Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the Environment

WINTER ROAD MAINTENANCE IN THE NETHERLANDS
a quantitative analysis of recent and future activities

Alma de Vries

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WINTER ROAD MAINTENANCE IN THE NETHERLANDS

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ABSTRACT

The analysis in winter road maintenance data from DMI revealed an average of 46 sprinkling days per winter season over the 2007-2014 period. The analysis further showed condensation to be the main reason for winter road maintenance. The implementation of the KNMI'14 climate change scenarios revealed the total amount of days that need winter road maintenance will change considerably. The number of winter road maintenance days is likely to decline between 37% and 69% towards 2050. Also, winter precipitation is found to occur less frequently, and therefore remains condensation the main cause for winter road maintenance activities. For KNMI, this can have implications for more efficient resource planning within the KNMI forecast division, because they can expect longer periods with temperatures above zero. During these periods no supervision for winter road maintenance alerts is necessary or the supervision can be done as a side task next to other tasks. The results could further give practical implications for Rijkswaterstaat for long-term contracts with executors of winter road maintenance.

1. INTRODUCTION

1.1 Internship at the Royal Netherlands Meteorological Institute

The following report describes a four month internship at the Royal Netherlands Meteorological Institute (In Dutch: Koninklijk Nederlands Meteorologisch Instituut or KNMI). The internship is part of the MSc Urban Environmental Management program at the Wageningen University and Research Center. KNMI is an agency of the Ministry of Infrastructure and the Environment and provides meteorological and seismological data towards the government, governmental institutions such as Rijkswaterstaat, Schiphol airport, the shipping industry and many others[1]. The overall aim of the internship was to get more familiar with the application of meteorological data in scientific research and at the same time experience working in a knowledge/research institute.

Figure 1. The KNMI building in the Dutch village the Bilt. The image further shows the precipitation radar on top of the large tower. Source: KNMI, 2014.

[1] KNMI also has various collaborations with international institutes and research centers, such as the European Center for Medium-Range Weather Forecasts located in Great Britain. KNMI is also known for its work as the national data and knowledge institute for climate sciences. The organization advises the Dutch government on climate change and contribute to international climate research by for example representing the Netherlands in the Inter-governmental Panel on Climate Change (IPCC). An output from this collaboration is the recently published Climate Change Scenarios'14 report (KNMI, 2014).

1.2 Winter road maintenance

The main subject of the internship study was winter road maintenance. Winter road maintenance encompasses all activities that ensure safe mobility on roads in winter season, because slippery roads sometimes lead to very dangerous situations. There are three main causes for slippery streets, which are 1) winter precipitation such as snowfall or (freezing) rain, 2) condensation of road surfaces, and 3) freezing of puddles. Prerequisite of all causes is a sub-zero degree Celsius road surface. To prevent such conditions on roads, salt is used as a de-icing agent. Although the use of salt can improve traffic safety, it also has some negative effects. Examples are the corrosion of vehicles and pollution of ground water or vegetation near salted roads (Venäläinen, 2001).

This study focuses on roads as part of the Dutch highway system which is owned and maintained by the National road authority Rijkswaterstaat (RWS). RWS performs winter road maintenance in close collaboration with various regional contractors and meteorological agencies, such as KNMI. Interestingly, winter road maintenance practices are difficult to plan a few weeks (or sometimes even days) ahead since weather conditions, such as the amount of days with sub-zero temperatures and snowfall are difficult to forecast for longer forecast lead-times. Each winter is therefore unique in work-load and expenses.

1.3 Internship objectives

According to KNMI (2014), slippery road conditions will become less prevalent and salt sprinkling will probably be required less often in the future under the KNMI'14 Climate Change scenarios. However, it is unclear how the frequency and the distribution of road maintenance activities during a winter season should change. Therefore, it would be valuable for KNMI to get more knowledge for the relationship between the frequency of winter road maintenance practices and the accompanying meteorological circumstances.

The knowledge can further give useful indications for required resources on the business level. More specifically, the results will contain more fundamental knowledge about future practices which may be used for more efficient resource planning within the KNMI forecast division or can give practical implications for Rijkswaterstaat, especially for long-term planning and policy decision-making. This fundamental knowledge and practical implications in turn can give useful but somewhat far-reaching insights in future expenses.

The primary scientific objective of this internship is thus to explore future winter road maintenance practices and associated costs for the Dutch main roads. The specific objectives to be addressed in the pursuit of this overall objective are:

1. To analyze the current activities regarding winter road maintenance in the Netherlands for the main roads that are owned and supervised by Rijkswaterstaat.
2. To explore the KNMI'14 climate change scenarios.
3. To explore the effect of climate change on winter road maintenance and associated costs.

Consistent with the research objectives, this study addresses the following major research question: To what extent change the winter road maintenance practices, i.e. frequency and costs attributable to climate change? To answer this central question, the following specific questions will be addressed:

1. How does the current road maintenance practices look like in relation to the meteorological circumstances?
2. How will the KNMI'14 climate change scenarios change winter road maintenance in 2050?

1.4 Report organization

With the background given in the first chapter, the remaining part of the internship report will be outlined as follows: chapter two presents a brief summary of related literature pertinent to winter road maintenance; chapter three outlines the methodological approaches of the internship; chapter four presents results, and chapter five concludes.

The internship report continues with an evaluation of the personal learning goals that have been set at the beginning of this internship and go beyond the scientific objectives.

2. LITERATURE REVIEW

2.1 Winter road maintenance

This section gives a brief summary of relevant findings pertinent to winter road maintenance research. The literature review is divided into two parts. The first part discusses the sensitivity of roads to weather and climatic factors, followed by two Dutch case studies. The second part discusses winter road maintenance costs.

2.1.1 Sensitivity of roads to weather and climatic factors

Road transport is relatively vulnerable to the effects of weather and climatic factors. According to SYKE, the Finnish environmental institute, three major weather factors can be distinguished that affect road transport: air or road temperature, rain, and wind (SYKE, 2010). Especially low temperatures in combination with precipitation create circumstances that often cause slippery roads that need winter maintenance. Naturally, if the road temperature is above zero and there are no humid road conditions, there is no need to use salt. In addition, Venäläinen (2001) recognize that salt is needed most when the temperatures are only a few degrees below freezing point, because near zero temperatures often cause the most slippery roads. Interestingly, very cold temperatures often cause less slipperiness, because low temperatures often induce low humidity and this 'dry air' does not cause slippery roads. Venäläinen and Markku Kangas (2003) confirm that near-zero conditions lead to most slippery road surfaces.

Furthermore, Andersson and Chapman (2011) researched winter road maintenance in the United Kingdom. The authors found similar results as Venäläinen and Markku Kangas (2003) since their analysis revealed that 'marginal nights', where temperatures are close to freezing, are most problematic in terms of slipperiness. They further looked into future projections for winter maintenance and found that climate change is expected to decrease the amount of days with low freezing temperatures and therefore this will shorten the winter season. Moreover, they found on average 69 frost days per year in 2011 and this number will decline towards 28 days by 2080. This still means that a winter maintenance service will be required in the future to secure road safety.

Furthermore, SYKE- the Finish environmental institute (2010) researched the implications of climate change on the need for winter road maintenance in Finland. They found that mild winters are expected to mean fewer days of sub-zero temperatures in Southern Finland. This reduces the need for winter road maintenance and salt use for roads mainly in the southern parts of the country. The need for winter road maintenance is likely to increase in Central Finland and Northern Finland, and therefore SYKE suggests to shift the focus for winter road maintenance further north. Since climate change is expected to increase both the overall volume of rainfall and the likelihood of rainstorms in the south, they foresee an erosion increase for roadsides and around bridges in the south.

Finally, it was said by Andersson and Chapman (2011) that decision makers are tempted to base policies and budgets on average temperature increases because this usually gives a rather good view on general practices. However, extreme winters with increased winter road maintenance, such as the winter of 2008-2009 where the Netherlands run out of salt, should also be taken into account for policy formulation.

2.1.2 Dutch case studies in winter road maintenance

The Dutch road system is unique in their reliance on porous asphalt. This type of asphalt is characterized by a high percentage of interconnected voids in the top layer of the pavement. Some advantages are noise reductions and improved drainage that lowers the probability of aquaplaning or the formation of puddles. A major disadvantage is its limited lifespan (mainly due to frost damage). The Dutch road network is now constructed with 90% porous asphalt and for 10% of regular asphalt (Kwiatkowski et al., 2014). Two case studies pertinent to winter road maintenance for Dutch roads were found and this section summarizes both.

The KNMI’14 scenarios translate global findings in the IPCC 2013 report to the Dutch situation and serves as an update to the previous climate scenarios KNMI’06 issued in 2006. The report depict four different scenarios that together span the likely changes in the climate of the Netherlands. One of the findings is that more frequent occurrence of extreme weather, such as extreme precipitation, is a forecasted feature that could disrupt road traffic. Global warming, on the other hand, also has positive (road) effects. It was found that the number of snow days or precipitation under thawing or freezing conditions become less prevalent.

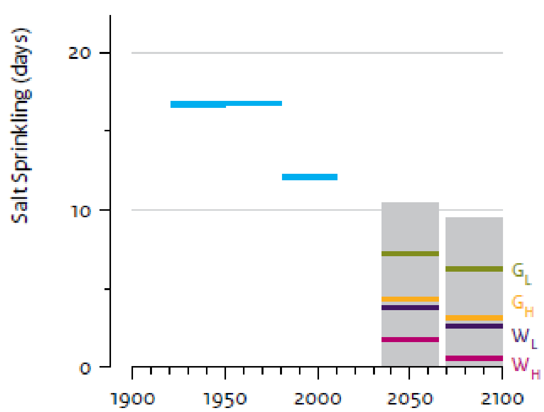


Figure 2. Indicator for the observed number of days per year at de Bilt requiring salt sprinkling on icy roads due to precipitation, and KNMI'14 scenarios for 2050 and 2085.

Figure 2 indicates the observed number of days per year at the Bilt requiring salt sprinkling on icy roads due to winter precipitation. From that, the left most blue line indicates 17 sprinkling days for the 20th century and the right-most blue line indicates 12 days for the current situation. This number is expected to continue to decline in 2050 and 2080 for all four scenarios (colored lines).

Furthermore, MeteoGroup - Europe's largest commercial weather institute investigated the winter road maintenance for Limburg commissioned by the province of Limburg. The analysis used the KNMI'06 climate scenarios to develop a model that could predict the number of sprinkling days for 30 years from now: 2044. The model revealed an average of 19 sprinkling days per winter season over 30 years with current climate conditions (Climate 2014). Measurements from 1984/1985-2013/2014 are transformed to climate scenarios as of 2044 and from that they expect a decline of 40% towards 2044 as can be seen in figure 3. However, it was found that very cold and snowy winters with a large number of sprinkling days still may occur (MeteoGroup, 2014).

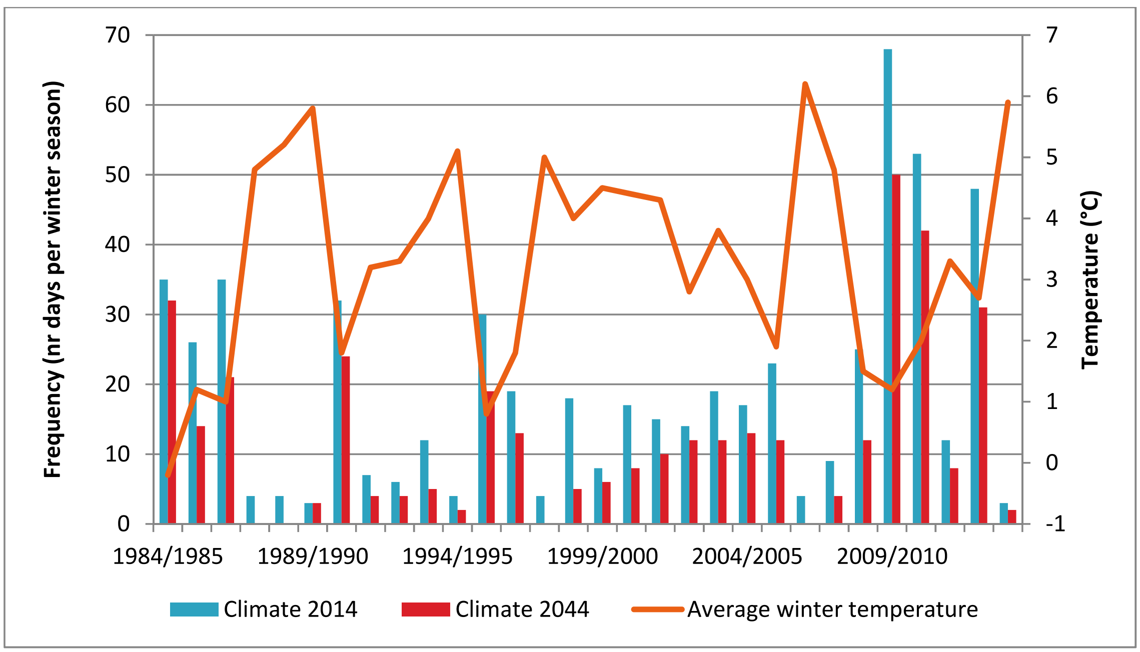


Figure 3. Winter road maintenance trends for 2014 and 2044 for the provence of Limburg, adapted from MeteoGroup, 2014.

Finally, Meteogroup also researched the meteorological reasons behind winter road maintenance and the analysis revealed that climate change is not likely to change the current pattern of ripe, snow, and the freezing of puddles. Snow is expected to remain the main cause of winter road maintenance.

2.2 Winter road maintenance costs

The possibility to gain economic savings are often incentives for institutions to understand weather and climatological data (Frei et al., 2014). For instance early knowledge about possible effects of climate change can help decision makers to gain economic savings in the long term. Only a few scientific articles make some arguments regarding (future) costs for winter road maintenance. And also, most of these articles include general road damage due to frozen pavement in overall winter road maintenance costs.

Kwiatkowski et al. (2014) for example, find that freeze-thaw cycles contribute to pothole damage. They further find that freeze-thaw cycles may increase in occurrence and are therefore expected to significantly contribute to future winter road maintenance costs. Venäläinen and Markku Kangas (2003) found the amount of snowfall, the number of snowfall cases, the number of cases when the temperature dropped below freezing point and the winter season mean temperature are the best climatological predictors of maintenance costs. The amount of snowfall, however, seems to be a better predictor for the costs than the number of snowfall cases. SYKE (2010), found that climate change might lower road maintenance costs, for example, by decreasing the need for anti-icing, de-icing, and snow removal in Southern Finland. According to Venäläinen & Tuomenvirta (1998), the increase in temperature could lead to a decrease in road maintenance costs in November and March and an increase in January and February. December is not expected to change.

However, Venäläinen and Markku Kangas (2003) acknowledged the possibilities of modelling winter road maintenance costs using climatological parameters to be slightly limited and involved by much uncertainty. Arguments that support this statement are that climate change is very hard to predict, maintenance standards and the road network itself may vary from year to year, and winter road maintenance is influenced by subjective decisions of the personnel involved.

To sum up, it was found that air- or road temperature seems to be a good indicator to estimate winter road maintenance frequency. For the Dutch province of Limburg, Meteogroup found that snow is the best indicator to declare winter road maintenance. and From two Dutch case studies it was revealed that winter road maintenance is expected to decrease because of climate change. However, it was also found that future winter road maintenance activities are hard to predict since the use of climatological parameters involves high uncertainty.

3. METHODOLOGY

3.1 Internship

The overall aim of the internship study was to explore recent and future winter road maintenance practices and the associated costs for the Dutch main roads. The activities regarding this aim and the approaches will be described in this section. The list of activities encompasses the data collection and analysis, two meetings at the winter road maintenance department of Rijkswaterstaat, and one meeting with the director of Data Mining Innovators (DMI), a company responsible for the software for winter road maintenance.

3.2 Terms and definitions

Before the choices made regarding the data analysis will be discussed, we have listed some relevant terms and definitions to understand the graphs and figures that will be presented in the result section.

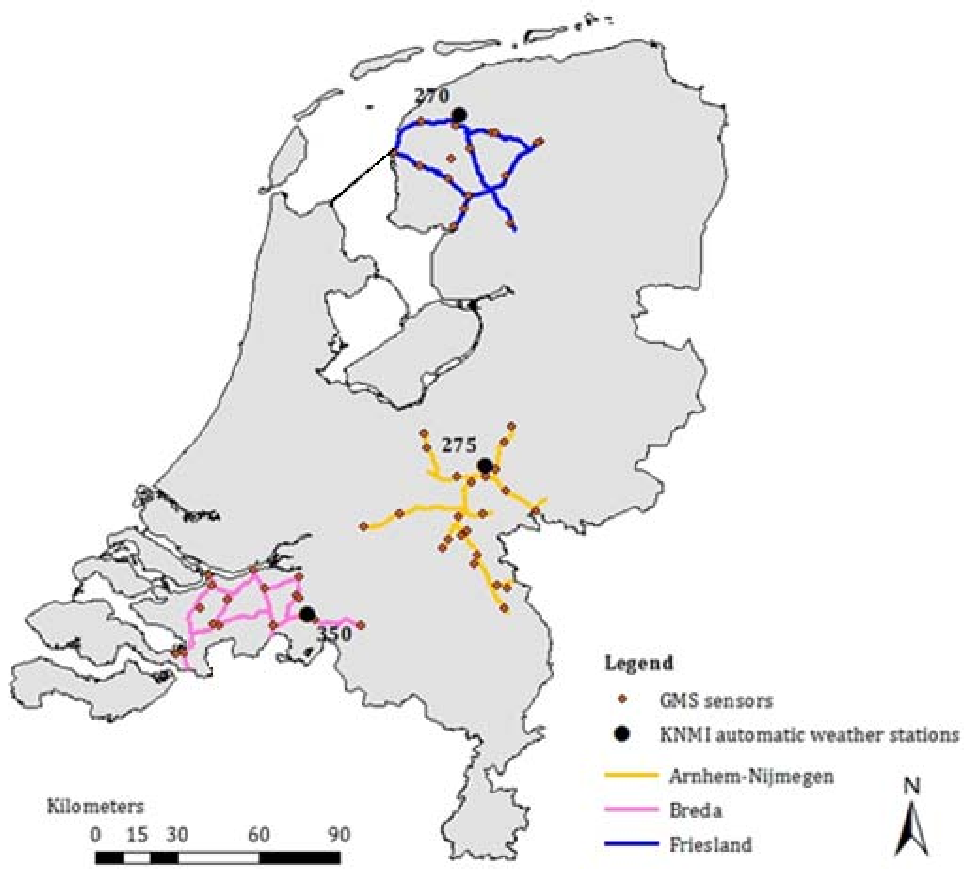
Term	Definition
Sprinkling day	A day with at least one winter road maintenance action.
Winter road maintenance	Salt-sprinkling and snow shovel activities that ensure safe mobility on roads during winter season.
Winter season	All months that regularly need winter road maintenance. A winter season goes beyond one calendar year, i.e. season 2009/2010 represents the months October - December of 2009 and January - March of 2010.

3.3 Area of interests

The Dutch road grid can be divided into three layers which are national highways, provincial roads and regional roads. All of them are owned and maintained by different governmental institutions, i.e. regional roads are owned and maintained by municipalities, provincial roads are owned and maintained by provinces and national highways are owned and maintained by Rijkswaterstaat. This study focuses on the Dutch highway system- the most busy and important road system of the Netherlands. Rijkswaterstaat administers a large dataset with information about each winter road maintenance action for the past 8 years.

The decision has been made to analyze three different districts within the highway network, which are Arnhem/Nijmegen, Breda and Friesland, because (Donker, Rijkswaterstaat, personal communication, October 9th , 2014) 1) the districts have more or less been consistent in total road acreage for the given period, 2) the districts have different local climates. The country is appointed to have a temperate maritime climate, where the northern provinces usually show a bit lower temperatures compared to the south and eastern provinces show a more inland (dry) climate compared to a more maritime (wet) climate in the west. The three different road districts are geographically well spread through the country. Therefore by combining the three districts, our findings allow us to write recommendations for the Netherlands as a whole.

Meteorological data can be obtained from either a local KNMI automatic weather station or a local Road Weather Information System (in Dutch GMS; Gladheid Meld Systeem). The GMS is a continuous monitoring system for early warning of slipperiness on highway pavement surfaces. A total of 330 sensors are used to produce warnings of potentially upcoming slippery situations. Another potential source of meteorological information contains KNMI automatic weather stations. These stations measure more variables than the GMS system, such as wind speed and radiation. Map 1 shows the three road districts and the nearest automatic weather stations and GMS sensors.



Map 1. This maps shows the location of three Rijkswaterstaat districts within the Netherlands and the nearest KNMI automatic weather stations and GMS sensors. Made with Arc GIS map 10.1.

3.4 Data collection

3.4.1 Winter road maintenance data

All winter road maintenance activities are continuously monitored via integrated sensors in the sprinkling installations. The salting routes, amount of salt and total treated acreage are just a few variables that are continuously measured during an action. As part of the internship, I visited DMI- the company that is hired by Rijkswaterstaat to develop and manage the software behind this information. During the meeting, they showed me the software behind the system and its application and the software collects information for the following variables (Joosten, DMI, personal communication, September 1st, 2014):

- Date
- Location and route
- Amount of salt (kg)
- Total distance (km)
- Total treated acreage (m^2)
- Total treatment distance (km)
- Total treatment time (h)
- Speed (km/h)
- Type (curative/preventive)

As the length of the road network varies between districts, the total treated acreage must be made comparable. Data on the total acreage of each district were available for 2011 (Kerkstra, DMI, personal communication, September 17th , 2014). By dividing the total treated acreage by the total acreage of a specific district, it was possible to calculate treated acreage in percentage (%). The total acreage per road district are Arnhem/Nijmegen: 5,799,159 m^2, Friesland: 4,831,779 m^2, and Breda: 5,576,876 m^2.

The information is used to analyze winter road maintenance for the winters of 2006/2007-2013/2014. For road district Breda no information is available for winter 2006/2007, and therefore this district was not taken into account for the analysis of that specific winter season. The data is analyzed using Microsoft Office Access software, figures are made using Microsoft Office Excel.

3.4.2 Meteorological- and climatological data

As has been explained in the previous section, detailed meteorological data for this study can be obtained from either a local KNMI automatic weather station or a local Road Weather Information System (in Dutch GMS; Gladheid Meld Systeem). Figure 4 illustrates the correlation between a GMS sensor and a KNMI station, showing a high correlation between the two so basically both sources can be used. In order to decide which source of information we could use best, we compared the measurements by the KNMI automatic weather stations to various nearby GMS sensors. From figure 5 we can see that station 350 shows a normal temperature pattern with cold temperatures in the first and last months of the year and warmer temperatures during the summer months. The GMS sensors (714, 716 and 952) show a more inconsistent pattern with various discrepancies and missing values. An explanation for this is that GMS sensors are more vulnerable to local variations and circumstances, such as shade. Although we know that GMS sensors can provide valuable information, from figure 4 we signaled some inconsistencies and incorrect values.

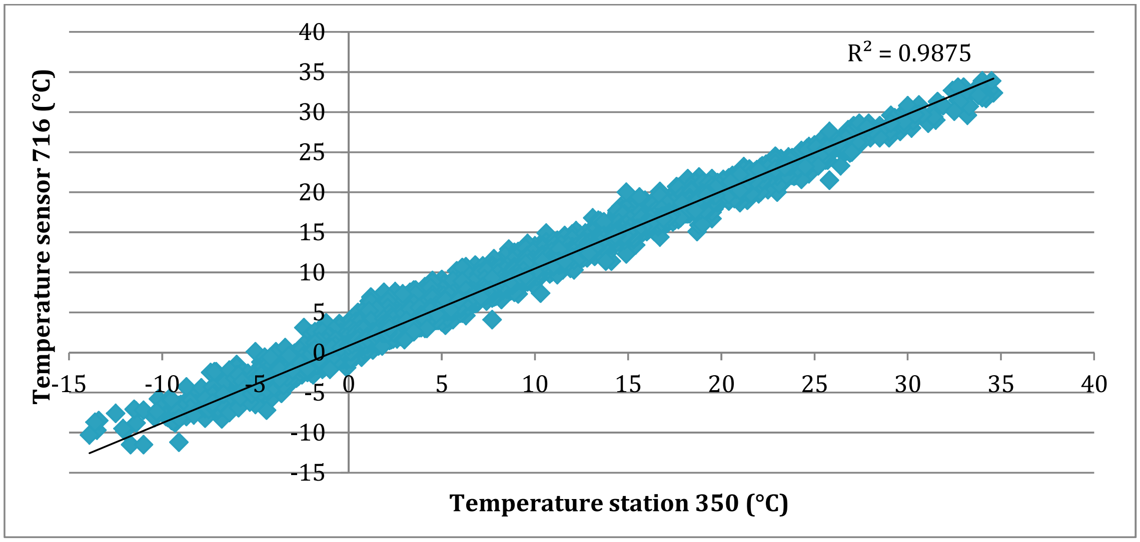


Figure 4. Air temperature correlation of KNMI automatic weather station 350 and GMS sensor 216 for 2010/2011.

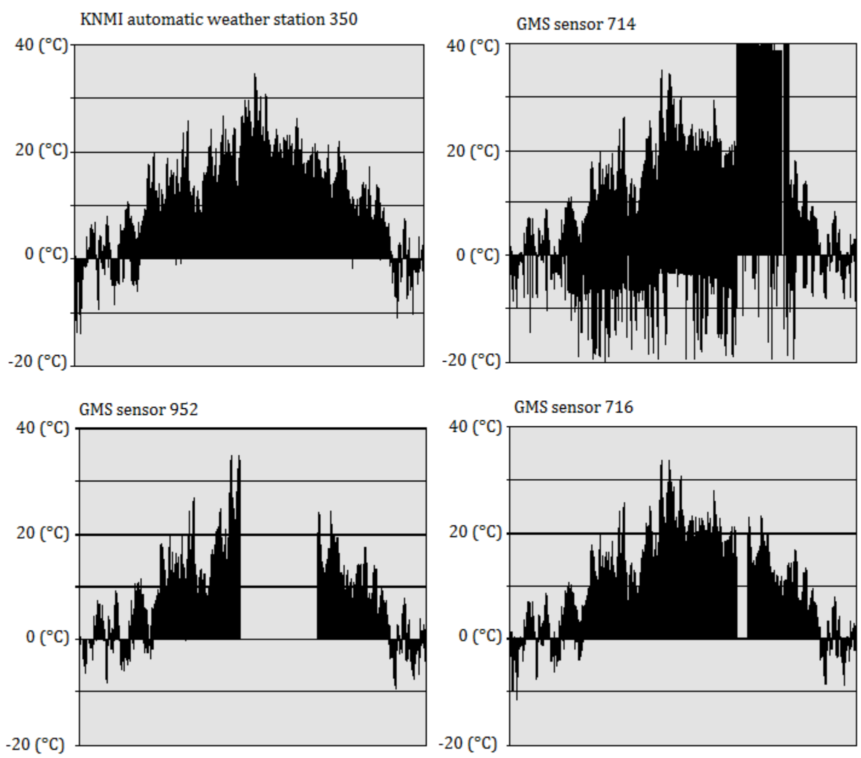


Figure 5. Plot of air temperatures of KNMI automatic weather station 350, and GMS sensors 714, 716 and 952 for 2010.

Also the availability of the data differs since GMS data is available since 2008 compared to measurements at KNMI weather stations from over 50 years. For this reason and the reasons mentioned above, we finally decided to use meteorological information obtained from the KNMI automatic weather observing stations. More specifically, we selected stations 270 Leeuwarden, 350 Gilze-Rijen and 275 Deelen for the three different districts. For these stations we used the following variables in the analysis:

- Average daily temperature: TG (°C)
- Daily minimum temperature: TN (°C)
- Total daily precipitation: RH (mm)

Based on these variables, we developed a query to indicate days with slippery roads, and more specifically designate potential days of condensation or winter precipitation. Condensation describes a situation where humid air condensates and freezes causing an icy layer on roads, and winter precipitation describes a situation where (freezing) rain or snowfall cause slippery roads. Condensation and winter precipitation cause slipperiness at days with a sub-zero average daily temperature, or an above-zero average daily temperature and a sub-zero daily minimum temperature. We define days with winter precipitation if the total daily precipitation is above 0.2 mm. In short:

- Condensation: *TG<0*°C*; RH=0mm* or *TG=>0*°C*, TN=<0*°C*; RH=0mm*
- Precipitation: *TG<0*°C*; RH>0.2mm* or *TG=>0*°C*, TN=<0*°C*; RH>0.2mm*

3.5 Assumptions and limitations

Based on the methods described above, there are some assumptions and limitations that need to be explained. The assumptions are mostly grounded in the fact that we highly simplified our meteorological query which in turn have led to some uncertainties in our conclusions. First of all, our meteorological query is based on only three variables, which are the average temperature, minimum temperature and total precipitation. There are, however, more meteorological variables that have an influence on winter road maintenance, such as cloudiness or humidity. Due to time restrictions, we have chosen to develop a simple model which we apply to describe a general overview. Furthermore, because of limitations in the number of climatological parameters available for the assessment of the effects of climate change, the meteorological variables used in the analysis should be restricted to those available climatological parameters. TG, TN and RH are parameters available for meteorological as well as climatological analyses.

Another limitation of the query is that it does not take hourly variation into account, which means that the exact moment of an event, such as rainfall, doesn't influence the query results.

Figure 6 illustrates an example. The two graphs represent a day with an average temperature (TG) below 0°C, precipitation (black dots), and the blue areas indicate periods of below-zero temperatures. Our query counts both situations as a day with temperatures below zero and winter precipitation. However, as figure 6 illustrates this precipitation can either fall as rainfall during a period of temperatures above 0°C (left) or during a period of temperatures below 0°C (right). Our query is not capable to distinguish variations during the day. However, there is a possibility that this rain will cause slipperiness since it follows a period of freezing temperatures and road temperatures therefore may still be subzero. In this situation winter road maintenance is often set into action for safety reasons (Donker, Rijkswaterstaat, personal communication, October 9th , 2014).

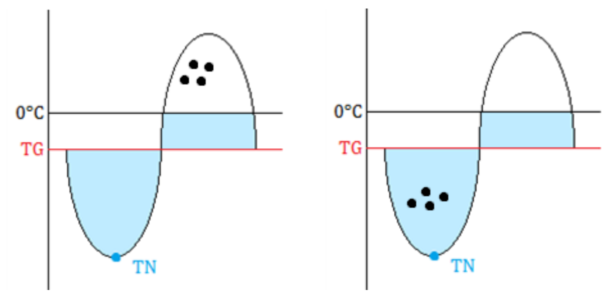


Figure 6. Illustrates of daily precipitation variations and possible temperatures. The left image represents rain and right snow.

Furthermore, external effects such as technological innovations have not been taken into account in this research. It can be that due to technological innovations less winter road maintenance activities are necessary or less salt is needed. We assume the need of salt per m^2 to be constant over time and no technical changes in winter road maintenance practices.

Finally, we combined our meteorological winter road maintenance query with the KNMI'14 climate scenarios in order to make a prediction for future winter road maintenance. Climate change is induced with a lot of uncertainty and logically the application of it too. By using the four climate scenarios that have been formulated by KNMI, the range of what might occur and the corresponding uncertainty can be visualized. In this way, we show different possibilities of future winter road maintenance. Since the climate scenarios are formulated for the Netherlands as a whole and no regional patterns are available, we cannot determine the local effect for the three regions. However, we assume the three regions together to be representative for the country as a whole. In this way we can use our meteorological query to determine future winter road maintenance trends for the Netherlands.

4. ANALYSIS AND RESULTS ON ROAD MAINTENANCE

4.1 Recent winter road maintenance

The following section presents the results based on the information collected in Section 3. First, we analyzed the frequency of winter road maintenance occurrence. To do so, we looked at days where at least one gram of salt has been sprinkled in a region. Those days are presented in graphs per month and winter seasons. A winter season goes beyond one calendar year, i.e. season 2009/2010 represents the months October - December of 2009 and January - March of 2010. The dataset includes winter seasons from 2007 until 2014 for three Rijkswaterstaat districts Arnhem/Nijmegen, Breda and Friesland. Second, as part of our meteorological analysis we developed a query which counts days where meteorological conditions can cause slipperiness. The results from this query were used to find meteorological reasons behind winter road maintenance for the years 1981-2011. Third, this section analyses the cost involved in recent winter road maintenance activities. And fourth, based on the above findings we use the KNMI'14 Climate Scenario's to determine how winter maintenance could change towards 2050.

4.1.1 Annual distribution of winter road maintenance

Figure 7 shows the total number of sprinkling days per winter season for 2007/2008 until 2013/2014. From that we see large annual variations. For example, the winters of 2006/2007, 2007/2008, 2011/2012 and 2013/2014 show relatively low numbers compared to other years. It can further be seen in figure 7 that the three regions show a more or less similar pattern. On average 46 annual sprinkling days per region have been found. More specifically, for the three different road districts Arnhem/Nijmegen, Breda and Friesland we found respectively an average of 52, 41 and 53 days.

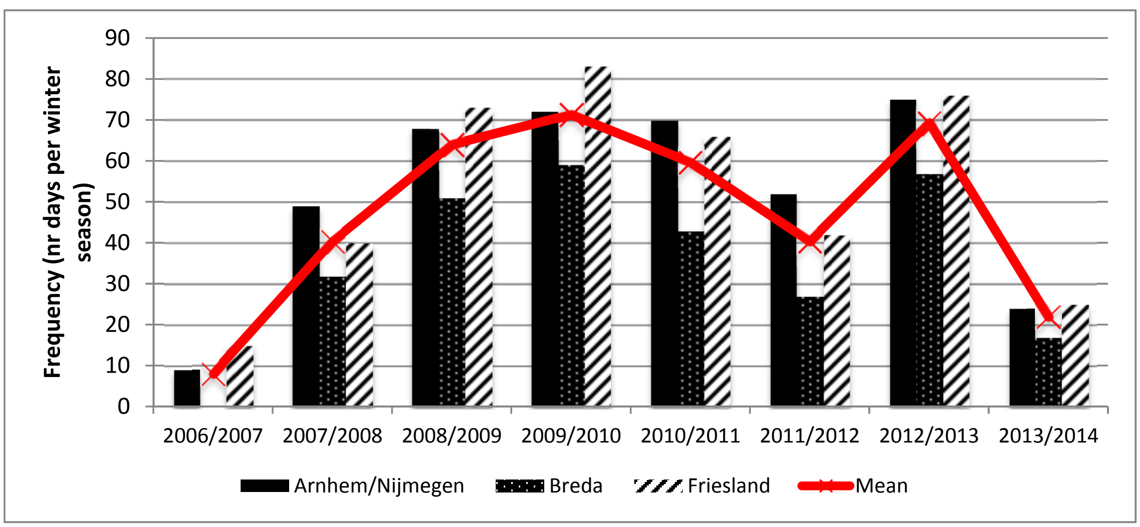


Figure 7. The total amount of sprinkling days per winter season presented per road district. The red line is the calculated mean for all three regions together.

Figure 8 represents winter road maintenance per month (black rhombs) and the standard variation (black lines). The graph shows that on average 13 of all sprinkling days occur in either December or January, compared to an average of 5 days in October, November and March. In addition, the standard deviation especially shows for December and January a large range, more or less between 5 and 20.

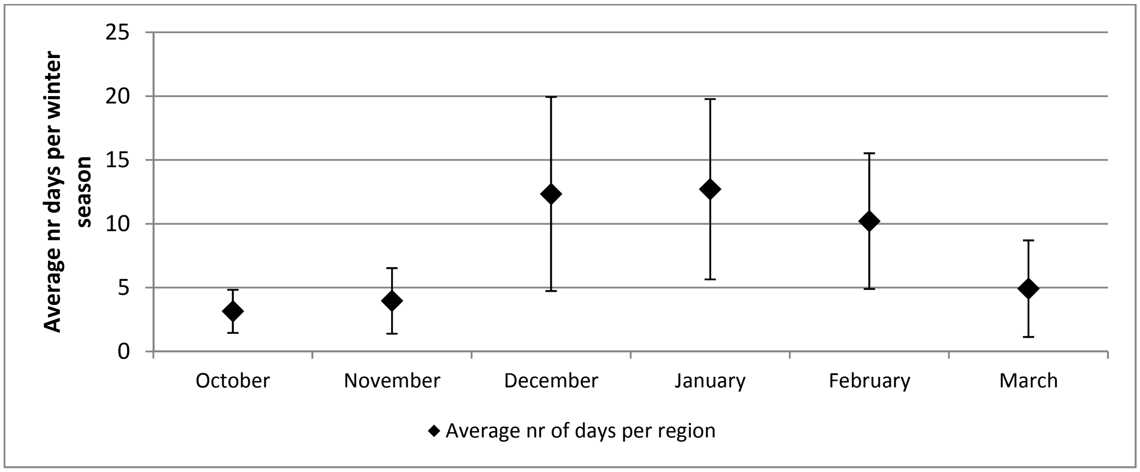


Figure 8. Average number of sprinkling days per month for 2007-2014. The black squares represent the average and the black lines the standard deviation.

Since the dispersion per month is the largest for December, we thought it was interesting to further analyze this month in more detail. Figure 9 displays different December months over the years. Note that December 2007 belongs to the 2008 winter season. The red line is the long term average of 13 sprinkling days per month. From figure 9 we can see that Decembers of 2008-2010 show above average numbers. For example in December 2010, 23 days out of 31 are found. Years 2007 and 2011-2013 on the other hand show considerably less days.

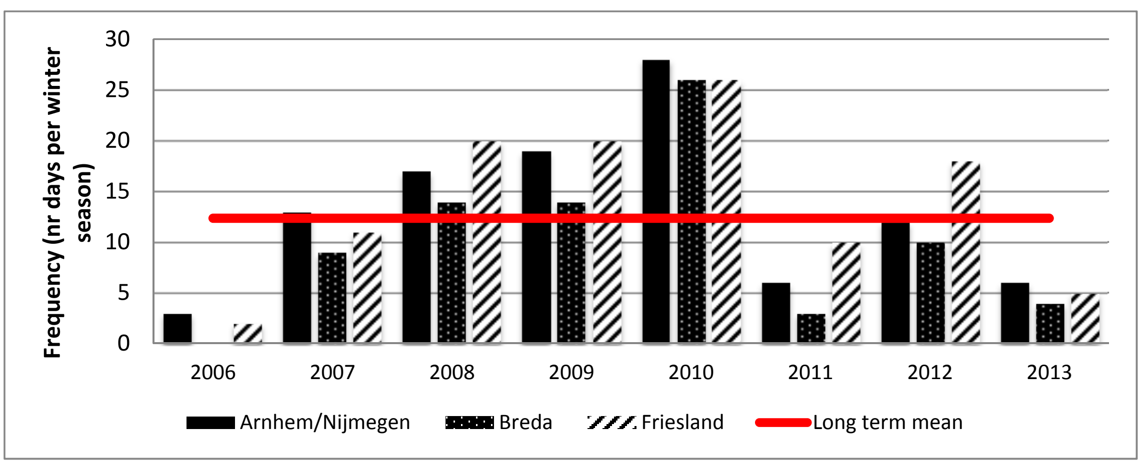


Figure 9. Distribution of sprinkling days for December over the years 2006-2013 for the three road districts.

4.1.2 Regional differences

During each winter road maintenance action, a certain acreage will be treated, depending on the expected impact of the winter weather. The following histogram shows the frequency of occurrence of the possible acreages. Logically, a low acreage stands for a small winter road maintenance action, while a large treated acreage stands for a large action. For each region the total acreage that has been treated is divided by the total acreage of the individual regions. By doing this, we are able to compare the different regions. The graphs shows a so-called U-shape, because from the different bars it can be seen that both 0-24.99% acreages and >100% acreages occur very frequent. In other words: either days with very little or very much winter road maintenance are seen most. The three regions show more or less a similar pattern, with a total average of 1.68 the total acreage of an region per winter road maintenance action.

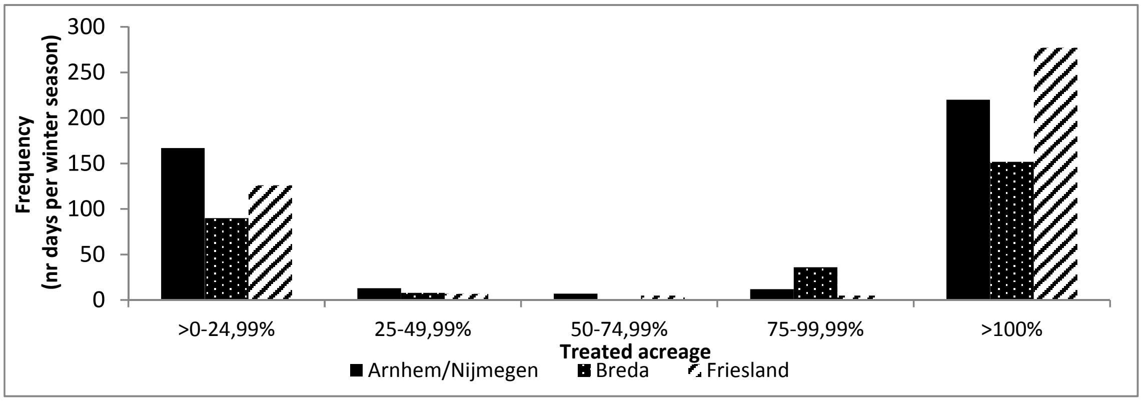


Figure 10. Histogram pointing out the frequency of different treated acreages (%) for the three road districts for winter seasons 2007-2014.

Table 1 zooms in at the >100% cases at the right end of the histogram; the days with more than 100% treated acreage. Table 1 demonstrates the five most extreme cases in term of total treated acreage and corresponding salt use in kg for winter seasons 2007-2014. From that it can be seen that four days are found in the Arnhem/Nijmegen region and one in Friesland. From the frequency analysis we cannot certify the underlying reasons.

Table 1. The five most extreme cases in term of total treated acreage in percentage and corresponding salt use in kg for seasons 2007-2014.

Road district	Datum	Winter Season	Treated acreage (%)	Salt (1,000,000 kg)
Arnhem/Nijmegen	20-01-2013	2012/2013	2,311	2.27
Arnhem/Nijmegen	20-12-2009	2009/2010	2,193	2.16
Arnhem/Nijmegen	15-01-2013	2012/2013	2,041	1.90
Arnhem/Nijmegen	14-02-2013	2012/2013	1,761	1.68
Friesland	16-12-2009	2009/2010	1,702	1.11

The table further indicates the most extreme winter road maintenance action as 2311% (23 times the whole region) with corresponding 2.3 million kilograms of salt. The same day in the other two regions only 1,562% and 131% of the region have been treated. The most logical reason for the differences is the presence or absence of snowfall. The two images in figure 11 confirm this assumption, since an ice skating scenery in Friesland and a snow landscape near Arnhem were found, both pictures were taken on 20-01-2013.

Figure 11 a, b. Two photographs taken at 10-01-2013. The left photograph shows an ice skating scenery in Friesland, while the right photograph shows a snow landscape near Arnhem. Source: Google images, 2014.

4.2 Meteorological analysis

This chapter presents the results from the meteorological analysis for the Arnhem/Nijmegen, Breda and Friesland road districts. The following variables have been used in the query (for more information; see chapter 3.5.2) to predict winter road maintenance activities: condensation and precipitation based on daily average temperature (TG, in Celsius), daily minimum temperature (TN, in Celsius) and the daily amount of rainfall (RH, in mm):

- Condensation: *TG<0*°C*; RH=0mm* or *TG=>0*°C, *TN=<0*°C*; RH=0mm*
- Precipitation: *TG<0*°C*; RH>0.2mm* or *TG=>0*°C, *TN=<0*°C*; RH>0.2mm*

Figure 12 presents the simulated query output and the results from the DMI-data analysis. As can be seen in the figure, the bars show a more or less similar pattern. However, fewer days were found for our query compared to the DMI-dataset. An average of 20% deviation between the simulated and the measured number of days has been found. However, we think that this is a logic result, because decisions in preventive measures in winter road maintenance are based on projections and weather forecasts while our query is based on weather observations.

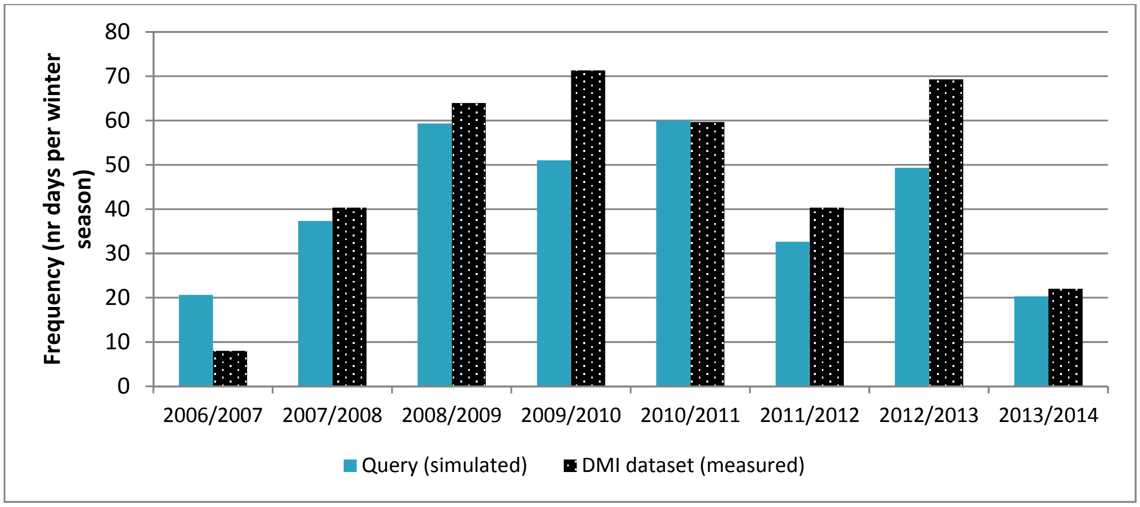


Figure 12. The amount of sprinkling days per winter season as found in the DMI dataset and our simulated query for 2006-2014.

In addition, the simulated results from our query can be further divided into days with slippery roads as a result of condensation or winter precipitation. Figure 13 illustrates this distribution. From that, it can be seen that each year a significant number of days with condensation are found. On the other hand, winter seasons 2008/2009, 2009/2010, 2010/2011 and 2012/2013 show the high numbers of sprinkling days due to precipitation.

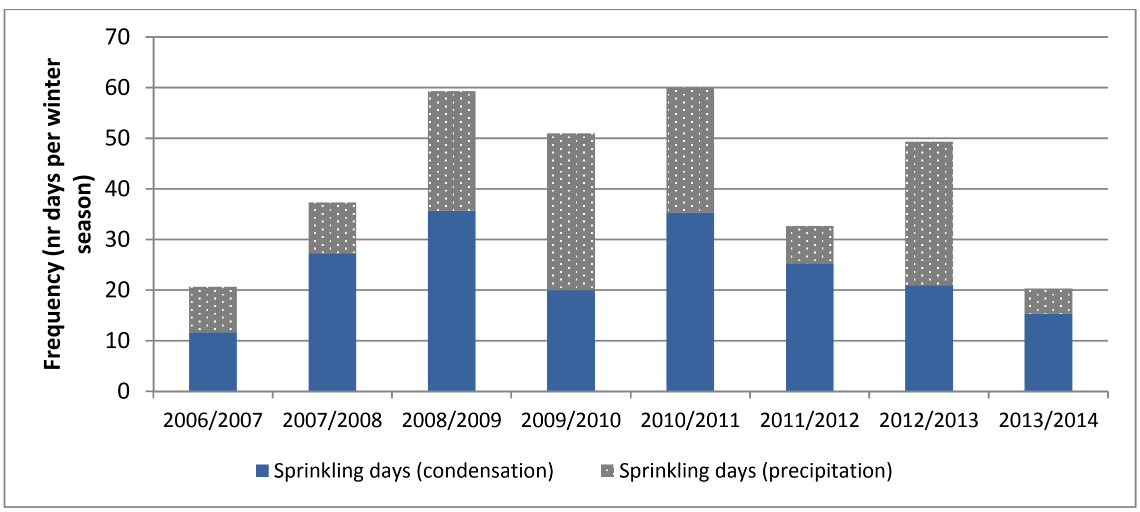


Figure 13. Meteorological reasons behind the number of sprinkling days per winter season for 2006-2014.

Figure 14 further divides condensation and precipitation into days with average temperatures (TG) above or below zero degrees Celsius. From that it can be seen that for each winter season many sprinkling days due to condensation can be found for both under freezing and thawing conditions. For precipitation on the other hand, we see a different pattern. The average amount of days with winter precipitation and below-zero temperatures not really high compared to precipitation under above-zero temperatures. Only winter seasons 2009/2010, 2010/2011 and 2012/2013 show a considerable amount of sprinkling days due to precipitation and freezing temperatures.

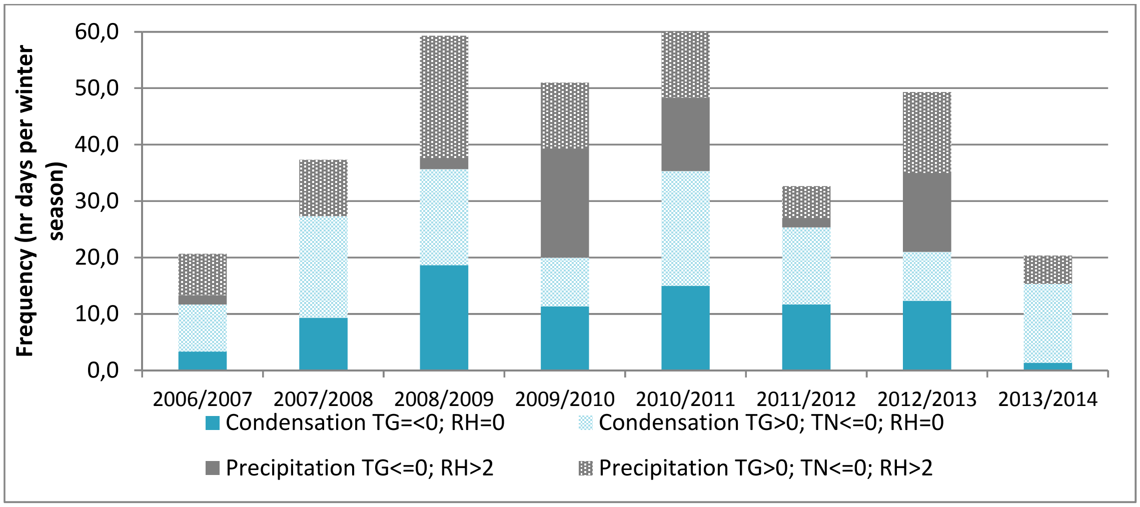


Figure 14. The average number of sprinkling days as have been found in the query. The total number of days is divided into days with condensation or precipitation. The secondary as represents the average daily temperature.

We then combined our DMI-data with the query results to be able to discover the specific weather type for the dates in the DMI-dataset. Our goal was to find the meteorological conditions behind the size of the maintenance action. In other words, what weather type causes the small and large actions we found in figure 10. Figure 15 reveals that small maintenance actions (>0-24.99%), such as the treatment of bridges or driveways, usually are caused by condensation, while maintenance actions that include an entire district (>100%) are mainly a result of precipitation.

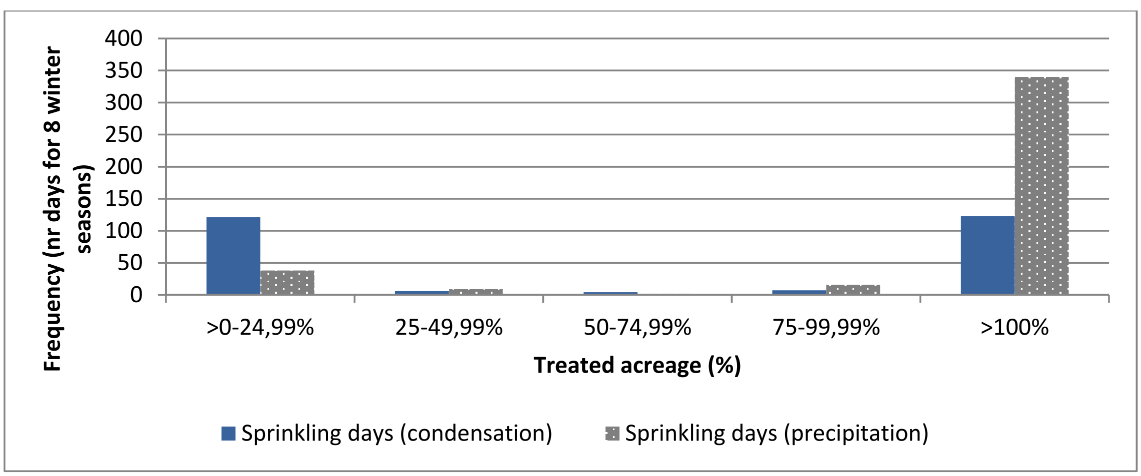


Figure 15. Histogram showing the meteorological conditions behind the treated acreages.

4.3 Implementation climate scenarios

The KNMI climate scenarios cover the vertices of presumable changes in the Dutch climate. The four KNMI'14 scenarios differ in the extent to which the global temperature increases ('moderate' or 'warm') and the possible change in the air circulation pattern ('low value' and 'high value'), see figure 16. In short, the KNMI'14 climate scenarios predict a picture of higher temperatures, accelerating sea level rise, wetter winters, more intense showers and (increased?)chances on drier summers. The extent to which the living environment will chance differs slightly per scenario, but in general it can be said that G_l is the scenario that shows the lowest change and W_h the highest change compared to our current climate.

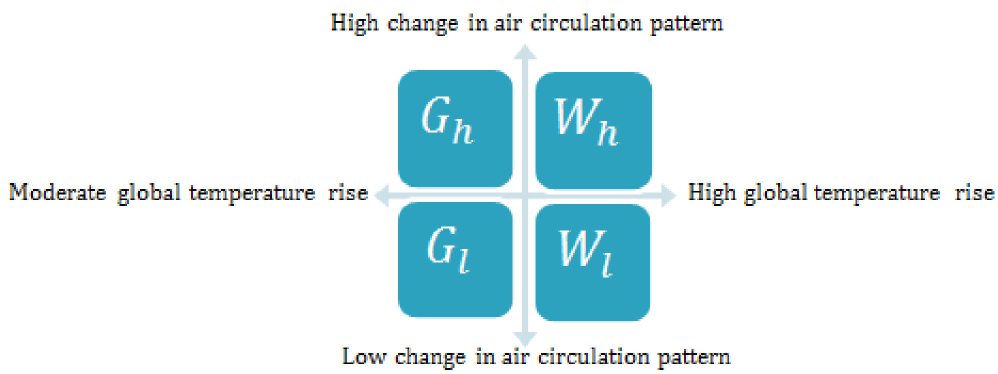


Figure 16. The two parameters that drive the four KNMI'14 scenarios: change in air circulation pattern and global temperature rise. *Source: KNMI, 2014.*

We used the transformation program, which can be found at the KNMI website[2], to determine the average temperature, minimum temperature and precipitation for different scenarios. The program converts a historical daily precipitation or temperature series in a range that fits the future climate under one of the four KNMI'14 climate scenarios. In other words, it uses likely changes in temperature, precipitation and extreme values from one of the four scenarios to transform measured values that actually have happened in the past into a series that are likely to happen in the future scenario.

The program produces time-series for the average- and minimum temperature, and precipitation. The amount of precipitation is calculated in three ways, resulting in time-series with an upper, center and lower range. The difference is not grounded in the amount of precipitation, but in how that amount is diverged over the days. In other words, meteorologist expect that more precipitation will fall in less days (more extremes), but it is unsure how this will be dispersed over days. To be able to view the uncertainty that involves climate change science, we decided to visualize the most extreme and least extreme scenarios. We therefore

[2] http://climexp.knmi.nl/scenarios_knmi14_form.cgi

present the G_l scenario and W_h scenario for 2050, for both precipitation possibilities under the lower and upper range. Figure 17 presents the scenarios for the lower range and figure 18 presents the scenarios for the upper range. For the upper range scenario there is also a general climate change scenario for 2030 available (orange line).

As can be seen from the two figures, there is not much difference between the two precipitation ranges. On a yearly basis, we see some differences, but these are negligible for long term averages. From table 2 we can see for 2030 a 39% decline in the average amount of sprinkling days and for 2050 a decline between 37% and 69%.

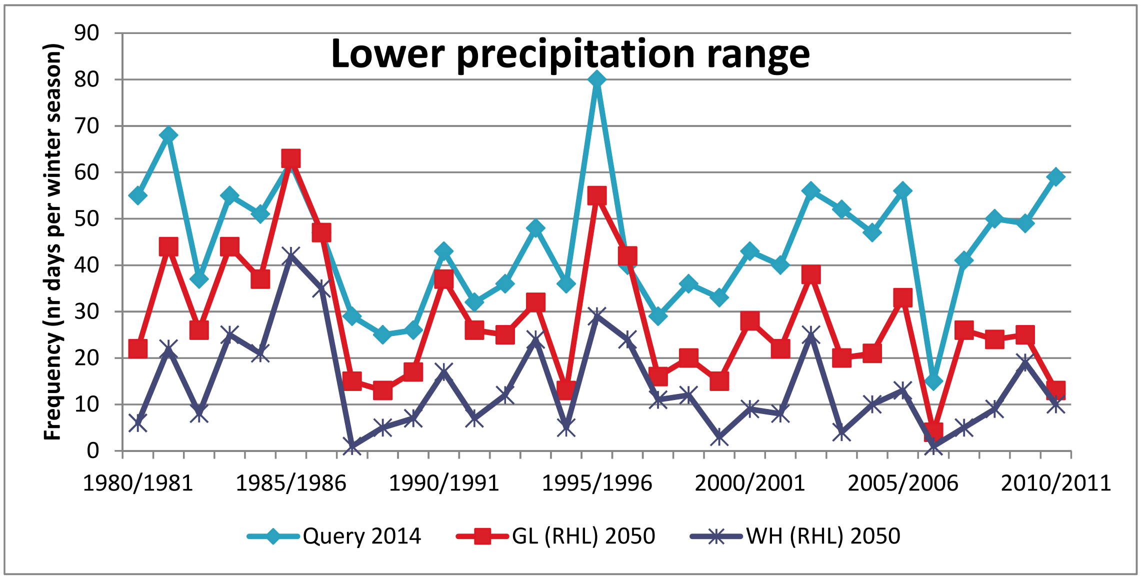


Figure 17. The total number of sprinkling days per winter season for different climate scenarios under lower precipitation range.

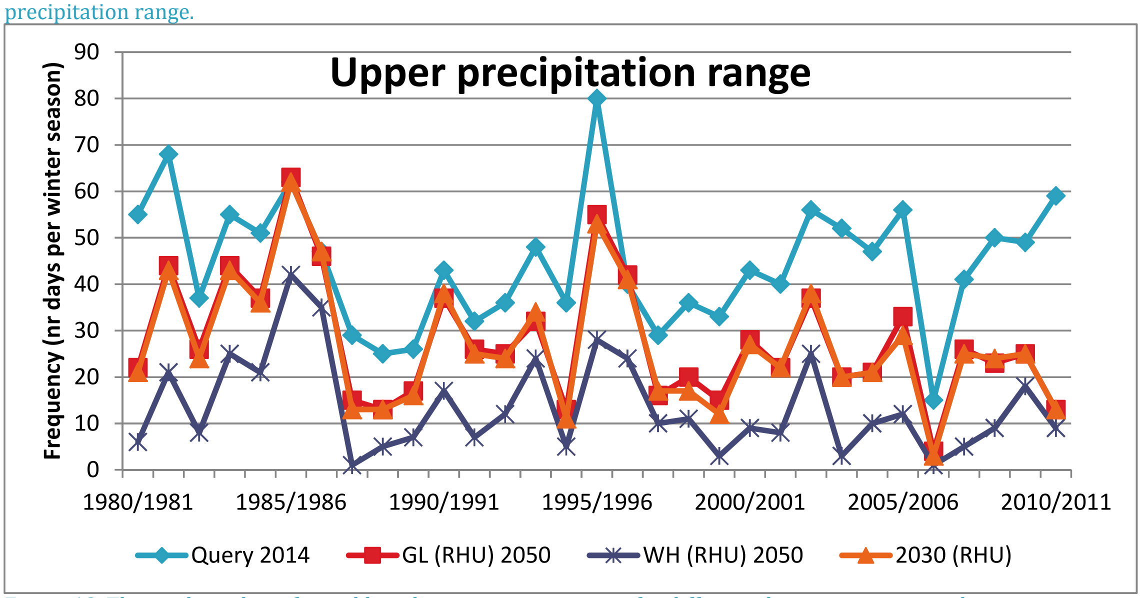
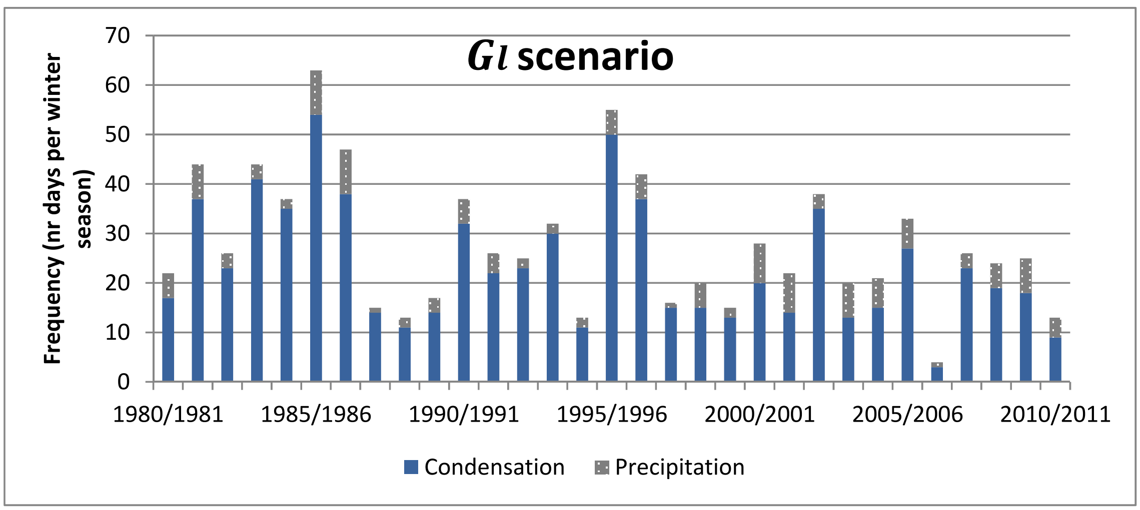


Figure 18. The total number of sprinkling days per winter season for different climate scenarios under upper precipitation range.

Table 2. The daily average amount of sprinkling days per year and the corresponding changes for the 2050 climate scenarios used.

	Query 2014	G_l (RHL) 2050	G_l (RHU) 2050	W_h (RHL) 2050	W_h(RHU) 2050	(RHU) 2030
Average amount of days /year	44,39	27,74	27,84	13,58	13,84	27,0
Decline compared to 2014	-	**37%**	**37%**	**69%**	**69%**	**39%**

Furthermore, as we have seen before, sprinkling days can be divided into days with precipitation or condensation. We found that the current distribution of 58% condensation and 42% winter precipitation is going to change comprehensively. Figure 19 and 20 show the average number of days for the G_l and W_h (RHL) scenario. From that, we can say that winter road maintenance for winter precipitation reasons is expected to decline in all scenarios. For the WH scenario, even some years without winter precipitation can be expected. Condensation thus will remain the main cause for winter road maintenance activities.



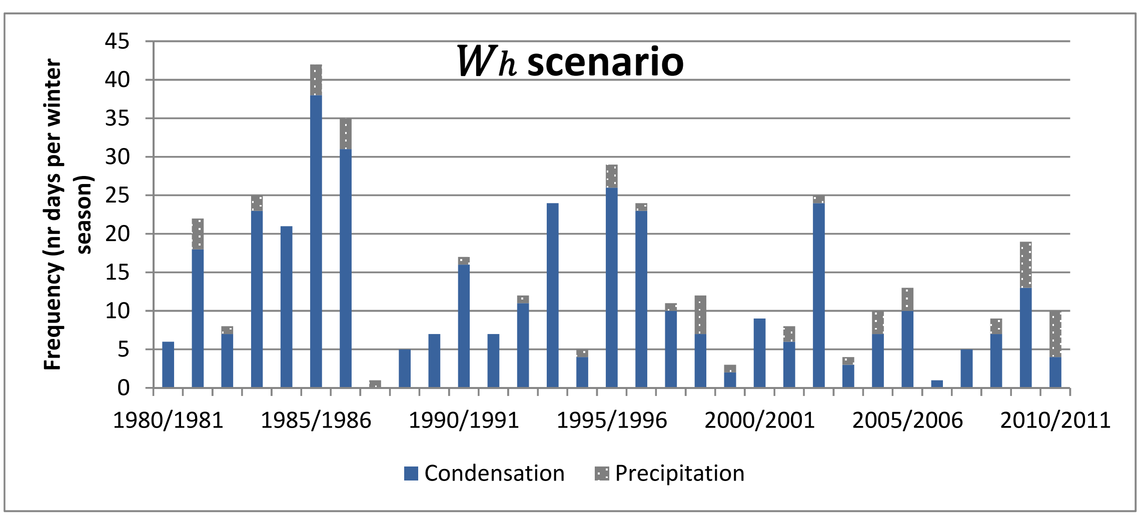


Figure 19 a,b. The average number of days for the G_l and W_h (RHL) scenario as have been found in the query. The total number of days is divided into days with condensation or precipitation.

In summary, the climate change analysis indicated less days with winter road maintenance towards 2050. Since we have found a linear relation between the amount of days that need winter road maintenance and the total costs, we assume these costs to decline in line with the maintenance activities.

5. DISCUSSION AND CONCLUSION

The analysis in winter road maintenance data from DMI revealed an average of 46 sprinkling days per winter season over the 2007-2014 period. More specifically, for the three different road districts Arnhem/Nijmegen, Breda and Friesland we found respectively an average of 52, 41 and 53 days. Moreover, we further have found that December and January are the months that usually have the largest number of sprinkling days compared to other winter months. Besides that, sprinkling days can be divided into days with either very small or very large actions. If we compare our results to the findings by KNMI and Meteogroup (as described in the Section 2), we have found a (in several winters considerable) higher amount of simulates salt sprinkling days per winter. As part of our meteorological analysis we developed a query which counts days where condensation or winter precipitation might occur. The query proved condensation to be the main reason for winter road maintenance. Specifically, we have found a distribution of 58% actions due to condensation and 42% actions due to winter precipitation. Which is also different to MeteoGroup that found snow to be the main cause of winter road maintenance. However, we did find winter precipitation to cause the largest actions in terms of salt use and working hours. The differences with MeteoGroup are most likely due to a different method and query formulation.

The implementation of the KNMI'14 climate change scenarios revealed the total amount of days that need winter road maintenance to change considerably. The number of winter road maintenance days is likely to decline between 37% and 69% towards 2050. Also, winter precipitation is found to occur less frequently, and therefore remains condensation the main cause for winter road maintenance activities. For contractors, this means that they can expect more often small winter road maintenance actions instead of days that need treatment for an entire district. However, occasionally we can still expect extreme winter weather and thus large winter road maintenance actions. Based on the results, we found that a winter maintenance service will still be required in the future to secure road safety, but overall operational costs will most probably decline coherently.

Furthermore, based on the research we can define various policy implications due to a changing climate for the decision on road maintenance. The knowledge gives useful indications for required resources on the business level since the analysis indicated a declining winter road maintenance service. For KNMI, this can have implications for more efficient resource planning within the KNMI forecast division, because they can expect longer periods with temperatures above zero. During these periods no supervision for winter road maintenance alerts is necessary or can be done as a side task next to other tasks. This will change the distribution of meteorologist in the weather department.

Finally, some suggestions for future research are first of all to improve the query by adding additional meteorological variables, such as more detailed information on air- and road temperatures, humidity and wind direction. By doing this it would be possible to distinguish different types of winter precipitation, such as snow and icy rain. Second, the query can also be improved to study daily variations in more detail. Especially more detailed information from previous days, such as frost, can give useful insights. And third, it would be very interesting to study the effects of a declining winter road maintenance service on the purchase of salt, policy making and the formulation of future contracts for Rijkswaterstaat.

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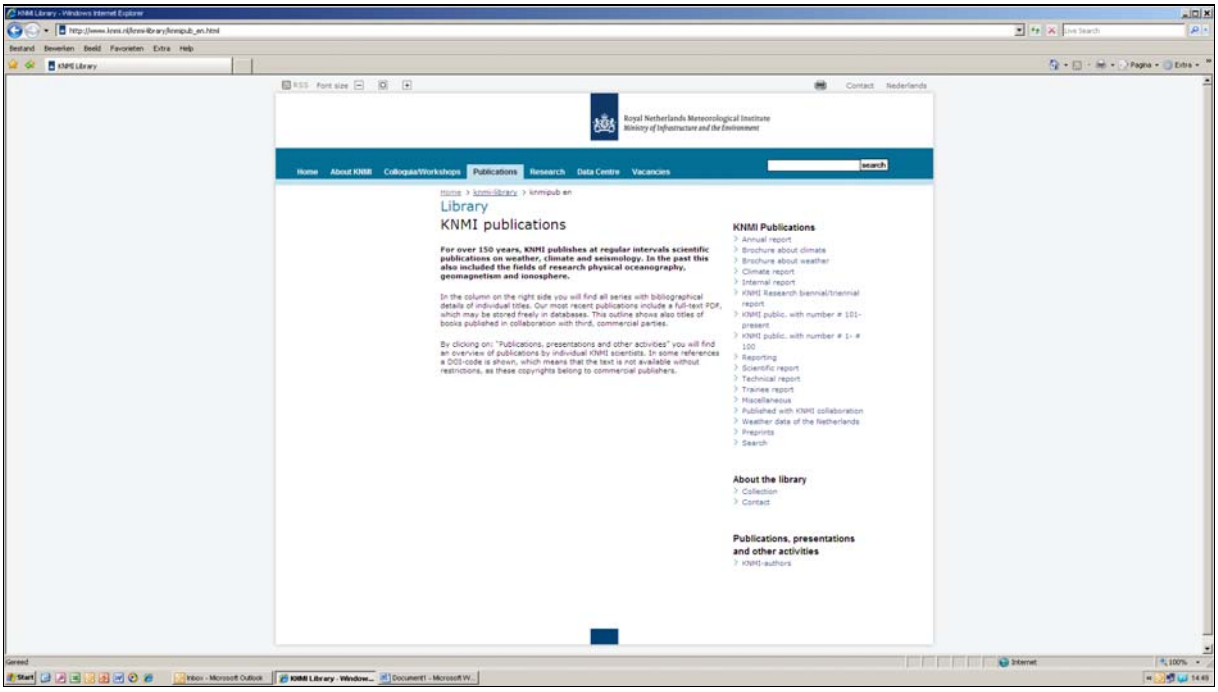

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