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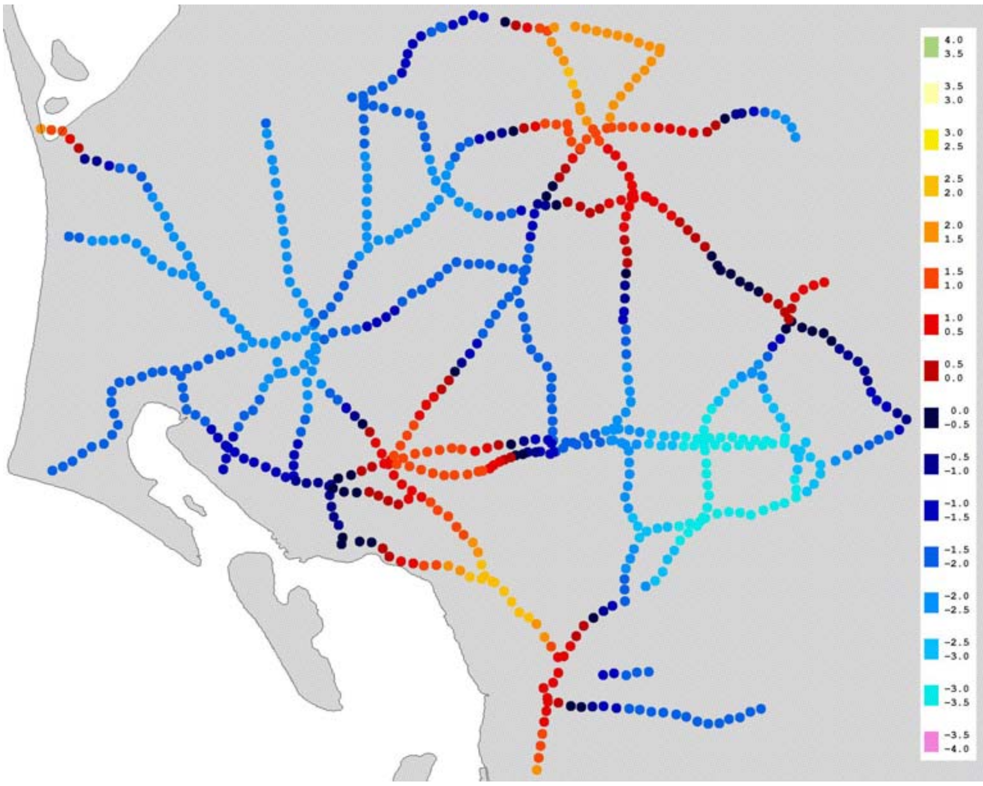
Road Stretch Weather Forecasting: Thermal Mapping Data Applicability



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Abstract

In this study, which is a part of the VIKING-6 project, the vehicles measurements of the road conditions (road surface and air temperatures - thermal mapping data) from Ribe and Vestsjælland Communes roads (VA-4, RI-1, GR-2, and 102-KS-L) have been used for verification of performance of the Danish Road Weather Model (RWM) system. During 2006-2007, in total 209 cases/dates with road salting activities have been identified and analyzed by comparing observed and 3 hour forecasted road surface and air temperatures at 89 selected stretches (each with a length of 2 km) of the road.

It is found that the RWM system has a good predictive skill for the road surface temperature at the road stretches having a mean absolute error of 0.90ºC (bias is 0.34ºC) for all stretches during the season. For the air temperature, the mean absolute error is 1.30ºC (bias is 1.44ºC). On a diurnal cycle, for the road surface temperature the nighttimes had the best quality of prediction. Only in 17% of the cases for the road surface temperature, the forecast's mean absolute error is higher than 1.5ºC. There was found a strong dependence of the road surface temperature forecasts as a function of the road stretches heights. It is well predicted for stretches located below 30 meters whereas the mean absolute error larger than 1 ºC for higher elevations. This outcome needs to be further investigated using results of forecasting from all of the Danish road network stations and road stretches.

Resumé

I dette studie, som er en del af VIKING-6 projektet, er målinger fra køretøjer af vejforholdene langs vejstrækninger i Ribe og Vestsjælland amter (VA-4, RI-1, GR-2 og 102-KS-L) anvendt til at verificere kvaliteten af DMI's vej vejr model (RWM) system. I løbset af vintersæsonen 2006-2007 er der rapporteret 209 tilfælde af vej saltningsepisoder og disse er blevet analyseret og sammenlignet med observerede og 3 timers prognoser af vej- og lufttemperatur for 89 udvalgte vejstrækninger, hvor hver vejstrækningen er af ca. 2 kilometers længde.

Det er fundet at RWM systemet har gode forudsigelsesevner for vejtemperaturen med en middel absolut fejl på 0.90ºC (BIAS er 0.34ºC) summet over alle vejstrækninger og alle tilfælde. For lufttemperaturen er middel absolut fejlen 1.30ºC (BIAS er 1.44ºC). På daglig basis er vejtemperaturen bedst forudsagt for nattetimerne. Kun i 17 % af tilfældene er middel absolut fejlen større end 1.5ºC. Yderligt blev det konstateret at middel absolut fejlen var stærkt afhængig af højden af vejstækningen. Vej temperaturen er velforudsagt for vejstrækninger beliggende under 30 meters højde, hvorimod middel absolut fejlen er mere end 1ºC større for større højder. Disse resultater lægger op til yderligere analyser af prognoser for alle danske vejstationer og vejstrækninger.

1. Introduction

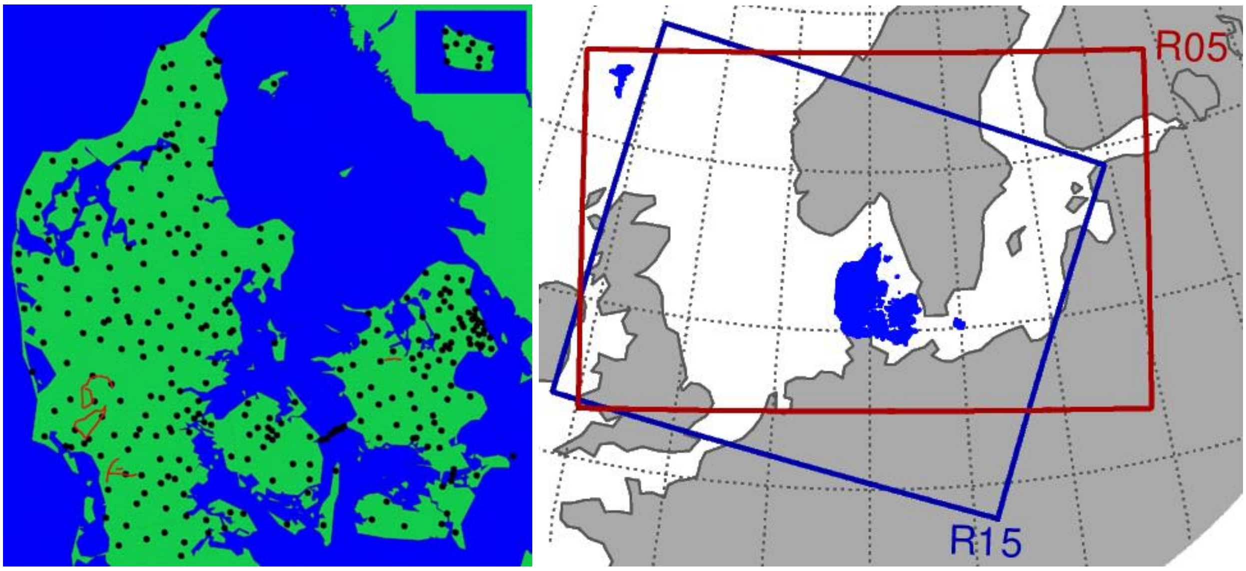
The continuous development of more refined numerical weather prediction (NWP) models and increased computer power allow an increasing model resolution which might provide more local and accurate forecasts. There are several important issues which should be mentioned. Satellite data for cloud cover are now assimilated and routinely used for the road weather forecasting. Second, a high resolution model is already available, i.e. Danish Meteorological Institute (DMI) is running the HIgh Resolution Limited Area Model (HIRLAM) with a resolution of 5 km for the operational daily runs. Also a research version of this model has been tested with a resolution of 1.4 km (covering territory of Denmark and surroundings). Third, in Denmark, the road services already have started to use observations from vehicles allowing to get additional information on road conditions which can also be used for forecasting purposes. During the 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. The process of recording and quantifying of temperature pattern variations is known as the thermal mapping (done by special infra-red thermometers mounted on vehicles).
This third item is a focus of our study. Such kind of data provide more details of the road conditions along road sections/stretches (located at short distances from each other), and can be used to improve the forecasts by providing more local information. This allow optimizing of the amount of salt spreaded over the road surface to prevent the icing/freezing as well as better planning and timing of the schedule for such operations by the road authorities. This improves the safety of road traffic.
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 thermal mapping data can give more detailed information and improve existing forecasts of road conditions at selected points along the Danish road station network.
Therefore, evaluation, forecasting, and verification of road conditions at stretches along the road pathways of the Danish road network using observational data from the road vehicles (thermal mapping measurements) is a focus of our study (as a part of the joint Danish Road Directorate (DRD) and DMI project entitled “Road Segment Forecasts” (2006-2008) within framework of the VIKING-6 Projects. This report also covers the first and second year of this project activities.

2. Methodology

2.1. Forecasting Using DMI-HIRLAM Road Weather Model System

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 (RWM) system. This system provides monitoring and forecasting of road conditions at selected locations in Denmark. There are more than 300 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*).
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 and having a 15 km resolution; from Fall of 2007 – testing of DMI-HIRLAM-R model at 5 km resolution) and network of road stations are shown in **Figure 1**. Detailed description of the road conditions model is given by *Sass (1992, 1997)* and documentation for the HIRLAM model used is provided by *Sass et al. (2002).* A summary of recent research developments done for the RWM system is given in publications/presentations by *Sass & Petersen (2004); Petersen (2005); Petersen & Sass (2005); Sass et al. (2005, 2006); Petersen et al. (2006abcd).*



(a) (b)

Figure 1. (a) Danish road stations network and (b) model domains of the DMI-HIRLAM RWM system having 15 (R15) and 5 (R05) km resolutions (testing starts from fall of 2007).

2.2. Selected Roads and Activities

During the road winter season of 2006-2007 additional thermal mapping measurements have been conducted along several Danish roads/driving lanes (see **Table 1**). Three of these roads are located on the Jylland Peninsula in the Ribe county, and one road – on the Sjælland Island in the Vestsjælland county (see road stretches – in **Appendix A**). Extraction of records from the Danish Road Directorate (DRD) on-line database showed that there are **209** available road salting activities corresponding to these four roads. Due to a relatively warm winter weather conditions the earliest salting road activity are from 17 December 2006. The longest duration of salting activity is more than 4 hours. The largest number of activities – 75 – was carried out for the road GR-2 located in the Ribe County, and the smallest – 24 – for the 102-KS-L road located in the Vestsjælland County.

Table 1. Characteristics of selected Danish roads with thermal mapping measurements conducted during the road winter season of 2006-2007.

Road/ Route	Region/ County	Route length (km)	N Road Stretches	Closest Road Stations	Salting Road Activities		
					Start Date	End Date	N
VA-4	55- Ribe	57.2	30	5504, 5505, 5506/5519	17-12-2006	04-03-2007	59

RI-1	55-Ribe	46.1	24	5514, 5002, 5009	17-12-2006	03-03-2007	51
GR-2	55-Ribe	66.2	30	5508, 5507, 6529	17-12-2006	10-03-2007	75
102-KS-L	30-Vestsjælland	35.7	6	3005	05-01-2007	10-03-2007	24

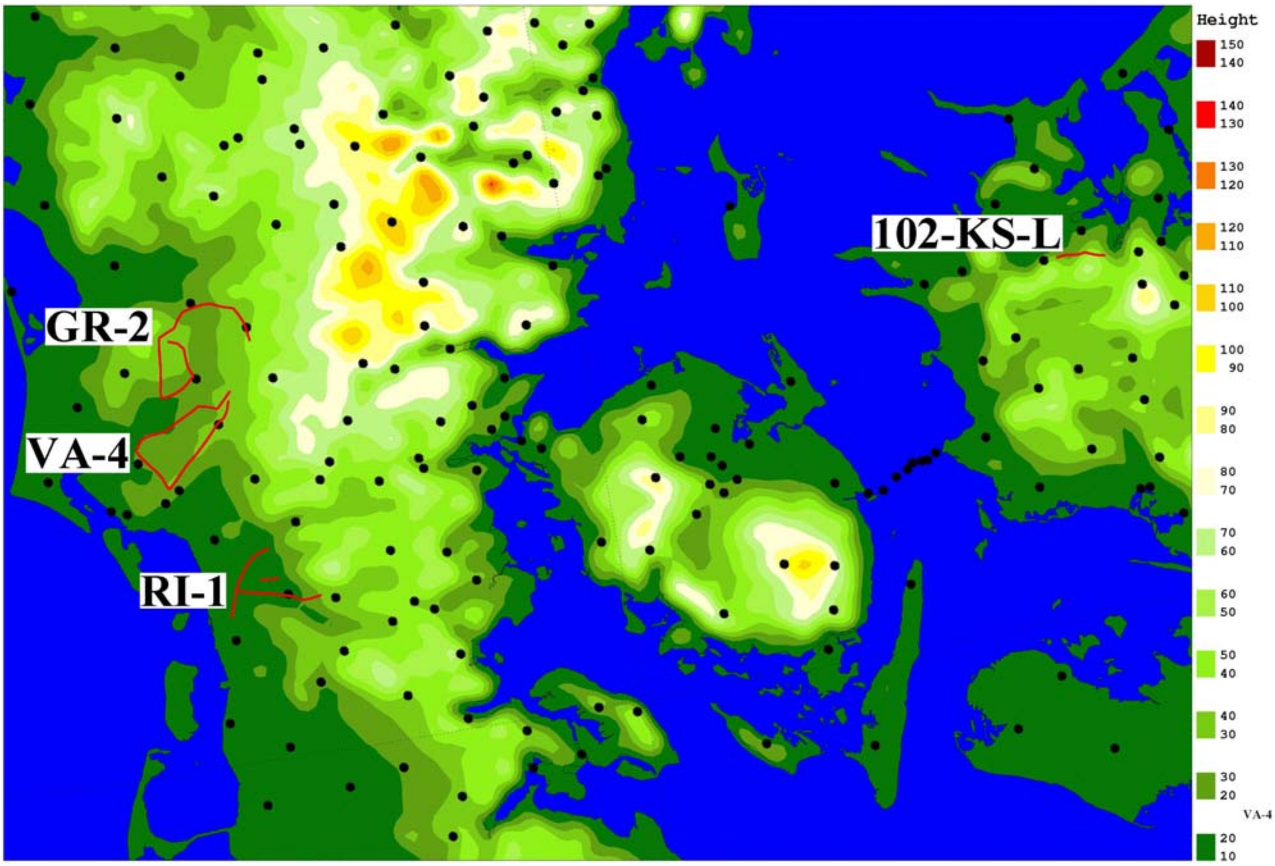


Figure 2. Geographical location of the routes (shown in red) where the thermal mapping measurements were conducted during the road winter season of 2006-2007.

2.3. Thermal Mapping Measurements

Thermal mapping is a process of measurement of spatial variation of road surface temperature under different weather conditions. The equipment used to make such kind of accurate measurements is an infrared thermometer. In particular, the RoadWatch Safety System (RWSS) temperature sensors are used to measure the road temperature. This device measures temperature within a range from -40ºC to +90ºC with an accuracy of 0.5ºC. The device is mounted on the vehicle in a way that sensor should have a clear sight to the road surface. The measurements are done continuously during the road salting activities at intervals of less than 100 meters and when the spreader changes settings. Mostly these measurements are performed during road winter seasons with a focus on nighttimes since some cooling of the roads is most common during night, because of nocturnal cooling which often is a very local phenomenon. Differences in temperature along the roads can vary up to several degrees, and hence, some parts of the road can be near or below the icing/freezing point and others - may be not. Note that this pattern and distribution of warm and cold sections is determined by local scale conditions as well as synoptic scale dominating weather conditions. The cooling of the road may lead to slippery road surfaces if roads are already wet, or as

a consequence of a dew deposition. This also means that forecasting of precipitation and humidity should be of high resolution.
For each road the energy balance is affected by complex interactions between various factors including: weather conditions; sky view factor or shadowing effects from trees, buildings, constructions, etc.; height of the road section; geographical location with respect to major water objects; effects of urban areas resulting in building up of so-called urban heat islands; road and traffic related peculiarities; etc. Combination of all these factors will create a unique "temperature fingerprint" for each road. Thermal mapping procedure recreates a relationship between all these factors and how these interact with each other. A large number of continuous measurements can allow to build temperature profiles which will be unique for each road. From analysis of profiles the thermal maps can be constructed for each dominating weather conditions identifying variations in road surface temperature and underlying possible relative differences, for example, as colored temperature intervals.

2.4. Thermal Mapping and Forecasted Data Treatment

2.4.1. Thermal Mapping Data for Road Weather Season of 2006-2007

The thermal mapping data has been provided by the Danish Road Directorate (DRD) through the database access using the so-called VINTERMAN software package. The database contains detailed information about number of the driving, measuring, and salting activities' parameters. The focus of this study is on data/measurements of road surface temperature (*Ts*) and air temperature (*Ta*) (i.e. a set of so-called the thermal mapping data, ThMD) obtained from special instrumentally equipped vehicles. These measurements are mostly done during days when salt is spreaded along the roads to prevent icing conditions. Note, that these data are irregularly measured depending on the road authority programmes, and the measurements are done at discrete time and space intervals. During the recent seasons 2006-2007, the ThMD measurements were conducted along 4 roads shown in **Figure 2** (see also **Appendix A**).

Table 2. Summary of thermal mapping data screening, interpolating and assigning to road stretches based on the road winter season of 2006-2007.

Danish Road/ Route	N Road Stretches	Thermal Mapping Data, ThMD			
		Raw data	Interpolated at 1 minute interval	Assigned to road stretches	Left corresponding road activities
VA-4	30	29769	4343	2256	53
RI-1	23	15280	2549	1221	38
GR-2	30	28877	4390	1795	56
102-KS-L	6	4007	1000	135	14
All Roads	**89**	**77933**	**12282**	**5407**	**161**

In this study, the ThMD for these roads were extracted. For the previous road season 2005-2006, for the VA-4 road 102 specific cases/dates with the ThMD measurements were identified (*Mahura et al., 2006*). During recent season 2006-2007, only 59 cases were identified for this road (as shown in **Table 1**). A summary of original raw ThMD data screening, interpolation and assignment to the road stretches of all 4 roads is given in **Table 2**. From original data (with corresponding thermal mapping measurements), dates with missing measurements of one of the temperatures, activity's duration of a less than 15 minutes, and missing geographical position system (GPS) coordinates were excluded. For example, for the VA-4 road, after processing, in total **29769** records containing a set of parameters (identificator of road activity; temporal - year, month, day, hour, minute, second; latitude and longitude based on the GPS values, and measurements of the road surface and air temperatures) were extracted from the DRD database.

2.4.2. Time Series of Forecasted vs. Thermal Mapping Data at Road Stretches

Since the thermal mapping measurements are done at non-equal discrete time intervals (due to different velocities of moving vehicle along parts of the road), the temperatures were recalculated by averaging at each 1 minute interval. For each interval the new values of temperatures were re-assigned to new interpolated latitude vs. longitude position (which is located exactly in the middle of the road section passed by the vehicle during the same 1 minute interval). Let us consider steps and details of procedure on example of the VA-4 road. As seen in **Table 2** it reduced the original dataset for the VA-4 road into **4343** records. Each new record contained a set of parameters including the same identificator of road activity; temporal - year, month, day, hour, minute; and new values of averaged temperatures, latitude and longitude; overall changes (as sign) in positions corresponding to initial and final points of driving path; and number of ThMD measurements during each 1 minute time interval (reflecting driving vehicle velocities) used for averaging.

Since our interest is related to verification, at first, of the road surface temperature for the thermal mapping vs. forecasting data, the focus will be only on the road stretches (see Figure in **Appendix A**). As seen, for the VA-4 road the heights of the road stretches vary between 20-35 meters, i.e. the selected road path can be considered as a relatively flat angled surface.

The dataset was subsequently restructured by re-assigning pairs of measured (or observed) temperatures at exact local times when simultaneously measuring and forecasting are done for corresponding locations of the road stretches. In order to build such unified dataset, the DMI-HIRLAM-RWM system recalculated output was used (at each 2 minute interval for all mentioned specific cases). Although recalculations were also tested at 30 and 5 minute intervals, the smallest interval was selected in order to include all possible available thermal mapping data into the verification procedure. Moreover, it was also found to be the most useful for the road stretches situated at 2 km distances from each other. Hence, for the VA-4 road in total only **2256** records corresponded to 30 road stretches.

In final dataset each record contained the following set of parameters: identificator of road activity; temporal - year, month, day, hour, minute; identificator of the road stretch with corresponding latitude and longitude as well as the 3 hour forecasted and observed/measured road surface and air temperatures. The overall distribution of available records for road stretches as a function of the identificators of the road activities for 3 roads is given in **Appendix 2**. Note, from all cases – only 3 road activities were represented by more than 100 ThMD measurements assigned to the stretches.

The overall distribution of available records by the identificators of the road stretches of 3 roads is shown in **Figure 3**. As seen, at stretches where the largest number of ThMD is observed, hence, this part of the road, probably, represents the highest concern for the salting activities. Examples of the previous season road activities with thermal mapping vs. 3 hour forecasted data were given by *Mahura et al., 2006*.

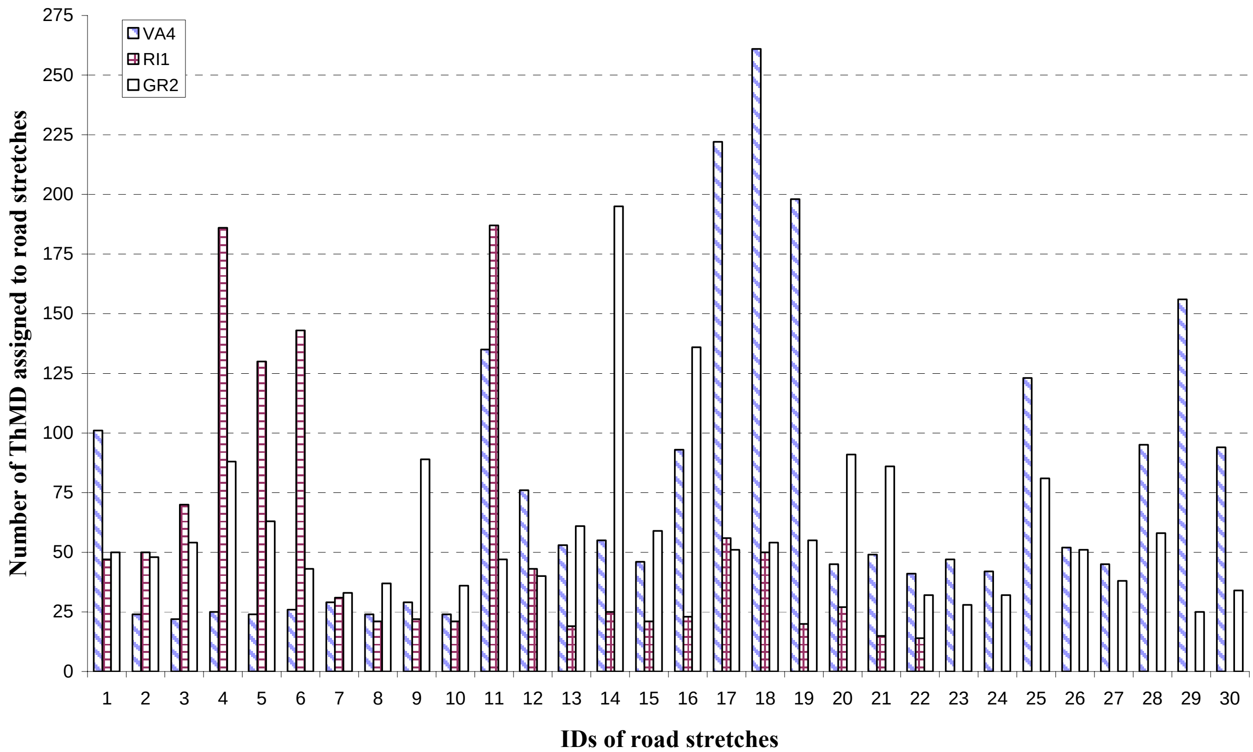


Figure 3. Distribution of the thermal mapping measurements as a function of the road stretches.

2.4.3. Evaluated Parameters

For tasks of the road segment forecasting it is important to predict temperature conditions leading to salting activities organized by the road authorities. At the same time, the RWM system should be capable to predict common typical meteorological situations as well as relatively rare events, such as heavy rain/snow conditions. Evaluation of the DMI-HIRLAM-RWM system forecasting performance was done by analysis of the mean absolute error, *MAE* and bias, *BIAS* for the road surface temperature (*Ts*) and the air temperature (*Ta*). The MAE and BIAS have been estimated using the following equations:

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

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

where: N is the number of pairs (interpolated measured ThMD value and forecasted value at the road stretch) or total number of observations/measurements, i denotes the i^{th} observation/measurement, T_f and T_o are the forecasted and observed values for temperatures, respectively.
For bias, the positive difference sign shows over prediction (i.e. the forecasted value is higher compared with observed), and the negative – under prediction (i.e. the forecasted value is lower compared with observed) of temperatures compared with observed value.
Evaluations of these parameters were done as a function of the road stretch identificator, road activity, by month, road season, and on a diurnal cycle.

3. Results and Discussions

3.1. Summary of Verification for 2006-2007 Road Weather Season

For the last (2006-2007) road season, the score for the 3 hour forecasts of the road surface temperature with an error of less than ±1ºC was 83% based on more than 259 thousand corresponding forecasts (see details in *Petersen et al., 2007*). The highest score was 97% in October 2006 (but it is based only on a relatively small number of forecasts) and the lowest was 75% in December 2006. The scores has improved during spring months of 2007 due to changes (29 Jan 2007) of the heat conductivity constant for roads (i.e. from 2.0 to 1.5).
The overall seasonal averages of the bias and mean absolute error are 0.22ºC and 0.74ºC. It showed a slightly better performance of the road conditions model compared with the previous season 2005-2006, where the bias and mean absolute error were 0.31ºC and 0.78ºC, respectively.
For the air temperature, *Ta,* the bias has been improved from 0.15ºC to –0.02ºC, and the mean absolute error changed from 0.80ºC to 0.77ºC. For the dew point temperature, *Td,* the bias has changed from 0.27ºC to 0.33ºC, and the mean absolute error remained the same of 0.86ºC.

3.2. Spatial and Temporal Variability of Thermal Mapping vs. Forecasting Data

3.2.1. Monthly Variability

Evaluation of the RWM system forecasting performance (employing DMI-HIRLAM NWP model with a horizontal resolution of 15 km) was done by analysis of the mean absolute error, MAE and mean error, BIAS for both *Ts* and *Ta* as a difference between the 3 hour forecasted and observed values. In terms of MAE and BIAS the overall *Ts* verification scores for the studied period were relatively good. For all road stretches considered, on average, for *Ts* the BIAS and MAE were 0.34 and 0.90ºC, respectively; and for *Ta* these were 1.30 and 1.44ºC, respectively. A summary by months for 3 roads is given in **Table 3**.
Moreover, the results of verification for the 102-KS-L road, which has only 6 stretches, are given in **Appendix G**. In particular, for this road due to small number (135) of ThMD observations vs. forecasts, only the overall seasonal BIAS and MAE for *Ts* are analyzed.
Month-to-month variability of *Ts* showed that the lowest/best values are observed for the RI-1 road. For this road, the lowest BIAS (0.02ºC) and MAE (0.38ºC) were in December 2006. For VA-4 road, the lowest BIAS (-0.13ºC) and MAE (0.67ºC) were in January and March of 2007, respectively. In general the BIAS is always negative, except for December. For the GR-2 road, during this season both BIAS and MAE were more than 1ºC. It could be due to the fact that the stretches (i.e. 18 from 30 stretches are situated at more than 30 meters asl) of this road are situated at higher altitudes compared with other roads. I.e. for the RI-1 road there is only 1 of 23 stretches, and for the VA-4 road there are 10 of 30 stretches. The evaluation as a function of the stretches' heights is given in **Section 3.2.4.** For *Ta*, in general, the month-to-month variability showed overpredicted values which were more than +1ºC. Although in March, for the VA-4 road, the BIAS and MAE were 0.82 and 0.93ºC, respectively.
A summary of distribution for 3 hour forecasts of *Ts* and *Ta* is given in **Tables 4** for different temperature intervals: 1) –0.5 ÷ +0.5ºC, 2) –1 ÷ –0.5ºC and +0.5 ÷ +1ºC, 3) –1.5 ÷ –1ºC and +1 ÷ +1.5ºC, and 4) >+1.5ºC and <–1.5ºC. For *Ts*, these were contained within a range of less than |±1ºC| in more than 60% (with the highest – 81% for the RI-1 road, and the lowest – 34% for the GR-2 road) of the road salting activities. They were higher than |±1.5ºC| in less than 17% (with the highest – 34% for the GR-2 road, and the lowest – 5% for the RI-1 road) of the activities. For *Ta*, the MAE and BIAS showed values of less than |±1.5ºC| in 62% of the performed road activities.

Table 3. Summary for 3 hour forecasts of monthly variability of the BIAS and MAE of the road surface (*Ts*) and air (*Ta*) temperatures for the selected roads during the road winter season of 2006-2007 /N – number of cases used in calculation of statistics; values of less than | ±1| ºC are marked in **bold**/.

		Road	GR-2		RI-1		VA-4		All	
	Parameter	Month	Mean	N	Mean	N	Mean	N	Mean	N
Ts	*BIAS*	*Dec*	1,63	76	**0,02**	91	**0,42**	117	**0,61**	284
		Jan	1,20	461	**-0,10**	287	**-0,13**	609	**0,33**	1357
		Feb	1,15	1208	**0,08**	798	**-0,24**	1469	**0,32**	3475
		Mar	1,11	50	**0,47**	45	**-0,51**	61	**0,29**	156
		Season	1,18	1795	**0,05**	1221	**-0,18**	2256	**0,34**	5272
	MAE	*Dec*	1,65	76	**0,38**	91	**0,78**	117	**0,89**	284
		Jan	1,45	461	**0,71**	287	**0,77**	609	**0,99**	1357
		Feb	1,20	1208	**0,59**	798	**0,75**	1469	**0,87**	3475
		Mar	1,11	50	**0,65**	45	**0,67**	61	**0,80**	156
		Season	1,28	1795	**0,60**	1221	**0,76**	2256	**0,90**	5272
Ta	*BIAS*	*Dec*	1,53	76	1,86	91	1,97	117	1,82	284
		Jan	1,50	461	1,82	287	1,07	609	1,37	1357
		Feb	1,17	1208	1,83	798	**0,96**	1469	1,23	3475
		Mar			1,76	45	**0,82**	61	1,22	156
		Season	1,27	1795	1,83	1221	1,04	2256	1,30	5272
	MAE	*Dec*	1,64	76	1,86	91	1,97	117	1,85	284
		Jan	1,59	461	1,96	287	1,35	609	1,56	1357
		Feb	1,38	1208	1,84	798	1,08	1469	1,36	3475
		Mar			1,76	45	**0,93**	61	1,28	156
		Season	1,45	1795	1,86	1221	1,19	2256	1,44	5272

Table 4. Summary of distribution for 3 hour forecasts of the road surface temperature (*Ts*) and air temperature (*Ta*) for different temperature intervals of the mean absolute error, MAE /where: N – number of cases, % - percentage of cases from entire dataset, ∑% - cumulative percentage of cases).

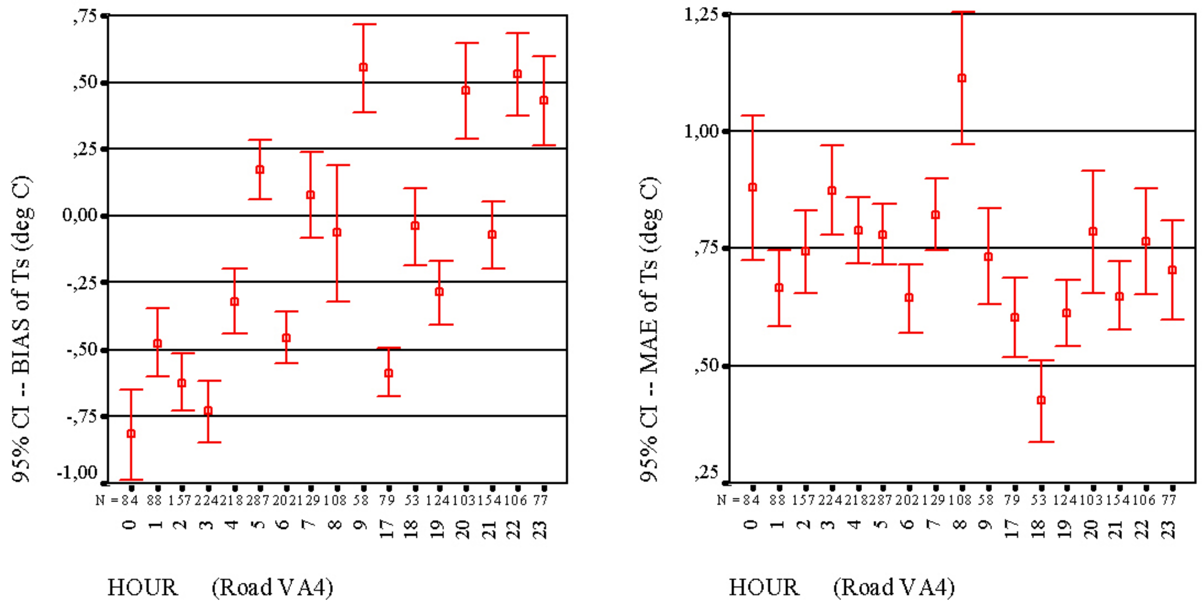
Temperature interval, ºC		***Distribution for Ts***											
		GR-2			**RI-1**			**VA-4**			**All**		
		N	%	∑%	N	%	∑%	N	%	∑%	N	%	∑%
–0.5 ÷ +0.5	**1**	206	12		618	51		898	40		1722	33	
–1 ÷ –0.5 & +0.5 ÷ +1	**2**	403	22	*34*	366	30	*81*	721	32	*72*	1490	28	*61*
–1.5 ÷ –1 & +1 ÷ +1.5	**3**	575	32	*66*	177	14	*95*	398	18	*90*	1150	22	*83*
<–1.5 and >+1.5	**4**	611	34	*100*	60	5	*100*	239	10	*100*	910	17	*100*

Temperature interval, ºC		***Distribution for Ta***											
		GR-2			**RI-1**			**VA-4**			**All**		
		N	%	∑%	N	%	∑%	N	%	∑%	N	%	∑%
–0.5 ÷ +0.5	**1**	215	12		72	6		454	20		741	14	
–1 ÷ –0.5 & +0.5 ÷ +1	**2**	318	18	*30*	158	13	*19*	637	28	*48*	1113	21	*35*
–1.5 ÷ –1 & +1 ÷ +1.5	**3**	606	34	*64*	223	18	*37*	582	26	*74*	1411	27	*62*

<–1.5 & >+1.5	**4**	656	36	*100*	768	63	*100*	583	26	*100*	2007	38	*100*

3.2.2. Diurnal Cycle

Although, the RWM forecasting is done on a 24 hour time scale, the salting activities are conducted during night and late evening times, and hence, the ThMD are available only during a limited time interval, as shown in figures below – the diurnal cycle is represented by interval starting from 17/18 hours to 08/09 hours of local standard time (LST).
For the **VA-4** road, on a diurnal cycle (**Figure 4ab)**, in general, the MAE for *Ts* is 0.75±0.2ºC with the lowest value of 0.42ºC at 18 LST. The BIAS is within a range of ±0.75ºC, and it is negative during nighttime hours and it is positive during evening hours. The lowest values of BIAS are observed in the early morning hours (±0.07ºC at 07-08 LST). For *Ta*, the MAE is mostly higher than 1ºC (**Appendix F, Figure F1c**) and it is higher in evening hours compared with morning hours. The minimum value of MAE is 0.63ºC at 18 LST. The BIAS is in general within a range of 1±0.2ºC (**Appendix E, Figure E1c**) with the minimum value of 0.43ºC at 03 LST.



(a) (b)

Figure 4. (a) Mean error, BIAS and (b) mean absolute error, MAE (at 95% confidence interval) of the road surface temperature (*Ts*) as a function of time for the VA-4 road /N – number of cases used in calculation of statistics/.

For the **RI-1** road, on a diurnal cycle (**Figure 5ab)**, in general, the MAE for *Ts* is 0.6±0.2ºC with the lowest value of 0.28ºC at 20 LST. The BIAS is within a range of ±0.5ºC, and it is negative during early morning hours and it is positive during the night and evening hours. The lowest values of BIAS are observed in the night hours. For *Ta*, the MAE is mostly higher than 1.25ºC (**Appendix F, Figure F1b**) and it is higher in morning hours compared with the evening and night hours. The minimum value of MAE – 1.26ºC – is at 05 LST. The BIAS is always positive and in general within a range of 1±0.25ºC (**Appendix E, Figure E1b**) with minimum value of 1.16ºC at 05 LST.
For the **GR-2** road, on a diurnal cycle (**Figure 6ab)**, in general, the MAE for *Ts* is 1.25±0.25ºC during the nigh and morning hours, and it is 1.75±0.25ºC during the evening hours. The lowest value of 0.91ºC is at 04 LST and the highest value of 1.86ºC is at 22 LST. The BIAS is always positive and mostly it is within a range of 1.2±0.2ºC, except in evening hours. The lowest BIAS value of 0.65ºC is observed at 04 LST. For *Ta*, the MAE is mostly higher than 1ºC (**Appendix F, Figure F1a**). On a diurnal cycle, it is always lower during the night hours compared with early morning hours (06-08 LST - around 2ºC). The minimum value of MAE – 1.04ºC – is at 04 LST.

The BIAS is always positive and highly variable on a diurnal cycle. In general, it is higher than 0.75ºC (**Appendix E, Figure E1a**) with a minimum value of 0.80ºC at 00 LST and a maximum of 1.96ºC at 07 LST.

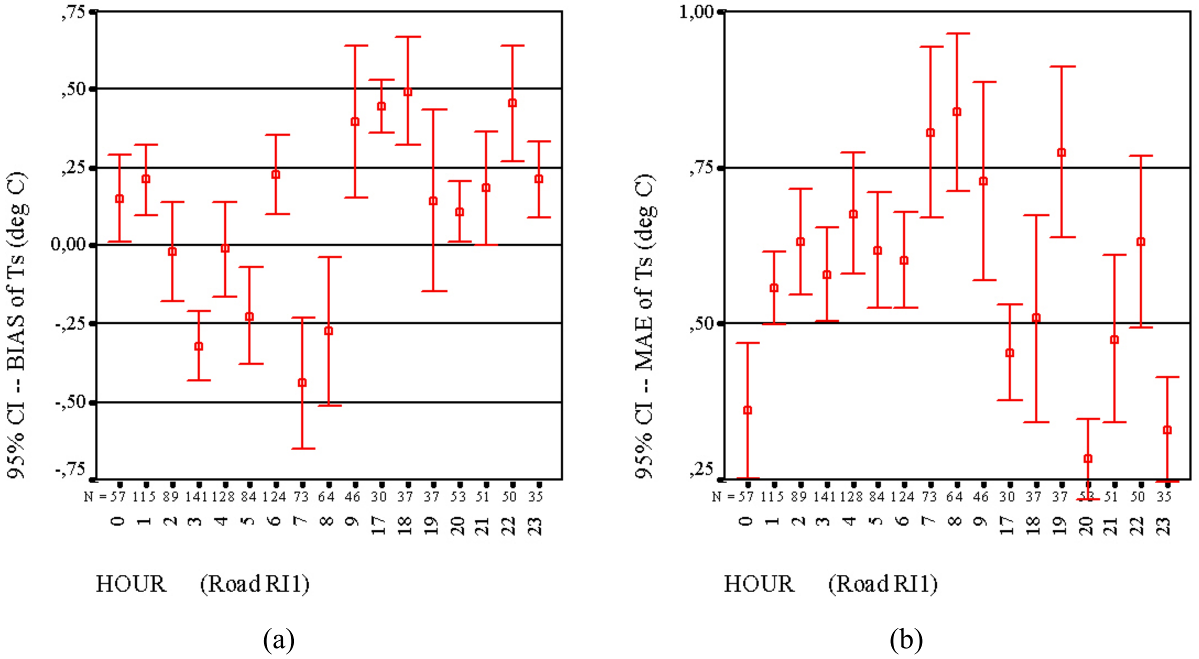


Figure 5. (a) Mean error, BIAS and (b) mean absolute error, MAE (at 95% confidence interval) of the road surface temperature (*Ts*) as a function of time for the RI-1 road /N – number of cases used in calculation of statistics/.

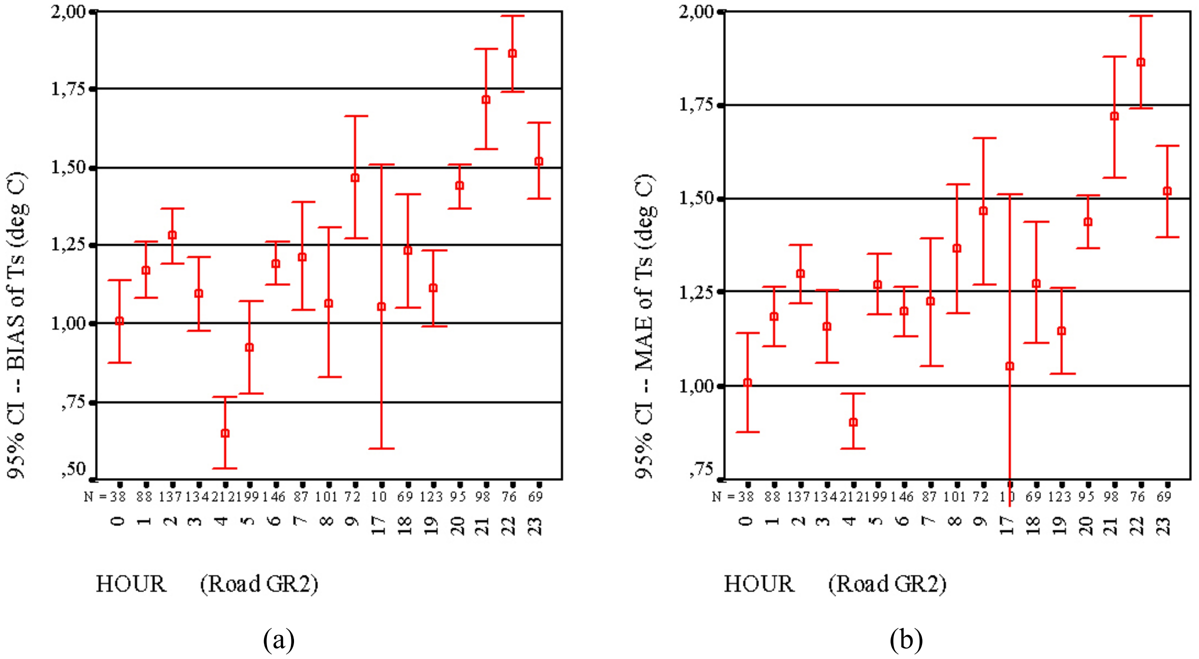
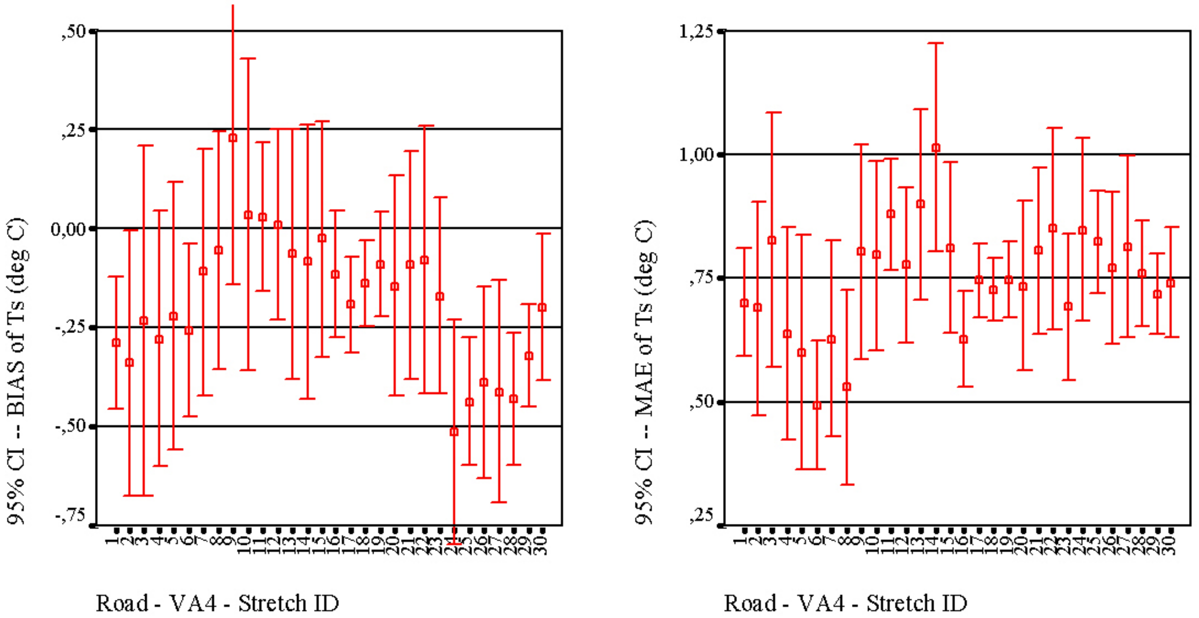


Figure 6. (a) Mean error, BIAS and (b) mean absolute error, MAE (at 95% confidence interval) of the road surface temperature (*Ts*) as a function of time for the GR-2 road /N – number of cases used in calculation of statistics/.

3.2.3. Road Stretches

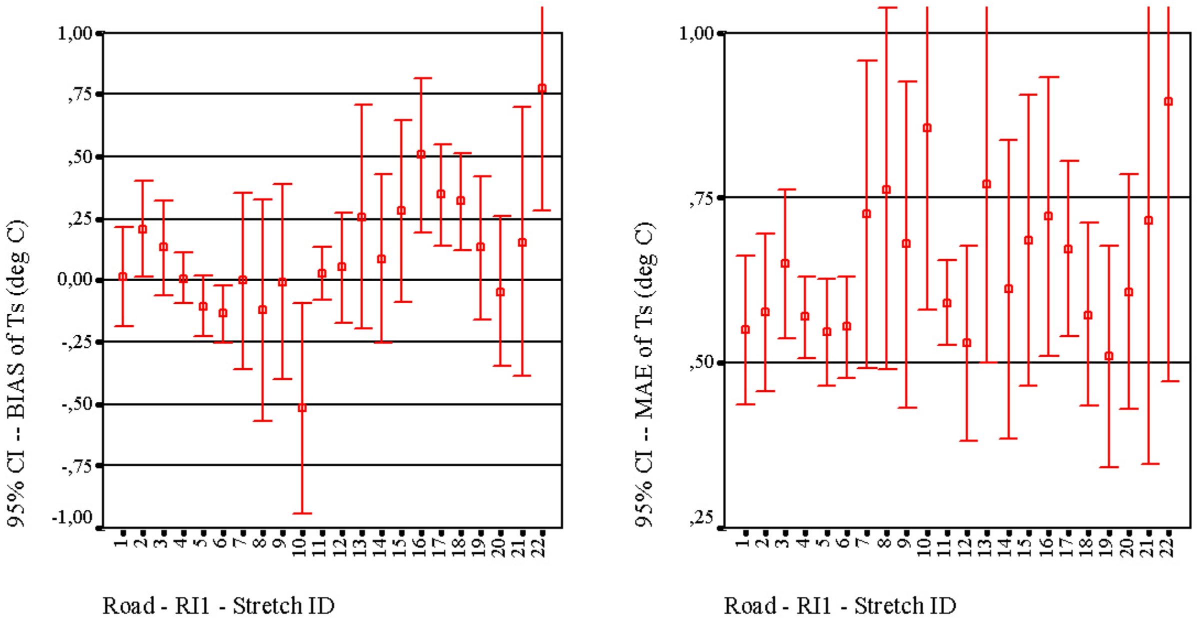
Detailed analysis by road stretches (**Figures 7-9, Appendixes C-D**) showed that the RWM overall performance to forecast *Ts* at road stretches was good for the VA-4 and RI-1 roads, and showed

MAE of more than 1ºC values for the GR-2 road.
For the **VA-4** road stretches, the mean absolute error at 95% confidence interval is within a range of 0.5-1ºC (and the bias -0.50ºC ÷ 0.25ºC). The part of the road between the stretches 10 and 16 is characterized by lower BIAS (±0.1ºC) compared with other parts of this road. For *Ta*, it always showed overprediction: MAE was within a range of 1-1.5ºC (same for BIAS, except for stretches 8-13 and 17-19, where it was below 1ºC).



(a) (b)

Figure 7. (a) Mean error, BIAS and (b) mean absolute error, MAE (at 95% confidence interval) of the road surface temperature (*Ts*) as a function of the VA-4 road stretches /N – number of cases used in calculation of statistics/.

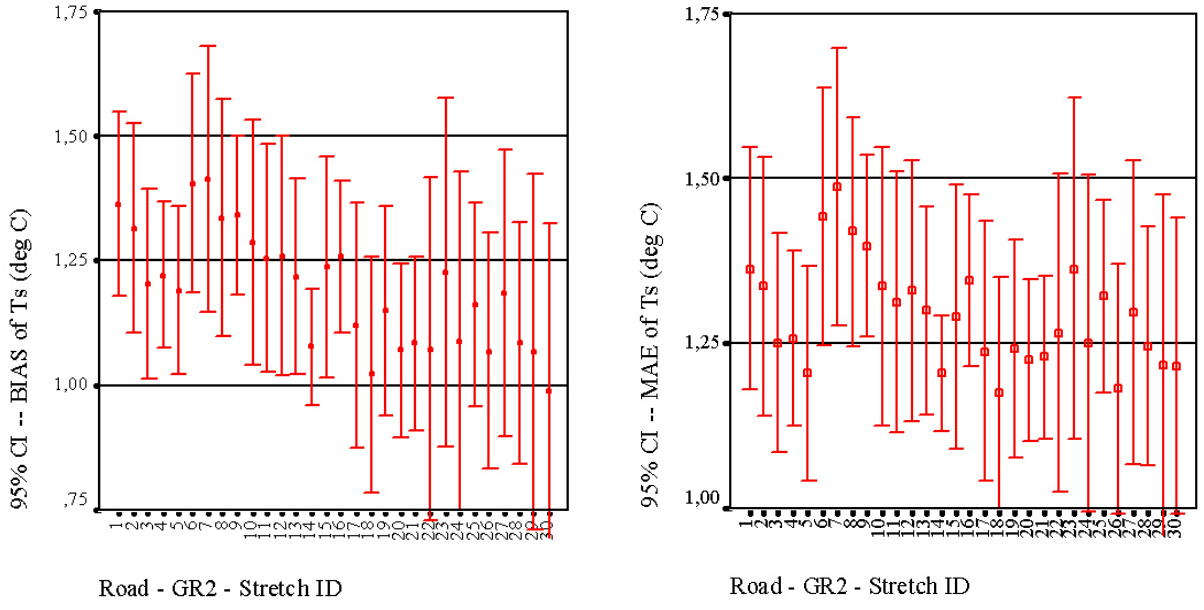


(a) (b)

Figure 8. (a) Mean error, BIAS and (b) mean absolute error, MAE (at 95% confidence interval) of the road surface temperature (*Ts*) as a function of the RI-1 road stretches /N – number of cases used in calculation of statistics/.

For the **RI-1** road stretches, the mean absolute error at the same confidence interval is mostly within a range of 0.50-0.75ºC (and the bias -0.25ºC ÷ 0.50ºC). For *Ta*, it always showed overprediction as

for other roads: MAE was more than 1.5ºC (and same for BIAS).
For the **GR-2** road stretches, the mean absolute error at the same confidence interval is within a range of 1-1.5ºC (and the bias 1-1.4ºC). For *Ta*, MAE and BIAS were within a range of 1-1.5ºC (similar for BIAS), except for stretches 22-27, where these were above 1.5ºC.

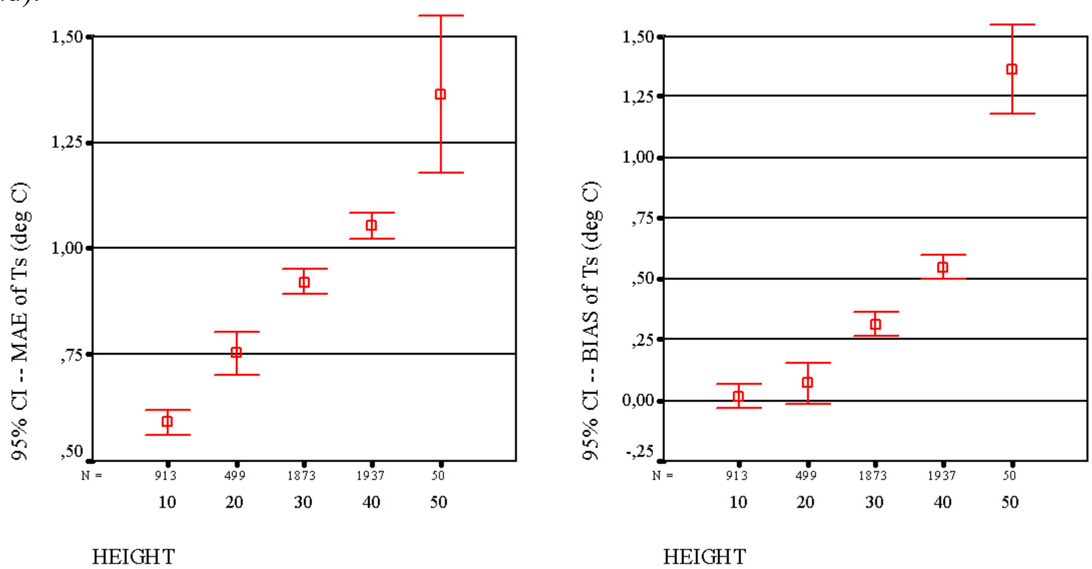


(a) (b)

Figure 9. (a) Mean error, BIAS and (b) mean absolute error, MAE (at 95% confidence interval) of the road surface temperature (*Ts*) as a function of the GR-2 road stretches /N – number of cases used in calculation of statistics/.

3.2.4. Altitude

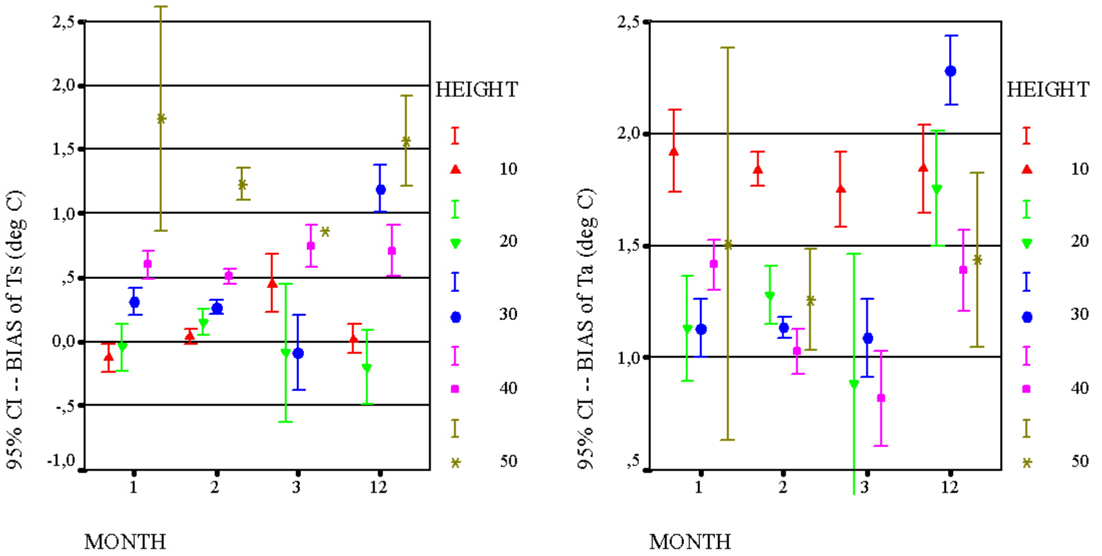
Regrouping road stretches by altitudes ranging within intervals of 0-10, 10-20, 20-30, 30-40, and 40-50 meters it was found that only 1 stretch (for GR-2 road) has the heights of the last interval. The heights within a 30-40 meters interval have 29 stretches; 20-30 meters – 28 stretches; 10-20 meters – 12 stretches (for the RI-1 and VA-4 roads); and 0-10 meters – 12 stretches (only for the RI-1 road).



(a) (b)

Figure 10. (a) Mean absolute error, MAE and (b) mean error, BIAS (at 95% confidence interval) of the road surface temperature (*Ts*) as a function of height /N – number of cases used in calculation of statistics/.

Detailed analysis for road stretches (**Figure 10**) showed a strong dependence of the *Ts* MAE and BIAS by altitudes at which the road stretches are located. As seen, the MAE is lees than 1ºC for the first 30 meters, and it increasing rapidly after that reaching a value of 1.36ºC at 50 m. The BIAS is less than 0.1ºC for the first 20 meters, but it is also large – 1.33ºC – at 50 m. The lowest MAE and BIAS - 0.59 and 0.02ºC, respectively - are for the stretches located within the first 10 meters. For *Ta*, the highest MAE and BIAS for the first 10 meters interval, i.e. 1.89 and 1.86ºC, respectively; and these are lower than 1.5ºC for all other intervals.



(a) (b)

Figure 11. BIAS (at 95% confidence interval) of the (a) road surface temperature, *Ts* and (b) air temperature, *Ta* as a function of height.

Monthly variability showed the same patterns (**Figure 11, Table 5**): during all months the BIAS was higher than 1ºC for *Ts* at 50 meters and more than 1.75ºC for *Ta* at 10 meters. For *Ts*, during all months for the first 20 meters the MAE and BIAS were less than 0.9ºC. The highest both MAE and BIAS were 1.74ºC in January at 50 meters. The lowest both MAE and BIAS - 0.34 and 0.02ºC, respectively - were observed in December at 10 meters.

Table 5. Summary of monthly variability of the road surface (*Ts*) and air (*Ta*) temperatures by altitudes for the selected road stretches during the road winter season of 2006-2007 /N – number of cases used in calculation of statistics; values of less than |±1| ºC are marked in **bold**/.

Month			Jan		Feb		Mar		Dec	
	Parameter	**Height**	**Mean**	**N**	**Mean**	**N**	**Mean**	**N**	**Mean**	**N**
Ts	***BIAS***	*10*	**-0,13**	223	**0,05**	591	**0,45**	33	**0,02**	66
		20	**-0,04**	128	**0,15**	319	**-0,09**	19	**-0,20**	33
		30	**0,31**	471	**0,27**	1259	**-0,09**	54	1,19	89
		40	**0,60**	525	**0,51**	1273	**0,74**	49	**0,71**	90
		50	1,74	10	1,23	33	**0,86**	1	1,57	6
	MAE	*10*	**0,70**	223	**0,58**	591	**0,63**	33	**0,34**	66
		20	**0,78**	128	**0,74**	319	**0,87**	19	**0,66**	33
		30	**0,99**	471	**0,87**	1259	**0,87**	54	1,30	89
		40	1,15	525	1,03	1273	**0,82**	49	**0,91**	90
		50	1,74	10	1,23	33	**0,86**	1	1,57	6
Ta	***BIAS***	*10*	1,92	223	1,84	591	1,75	33	1,84	66
		20	1,13	128	1,28	319	**0,88**	19	1,75	33
		30	1,13	471	1,14	1259	1,09	54	2,28	89

		40	1,41	525	1,03	1273	**0,82**	49	1,39	90
		50	1,51	10	1,26	33	.	1	1,44	6
	MAE	*10*	2,01	223	1,85	591	1,75	33	1,85	66
		20	1,50	128	1,46	319	1,23	19	1,75	33
		30	1,45	471	1,21	1259	1,09	54	2,28	89
		40	1,48	525	1,26	1273	**0,82**	49	1,48	90
		50	1,56	10	1,27	33	.	1	1,44	6

On a diurnal cycle (see **Appendix H**), the BIAS and MAE for *Ts* at all height intervals, except the last one, were of less than 1ºC during the night and morning hours (00-08 LST). At 10 meters interval, the highest MAE of 0.86ºC and BIAS of –0.67ºC were both observed at 07 LST; and the lowest values of these parameters – 0.25ºC and 0.15ºC, respectively – were at 00 LST. At 20 meters interval, the highest MAE of 0.95ºC and BIAS of –0.46ºC were at 08 and 03 LST, respectively. The lowest values of MAE and BIAS – 0.49ºC and –0.04ºC – were at 01 and 05 LST, respectively. During the evening hours (18-23 LST), the MAE and BIAS are less than 0.5ºC only at 10 meters interval, but it is increasing rapidly with increasing of the height. On a diurnal cycle (not shown), the BIAS and MAE for *Ta* at all height intervals were more than 1ºC at 40 and 50 meters intervals, except during 03-04 LST.
Such substantial visible changes with an altitude/height for the *Ts* MAE and BIAS might depend on two factors. First, it might be due to current interpolation procedure used to find the forecasted temperatures from the grids and road stations into positions of road stretches. Second, it could be related to the current resolution (15 km) of NWP model which does not allow to simulate and represent the small scale eddies' features (which might be more identifiable at higher resolution; for example, 5 km).

3.3. Road Stretches Forecasts and Need of New Improvements

The Danish road network is represented by a large number of the roads/driving lanes in various communes (so-called regions numbered from 15 to 80). In order to perform the road stretches forecasting the coordinates of the road stretches along the roads are needed. The GPS coordinates from the VINTERMAN database were extracted and recalculated at 1 km driving distances along the roads. In total, we identified more than 17 thousand road stretches covering the entire Danish road network (except, Island of Bornholm) as shown in **Figure 12**.
During the last season the thermal mapping measurements were done mostly in the former Ribe Amt commune for 3 selected roads. These roads – VA-4 (57 km), GR-2 (66 km), and RI-1 (46 km) – are located on the Jylland Peninsula and are represented by 84 road stretches from total of 714 and by 10 closely located road stations.
The examples of *Ts* 3 hour forecasts at the road stretches within the Ribe Amt region are shown in **Figures 13-15**. The *Ts* forecasts show significant variability along the roads. As seen some parts of the roads are warmer compared with others creating localized warm and cold spots. Areas between these spots along the roads underline both the importance of decision making related to salting activities, and can also influence traffic rules, i.e. require driver's decision for optimized and safe car's speed.
For the up-coming road season of 2007-2008, the RWM system with both resolutions of 15 km (operational mode) and 5 km (testing mode) will be running to forecast the road conditions at the road stations as well as road stretches of the former Ribe Amt region. It is planned that forecasts of these runs will be verified and compared with observations at road stations as well as available thermal mapping measurements in this region. In the next season of 2008-2009, the *Ts* forecasts will be done in a test mode at more than 17 thousand road stretches (located at 1 km distances) covering practically the entire network of the main Danish driving lanes.

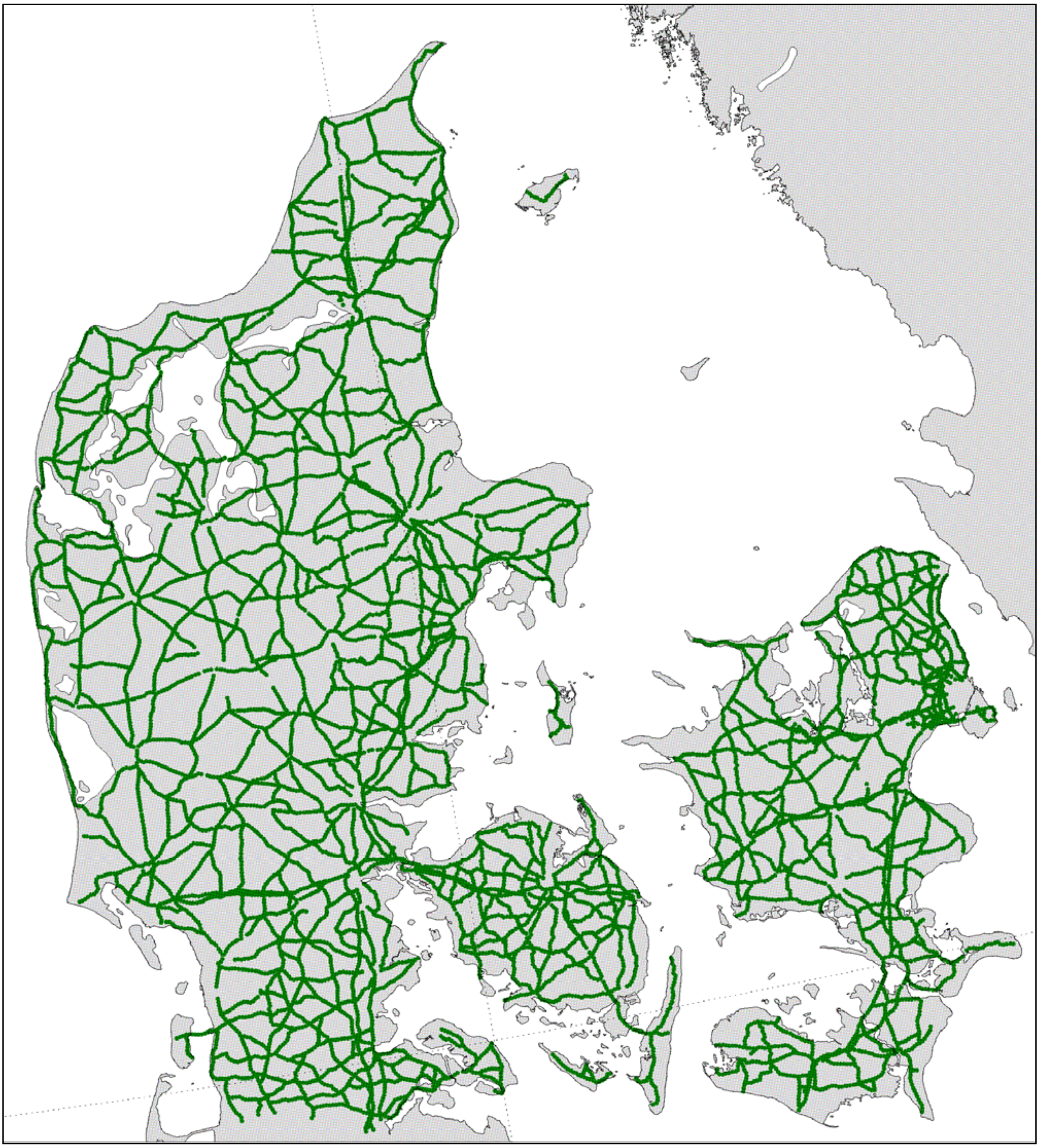
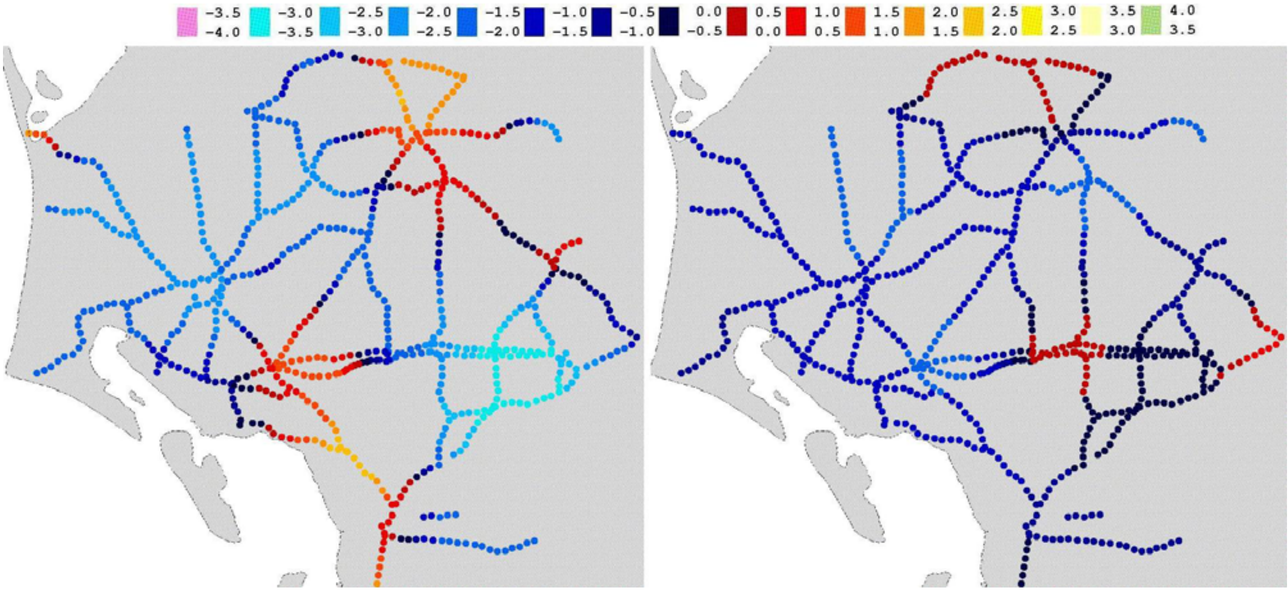


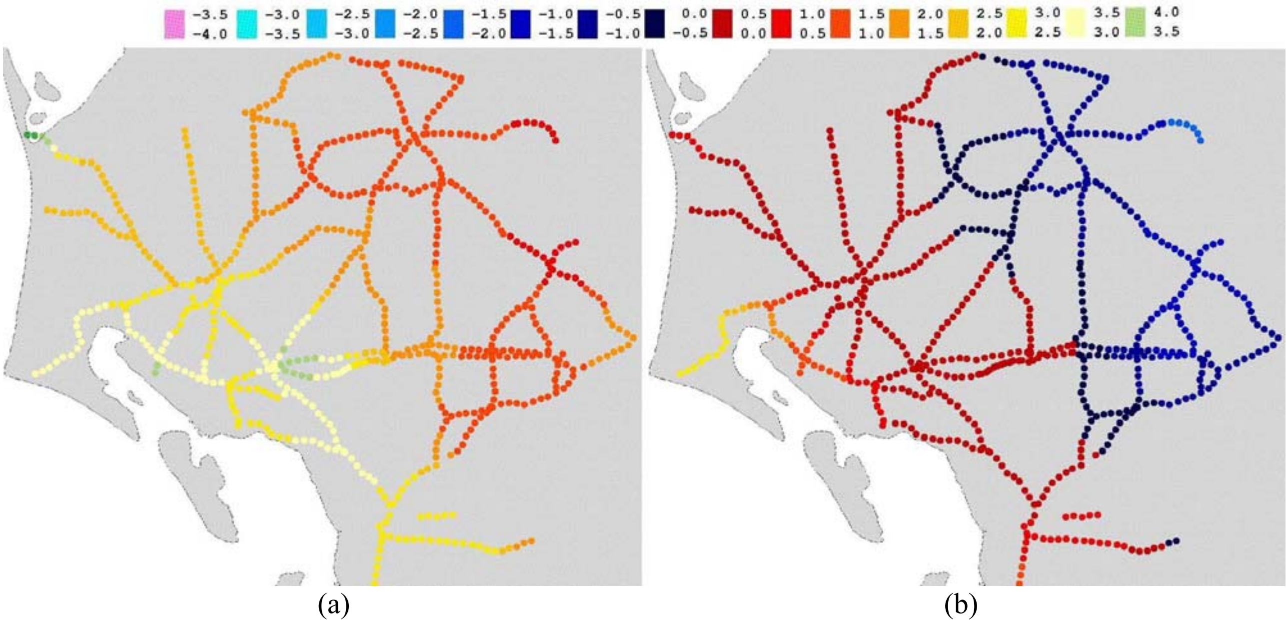
Figure 12. Road stretches of the driving lanes of the Danish road network.

Such detailed spatial forecasts will require additional information not only at the road stations but also at the road stretches. For that reason the road stations and road stretches should be classified into several groups depending on a number of various factors. First, it can be a division by its location: 1) road stations located near the seashore within a distance of less than 5 km – coastal station; 2) road stations located ways from the seashore at distance of more than 5 km away from seashore – inland station; 3) station located on bridges connecting different territories of Denmark – bridge station. Here, the distance from the station toward the seashore would be of importance. Second, the height at which each road station is located should be also considered. Moreover, if the station is situated in the complex terrain – i.e. on the top of hills, on the slopes of hills, and in valleys of different configuration, then a set of additional parameters needs to be evaluated. These are the following: the orientation of the slopes toward the north and south direction, the sizes of valleys or platoes.



(a) (b)

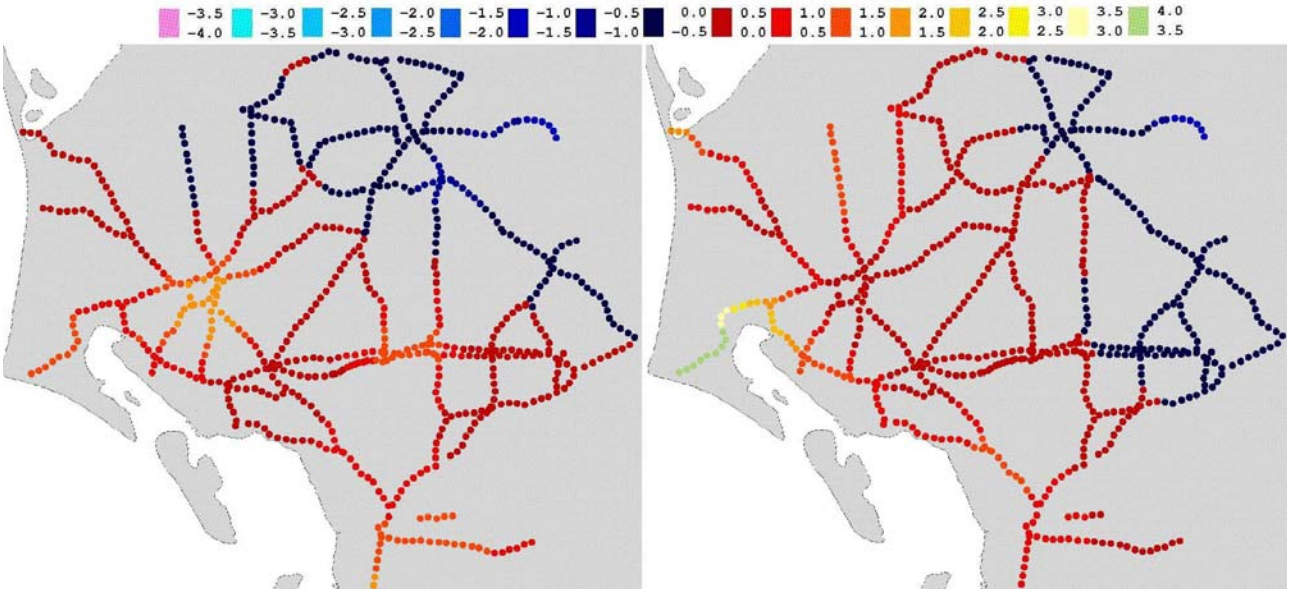
Figure 13. Three hour forecasts of the road surface temperature at the road stretches in the Ribe Amt region on (a) 22 Jan 2007 at 09 h and (b) 22 Jan 2007 at 06 h.



(a) (b)

Figure 14. Three hour forecasts of the road surface temperature at the road stretches in the Ribe Amt region on (a) 26 Jan 2007 at 05 h and (b) 06 Feb 2007 at 01 h.

In addition, the classification of the urban vs. rural type of the road station would be of concern too. 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. Such detailed classification of road stations can also give an insight on how the road stretches should be incorporated into the RWM and DRD database. This 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) employing GIS technology.



(a) (b)

Figure 15. Three hour forecasts of the road surface temperature at the road stretches in the Ribe Amt region on (a) 23 Feb 2007 at 02 h and (b) 06 Feb 2007 at 03 h.

Moreover, a substantially refined classification and following improved forecasts have an advantage. Based on road stretch forecasts it 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 spreaded during the road weather seasons. Moreover, consequently, it will positively influence the environmental conditions of the surrounding area.

4. Conclusions

In this study, the vehicles measurements (the so-called thermal mapping data) of the road conditions including the road surface and air temperatures have been used for verification of the Danish Road Weather Model (RWM) system at road stretches. At the current moment this system is employing the DMI-HIRLAM NWP model with a horizontal resolution of 15 km (in 2007 – 5 km). During 2006-2007, in total 209 cases/dates with the road salting activities of four roads (VA-4, GR-2, RI-1, and 102-KS-L) have been identified, extracted, and statistically analyzed. The comparison of the observed and forecasted the road surface and air temperatures was done at 89 selected road stretches of selected roads each with a length of 2 km.

It should be noted, that although ThMD data showed that they are very useful for verification of the performance of the RWM system, these are less useful and valuable for on-line assimilation into the system due to sparse and irregular measurements. But they can be used for possible correction of the road surface temperature forecasts by integration of these into a neural network based on long-term road surface temperature dataset over the Danish road network domain which will be further investigated later in this project.

It was found that the RWM system showed a good predictability of the 3 hour road surface temperature forecasts at the road stretches. The mean absolute error was 0.90ºC and the bias was less than 0.34 ºC. For the air temperature, the mean absolute error and bias was around 1.44ºC and 1.30ºC, respectively. On a diurnal cycle, for the road surface temperature the nighttimes had the best quality of prediction. A larger diurnal variability of deviations was observed for the air temperature as compared with the road surface temperature, which might be caused by cloudiness and

shadowing effects.
Moreover, note that the mean absolute error was higher than 1.5ºC in 17% of the cases for the road surface temperature. The scores were higher for the RI-1 and VA-4 roads (i.e. 5 and 10%, respectively) compared with the GR-2 road. It is caused by the altitudinal differences of road stretches, i.e. more stretches has been located at higher altitudes compared with other road stretches. Our analysis showed an importance of further investigation of the road surface temperature forecasts as a function of the height as well as other road and environmental characteristics mentioned in section 3.3.

5. Acknowledgments

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The funding was provided within the frameworks of the joint DRD and DMI project entitled "*Road Segment Forecasts*" (2006-2008) within the framework of the VIKING-6 Projects.

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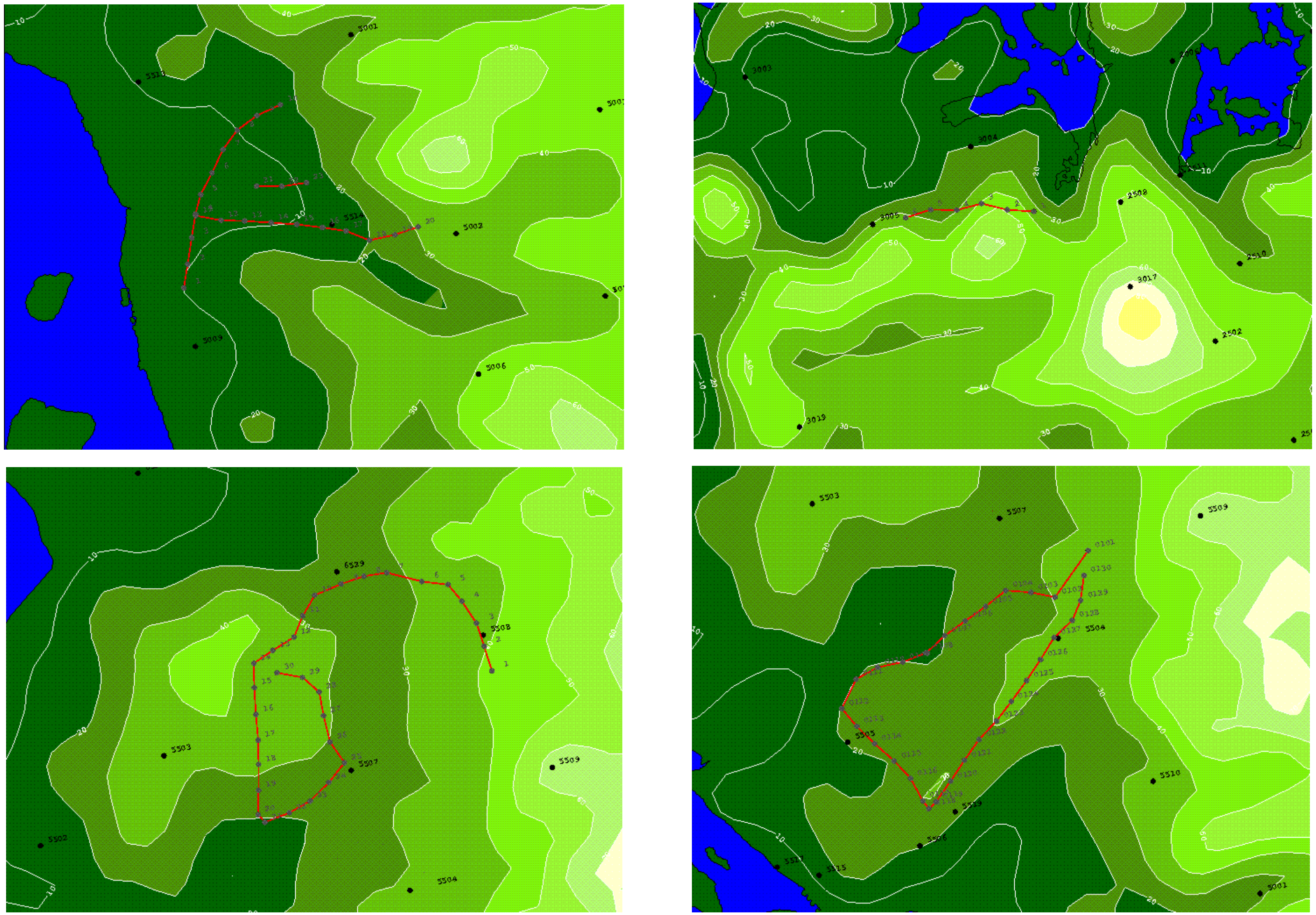
Appendix A : Road Stretches of Selected Danish Driving Lanes



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

Figure A1. Locations of road stretches for 4 Danish roads: (a) RI-1, (b) 102-KS-L, (c) GR-2, and (d) VA-4.

Appendix B : Distribution of Thermal Mapping Data at Road Stretches by Road Activities

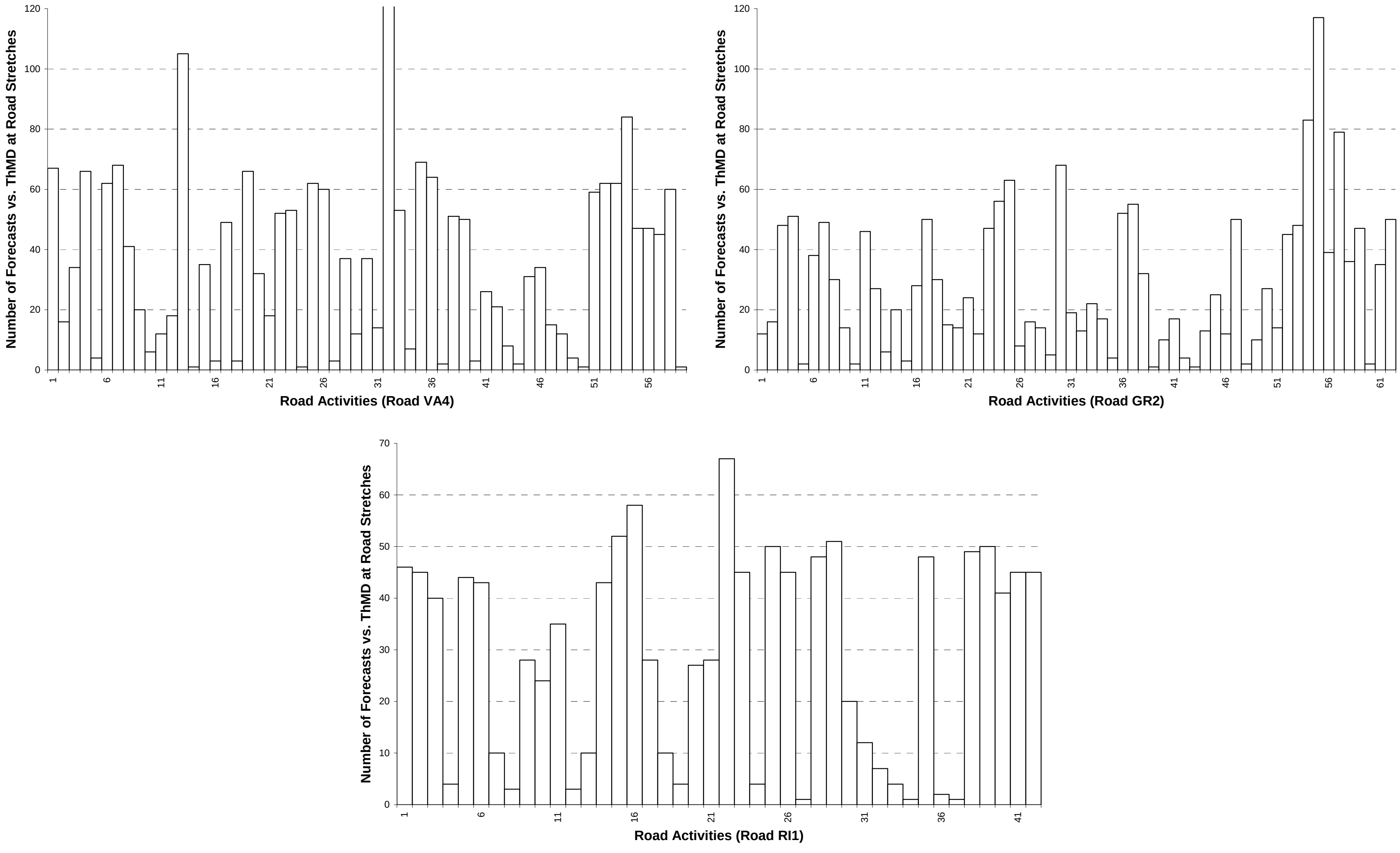


Figure B1. Distribution of the thermal mapping measurements assigned to the road stretches as a function of the road salting activities for the VA-4 (top-left), GR-2 (top-right), and RI-1 (bottom) roads.

Appendix C : BIAS of Air Temperature for Thermal Mapping Data by Road Stretches

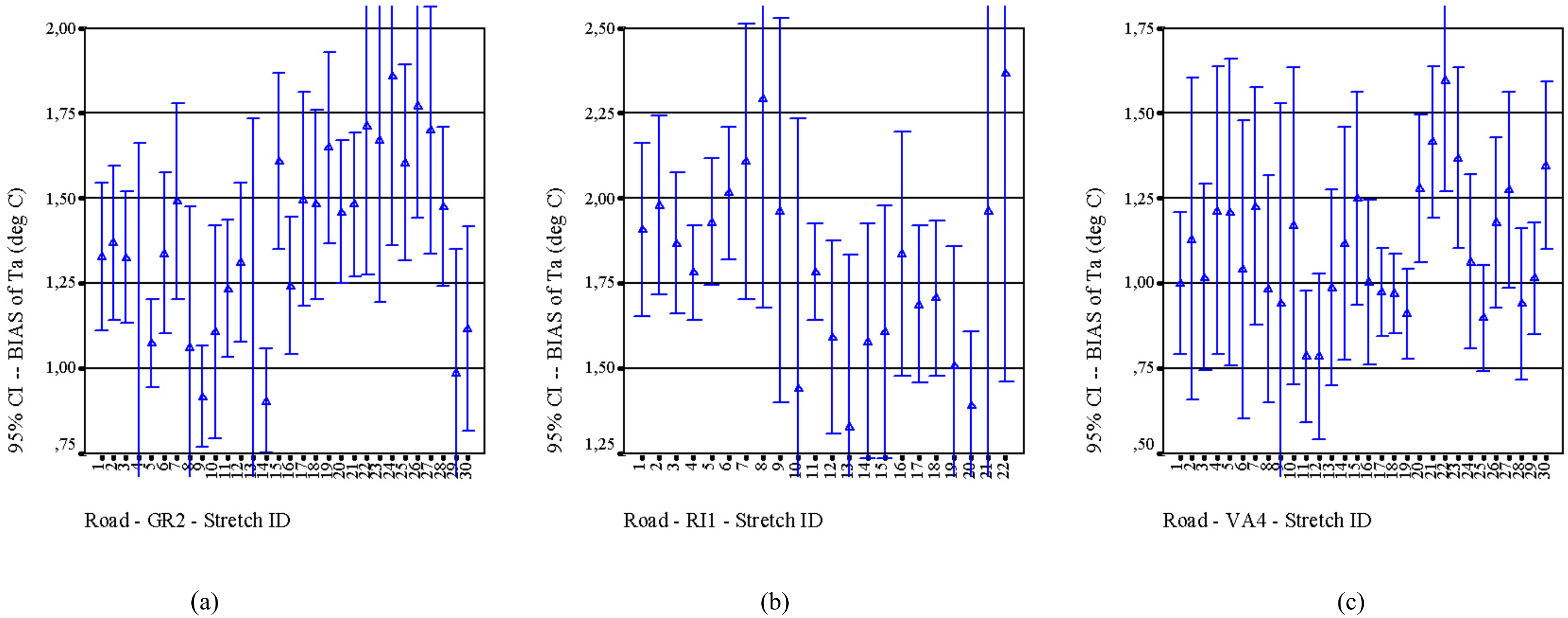


Figure C1. Mean error, BIAS (at 95% confidence interval) for the air temperature (*Ta*) as a function of the road stretch number (or identificator) for the a) GR-2, b) RI-1, and c) VA-4 roads /based on the entire thermal mapping dataset/.

Appendix D : MAE of Air Temperature for Thermal Mapping Data by Road Stretches

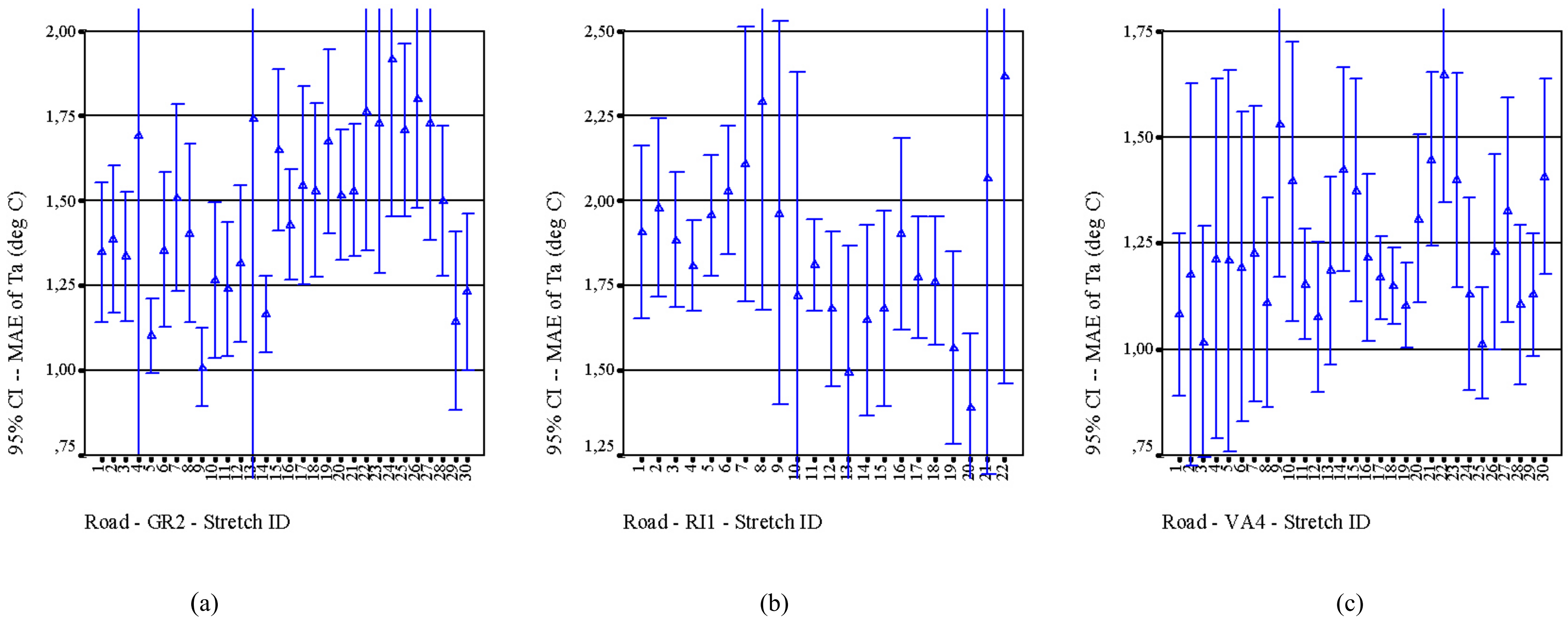
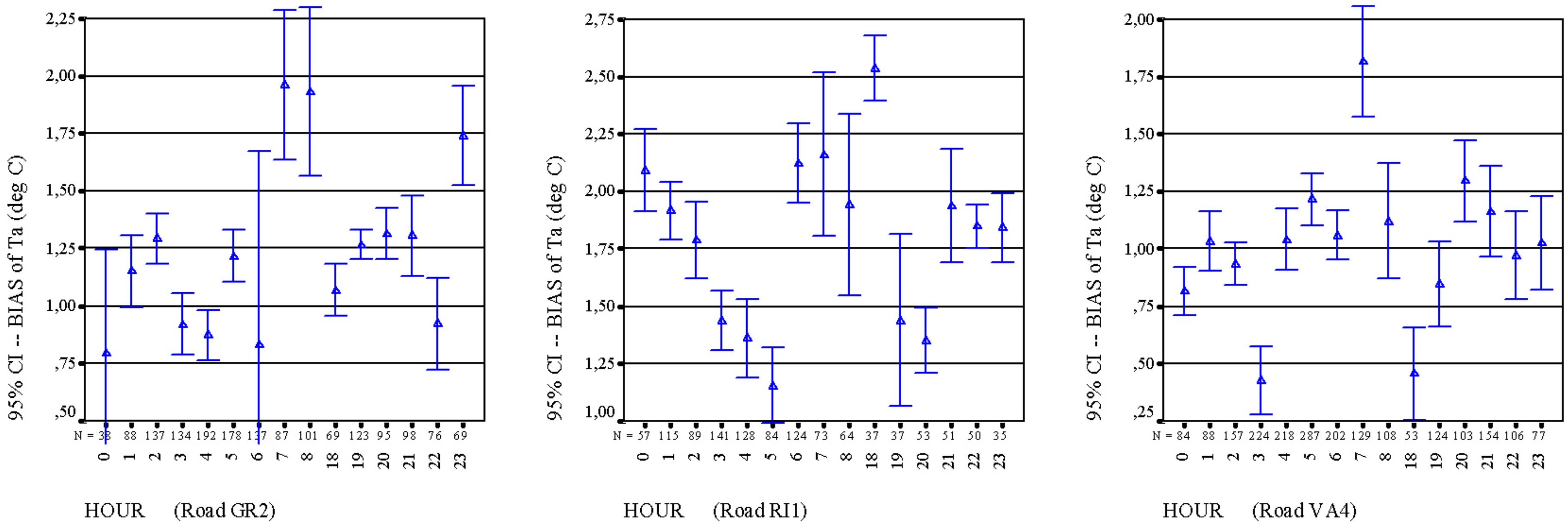


Figure D1. Mean absolute error, MAE (at 95% confidence interval) for the air temperature (*Ta*) as a function of the road stretch number (or identificator) for the a) GR-2, b) RI-1, and c) VA-4 roads /based on the entire thermal mapping dataset/.

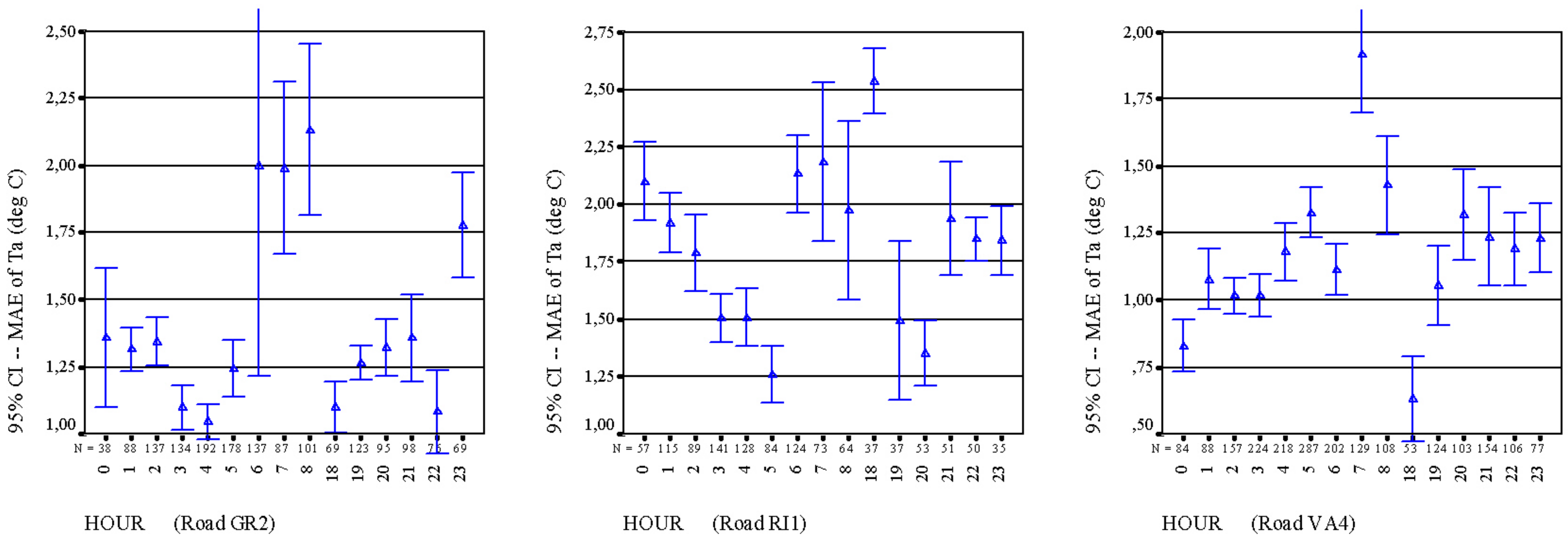
Appendix E : BIAS of Air Temperature for Thermal Mapping Data by Hours



(a) (b) (c)

Figure E1. Mean error, BIAS (at 95% confidence interval) for the air temperature (*Ta*) as a function of time on a duirnal cycle for the a) GR-2, b) RI-1, and c) VA-4 roads /based on the entire thermal mapping dataset; N – number of cases used in calculation of statistics/.

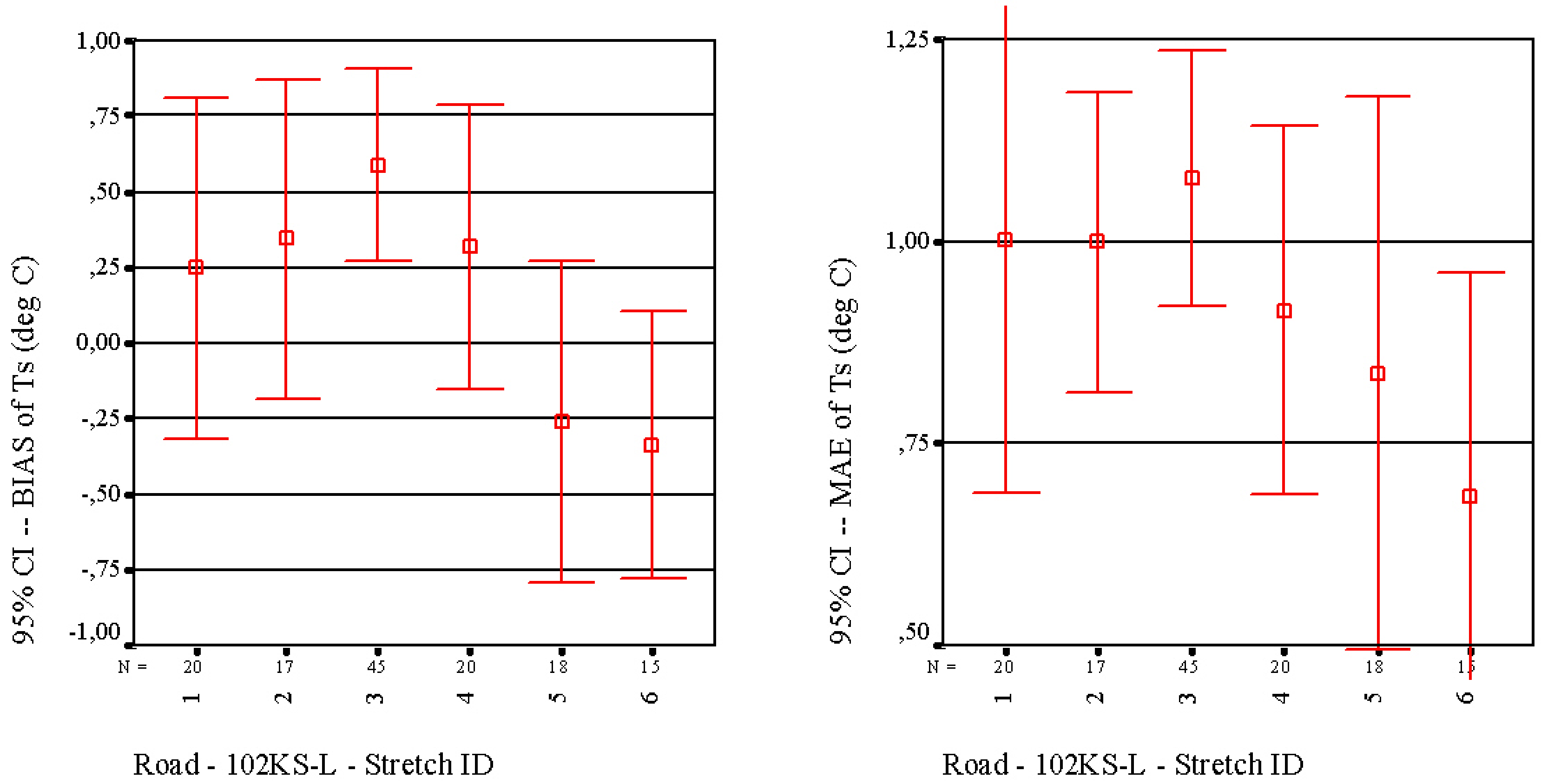
Appendix F : MAE of Air Temperature for Thermal Mapping Data by Hours



(a) (b) (c)

Figure F1. Mean absolute error, MAE (at 95% confidence interval) for the air temperature (*Ta*) as a function of time on a duirnal cycle for the a) GR-2, b) RI-1, and c) VA-4 roads /based on the entire thermal mapping dataset; N – number of cases used in calculation of statistics/.

Appendix G : BIAS and MAE of Road Surface Temperature for 102-KS-L Road



(a) (b)

Figure G1. (a) Mean error, BIAS and (b) mean absolute error, MAE (at 95% confidence interval) of the road surface temperature (*Ts*) for the 102-KS-L road / N – number of cases used in calculation of statistics/.

Comments : There are only 135 interpolated ThMD assigned to corresponding times for stretches of the 102-KS-L road. In such situation, a detailed evaluation of the hourly and monthly variability is useless from the statistical point of view due to small number of available data. Therefore, only verification for the road surface for road stretches temperature is shown in Fig. G1. For this road, the overall seasonal BIAS and MAE for *Ts* are 0.25 and 0.96ºC, respectively.

Appendix H : BIAS and MAE of Road Surface Temperature for Thermal Mapping Data by Altitude

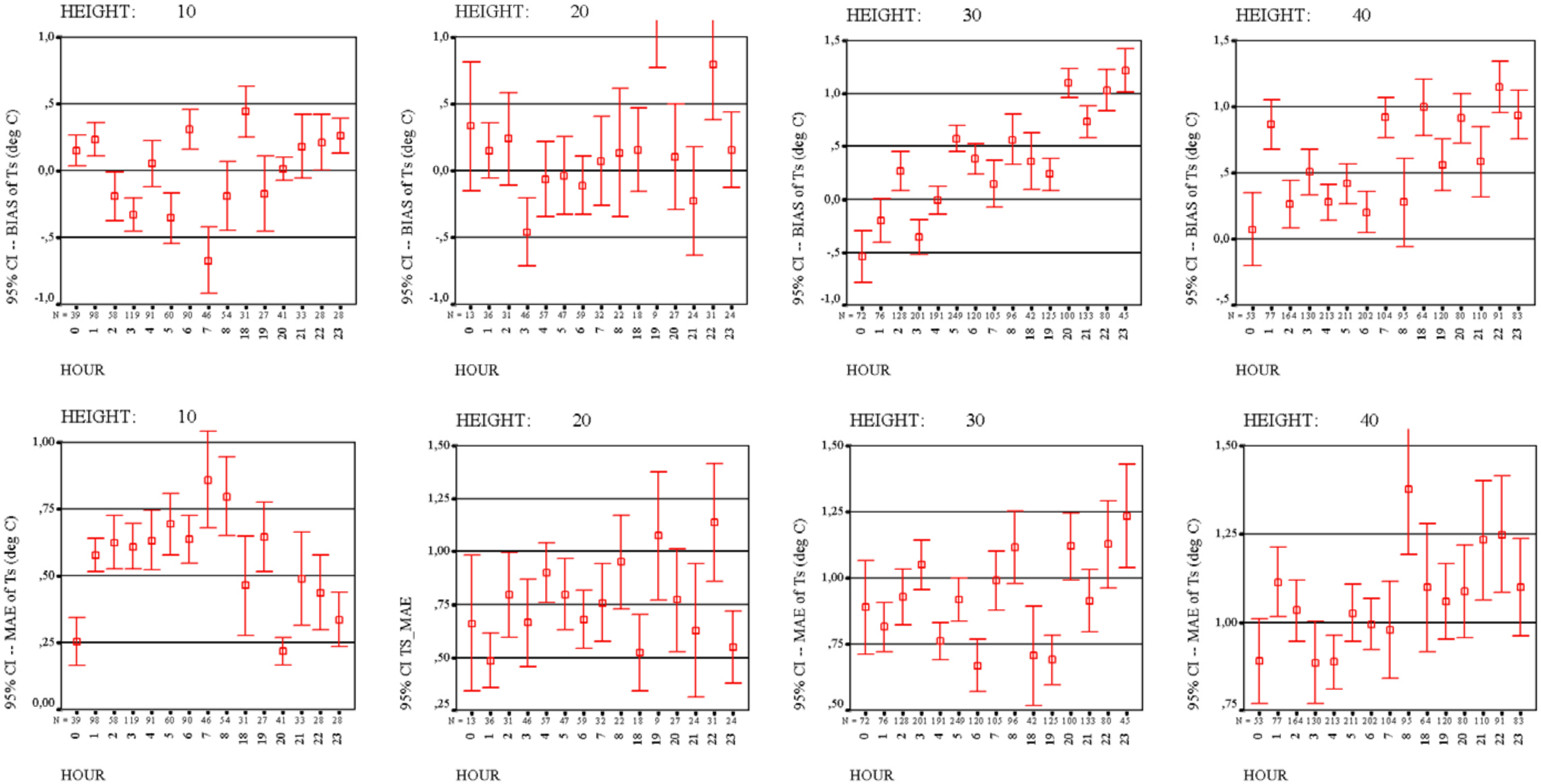


Figure H1. Mean error, BIAS (top) and mean absolute error, MAE (bottom) (at 95% confidence interval) of the road surface temperature (*Ts*) as a function of time on a duirnal cycle vs. altitude /N – number of cases used in calculation of statistics/.

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