THE EFFECTS OF CLIMATE CHANGE ON WINTER SERVICE IN GERMANY

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ABSTRACT

The European winter weather and climate is changing. However, many aspects must be considered by the interpretation of the interannual variability. Existing natural modes of variations in the Earth climate system (e.g. Quasi-Biennial Oscillation) are superposed by the observed temperature rise during the last decades, especially over the continents on northern hemisphere high- and mid-latitudes including regional characteristics.
Here, we focus our attention on the past and future climate variability in Germany over the winter season. For the time period 1951 to 2010, observation data from the German Weather Service and ensemble simulations until the end of this century using a statistical resampling scheme were analyzed with respect to impacts on the winter service.

1. INTRODUCTION

This paper is about the change of the winter service in Germany in a future climate. This question is of highly economical interest. Well-timed adaptions and preventions to the new conditions could not only save costs but also reduce risks relating to traffic security.

The winter season 2012/13 in Europe has demonstrated that the winter service is important than ever. Heavy snowfall events already in early winter and an extraordinary long winter period until the end of March had considerably damaged our sensible traffic system. Thus, research including different sectors are necessary, even though, the obtained results are preliminary and difficult to verify, because the projected period is too far in the future.

The northern hemisphere (NH) winter is strongly determined by the horizontal pressure gradient over the oceans. The resulting wind regimes effect the weather over the continents. This relation is represented by the North Atlantic Oscillation (NAO) index for Europe. Usually this index has a positive sign, which is connected with low pressure over the northern part of the North Atlantic sector (Iceland) and high pressure over the southern part (the Azores). Consequently, westerly winds transport mild and wet air mass to central Europe. In late winter 2013 (February/March) the configuration of this system reversed (strong negative NAO index) and was stable over several weeks. This situation caused heavy snowfalls and cold over the eastern part of Central Europe, because cold air from Scandinavia met warm and wet air from the south. The winter service was rather busy with ploughing, spreading and salting of roads and highways during this period.

However, long-term monthly mean temperature records reveal a return interval for such extreme events of about 6-10 years. One possible explanation for such an European blocking situation in late winter can be found in literature [3,12,13]. They reveal a troposphere-stratosphere coupling and a connection between Equatorial wind regimes in the lower stratosphere and regions on middle- and high latitudes. Phases of east and west winds oscillate with a period of about 28 month. This is well-known as the quasi-biennial oscillation (QBO). By separating the two different phases of QBO (west/east) and mapping fields of the surface temperature differences, negative values dominate over the European continent [12]. Only in winter, if the prevailing winds in the lower stratosphere on winter hemisphere is directed from west to east (westerly), such a coupling can happen. The mechanism behind this is the modulation of the wave guide dependent on the QBO phase and its effect on the polar vortex intensity.

Natural variations in the atmosphere system will be increasingly superposed by the climate warming signal. Until the end of this century global climate model simulations driven by the strongest emission scenario (RCP 8.5) result in a temperature rise for Central Europe of more than 4 °K [16]. Possible changes in the atmosphere circulation and static stability could lead to new state of extremes of different nature (e.g. floods, droughts and thunder storms), which will crucially effect our future live.

Especially the northern European countries (e.g. Norway, Sweden and Finland) are already affected by the observed climate change and will be stronger affected in future, if the most pessimistic scenario becomes real. The recently finished report of the RODEX project [4] describes a likely climate evolution for the Northern Periphery based on the previous scenario family (A2). In spite of milder winter months in future the winter services on road networks will be still necessary in order to assure the safety of the traffic system.

In the following course of this paper we introduce the regional climate data and statistical model scheme that are used to simulate ensemble projections for the future climate (section 2). Next, the obtained results for the past and future climate are presented and discussed with respect to the changes during the winter season and their impact on the winter services for selected road and highway maintenance areas in Germany (section 3). Finally, this paper ends with a conclusion in which the uncertainty of the future climate simulations are given.

This report is based on parts of the research project carried out at the request of the Federal Ministry for Transport, Building and Urban Development, represented by the Federal Highway Research Institute, under research project No. 04.0251/2011/LRB. The authors are solely responsible for the content [17].

2. METEOROLOGICAL DATA AND MODEL

2.1 Meteorological parameters on road maintenance areas

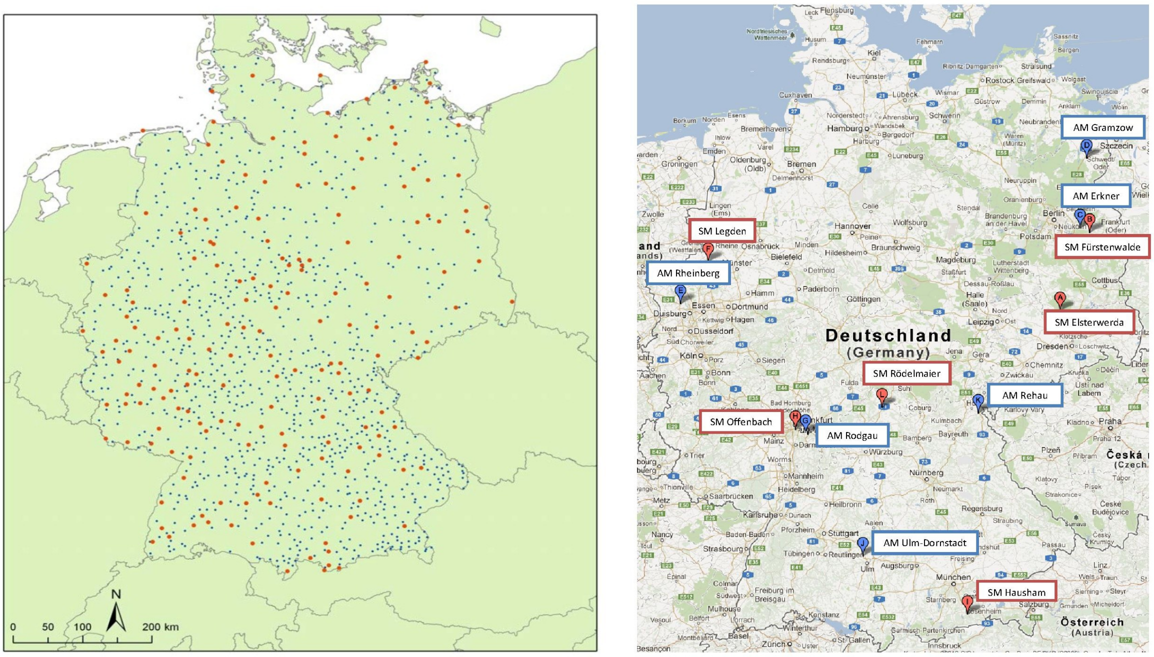


Figure 1:

left: Map of the climate stations (red circles) and precipitation records (blue dots) network operated by the German Weather Service.

right: Map of selected road maintenance areas in Germany which were considered in the research project "Klibet".

The German Weather Service (DWD) operates a dense network of long-term synoptical stations (180) and additional 1038 records of precipitation (see Fig.1, left). All together 1218 stations on a daily basis from 1951 to 2010 were controlled and homogenized [6]. Furthermore, parameters (e.g. temperature, humidity etc.) from climate stations have been interpolated to the entire station grid. These high resolution observation data are the basis for the statistical climate model described in the following subsection (2.2).

Within this project all available stations within the 12 selected maintenance areas (see Tab.2 and Fig. 1, right) were collected and averaged in order to describe the weather and climate characteristics, respectively. Finally, the secondary winter parameters (Tab.1) are derived from the primary indices. The most relevant ones for the winter service are, e.g., the sum of the new snowfall depth (SSD), days with snowfall (NFS), days with freezing rain (NFR) and days with rime (NRM). A possible connection to records of winter service parameters on the maintenance areas will be presented in subsection 3.4.

Primary parameter				Unit
daily minimum temperature			Tmin	°C
daily sum of precipitation			RR	mm
relative humidity			RF	%
new snowfall height			SN	cm
snow height			SH	cm
Secondary parameter			**Combinations of primary parameters**	**Unit**
sum of new snowfall depth	x_1	**SSD**	SN > 0 cm	cm
days with snowfall	x_2	**NSF**	SN > 0 cm	d
days with freezing rain	x_3	**NFR**	Tmin < 0 °C & RR > 0 mm	d
days with rime	x_4	**NRM**	Tmin < 0 °C & RR = 0 mm & RF > 90 %	d

Table 1: List of the most important primary and secondary meteorological parameters with respect to the winter road service.

maintenance areas	°N	°E	m	Obs.	km
SM Elsterwerda	51,5	13,5	89	6	271
SM Fürstenwalde	52,4	14,1	89	5	309
AM Erkner	52,4	13,8	32	4	51
AM Gramzow	53,3	14,0	52	4	97
SM Hausham	47,8	11,8	752	5	202
SM Rödelmaier	50,3	10,3	325	4	375
AM Rehau	50,3	12,1	551	4	63
AM Ulm-Dornstadt	48,5	10,0	580	6	70
SM Offenbach	50,0	8,9	114	5	248
AM Rodgau	50,0	8,9	114	6	77
SM Legden	52,0	7,1	61	5	n/a
AM Rheinberg	51,5	6,6	19	4	97

Table 2: List of parameters which characterize the selected road- (SM) and highway (AM) maintenance areas in Germany.

2.2 The statistical climate model

The estimation of the future climate for Germany is carried out using the STatistical Analogue Resampling Scheme (STARS). This approach combines long-term observations with information about the temperature regime in future taken from general circulation models

(GCMs) over the regions of interest [1,15]. The linear trend of the Coupled Model Intercomparison Project Phase 5 (CMIP5) [10] ensemble mean driven by the high emission scenario RCP 8.5 [2] was extracted and is externally prescribed for the rearrangement of the observation data. All other parameters, e.g. daily minimum and maximum temperature as well as the daily precipitation sum, are carried along with the leading variable, which ensures the physically consistency to each other and the conservation of a realistic seasonal cycle. However, new single extreme values cannot be generated (e.g. heavy precipitation events) in the presently used model version.

Finally, randomly generated realisations by Monte Carlo simulations provide ensembles for the present scenario. In order to save computation time a pre-processing step is interconnected that spatially clusters all stations into 5 regimes relating to their mean temperature and precipitation climatology. The respective centroids (stations) are used for the just described STARS algorithm. In the end, a post-processing step rearranges each observation corresponding to its representative station.

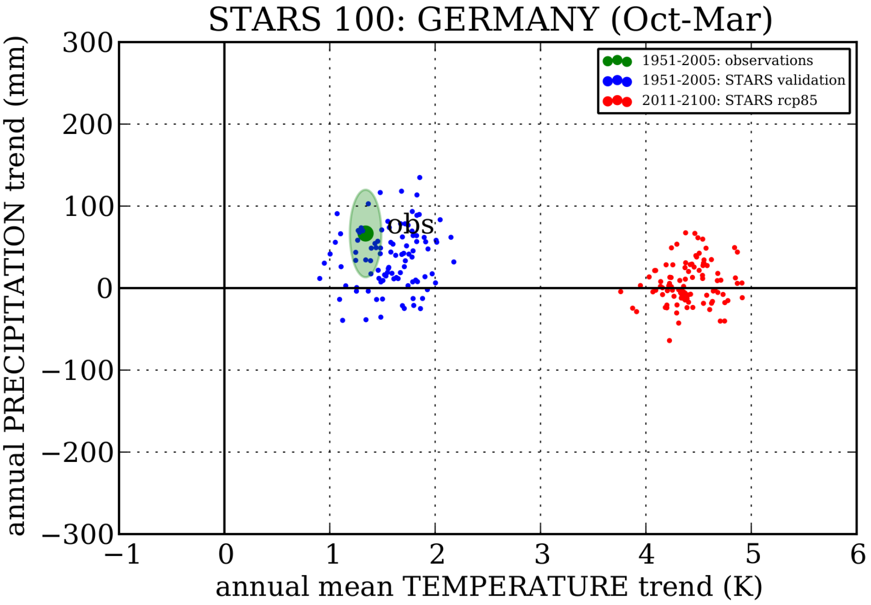


Figure 2: Distribution of trends in annual mean temperature and annual precipitation sum over Germany (only winter half). The observed combination and its standard deviation is given in green color. The 100 simulated realisation with STARS (October-March) for the validation period 1951-2005 (blue dots) and future period 2011-2100 (red dots) are added.

The linear trends of the annual mean temperature versus the annual sum precipitation over Germany for the validation period (1951-2005) observed (green) and simulated with STARS (blue dots) are shown in Figure 2. Notice, that the realisations only represent the winter half (October-March). The spatially standard deviations (sigma) in temperature and precipitation for the 5 reference stations are represented by the light green oval. The 100 realizations with STARS for the hole year in comparison to the observed trend during the historical period result in a somewhat too dry reality. About 25% of the ensemble members lay within the one sigma range of the observations and reproduce the positive precipitation trend (not shown).

This tendency continues for the simulations until the end of this century. However, the future realizations for the winter season indicate a somewhat stronger warming than the prescribed temperature trend of 4°K and the tendency in the precipitation is slightly positive. This is consistence with results obtained by [11], which show a strong model uncertainty for Central Europe with respect to the trend direction in the annual precipitation sum.

Model comparisons between statistical and dynamical regional climate models for South Africa have already published by [14]. They showed that the statistical approach reproduce the annual mean precipitation pattern qualitatively much better than one single realisation using the dynamical regional climate model COSMO CLM. However, the development and improvement of the STARS model will carry on.

3. RESULTS

3.1 Natural variability

One of the most important natural component in the atmosphere variability is analyzed using monthly NCEP/NCAR reanalysis data [9]. The spectral component with a period of 28 months was extracted from the mean zonal wind. This low frequency component corresponds to the signature of the QBO. Its amplitude distribution is shown in Figure 3. The strongest signal is visible in the equatorial lower stratosphere. Here, phases of westerly- and easterly winds alternate regularly. Also connections to higher latitudes in the troposphere are found via the modulation of the prevailing wind regimes and the vertical propagation of planetary waves forced in lower atmosphere layers. However, this coupling mechanism appears more clearly on winter hemisphere while westerly winds dominate the troposphere-stratosphere system.

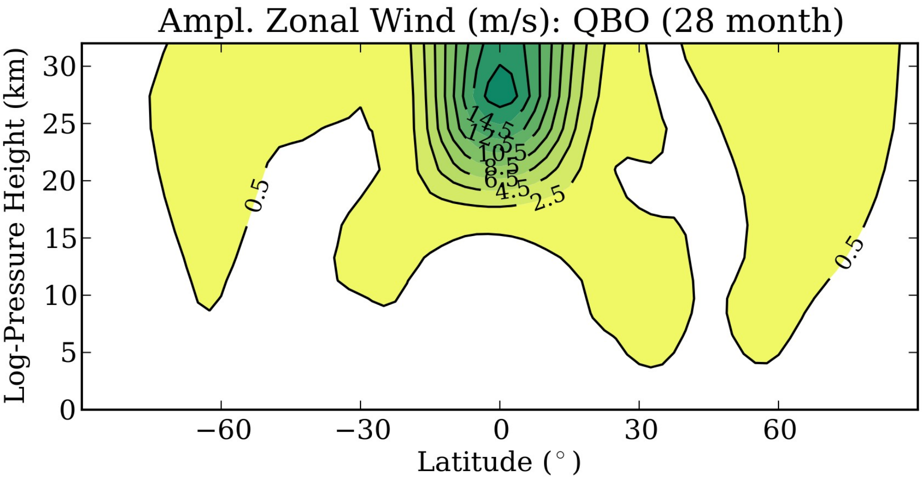


Figure 3: Height-latitude cross section of amplitudes in zonal wind with a period of about 28 months, corresponding to the QBO.

A possible response of this low frequency oscillation in the tropics is also found in surface parameters for Germany. Figure 4 shows the time series of the monthly mean daily minimum temperature ($Tmin$) for March from 1951-2005 (full color). Red bars indicate values above

0°C and the blue ones below 0°C. From visual inspection of the temperature records (averaged over Germany) we found a quasi regular behavior in the frequency of extreme cold March months. At least, once per decade the considered parameter ($Tmin$) falls below -2°C. This could be the result of a superposition of the annual cycle with a quasi 28 month oscillation.

In the realisations for the future climate (light color bars) we still find such regularity. The 10%-percentile of $Tmin$ reveals a positive trend. In the second half of this century such cold events will slowly disappear due to the dominant temperature rise. Notice, that Fig. 4 is no climate prediction for a specific month. Only the return interval of a special characteristic can be taken from this chart.

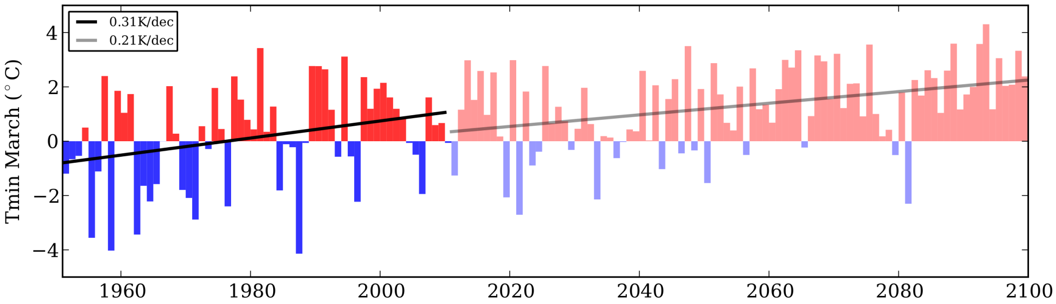


Figure 4: Daily minimum temperature records averaged temporally for March and spatially for Germany since 1951 to 2010 (observations). The 10% percentile of 100 realisations with the statistical climate model "STARS" is given in light colors beginning from 2011 to 2100.

3.2 Projections of the winter climate change

Based on 100 STARS realizations for the primary meteorological parameters, the secondary parameters which are the most relevant ones for the winter service were derived (see Tab.1). The projection of days with snowfall (Fig.5a), with freezing rain (Fig.5b) and with rime (Fig.5c) in Germany for three 20-years periods (2011-2030, 2031-2050, 2061-2080) in comparison to the state for the historical period (1991-2010) indicates a significant decrease in the second half of this century. The blue dots represent the ensemble mean over all maintenance areas and the horizontal black lines mark the standard deviation. In near future (2011-2030) the days with snowfall rise from 18 days to 22 days. In the late period only about 10 days with snowfall are expected. This model behavior seems consistent with the experiences during the last decade.

Results from the ENSEMBLE project [9], finished 2009, with the aim to represent regional climate changes and impacts on several time scales also showed a much weaker temperature rise over Scandinavia in near future than at the end. Strong decadal variations are visible in the dynamical model simulations, which could be responsible a weak cooling effect until about 2030.

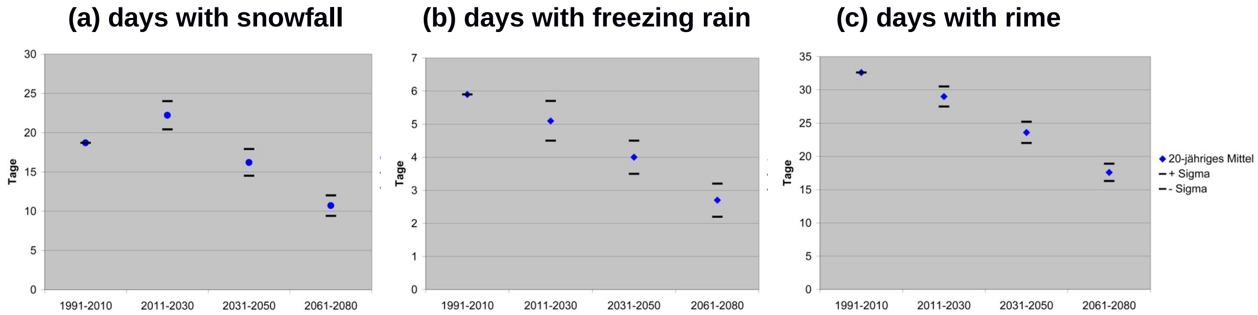


Figure 5: Projections of different secondary indices, which are important for the winter service. The following 4 climate periods are considered: 1991-2010, 2011-2030, 2031-2050, 2061-2080.

3.3 Regional characteristics

In order to demonstrate the different regional characteristics each of the 12 considered maintenance area (Tab.2) were mapped with respect to their averaged geographical position. The respective winter parameter is represented by the size and color of the circles, both absolute value for the historical period (1991-2010) and anomalies for the three periods in the future. Additionally, a dependency in terms of height, latitude and longitude is considered, respectively. Thus, a possible shift in the regional climate regimes can be identified. The largest one (AM Rödelmaier) is situated in the center of Germany and cover a highway network of approximately 375 km. In the following paragraphs, regional characteristics for two parameters (new snow depth sum and day with freezing rain) are described.

Example: New snow depth sum (SSD)

The spatially distribution and temporally evolution of the new snow depth sum (SSD) parameter shown in Figure 6 illustrates the existing winter regimes in Germany. The southern part is rather mountainous and the northern part is rather flat. Consequently, SSD is higher in the maintenance areas above 500 m a.s.l. (e.g. SM Hausham, AM Rehau) than AM Rheinberg (16 m a.s.l) for example close to the border of Holland. The changes with respect to 1991-2010 indicate a slightly positive tendency of more SSD especially in the northern low mountain ranges represented by the maintenance areas (AM Rödelmaier and AM Rehau) and the easternmost districts (SM Fürstenwalde, AM Erkner and AM Gramzow). In far future those maintenance areas with a huge amount of snow must expect the largest loss.

A systematical shift of the winter regimes in Germany can be considered by comparing the existing dependencies related to the average height of the maintenance areas, the latitude and the longitude for the different periods in the future. Figure 7 shows scatter plots for one winter variable. Each dot represents one maintenance area and the color corresponds to the 4 climate periods: 1991-2010 (black), 2011-2030 (green), 2031-2050 (blue) and 2061-2080 (red). A linear fit is added, respectively.

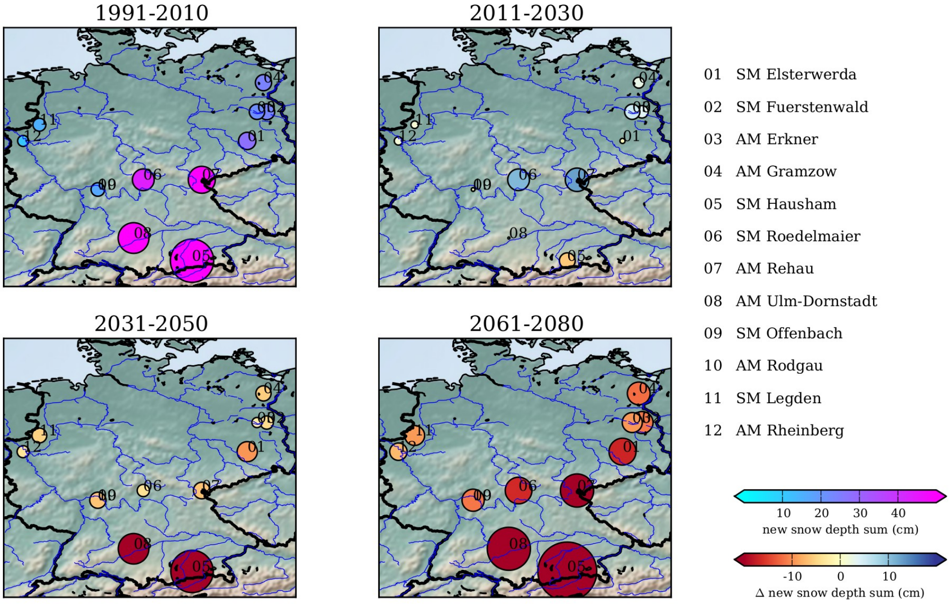


Figure 6: Maps of the averaged "new snow depth sum" for the 12 maintenance areas and from 1991-2010 (upper left).

The other maps represent the changes relating to the reference period: 2011-30, 2031-50, 2061-80.

For the reference period 1991-2010 (black lines) the SSD is clearly controlled by altitude (Fig.7, left). This characteristic is changing in much warmer winter conditions (e.g. 2061-2080). The red line reveals a slope that is different from the black one. We conclude with a decreasing SSD the winter service becomes more independent on altitude. A slightly shift of the green line (2011-2030) to the right indicates an intensification of this parameter to higher values. The latitudinal consideration of the SSD parameter (Fig.7, middle) reveals a similar behavior as before, because the control by altitude is included. However, small differences are visible between the first two periods of time (black and green). In 2011 to 2030 the SSD parameter grows with latitude. The dependency with longitude is rather weak with a tendency to more SSD from west to east (Fig.7, right).

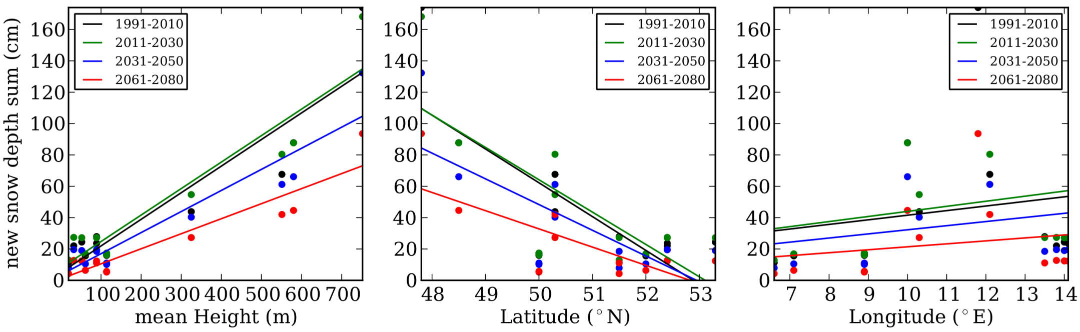


Figure 7: Changing of the height-, latitude- and longitude dependent consideration of the winter parameter "new snow sum" for the German maintenance areas in the past 1991-2010 (black) and in the future 2011-2030 (green), 2031-2050 (blue) and 2061-2080 (red).

Example: Days with freezing rain (NFR)

Analogue to the previous paragraph and figures the second parameter of interest, the number of days with freezing rain (NFR), is shown. Here we find a significant dependency on longitude. The number of days increases from west to east (see Fig.8 and Fig.9). This applies for all simulated climate periods from 1991-2010 to 2061-2080. Until the final period the NFR will go down by 50%, especially in eastern Germany.

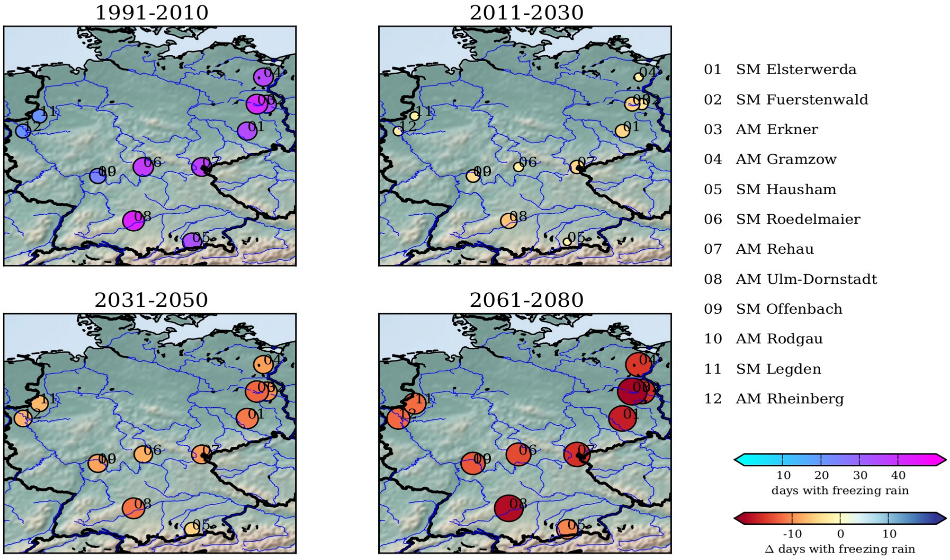


Figure 8: Maps of the averaged "days with freezing rain" for the 12 maintenance areas and from 1991-2010 (upper left).

The other maps represent the changes relating to the reference period: 2011-30, 2031-50, 2061-80.

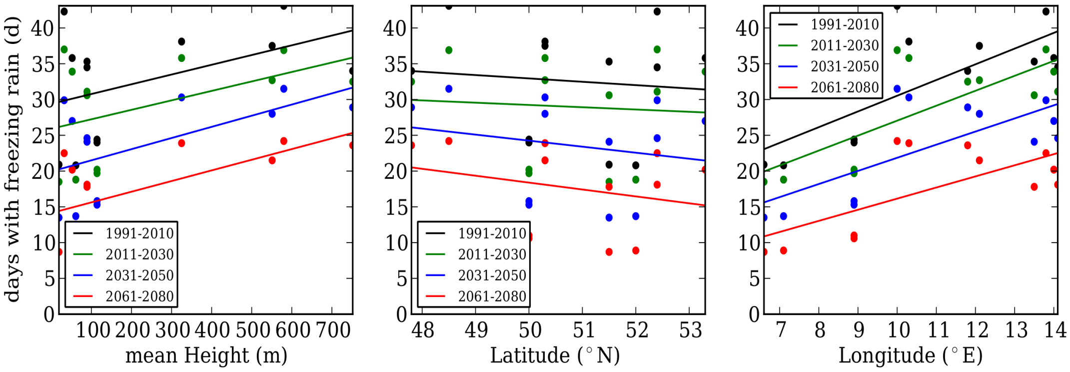


Figure 9: Changing of the height-, latitude- and longitude dependent consideration of the winter parameter "days with freezing rain" for the German maintenance areas in the past 1991-2010 (black) and in the future 2011-2030 (green), 2031-2050 (blue) and 2061-2080 (red).

3.4 Impacts on the winter road service

A functional dependency between the winter service determining climate parameters and the man-hours corresponding to the service sectors, respectively, could be derived from records for different road- and highway maintenance areas in Germany (see Tab.2). Based on 5 years data (2006-2010) a linear regression model (Eq.1) was developed:

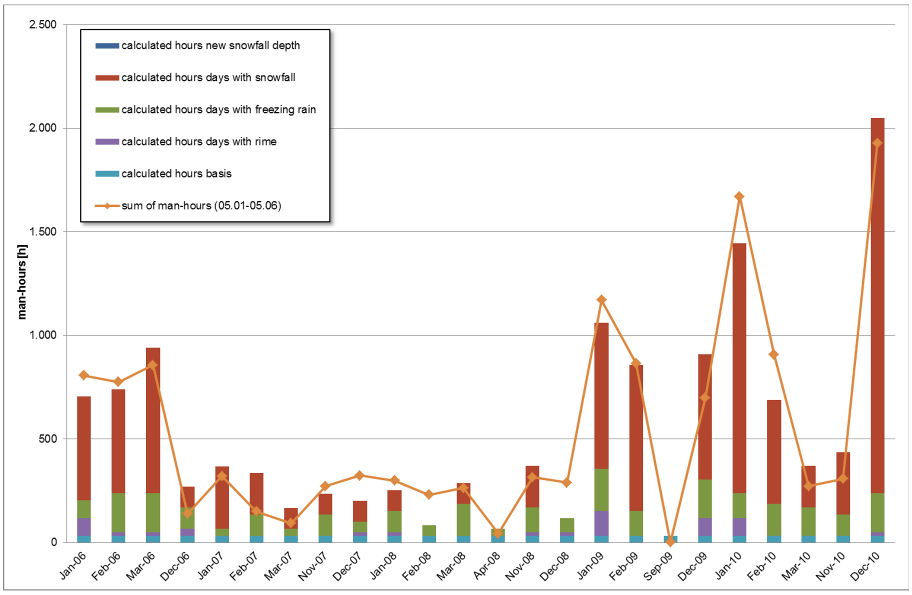
$$y = ax_1 + bx_2 + cx_3 + dx_4 + e \quad (1)$$

The variable y represents the total sum of man-hours for the winter service (including ploughing and spreading of roads and highways in the considered maintenance area). The weather and climate component in this equation is represented by x_1 (sum of new snowfall depth), x_2 (days with snowfall), x_3 (days with freezing rain) and x_4 (days with rime). The coefficient e refers to a monthly fixed sum of man-hours.

The results of this linear fitting are presented in Figure 10 and Table 3. Exemplary demonstrated for two maintenance areas, SM Elsterwerda (Fig. 10, left) and AM Rehau (Fig. 10, right), the simulated curves correspond quite well with the sum of the recorded man-hours for the different sectors to the secondary winter parameters, respectively. Most of the working hours are spent with ploughing and spreading of the roads and highways after new snowfall events (red bars). Both the regression coefficients and the correlation coefficients can be found in Table 3. For most of the maintenance areas the goodness of this linear relation is better than 0,9. This fact allows to estimate the winter service activities in a changing climate.

For every maintenance area (Tab. 3) the parameters a to e based on the detected operating hours were determined that the sum of the deviations between actual and calculated hours per month is minimal (method of least squares), and the total amounts over the five years are identical. For each maintenance area different parameters a to e were indicated, so that different network lengths or structures as well as different operations strategies don not affect the weather correlation. The same systematic was followed to indicate the needed salt amounts in the future (not shown). The only difference to the linear model for calculating the needed hours is that the parameters a to e were determined based on the amount of the salt consumption over the five-year-period. The correlation indicators for the actual and calculated operating hours as well as for the salt consumption are really high. The average over all 12 maintenance areas for the winter service hours is 0,9104 and for the required amount of salt 0,8882.

SM Elsterwerda



AM Rehau

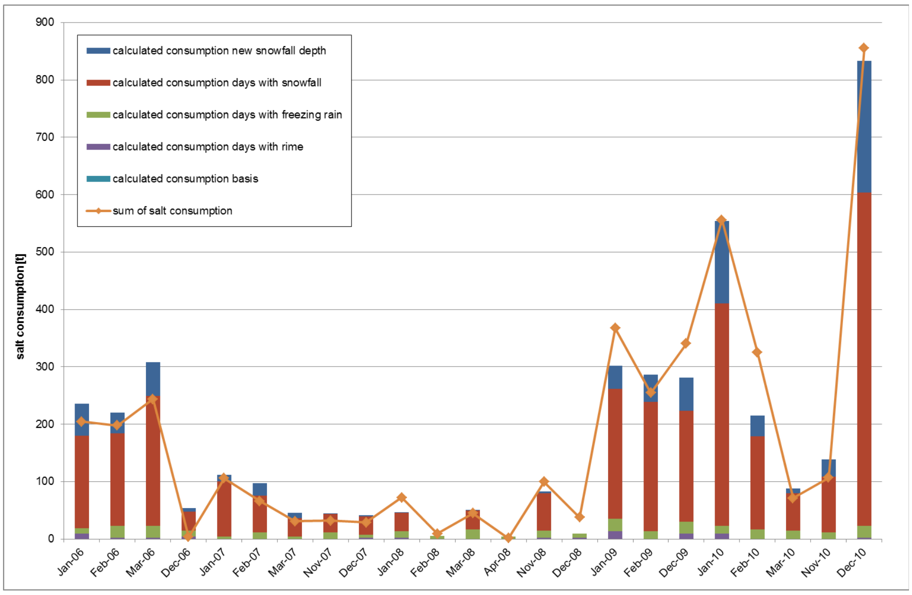


Figure 10: Time series of modeled (lines) and recorded man-hours (bars) for different sectors of the winter service relating to the secondary parameters for the winter extremes at two different road maintenance areas: new snow depth sum (dark blue), days with snowfall (red), days with freezing rain (green), days with rime (purple) and basis hours (light blue). The y-axis is given in man-hours.

maintenance areas	**a [h/cm]**	**b [h/d]**	**c [h/d]**	**d [h/d]**	**e [h/mon]**	**Correl.**
	new snow sum	days with snowfall	days with freezing rain	days with rime	fix	
SM Elsterwerda	0,00	100,63	17,06	17,06	32,58	**0,9377**
SM Fürstenwalde	21,56	5,63	24,87	16,56	0,00	**0,9302**
AM Erkner	8,99	106,17	24,31	24,31	0,00	**0,9281**
AM Gramzow	0,00	114,18	20,06	20,06	15,58	**0,9463**
SM Hausham	1,60	30,60	31,54	31,54	62,23	**0,8343**
SM Rödelmaier	17,78	55,55	43,75	43,75	35,02	**0,9435**
AM Rehau	8,07	80,83	44,00	27,02	25,78	**0,9219**
AM Ulm-Dornstadt	6,99	84,63	13,32	13,32	0,00	**0,8373**
SM Offenbach	7,97	61,86	14,15	14,15	103,46	**0,8814**
AM Rodgau	17,64	144,50	13,42	13,42	199,32	**0,8661**
SM Legden	50,03	0,00	22,54	22,54	0,00	**0,9780**
AM Rheinberg	0,00	98,81	36,91	36,91	0,00	**0,9197**

Table 3: Overview about the obtained regression coefficients between the climate parameters and man-hours for the winter service on several maintenance areas in Germany.

4. CONCLUSIONS

Future regional climate realisations for Germany simulated with the statistical resampling scheme (STARS) are available within an acceptable time frame of several days. By prescribing the linear trend taken from the CMIP5 ensemble [10] for the RCP 8.5 scenario the future climate in central Europe will be about 4°C warmer than at present. However, there exists an essential difference between the possible winter climate in the near and far future (2011-30 and 2061-80). The results obtained by the statistical climate model indicate a slightly intensification of the winter parameters and consequently of the road winter services in Germany for the next 20 years. This results in a slight increase about 10 % of operating hours and required salt (see Fig. 11). Later on, in the decades after 2030 the climate warming signal seems to superpose low-frequency variability in the atmosphere system. Less snowfall days and days with freezing rain and rime of more than 50% will strongly reduce the man-hours as well as the salt consumption in the winter service by 23 % till 2050 and 29 % till 2080 based on the considered scenario. In summary it can be assumed with an increase in winter service and salt consumption until 2030 and although after that there will be a massive decline in winter service, large fluctuations from year to year are possible. In addition, no regional differences for the different maintenance areas have been identified.

The results presented here show only one possible scenario including model uncertainty. However the extreme winter 2010 is covered by the realizations. Until the end of 2013 dynamical model simulations for the European domain will be available for the public and impact researchers within the COordinated Regional climate Downscaling Experiment [7]. A combination of both dynamical and statistical approaches could improve the projection of the future climate. From the CORDEX simulations we hope for additional information about the temporally evolution of extreme events in a warming climate.

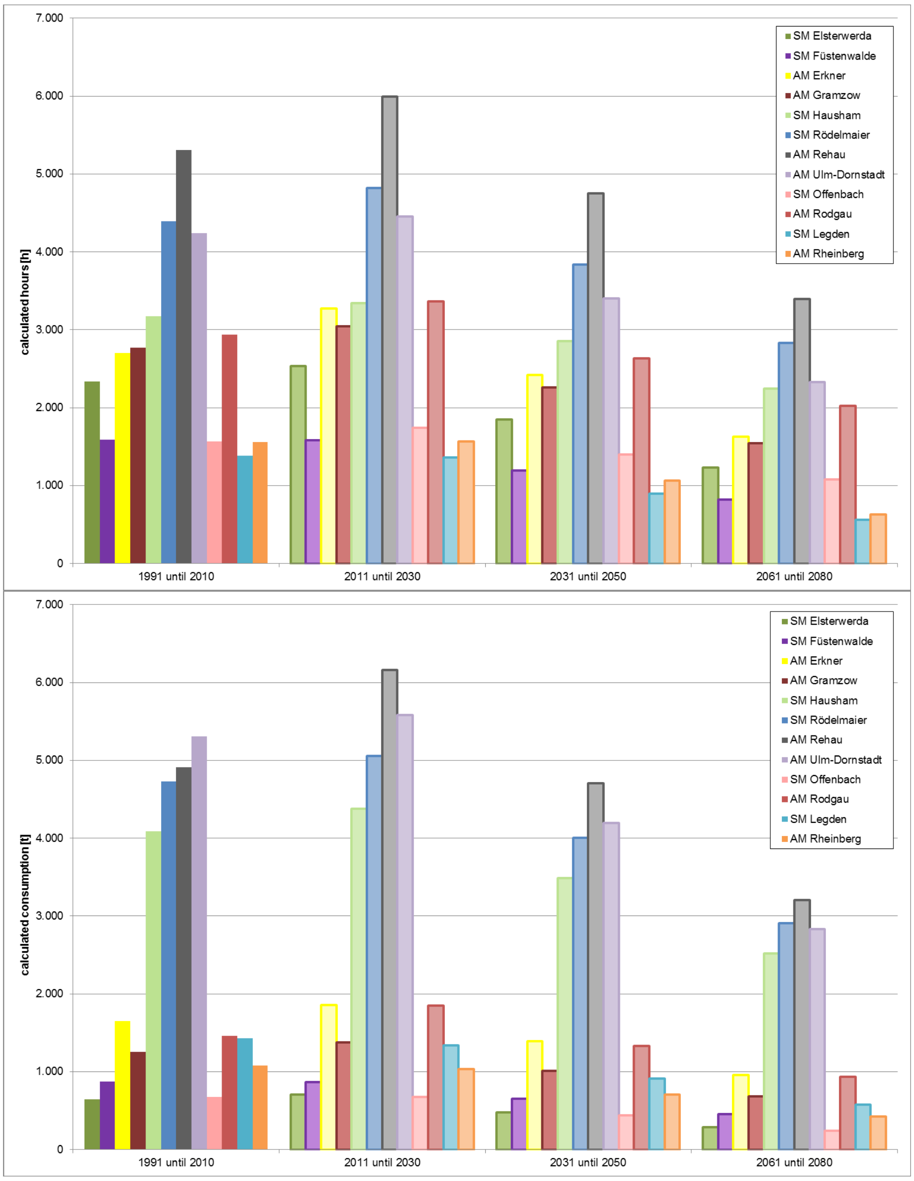


Figure 11: Calculated operating hours for winter service (left panel) and salt consumption (right panel) per year (mean values) for the different periods in each maintenance area.

ACKNOWLEDGMENTS

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