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RESEARCH ARTICLE

Winter hoar frost conditions on Swedish roads in a warming climate

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As one of the most common reasons for slippery roads in wintertime, hoar frost can reduce surface friction and affect traffic safety. The risk of winter road hoar frost is subjected to changes in the warming climate. A better understanding of these changes could lead to improved forecasting of hoar frost risk and provide information to policymakers in making climate adaptation strategies. In this work, the decadal variation in winter road hoar frost risk between 2000 and 2016 in Sweden was examined by using in situ observations from 244 stations in the Swedish Road Weather Information System. Results show that hoar frost risks have decreased in the south of Sweden (south of 59°N), whilst increasing in central Sweden (approximately 59°–65°N). Hoar frost risk tends to increase (decrease) in regions where there is a relatively high (low) mean number of hoar frost risk days. Further analysis indicates that the strengthened winter North Atlantic Oscillation (NAO) over the last few decades, which resulted in warmer and wetter winters in Sweden, is the main cause of the changes. During strong positive NAO winters, the frequency of blocking anticyclones centred to the south-west of Sweden significantly decreased and led to more warm and moist air from south-west being transported to Sweden. The reduction in hoar frost risk in the southern part of Sweden is mainly due to an increase in road surface temperature, while the increasing hoar frost risk in central Sweden is dominated by the increase in relative humidity, which favours the occurrence of hoar frost.

KEYWORDS

climate change, hoar frost risk, North Atlantic oscillation, relative humidity, road surface temperature, Sweden

1 | INTRODUCTION

In wintertime, transport systems in cold regions are often negatively affected by winter weather events. The low visibility and reduced road surface friction in the adverse weather conditions often result in an increase in the number of road traffic accidents, whilst reducing the average speed of vehicles (Andreescu and Frost, 1998; Norrman *et al.*, 2000; Kyte *et al.*, 2001; Strong *et al.*, 2010; Rehborn and Koller, 2014). In order to ensure the safety and mobility of road users, winter road maintenance (WRM) activities are often carried out to reduce slipperiness. Depending on what has caused the slipperiness, WRM activities can include snowploughing, salting and gritting. Due to the frequent occurrence of winter weather events, WRM expenditure for local government can be very high. The cost of WRM in 2010 for Sweden was around SEK 2.1 billion (Swedish Transport Administration, 2011). In order to improve the efficiency of WRM and reduce its cost, it is important to understand the influence of weather and climate change on slippery road conditions.

Hoar frost, which forms on the road surface as a result of direct desublimation, reduces surface friction (Karlsson, 2001) and can lead to traffic accidents. The influence of hoar frost on traffic safety has been reported in many countries in the northern hemisphere (e.g., Gustavsson and Bogren, 1990; Takle, 1990; Hewson and Gait, 1992; Karlsson, 2001; Greenfield and Takle, 2006; Andersson *et al.,* 2007; Bulygina *et al.,* 2015; Galek *et al.,* 2015; Toms *et al.,* 2017). Of these countries, Sweden suffers severe hoar frost problems (Gustavsson and Bogren, 1990; Hewson and Gait, 1992). Norrman (2000) reported that about 31% of slippery roads between 1991 and 1996 in south-west Sweden were caused by hoar frost. In addition, Andersson and Chapman (2011) also found that, of all traffic accidents caused by severe weather, 24% happened during hoar frost conditions in the winter of 2004–2005 and 23% in the winter of 2005–2006, over the whole of Sweden. Therefore, the change in the risk of hoar frost forming on road surfaces is very important for road safety and needs to be explored.

Theoretically, hoar frost will form when the road surface temperature (RST) is equal to or less than zero, and the dew point temperature (T_d) is higher than the RST. Usually, hoar frost forms under one of two circumstances: either when a warm front passes over a cold surface or when a road surface cools faster than the air directly above it, due to radiative cooling (Gustavsson and Bogren, 1990; Hewson and Gait, 1992). The occurrence of hoar frost is closely related to air temperature (T_a), relative humidity (RH) and wind speed (Hewson and Gait, 1992), the previous weather (Gustavsson and Bogren, 1990; Takle, 1990; Hewson and Gait, 1992), the difference between T_d and RST (Karlsson, 2001) and local topography (Gustavsson, 1991). Of these, wind speed, the difference between T_d and RST and the previous weather are the main factors affecting the intensity of hoar frost (Karlsson, 2001), while the occurrence of hoar frost is strongly affected by temperature and RH (e.g., Andersson and Chapman, 2011).

Over the last few decades, climate change has been reported globally (Stocker *et al.,* 2013; Huang *et al.,* 2017). According to most of the existing climate models, one of the main consequences of climate change is an increase in global temperatures. Such warming can lead to an increase in RST, which reduces the occurrence of hoar frost. Bulygina *et al.* (2015) indicated that the occurrence of winter icing and hoar frost decreased with a temperature increase in Russia between 1977 and 2013 based on visual observations. Nevertheless, a warming climate can also enhance the hydrological cycle, which may lead to an increase in RH and the potential for near-surface air to be saturated. This favours the occurrence of hoar frost. Sweden has become warmer and wetter over the last few decades. The Swedish Meteorological and Hydrological Institute (SMHI) reports that winter surface air temperature has risen up to 3 °C over Sweden between 1991 and 2016 relative to the reference period of 1961–1990 (SMHI, 2017). Accompanying the warming, near-surface RH has also risen in Sweden over the last few decades (Dai, 2006; Simmons *et al.,* 2010). Considering the opposite effects of changes in temperature and RH, it is necessary to examine the response of winter hoar frost risk to recent climate change. Understanding this response could be useful in predicting the future hoar frost risk and prepare WRM activities in advance. In addition, this knowledge could also be used by transportation policymakers for creating road-related infrastructure adaptation strategies to help mitigate the effects of climate change. Therefore, it is of great importance to study how hoar frost risk has changed over the last few decades in Sweden and how the change is related to the recent climate changes. In this work, these questions were explored by using in situ observations from the road weather information system (RWIS), from a climate perspective with the focus on decadal change.

2 | DATA AND METHODS

2.1 | RWIS data

In situ observations from RWIS, provided by the Swedish Transport Administration (STA), were used to examine the change of hoar frost risk in Sweden. The RWIS stations are located by the sides of roads and record meteorological information every half hour. The observed RST, T_a at 2 m level, RH at 2 m level, precipitation, and T_d (calculated from T_a and RH by the STA) for the winter season (December, January and February) from 2000 to 2016 were used in the analysis. Here, the winters are defined as being from December to February inclusive for example, the winter of 2000 is from December 1999 to February 2000. As there are no direct measurements of hoar frost in the system, the above variables were used to calculate the hoar frost risk on the roads. Quality controls were applied to the RWIS observations before the analysis. First, out of bounds records, such as negative RH, were treated as missing data. Second, outliers with respect to the diurnal cycle for T_a and RST of each station were treated as missing data for each winter month. For each station, the mean and standard deviation of temperature were calculated at each observed time in a day for a selected month during the study period. Outliers, with respect to four times standard deviation, were treated as missing data. Third, the same approach was used to identify outliers in the difference between T_a and RST, but with six times standard deviation used as the criterion.

For each month, records with less than 85% valid data were treated as missing data. For the entire study period, stations with more than 7 months (85%) of missing data were excluded. In order to reduce the data end effect in the calculation of linear trend (Liebmann *et al.,* 2010), stations with missing data in the first or last winter were excluded. Finally, observations from 244 RWIS stations were used in this study. It should be noted that roads in the northern part of Sweden are often kept "winter white" (Ihs, 2002; Nordin, 2015), which may result in difficulties analysing the

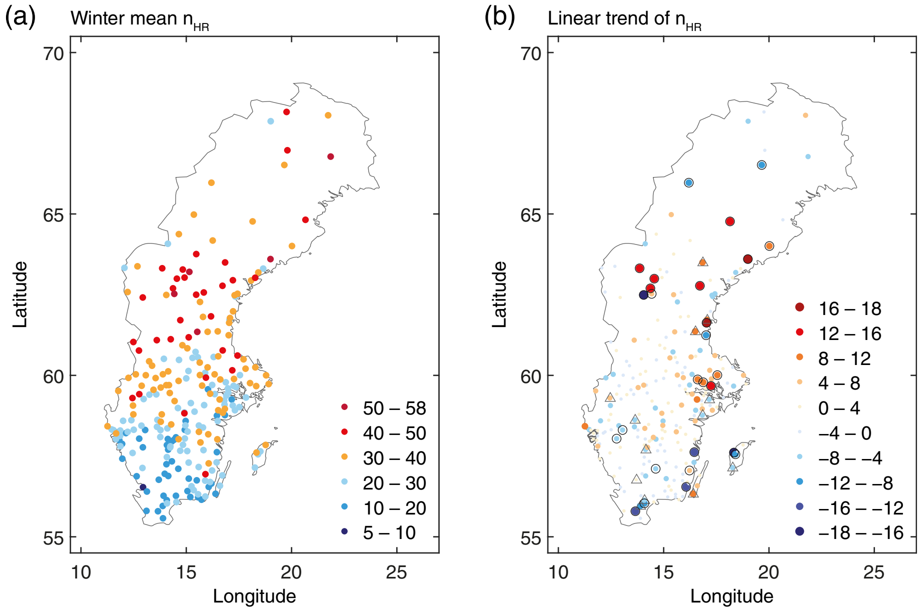

FIGURE 1 The average number of road hoar frost risk days (n_{HR} in days) over the 17 winters between 2000 and 2016 and (b) the linear trends of n_{HR} (days/10 years) for the same period. Stations marked with a black circle are statistically significant at $p < .05$ level; stations marked with a grey triangle are statistically significant at $p < .1$ level [Colour figure can be viewed at wileyonlinelibrary.com]

occurrence of hoar frost risk in the region. However, due to the difficulty in identifying the spatial distribution of "winter white" roads, the analysis was carried out for the whole of Sweden.

2.2 | Methods

In this work, occurrence of hoar frost is defined as being when there is no precipitation, RST ≤ 0 and $T_d >$ RST. T_d is calculated using the following formula, which is derived from Stull (2000):

$$T_d = \left[\frac{1}{T_a} - c \times \ln(\mathrm{RH})\right]^{-1} - 273 \tag{1}$$

where $c = \frac{461}{2830000}$ K, T_a is air temperature at 2 m level and RH is relative humidity at 2 m level.

In Sweden, traffic is affected when road surface friction is less than 0.4 (Al-Qadi *et al.*, 2002). Karlsson (2001) pointed out that road surface friction can decrease close to 0.4, 2 hr after the first occurrence of a hoar frost (see figure 3a in the reference). In order to cover all the possibly dangerous road conditions caused by hoar frost thoroughly, in this work a hoar frost risk day is identified as being when the occurrence of a hoar frost lasts longer than 2 hours (four consecutive measurements) in a day. Considering the frequent occurrence of hoar frost at night, a day is defined as being the 24 hr from 12:00 noon local time to the following 12:00 noon.

The number of hoar frost risk days (n_{HR}) was calculated for each month and used for the trend calculation. To fill the gap created by the missing data, the mean n_{HR} for each winter month over the studied 17 years for each station was calculated and used to replace the corresponding monthly missing value. This technique was also used for the calculation of the monthly means of RH and RST. The least squares regression method, which minimizes the sum of squares of the errors between predicted and observed values, was used to calculate the linear trend of the data.

3 | RESULTS

3.1 | Spatial and temporal features of hoar frost in Sweden

In wintertime, hoar frost is seen over the whole of Sweden (Figure 1a). The mean n_{HR} over 17 winters is relatively lower in southern Sweden than elsewhere in the country, with a minimum of 7 days. For the majority of stations in this region, the winter mean n_{HR} is fewer than 30 days. The most frequent occurrences of hoar frost were found in the central part of Sweden between 61°N and 64°N, up to a maximum of 57 days. For the majority of stations in this region, the winter mean n_{HR} is more than 40 days. In the rest of Sweden, the winter mean n_{HR} mainly ranges between 30 and 40 days.

The trend of winter n_{HR} over the period 2000–2016 was analysed, showing a strong regional pattern (Figure 1b). There is a decreasing trend of winter n_{HR} in the southern and northern parts of Sweden, while a general increasing trend can be seen for the majority of stations in the central part of Sweden.

In order to examine the overall changes of hoar frost risk in Sweden between 2000 and 2016, the probability distribution functions of n_{HR} were analysed for the first five (2000–2004) and the last five (2012–2016) winters in the study period (Figure 2). For both periods, the winter mean n_{HR} was around 30 days and no obvious change was found. However, compared to the first five winters, the number of stations with a winter mean n_{HR} between 25 and 40 days was lower for the latter five winters. Instead, there was an increase in the number of stations that had an n_{HR} either

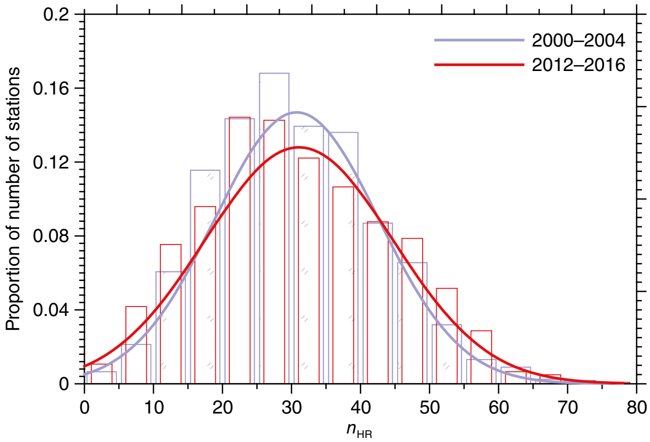

FIGURE 2 A histogram showing the number of winter hoar frost risk days (n_{HR}), with normal distributions fitted (lines). The blue bars and line relate to the winters from 2000 to 2004, while the red bars and line relate to the winters from 2012 to 2016 [Colour figure can be viewed at wileyonlinelibrary.com]

below 15 days or above 45 days. This implies that more stations tended to have very high or low hoar frost risk, which is consistent with Figure 1. It is obvious from Figure 1 that the n_{HR} decreases in the southern part of Sweden, where the mean n_{HR} is relatively low. Meanwhile, the n_{HR} increases in the central part of Sweden, where the mean n_{HR} is relatively large.

3.2 | Link between hoar frost occurrence and climate variables

In this part, the causes for the change in winter hoar frost risk in Sweden are explored. As RH, T_a and RST exhibit a dominant role in the occurrence of hoar frost, the contribution of these climate variables to the change in winter hoar frost risk in Sweden was analysed. As defined in this study, hoar frost only occurs when there is no precipitation (see section 2.2). The change in precipitation may affect the occurrence of hoar frost and its influence was also examined.

3.2.1 | RH

The decadal trends of winter RH over the 17 years are shown in Figure 3a. Generally, RH increases over most of Sweden, especially in the central and south-eastern parts where the trends are statistically significant at $p < .1$ level. The rising RH may increase the potential for the near-surface air to be saturated, which may lead to an increase in n_{HR}. A few stations in the south-west of Sweden and on the island of Gotland measured a decreasing trend in RH.

3.2.2 | T_a

The decadal trends of winter T_a over the 17 years are shown in Figure 3b. For T_a, there is generally an increasing trend in the central and northern parts of Sweden, with a mixed trend in the south of Sweden. The increase in T_a may lead to an increase in RST and so fewer occurrences of hoar frost. On the other hand, the increase in T_a may also increase T_d, which may then also increase the potential for the near-surface air to be saturated.

3.2.3 | RST

As defined in section 2.2, having RST equal to, or less than, zero for at least 2 hr is the prerequisite for the appearance of dangerous hoar frost conditions on road surfaces. Therefore, the change in the number of days ($n_{RST} < =0$), when the condition was met, was examined. The decadal trends of winter $n_{RST} < =0$ over the 17 years are shown in Figure 3c. The majority of stations in the southern part of Sweden showed a strong decreasing trend, while the trends were much smaller in the central and northern parts of Sweden (Figure 3c). In order to understand the changes in RST better, the probability distribution functions of RST for the first five (2000–2004) and the last five (2012–2016) winters were examined for different regions (Figure 4). For both periods, a similar change in the probability distribution functions can be found for the three regions. The mean RST slightly increased for the three regions, with the relative frequency of the part with low (high) RST decreased (increased). However, having RST $< =0$ is more important for the occurrence of hoar frost than the mean value. In this regard, the changes are different for the three regions. It is clear that the relative frequency of RST $< =0$ decreased for the southern part of Sweden (south of 59°N), while the changes were not so obvious for the other two regions. This is due to the relatively high RST in the region (Figure 3d). With the mean RST close to freezing point, slight warming may change the RST from below zero to above zero. Therefore, the decrease in $n_{RST} < =0$ is much larger in the southern part of Sweden. For the central (59°–65°N) and northern (north of 65°N) parts of Sweden, the relatively high latitudes and altitudes lead to much lower RST (Figure 3d), so $n_{RST} < =0$ is not as sensitive to temperature changes. Having RST $< =0$ is essential for the formation of hoar frost, so the decrease in $n_{RST} < =0$ in the south may be regarded as the determining factor which leads to fewer hoar frost events in this region.

3.2.4 | Precipitation

In this study, in order to separate ice from hoar frost, one prerequisite for a day to be classified as a hoar frost risk day was when there was no precipitation over the period of a hoar frost. Changes in the precipitation frequency may affect the trends in winter n_{HR}. Therefore, the changes in precipitation frequency and their impact on the changes in winter n_{HR} need to be investigated. During the study period, the precipitation time increased over the whole of Sweden (Figure 5a). This has been confirmed by the SMHI, who have stated that the winter precipitation amount between 1991 and 2017 increased over most of Sweden in comparison to that

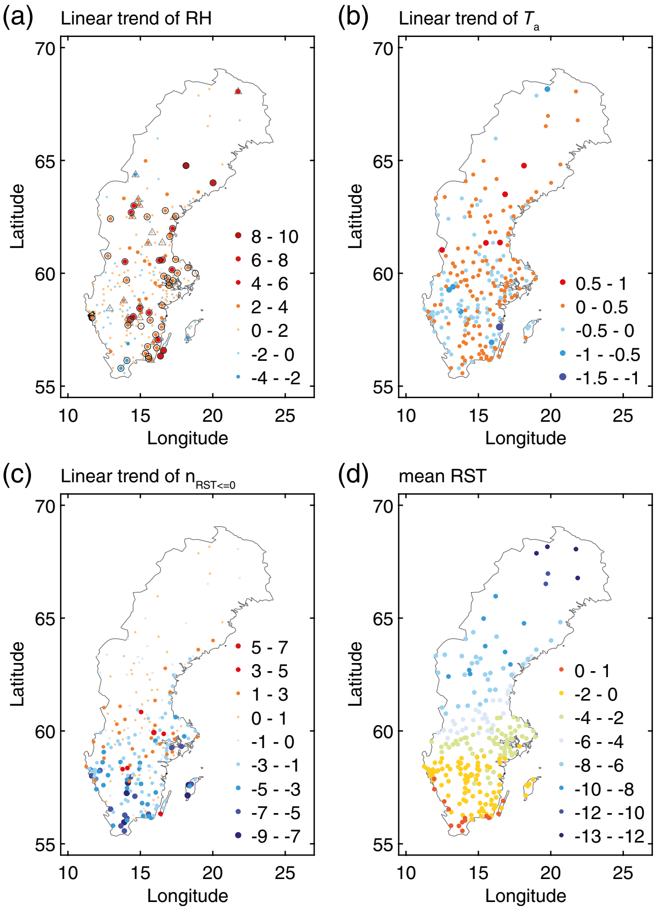

FIGURE 3 (a) The linear trend of winter mean relative humidity (%/10 years) over the 17 winters between 2000 and 2016. Stations marked with a black circle are statistically significant at $p < .05$ level; stations marked with a grey triangle are statistically significant at $p < .1$ level. (b) the same as shown in (a) but for air temperature (°C/10 years). (c) the same as shown in (a) but for the number of days with RST ≤ 0 (days). (d) the mean RST (°C) over the 17 winters between 2000 and 2016 [Colour figure can be viewed at wileyonlinelibrary.com]

between 1961 and 1990 (SMHI, 2017). In order to evaluate the influence of changes in precipitation on the trends of winter n_{HR} over the study period, the prerequisite "no precipitation" was excluded and the trends in winter n_{HR} were calculated (Figure 5b). As shown, a similar pattern in the trends of winter n_{HR} was found in comparison to Figure 1b, which implies that the spatial pattern of variation in winter n_{HR} is not influenced by precipitation. In addition, the difference between winter n_{HR} without identifying precipitation and winter n_{HR} when there was no precipitation was calculated; the trends are shown in Figure 5c. There is no significant difference in the changes in winter n_{HR} with and without precipitation being accounted for, which implies that the magnitude and the spatial pattern of the trends in winter n_{HR} (Figure 1b) are not influenced by the increase in precipitation. Therefore, the change in the amount and frequency of precipitation does not influence the result of this study.

3.2.5 | The dominating factors for each region

In order to compare the importance of RH, $n_{RST} < =0$, and T_a to the occurrence of hoar frost in the southern and central parts of Sweden, the relationships between n_{HR} and the three factors were investigated for each region separately (Figure 6). For the southern part (south of 59°N), the influence of $n_{RST} < =0$ on the change in winter n_{HR} is dominant, due to the large decrease in $n_{RST} < =0$ in the region (Figure 3c). Statistically significant ($p < .1$) decreasing trends in winter n_{HR} are often seen when $n_{RST} < =0$ decreases, and vice versa. For stations measuring a decreasing trend in RH, the decrease in winter n_{HR} is more intense. The decrease in T_a also amplifies the decrease in n_{HR}. In the central part of the country (59°–65°N), the change in $n_{RST} < =0$ is mainly below 3 days over 10 years and its influence on winter n_{HR} is not strong. Instead, the influence of increasing RH dominates and often leads to statistically significant ($p < .1$) increases in winter n_{HR}, especially when the increase in RH is more than 2% over 10 years. The increase in T_a amplifies the increase in winter n_{HR}. In the northern part of Sweden (north of 65°N), there were only a

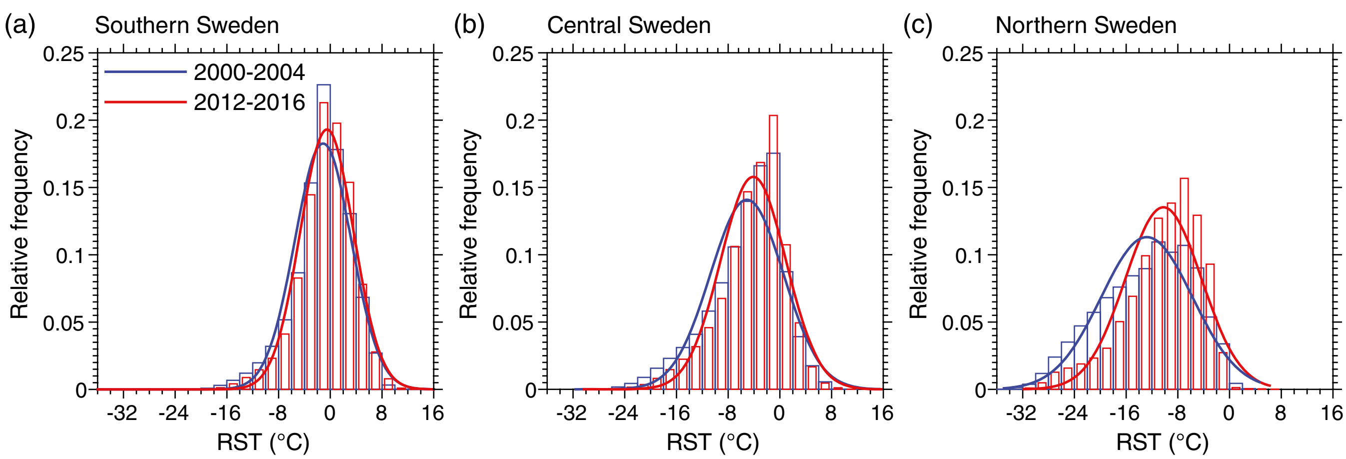

FIGURE 4 Histograms showing the distribution of RST over the (a) southern (south of 59°N), (b) central (59°–65°N) and (c) northern (north of 65°N) parts of Sweden, with normal distributions fitted (lines). The blue bars and line relate to the winters from 2000 to 2004, while the red bars and line relate to the winters from 2012 to 2016 [Colour figure can be viewed at wileyonlinelibrary.com]

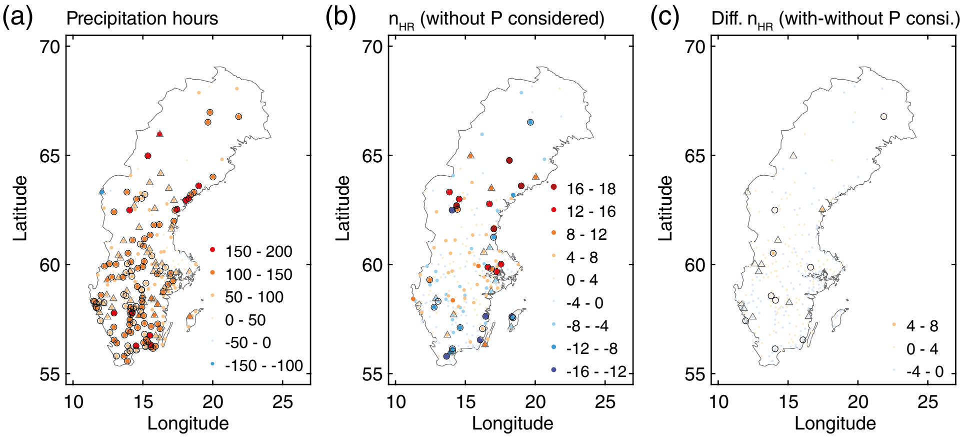

FIGURE 5 The linear trends of (a) precipitation hours (hr/10 years) over the 17 winters between 2000 and 2016, (b) the number of hoar frost risk days (n_{HR} in days/10 years) without accounting for precipitation over the same period as in (a), and (c) the difference between winter n_{HR} without accounting for precipitation and winter n_{HR} (days/10 years) when there was no precipitation for the same period as in (a). Stations marked with a black circle are statistically significant at $p < .05$ level, stations marked with a grey triangle are statistically significant at $p < .1$ level [Colour figure can be viewed at wileyonlinelibrary.com]

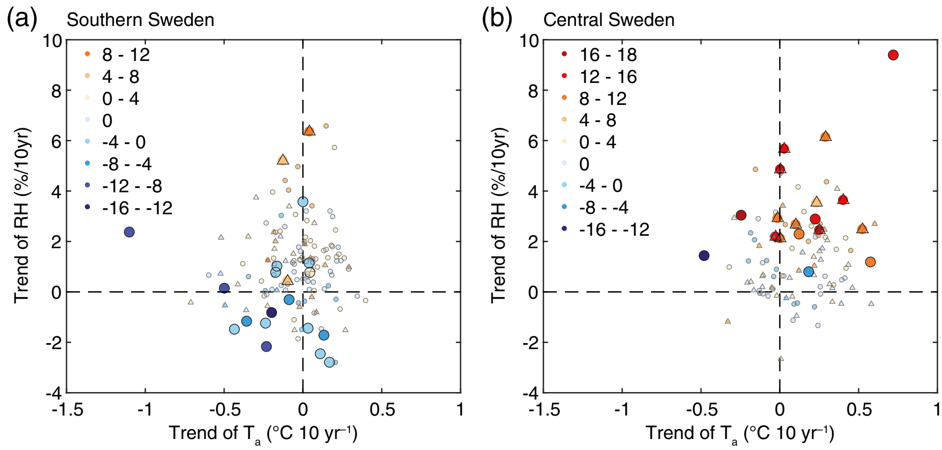

FIGURE 6 The change in number of hoar frost risk days (n_{HR} in days/10 years) and its relationship with changes in air temperature (T_a), relative humidity (RH) and number of days with RST < =0 consecutively for at least 2 hr (n_{RST} < =0) over the southern (south of 59°N) and central parts of Sweden (59°–65°N). Colours show different ranges of trend of n_{HR}; triangle: Positive trend of n_{RST} < =0, circle: Negative trend of $n_{RST\,<\,=0}$, large symbol: Statistically significant stations ($p < .1$) in the trend of $n_{HR,}$ (a) the southern part of Sweden, (b) the central part of Sweden [Colour figure can be viewed at wileyonlinelibrary.com]

few stations available for this study and the situation is more complex. The changes in RH, n_{RST} < =0 and T_a are all very small, so the decrease in winter n_{HR} is a combined effect of those changes in this region.

3.3 | The influence of recent atmospheric circulation changes

In Sweden, the winter climate is strongly influenced by the North Atlantic Oscillation (NAO), which is the dominant mode of atmospheric circulation variability over the middle and high latitudes of the Northern Hemisphere. Positive NAO often leads to mild and wet conditions and negative NAO often leads to cold and dry conditions in Sweden.

Over the last few decades, the winter NAO has strengthened, with more positive winter NAO years (Figure 7). In order to investigate the link between the changes in the winter NAO and the winter $n_{HR,}$ the spatial distribution of Pearson correlation coefficient between the winter n_{HR} and the NAO index in the 17 winters was calculated, and is shown in Figure 8. In the central and northern parts of Sweden, there tend to be more hoar frost risk days during the years with positive NAO, and vice versa (Figure 8). However, in the south-eastern part of Sweden, the positive relationship between the winter n_{HR} and the NAO is less pronounced and the winter n_{HR} even decreases with the strengthened NAO in the south-west part of Sweden. The increase in the winter n_{HR} is due to more water vapour being transported to Sweden in strong positive NAO years compared to strong negative NAO years (Figure 9a). This resulted in an increase in the relative humidity measured by most of the stations (Figure 3a). Such an increase is expected to increase the risk of hoar frost, provided there is little change in the temperature. Since hoar frost can occur either during clear calm nights or when a warm air front passes over a cold road surface (Gustavsson and Bogren, 1990; Hewson and Gait, 1992), the changes in the occurrence of blocking

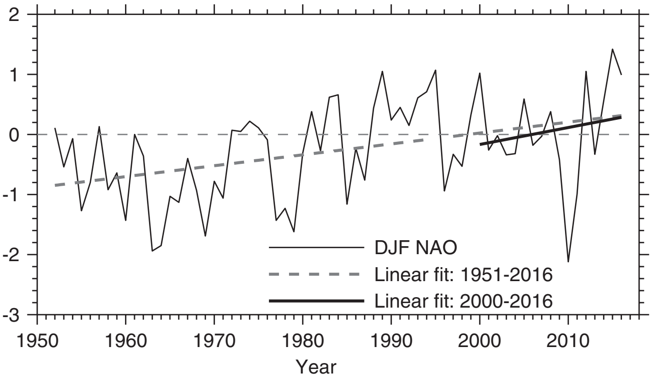

FIGURE 7 Winter (DJF) mean NAO index (data sets extracted from the climate prediction Centre, http://www.cpc.ncep.noaa.gov)

anticyclones were also examined and are shown in Figure 9b. The results show that the frequency of blocking anticyclones centred to the south-west of Sweden significantly decreased in strong positive winter NAO years (winter mean NAO index >0.4) compared to that in strong negative winter NAO years (winter mean NAO index < −0.4). The decreased number of days with blocking anticyclones led to less cold air transport from the north-west and more warm air from the south-west transported to Sweden. This then contributed to the increase in winter n_{HR} in the central part of Sweden, since warm air advection is a common cause of a hoar frost. However, due to the relatively high RST in the southern part of Sweden (Figure 4a), the warm air transported to the southern part of Sweden may reduce the potential for RST to be below zero continuously (Figure 3c) and hinder the occurrence of hoar frost in the region.

4 | DISCUSSION

This study shows a very clear regional pattern of changes in winter road hoar frost risk over the last few decades, with decreasing winter n_{HR} in the southern and northern parts of Sweden and increasing winter n_{HR} in the central part of Sweden. The results indicate that hoar frost risk does not necessarily decrease in a warming climate. Given sufficient water vapour supply in a region, the RST plays an important role in the changes in hoar frost risk. However, this was not the case for the northern part of Sweden. The hoar frost risk decreased in the region despite the slightly increased RH and low mean RST. This could be caused by the "snow covered" road surface conditions in the region. In Sweden, road salt is often used for de-icing in wintertime. However, a road surface with a low RST requires more salt to de-ice it than one with a higher RST. In order to minimize the usage of salt, roads in the northern part of Sweden are often kept "winter white" with the use of road salt being infrequent (Ihs, 2002; Nordin, 2015). The "white" surface influences the RST and makes it hard to evaluate the changes in winter n_{HR} in the region.

In this study, no obvious change was found in the winter mean n_{HR} (Figure 2), which means that the total number of hoar frost risk days was the same over the whole of Sweden for the two periods. However, Andersson and Chapman (2011) found that the total frequency of hoar frost risk decreased by 2.6% in a warmer and wetter January in comparison to a colder and drier January over the entire Sweden. The differences in the results could be caused by the different warming magnitudes between the two studies. In the study by Andersson and Chapman (2011), the January in 2005 was 5–8 °C warmer than the January in 2006 over the whole of Sweden. The warming magnitude was much larger than found in this study (Figure 3b) and larger than the projected change for Sweden to the end of the 21st century (Kjellström *et al.*, 2016). The large warming magnitude may result in more stations measuring a mean RST above zero and hence reducing the total frequency of hoar frost risk. This also suggests that the total hoar frost risk over the entire

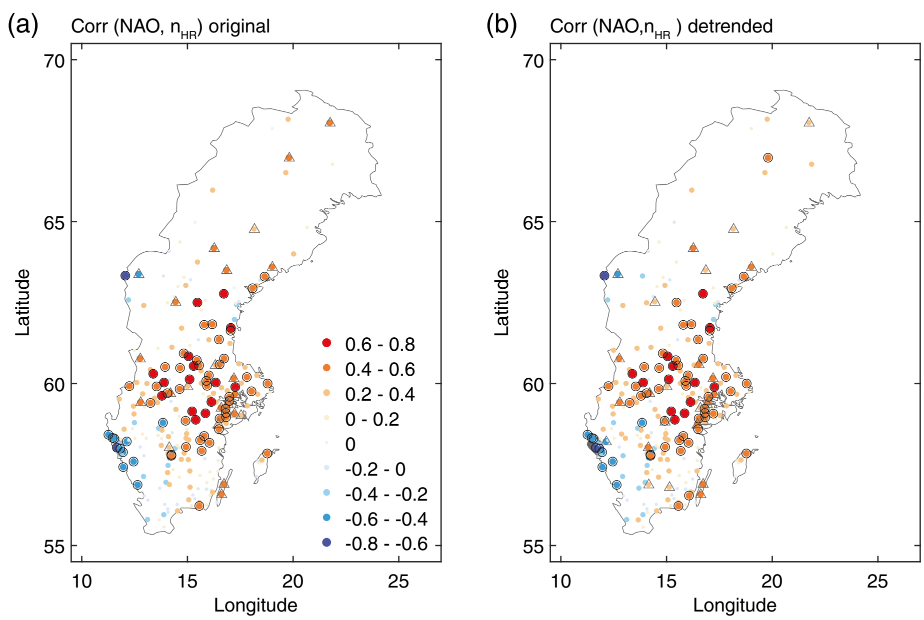

FIGURE 8 (a) Spatial distribution of correlation coefficient between winter (DJF) mean NAO index and the number of hoar frost risk days, (b) same as in (a) but with the linear trend of the data removed. Stations marked with a black circle are statistically significant at $p < .05$ level; stations marked with a grey triangle are statistically significant at $p < .1$ level [Colour figure can be viewed at wileyonlinelibrary.com]

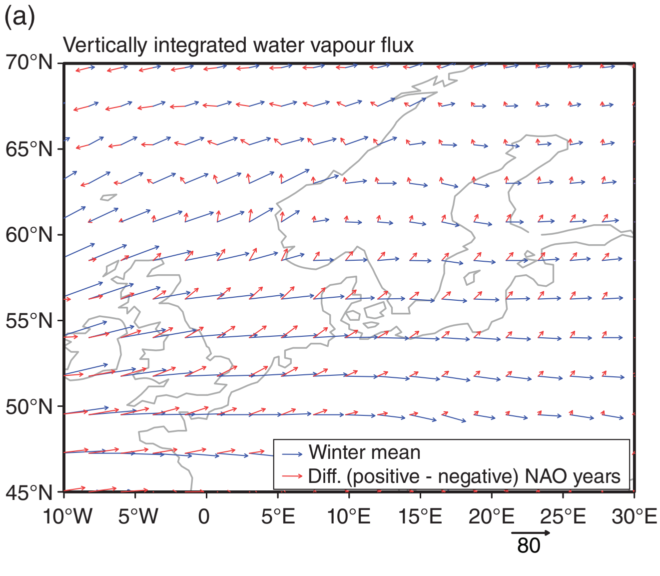

FIGURE 9 Composite maps for the spatial distribution of the differences of (a) the vertically integrated water vapour flux (units: $kg \cdot m^{-1} \cdot s^{-1}$) and (b) instantaneous blocking days between strong positive NAO winters (winter mean NAO index >0.4 that is, 2000, 2005, 2012, 2014, 2015, 2016) and strong negative winter NAO years winters (winter mean NAO index < −0.4 that is, 2009, 2010, 2011). In (b), the dashed line shows the region where it is significant at 0.05 level (the ERA-interim (Dee *et al.,* 2011) data have been used for the calculation. The vertically integrated water vapour flux is calculated same way as described in the work by Ou *et al.* (2011) but with the water vapour flux integrated from surface to 1mb. Instantaneous blocking days are defined as described by Davini *et al.* (2014) but with an additional constraint that the extent should cover at least 15° of continuous longitude, which fits the definition) [Colour figure can be viewed at wileyonlinelibrary.com]

country may decrease if the warming magnitude is very large.

Over the last few decades, the strengthened NAO, with more positive NAO years, has led to warmer and wetter winters in Sweden. In the southern part of Sweden, the warming effect has dominated and led to a reduction in hoar frost risk, while the influence of rising RH has dominated in the central part of Sweden and led to an increase in hoar frost risk. Future projections of the NAO show that the NAO between 2016 and 2045 will continue to strengthen, leading to warmer winters over the whole of Sweden and wetter winters in the south-western and central to northern parts of Sweden (Deser *et al.,* 2017). According to Kjellström *et al.* (2016), the winter temperatures over the rest of the 21st century will continue to increase across the whole of Sweden, especially in the northern part. Temperatures are forecasted to be higher in comparison to the period 1971–2000, by up to 4 °C until 2040. It is inferred that the warming effect will continue to dominate in the southern part of Sweden and lead to a reduction in hoar frost risk over the next 30 years. The reduction in water vapour transported to the south-eastern part of Sweden will further reduce the occurrence of hoar frost risk in the region. For the central part of Sweden, the increase in air temperature may lead to an increase in mean RST in that area and more stations in the central part may gradually start to record higher mean RSTs, as in the southern part. Higher mean RSTs may lead to a decrease in the winter n_{HR} measured at some stations in the central part of Sweden. The reduction in water vapour transported to the eastern coast around Stockholm may further reduce the hoar frost risk in the region. However, due to the low RST (Figure 3d) and increasing water vapour in the mountainous area in the central and northern parts of Sweden, n_{HR} may continue to increase over the next 30 years. Therefore, it is inferred that the region with the largest mean hoar frost risk over the last few decades may see an even greater hoar frost risk and continue to be the region most affected by hoar frost over the next 30 years.

This study provides some suggestions as to the possible changes in the hoar frost risk in a warming climate, which could be of interest to road users, WRM engineers and policymakers. The changes in hoar frost risk conditions over the country may lead to a higher risk of traffic accidents, since people may not be used to the new winter road conditions. Using the knowledge from this study, road users could adjust their behaviour and be better prepared for the future winter road conditions, thereby reducing the risk of traffic accidents. In addition, the changes in winter hoar frost risk conditions may lead to changes in the type of WRM in a region that is, from snowploughing to salting. The results of this study could be used by WRM engineers in planning maintenance activities as well as deployment of the equipment. Proper preparation might not only reduce WRM expenditure but also protect the environment from the overuse of salt. Finally, the results of this study could of interest to transportation policymakers in making road-related infrastructure adaptation strategies in the changing climate. Further research is planned into predicting the future winter road hoar frost risk conditions in Sweden.

5 | CONCLUSIONS

In this study, the focus was the influence of recent climate change on the regional change in hoar frost risk in Sweden. Utilizing in situ observations from the road weather information system, the decadal changes in the number of hoar frost risk days (n_{HR}) in winters in Sweden were investigated. It was shown that the winter n_{HR} mainly decreases in the southern and northern parts of Sweden and increases in the central part. The spatial pattern of the trend in the winter n_{HR} is robust, and is not affected by the changes in the frequency and amount of precipitation. More stations tended to be exposed to either very high or very low hoar frost risk, and the risk tended to increase in the regions where there was a higher mean risk of hoar frost, and vice versa. The changes have been mainly caused by the strengthened North Atlantic Oscillation (NAO) over the last few decades, which has resulted in more water vapour and warm air from the southwest transported to Sweden. This has led to warmer and wetter winters in Sweden. With the increase in RH for most of Sweden, the changes in hoar frost risk mainly depend on the regional RST. In the southern part of Sweden, the mean RST is close to freezing point and the possibility of RST $< =0$ is sensitive to warming. Therefore, the warming effect dominates in the region and results in a reduced hoar frost risk. In contrast, in the central and northern parts of Sweden, the mean RST is well below zero and the possibility of RST ≤ 0 is less affected by warming. Thus, the influence of rising RH is dominant and increases the risk of hoar frost. This study indicates that the hoar frost risk does not necessarily decrease in a warming climate, due to the wetting tendency of the region.

Over the next 30 years, the NAO will continue to strengthen and lead to warmer and wetter winters for the most of Sweden. The warming may increase the mean RST measured by some stations in the central part of Sweden and gradually intensify the decreasing trend in $n_{\mathrm{RST}} < =0$, which may eventually lead to a decrease in the winter road hoar frost risk at those stations. However, the winter road hoar frost risk may continue to increase into the near future in the mountainous area in the central and northern parts of Sweden, due to the much lower mean RST and the increase in RH in the regions.

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