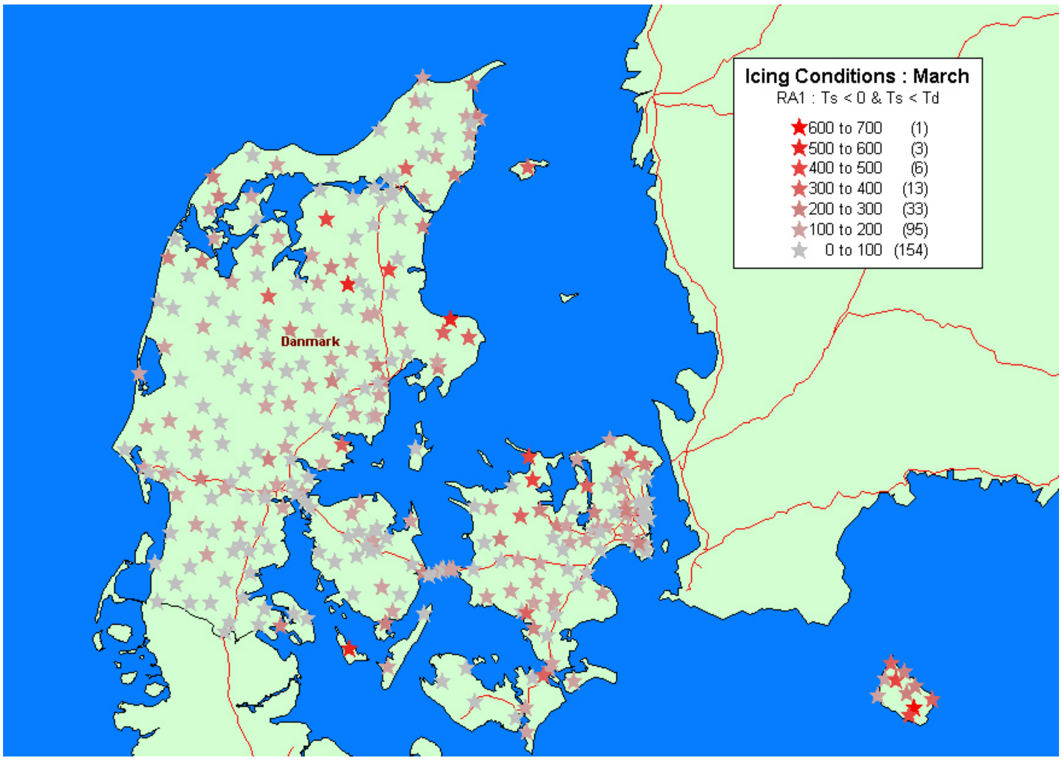


Figure A5 : (top) Distribution of icing conditions at road stations of the Danish road network during February (number in brackets corresponds to number of the road stations with similar conditions, and intensity of the colored symbol corresponds to higher likelihood of icing), and (bottom) Distribution of icing conditions by regions in January (maximum box height = 20,000 observations with icing conditions).



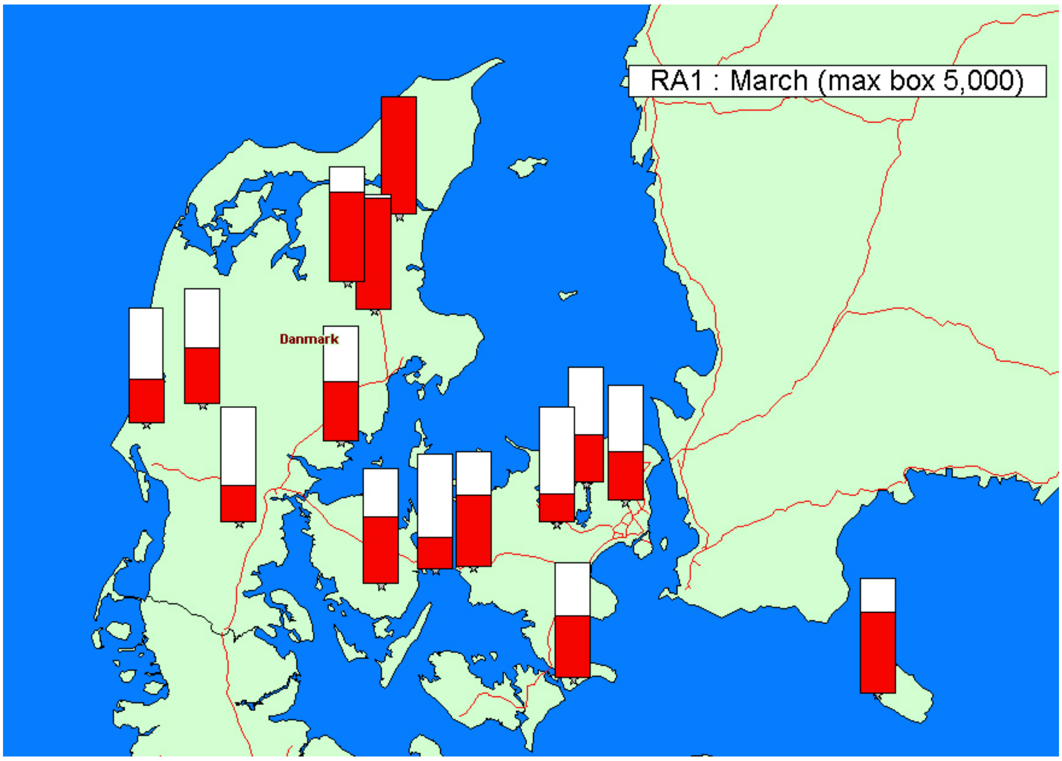


Figure A6 : (top) Distribution of icing conditions at road stations of the Danish road network during March (number in brackets corresponds to number of the road stations with similar conditions, and intensity of the colored symbol corresponds to higher likelihood of icing), and (bottom) Distribution of icing conditions by regions in January (maximum box height = 5,000 observations with icing conditions).

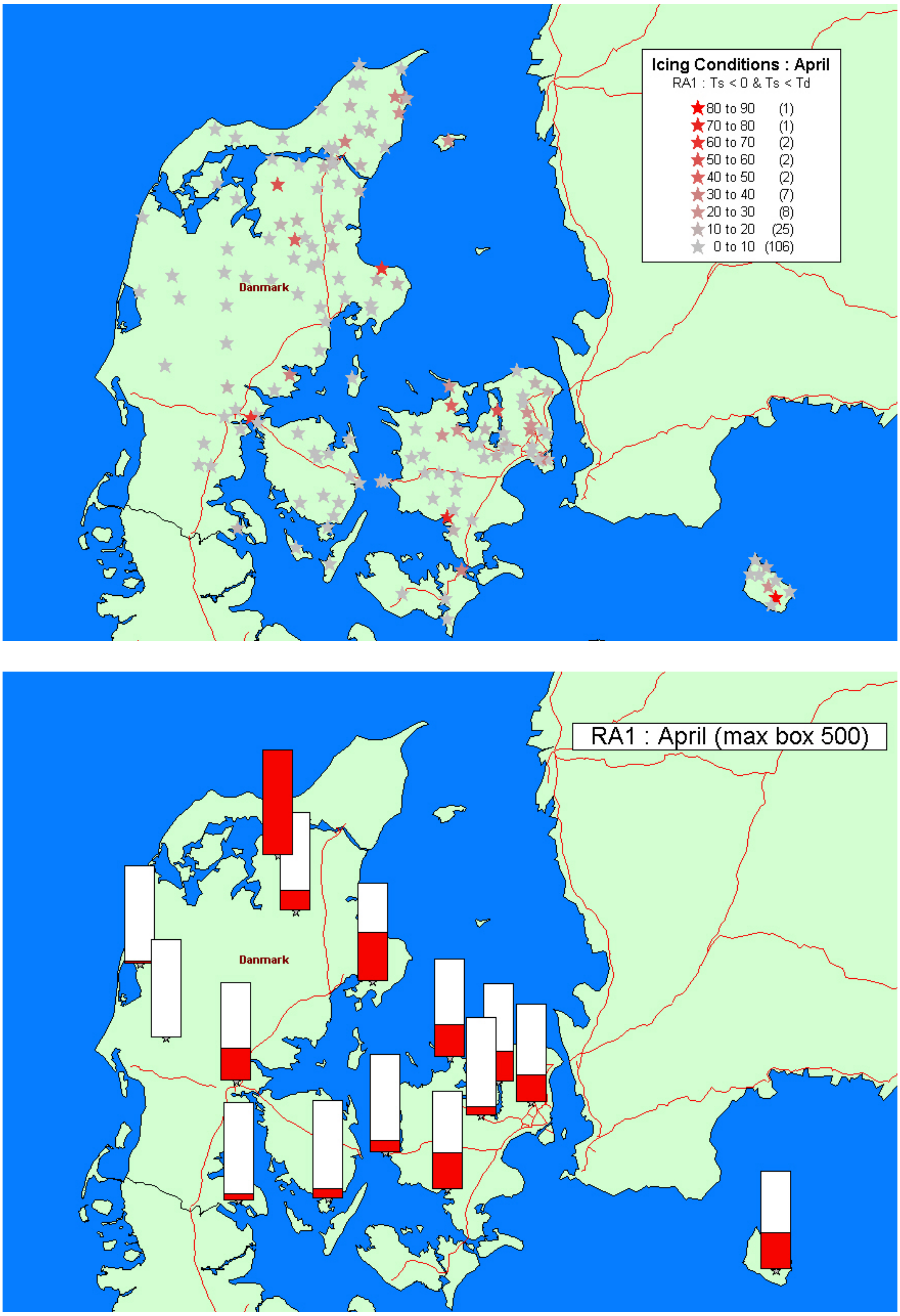


Figure A7 : (top) Distribution of icing conditions at road stations of the Danish road network during April (number in brackets corresponds to number of the road stations with similar conditions, and intensity of the colored symbol corresponds to higher likelihood of icing), and (bottom) Distribution of icing conditions by regions in January (maximum box height = 500 observations with icing conditions).