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METEOROLOGISKA INSTITUTET
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CONTRIBUTIONS

WEATHER RELATED PEDESTRIANS' SLIP RISKS AND PREDICTING SIDEWALK SLIPPERINESS

MARJO HIPPI

FINNISH METEOROLOGICAL INSTITUTE
CONTRIBUTIONS

No. 183

Weather Related Pedestrians' Slip Risks and Predicting Sidewalk Slipperiness

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Weather Related Pedestrians' Slip Risks and Predicting Sidewalk Slipperiness

Abstract

Wintertime slip injuries are a very common problem in Finland as well as in other countries where winter conditions are frequent. According to surveys, on average every third person in Finland slips each winter and more than 50,000 persons are injured needing medical attention. Slipping causes human suffering as well as significant financial costs due to medical expenses and sick leaves. On some of the most slippery days, the number of slipping injuries can be so high that the hospital emergency departments are crowded with patients requiring surgery. The severity of slipping injuries typically increases with age. In addition, the number of slips and slip related injuries are more common among women than men.

Finland has set a goal to increase the share of sustainable transport modes, such as walking and cycling, in the future. The aim is to reduce greenhouse gas emissions from transport and improve public health. Walking and cycling are to be the primary means of transport, especially for short distances in dense urban areas. In addition, the aim is to improve traffic safety and to develop walking and cycling infrastructure. This dissertation presents in which weather situations slips occur more than usual. In addition, the work presents a meteorological tool to help predicting weather conditions that cause pedestrian sidewalk slipperiness.

Weather has a significant role in pedestrian's wintertime slips and resulting injuries. In this dissertation, it has been investigated what are the weather situations that increase the risk of slipping and what is the spatio-temporal distribution of slips. Special attention has been given to situations with clearly more slips than usual, i.e. so called peak days of slipping injuries. The results show that snow and ice significantly increase the risk of slipping, and that most of the wintertime slips occur when the temperature is near zero degrees or slightly below it.

This dissertation presents a numerical model predicting slipperiness from the pedestrian's point of view. The model is developed at the Finnish Meteorological Institute. The thesis presents the physical principles of the model and how the slipperiness classification is implemented. The model is a tool for meteorologists to supports the decision making when issuing warnings about slippery sidewalk conditions. In addition, the model benefits winter road maintenance personnel and also public with better sidewalk condition and issued warnings.

Climate change will have a major impact on future winters, especially in the northern latitudes. The winter season is shortened and near zero temperatures are becoming more frequent also during mid-winter, meaning more slippery conditions during that period. It is expected that the slip period will become shorter but at the same time more intense.

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Tekijä

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Nimeke

Sään vaikutus jalankulkijoiden liukastumisriskiin ja jalkakäytävien liukkauden ennustaminen

Tiivistelmä

Talvikauden liukastumisonnettomuudet ovat hyvin yleinen ongelma Suomessa niin kuin myös muissa maissa, joissa talviolosuhteet ovat yleisiä. Kyselytutkimusten perusteella noin joka kolmas suomalainen liukastuu talvisin ja noin 50 000 liukastuu niin pahasti, että joutuu käymään sairaalassa tai ensiavussa liukastumisvammojen vuoksi. Liukastumista aiheutuu inhimillistä kärsimystä sekä merkittäviä taloudellisia kustannuksia niin sairaanhoitokulujen kuin sairauspoissaolojen kautta. Pahimpina päivinä liukastumisia saattaa tapahtua niin paljon, että sairaaloiden päivystykset ruuhkautuvat leikkausta tarvitsevista potilaista. Liukastumisvammojen vakavuus kasvaa yleensä iän myötä. Lisäksi liukastumisia ja niistä aiheutuvia vammoja sattuu enemmän naisille kuin miehille.

Suomi on asettanut tavoitteeksi lisätä kestävien liikennemuotojen, kuten kävelyn ja pyöräilyn, kulkutapaosuutta tulevaisuudessa. Tavoitteena on liikenteestä aiheutuvia kasvihuonepäästöjen vähentäminen sekä kansanterveyden parantaminen. Kävely ja pyöräily halutaan saada ensisijaiseksi liikkumismuodoksi etenkin tiiviillä kaupunkiseudulla lyhyillä matkoilla. Lisäksi tavoitteena on parantaa liikenneturvallisuutta sekä kehittää kävely- ja pyöräilyinfrastruktuuria. Tämä väitöskirjatyö esittelee säätilanteita, joissa liukastumisia sattuu tavanomaista enemmän. Lisäksi työssä esitellään meteorologinen työkalu, joka auttaa jalankulkuliukkautta aiheuttavien säätilanteiden ennustamisessa.

Säällä on merkittävä vaikutus jalankulkijoiden talvikauden liukastumismääriin. Tässä väitöskirjatyössä on tutkittu, mitkä säätekijät lisäävät liukastumisriskiä ja miten liukastumismäärät jakautuvat alueellisti ja ajallisesti. Erityishuomio on tilanteissa, joissa liukastumisia sattuu selvästi tavanomaista enemmän, eli ns. liukastumisten piikkipäivissä. Tulokset osoittavat, että lumi ja jää lisäävät selvästi liukastumisriskiä ja suurin osa talvikauden liukastumisista sattuu silloin, kun lämpötila on nollan vaiheilla tai vähän pakkasen puolella.

Tässä väitöskirjatyössä esitellään Ilmatieteen laitoksella kehitetty numeerinen malli, joka ennustaa jalkakäytävien liukkautta. Työ esittelee mallin fysikaalisen toiminnan ja sen, miten liukkauden mallintaminen on toteutettu. Malli toimii päivystävien meteorologien apuvälineenä ja päätöksenteon tukena, kun annetaan varoituksia erittäin liukkaista jalkakäytävistä. Meteorologien lisäksi mallista hyötyvät myös kaupungin teiden talvikunnossapito sekä varoitusten kautta myös kansalaiset.

Ilmastonmuutos tulee vaikuttamaan voimakkaasti tulevaisuuden talviin etenkin pohjoisilla leveyspiireillä. Talvikausi tulee lyhenemään ja nollan läheisiä lämpötiloja ennustetaan olevan tulevaisuudessa enemmän. Tämä tarkoittaa, että liukkautta esiintynee tulevaisuudessa enemmän myös keskitalvella. On odotettavissa, että liukastumiskausi tulee muuttumaan lyhyemmäksi mutta samalla intensiivisemmäksi.

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PREFACE

During this study, I worked as a research scientist at the Finnish Meteorological Institute, and was a PhD student at the University of Helsinki. I want to thank both organisations for giving me this opportunity. I thank my supervisors Doctor Markku Kangas and Professor Heikki Järvinen for their guidance and support for this thesis. Also, I want to thank Meteorological Research unit and Meteorological Applications group for the working opportunities. The head of the unit as well as the group leaders have changed during there years, so I want to thank all bosses equally for supporting my work.

I want to thank people involved with the early and later development of the RoadSurf and RoadSurf-Pedestrian models; Markku Kangas, Martti Heikinheimo, Johanna Ruotsalainen, Reija Ruuhela, Virve Karsisto, and Mika Heiskanen. Also, I am grateful to Sari Hartonen for her input and interest in pedestrian safety related issues. It has been great to see that pedestrian safety and risk of slips are taken now much more seriously than decades ago. Also, I want to thank all co-authors for their contributions, special thanks go to Nadine-Cyra Freistetter, Erika Médus and Antti-Ilari Partanen for their work and knowledge on the climate change related paper. I want to thank Virve Karsisto for proofreading this thesis.

I would like to thank all my colleagues at the FMI, especially people at the coffee and lunch breaks, for the official and non-official chats during these years.

My sincere gratitude goes to the Vilho, Yrjö and Kalle Väisälä Foundation for providing me a grant that allowed me to concentrate on writing this summary and preparing for the dissertation.

Last but not least I owe my gratitude to my family, for the support they have given me throughout these years.

Marjo Hippi
Helsinki, October 2022

CONTENTS

LIST OF ACRONYMS

DJF	December, January, February
FIOH	Finnish Institute of Occupational Health
FMI	Finnish Meteorological Institute
MAM	March, April, May
NWP	numerical weather prediction
PP	Percentage point
RCP	Representative Concentration Pathway
SON	September, October, November
TVK	Finnish Workers' Compensation Center
VTT	Technical Research Centre of Finland

LIST OF ORIGINAL PUBLICATIONS AND AUTHOR'S CONTRIBUTION

I Kangas, M., Heikinheimo, M. and **Hippi, M.**, 2015: RoadSurf: a modelling system for predicting road weather and road surface conditions. *Meteorological Applications*, **22**(3), 544–553. doi: 10.1002/met.1486

II **Hippi, M.**, Kangas, M., Ruuhela, R., Ruotsalainen, J. and Hartonen, S., 2020: RoadSurf-Pedestrian: a sidewalk condition model to predict risk for wintertime slipping injuries. *Meteorological Applications*, **27**(5), 1–18. doi:10.1002/met.1955

III **Hippi, M.** and Kangas, M., 2022: Impact of Weather on Pedestrians' Slip Risk. *International Journal of Environmental Research and Public Health*, **19**(5), 3007. doi:10.3390/ijerph19053007

IV Freistetter, N.-C., Médus, E., **Hippi, M.**, Kangas, M., Dobler A., Belušić, D., Käyhkö J. and Partanen A.-I., 2022: Climate Change Impacts on Future Driving and Walking Conditions in Finland, Norway, and Sweden. *Regional Environmental Change*, **22**(58). doi: 10.1007/s10113-022-01920-4

In **Paper I** the author performed the model simulations and visualizations. In **Paper II** the author had the main responsibility for all study phases excluding writing the model description in Section 3.1. In **Paper III**, the author was responsible for acquiring data, performing model simulations, data analysis and visualization, and writing most of the text. In **Paper IV** the author was involved in defining what was taken into account when comparing future road weather and pedestrian walking conditions with the current climate.

1 INTRODUCTION

Weather has a strong impact on all forms of transport. Traffic safety and fluency are the main aspects when talking about transport and mobility. Also, winter road maintenance is an important factor in enabling the safest possible driving and walking in all winter weather conditions. Wintertime weather may be challenging as slipperiness and visibility can change quickly, for example, in case of snowfall or rapid temperature variations.

This thesis concentrates on weather related pedestrians' risks and how the slipperiness can be modelled. Slip is defined in this thesis as an uncontrolled slide that results in a fall, and in the worst case, physical injury. According to Malin et al. (2022) half of the slipping injuries occur when the sidewalk condition is icy or snowy. People can prepare for slippery sidewalk conditions with studded shoes or footwear with good grip. Sidewalk slipperiness can be prevented by road maintenance activities, like gritting.

There has been a clear need for a special pedestrians' sidewalk condition model to predict weather related slipperiness from pedestrians' point of view, for example when meteorologists are issuing warnings about slippery sidewalk conditions. The focus of this thesis is to describe a model developed to predict sidewalk slipperiness. The developed model is a tool for duty meteorologists to support decision making when determining weather related pedestrians' slip risk. The model applications support also road maintenance personnel when planning and scheduling the road maintenance activities, like salting, snow ploughing and gritting. The physical principles of the road weather and sidewalk slipperiness models are presented in this thesis as well as model applications that can be used by end users. In addition, the thesis examines at what time of year slippery and hazardous sidewalk conditions typically occur based on slip injury statistics. This information is compared to weather data. Also, the effects of climate change on road and sidewalk conditions are studied in this thesis.

Sidewalk slipperiness and the risk of slips are complex phenomena, involving environmental and human factors (Courtney et al. 2001). Slipperiness is a combination of weather, winter maintenance activities, number of walkers, and footwear features as well as human behavioral and physical factors. Many of these factors are difficult, or even impossible, to take into account when studying the slip risk. Weather is the only factor taken into account in this thesis.

The cause of the slip is often reported as a surprising slippery spot, poor grip of the shoes, or poor winter maintenance. The importance of winter maintenance has been highlighted in several studies when considering safe walking (Mannola et al. 2021; Sundfør and Bjørnskau 2017). Properties of soling materials and tread designs of footwear are important for safe walking in icy conditions (Grönqvist and

Hirvonen 1995). Also, the use of anti-slip devices improves the safety of walking and reduces the number of slipping injuries (Aschan et al. 2009; Larsson et al. 2019; Vartiainen et al. 2009).

In this study, slipperiness means small friction, or poor grip, between the surface and shoe sole or car tyre. Friction is a dimensionless coefficient varying from 0 to 1 and lower values are more slippery than higher values. Walking is assumed to be safe if the friction is 0.2 or more (Ruuhela et al. 2005) whereas normal driving conditions exist when the friction is 0.3 or more (Juga et al. 2012). There are several devices developed to measure road surface friction. Nevertheless, none of those instruments is suitable for estimating operationally the sidewalk slipperiness from the pedestrians' point of view (Hippi 2012). Slip injury statistics have been used as indirect information to describe the daily slip level in this study because there are no real slipperiness or friction observations available.

The research questions of this thesis are summarized into three main topics:

1. **Can weather phenomena leading to slippery sidewalk conditions be numerically modelled?**
   Paper I describes the Finnish Meteorological Institute's (FMI) road weather model RoadSurf. The model predicts, for example, the road surface temperature and condition when atmospheric weather parameters are used as forcing at the upper boundary. The RoadSurf model has been developed further to predict the slipperiness conditions on sidewalks from pedestrians' point of view. The resulting model, RoadSurf-Pedestrian, is presented in **Paper II**. This thesis describes the way slipperiness is modelled by RoadSurf-Pedestrian model.

2. **What are the weather phenomena leading to slippery sidewalk conditions?**
   Paper III presents the spatio-temporal distribution of slip injuries in different cities around Finland. The number of daily slip injuries is presented and analyzed together with weather observations for different cities. The main interest is on days when the number of daily slip injuries is higher than normally. It can be assumed that sidewalks have been very slippery on those days and weather has an effect on slipperiness. The thesis studies weather on the days when the slip risk has been high.

3. **Factors affecting pedestrians' sidewalk slipperiness - do they change in the future when climate is changing?**
   In **Paper IV** the effect of climate change on the road weather and pedestrian's slip risk is studied. The impacts of climate change on future roads and sidewalks for mid- and end-century in Finland, Norway and Sweden were

simulated. The results show how surface temperature and slippery sidewalk condition are changing if the global greenhouse gas emissions continue to increase.

The thesis is structured as follows: the background and motivation of this thesis is described in Section 2. Section 3 briefly describes the data, models and methods that have been used in this thesis. Section 4 is dedicated to the main results of this thesis. Finally, there is a discussion of the important topics in Section 5 and the conclusions are summarized in Section 6. The original papers are re-printed at the end of this thesis.

2 BACKGROUND

2.1 WINTERTIME SLIP INJURIES

Pedestrians are one of the most vulnerable road user groups. Slipping injuries are also seen as an issue of equality, as women experience more slips than men. Weather and climate related health impacts are of increasing concern due to the ongoing climate change and demographic changes such as aging of the population that may increase vulnerability of people to weather related hazards.

Pedestrians' wintertime slipping and falling injuries are a very typical problem in countries where temperature drops below zero degrees and ice or snow exist. Wintry weather conditions increase the risk of slips and slip injuries. Also, slipperiness can be challenging for tourists encountering slipperiness for the first time when visiting Finland in wintertime (Lépy et al. 2016). Winter season lasts for about 100 days in southwestern Finland and 200 days in Lapland and it is the longest season in Finland (FMI 2022a). Slip related injuries are considered a major public health and economic problem (Penttinen et al. 1999). According to a national risk assessment, climate change is estimated to affect the number of slip injuries in Finland because the slippery days are expected to become more common in the future. Especially near zero temperatures are expected to become more frequent in the mid-winter compared to the present time (Tuomenvirta et al 2018).

Slip and fall injuries cause in worst cases long sick leaves and varying degrees of injuries, like bruises, sprains, and fractures (Andersson and Lagerlöf 1983; Björnstig et al. 1997; Eilert-Petersson and Schelp 1998; Emaus et al. 2011; Flinkkilä et al. 2010; Kemmlert and Lundholm 2001; Lund 1984; Strandberg 1985). The most common injuries due to falls and slips are fractures of the wrists and ankles, concussions, and other head injuries (Oxley et al. 2018; Vuoriainen et al. 2000). Typical places where slips occur are sidewalks, outdoor paths, courtyards and parking lots (Hautala and Leviäkangas 2007; Rantala and Pöysti 2015; Vuoriainen et al. 2000). Slipping occurs often when unexpected sudden loss of grip is encountered (Grönqvist et al. 2001).

Slipping and falling injuries can occur for everybody but there are some differences between the age and gender. Young people use to slip more often than elderly, but people between the ages of 35 and 65 are the ones who are most often injured and need medical attention (see Figures 1 and 2). About 4 percent of all slips and falls result in serious injuries (Malin et al. 2022). The severity of the injuries typically increases with the age. Swedish studies have found that fractures resulting from slips and falls among females aged 50 and older seem to be significantly more frequent than among males in the same age range (Björnstig

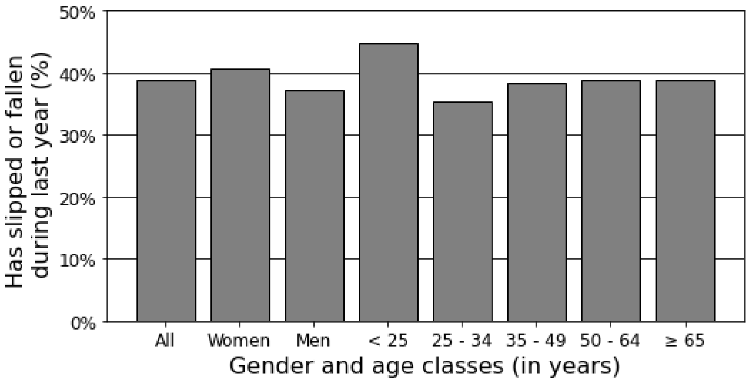

Figure 1 *Share of people having slipped or fallen during 12 months by gender and age classes based on a survey made by the Finnish Road Safety Council. The sample size was 1656. Information based on Rantala and Pöysti (2015). Figure from **Paper II** ©2020 Royal Meteorological Society.*

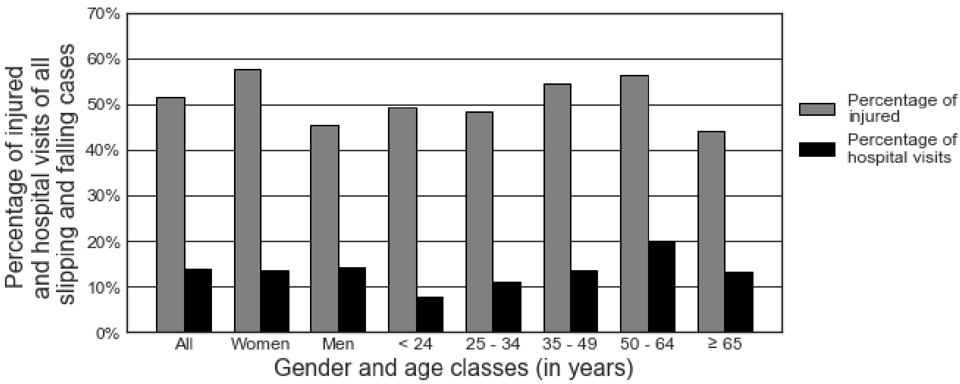

Figure 2 *Share of injured and those who needed hospital visits as a result of slipping or falling during 12 months by gender and age classes based on a survey made by the Finnish Road Safety Council. The sample size was 644. Information based on Rantala and Pöysti (2015). Figure from **Paper II** ©2020 Royal Meteorological Society.*

et al. 1997; Eilert-Petersson and Schelp 1998). This is partly explained by gender differences in walking habits as women use to walk more than men (Malin et al. 2022). Women over the age of 60 suffer the most serious consequences from slips and falls.

Slip and fall related injuries cause huge economic losses and suffering to the victims. However, the overall costs of slips are difficult, or even impossible, to determine as the slips and slipping injuries are not systemically recorded (Pilli-Sihvola et al. 2019). Injuries and accidents occurring to pedestrians and cyclists are typically highly under-reported as they are often single accidents (thus, without a collision with another party) and are not included in traffic accident statistics (Airaksinen 2018; Utriainen 2020). The information about pedestrians' slip injuries needs to be estimated from other data sources, like from the Finnish care register for Health Care (HILMO), ambulance transport, injury claim data, or databases of individual companies (Hippi et al. 2017; Karlsson 2013). Unfortunately, none of these sources gives the total amount of pedestrians' injuries.

Almost every second person slips and falls outdoors annually. Two-thirds of the slip and fall related injuries occur in wintertime when the surface is covered by ice or snow (Grönqvist and Hirvonen 1995; Vuoriainen et al. 2000). According to different sources, 50,000–75,000 pedestrians and cyclists are injured needing medical attention in Finland every winter (Anttila 2001; Malin et al. 2022). Technical Research Centre of Finland (VTT) has estimated that the slips and fall related injuries cost about 2.4 billion € annually when considering the costs of medical care, loss of work input and reduced well-being, the last one being the largest part of the sum covering 95 percent of the total (Hautala and Leviäkangas 2007).

There is no precise information available on the costs of winter maintenance of sidewalks and cycling paths, but they are estimated to be lower than the total costs of slipping injuries (Myllylä et al. 2006; Vuoriainen et al. 2000). In a study performed for Stockholm, Mattsson (2017) estimated that the costs related to wintertime slipping injuries are twice as high as the winter maintenance costs of sidewalks (15.5 million € versus 7.7 million €). Although slipping injuries incur significant costs each year, it is good to keep in mind that inactivity also causes major costs to society. For example, Kolu et al. (2022) have estimated that the total costs of low physical activity in Finland in 2017 were approximately 3.2 billion € with costs attributable to high sedentary behaviour been roughly 1.5 billion €.

2.2 WEATHER WARNING SERVICES

2.2.1 FMI WEATHER WARNINGS

The FMI's Weather and Safety Centre produces information about current and forecasted weather, oceanographic situation, climate and major natural disasters in Finland and other countries operating 24/7/365. It provides nationwide 10 day weather forecasts as well as weather or weather related warnings up to 5 days ahead. The warnings are updated every 3 hours, and more frequently, if needed

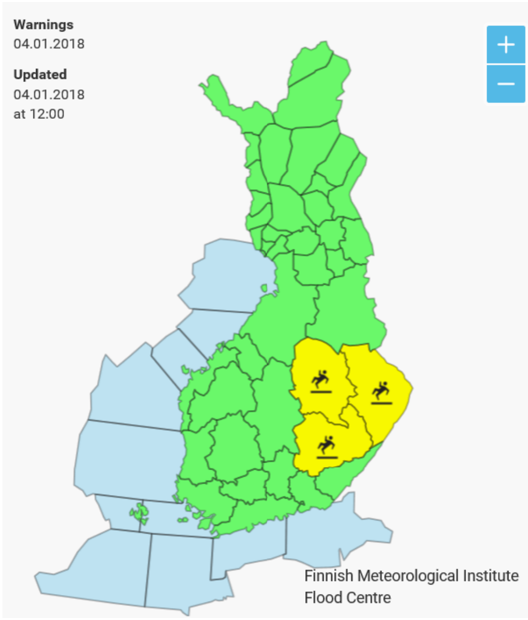

Figure 3 *An example of FMI's weather warning map. Slippery sidewalk condition warning has been issued to the eastern regions in Finland. Figure from* ***Paper II*** *©2020 Royal Meteorological Society.*

(FMI 2022c). Accurate weather forecasts are important when issuing weather related warnings.

Warnings are issued, for example, in cases when strong wind, heavy rain, extremely cold or hot temperature, or hazardous driving or slippery sidewalk conditions are to be expected. The severity of the warnings is indicated by the four level colour-coded map from red and very hazardous weather conditions, down through orange and yellow to green, indicating that severe weather is not expected (FMI 2022b). Warnings are issued to targeted regions (sea areas, counties or municipalities in Lapland) or to freely defined areas. The coloring is the same as provided by the European Meteorological Network, MeteoAlarm, at their website (www.meteoalarm.eu/) which gives information of expected extreme weather over the European geographical domain. An example of a weather warning map provided by Finnish Meteorological Institute (FMI) is presented on Figure 3. Up-to-date warnings are available on the FMI's internet site: https://en.ilmatieteenlaitos.fi/warnings.

2.2.2 SLIPPERY SIDEWALK CONDITION WARNINGS

Pedestrians' sidewalk slipperiness is one of the warnings that FMI issues. A warning is issued when the slip risk is expected to increase due to weather. Meteorologists consider the available weather observations and forecasts and use their own expert judgement and knowhow when issuing the warning. The warning specifies the cause, duration and area of slippery conditions. When warning is given, extra care should be exercised when walking by carefully choosing footwear and using anti slip devices, if possible. In addition to the warning map, the FMI provides commercial services (for example SMS Short Message Services or intranet) to cities and companies, to be used informing citizens or employees about slippery sidewalk condition (Hippi et al. 2017).

Warnings are issued when slipperiness is predicted to occur generally and widely in the region. In practice, small scale slipperiness, like local frozen areas, can occur even though warning is not issued. The beginning of the winter season and the first slippery days can be challenging for pedestrians and the threshold for issuing the warnings is kept lower than in late winter. The beginning of the winter season with the first snow falls and temperatures below 0 °C has often increased slip risk, as can be seen later in Section 4.1.

FMI started a pilot service to inform citizens about slippery sidewalk condition in Helsinki metropolitan area on winter season 1998-1999 (Penttinen et al. 1999). The warnings were read on YLE radio station together with local news. Later, starting from year 2004, the service was expanded to cover the whole of Finland (Ruuhela et al. 2005). Evaluation of the service clearly indicated a need for new tools and education for forecasters as dangerous weather may not be the same for drivers and pedestrians. The need for a more detailed study of the relationship between slip injuries and weather conditions was also identified.

In addition to that of FMI, there is also another service supplying the warnings about slippery sidewalk conditions for several cities in Finland provided by SVA-Konsultointi (SVA 2022). Worldwide, also, at least a couple of cities in other countries are, or have been, providing warnings of slippery sidewalk conditions for citizens. The city of Winnipeg launched a slip alert notification system to prevent wintertime slips in 2012 (Sylvestre 2016). The service, called SureFoot, classified sidewalk slipperiness into four classes from easy to hazardous. Sapporo in Japan have a service, called Walk Smart, providing tips for safe walking on snowy and icy roads as well as sidewalk slipperiness forecasts (Kawamura et al. 2019; WalkSmart 2022). The service has been running since 2006 and it evaluates the expected slipperiness into three classes: not slippery, slippery and extremely slippery.

3 MATERIALS AND METHODS

There are no observations available to determine the sidewalk slipperiness or friction. In this thesis daily slip injury amounts have been used as an indicator of days when the pedestrians' slip risk has been increased. The slip injury data is based on a register coordinated by the Finnish Workers' Compensation Center (TVK) and the details of the data are presented in Section 3.1. The number of daily slip injuries has been compared to daily weather observations to get information about what are the typical weather parameters when the number of daily slips is high. Weather observations used in this thesis are described in Section 3.2.1. The input data used in climate model runs is presented in Section 3.2.2. A special road weather model as well as pedestrians' sidewalk condition model have been developed at FMI. The models forecast the driving and walking circumstances on the roads and sidewalks. Details of the models are described in Section 3.3.1.

3.1 SLIP INJURY DATA

The number of pedestrians' and cyclists' accidents and injuries is highly under-reported as they are typically single accidents (without a collision with another party) and are not included into traffic accidents statistics (Airaksinen 2018). Complete statistics of slips and falls are not available. However, the number of pedestrians' slip and fall injuries can be estimated from other sources. In this thesis, information about the slip injuries is gathered from TVK's injury claim data. Even though the TVK's slip injury data don't cover all of the slip injuries occurring in Finland, it gives enough information about the daily slip amounts, especially when the daily number of slip injuries has been high. Also, the variation in the number of slips between the days can typically be seen from the data. If the number of the daily slips is high, it is assumed here that the weather is affecting slipperiness and slip amounts.

TVK coordinates the practical application of workers' compensation. In Finland, the employers are obliged to insure their employees against work related accidents and injuries. The analyzed data include injuries that have occurred while commuting (on the way from home to work or vice versa) and of which the insurance company has paid compensation from the occupational accident insurance. TVK's injury data are based on self-reported crashes handled by the insurance companies that have paid the compensation (Utriainen 2020).

Nine percent of all commuting trips in Finland are made entirely by walking (Pastinen 2018). Walking is more common in bigger cities compared to smaller cities. However, all road users are pedestrians at some point of their journey, because the driver or passenger of a vehicle is interpreted as a pedestrian in the case of slipping after leaving the vehicle.

TVK's data include the slip injury events presented on a daily and municipality level, so the exact time and location are not known. The information about neither the type and severity of the injury nor age and gender were used in this thesis. The data range was from 1st October 2005 to 30th September 2019 for 16 cities around Finland with the highest number of yearly slips. The cities are located around Finland (Figure 1 in **Paper III**), thus representing different climatological areas from coast to inland and from south to north. The number of citizens varies a lot between the cities and the results are more reliable for bigger cities compared to smaller cities where the number of daily slipping injuries can be quite low. More detailed information about the cities and the number of slip injuries is presented in **Paper III** table 1. Also, the forms of commuting (car, walking, biking, the use of public transport), the amount of public transportation, the number of pedestrians, and the winter maintenance practices may vary between the cities but that information was not available and thus has not been taken into account in this study.

Daily and monthly amounts of slipping injuries are studied in this thesis. Also, days with high number of slips, called peak days and potential peak days of slipping injuries, are analyzed. The threshold for the peak day and potential peak day are statistically determined.

Accidents are assumed to be Poisson-distributed as they usually occur randomly and independently (Nicholson and Wong 1993). The peak day of pedestrians' slipping injuries is determined as a day when the number of slipping injuries exceeds the threshold of the number with probability less than 0.01 percent in a Poisson distribution (Penttinen et al. 1999; Ruuhela et al. 2005). Similarly, a potential peak day with increased risk of slipping is defined with a probability less than 1 percent (there is a typing error in **Paper II** and probability was given as 0.1 percent instead of 1 percent). The thresholds for peak day and potential peak day are defined separately for each city. Typically, cities with larger population have higher peak day threshold as they have larger number of slips. In case of peak day or potential peak day of slipping injuries it is assumed that the slipping risk has been increased due to weather. Hereafter, the term "peak days" includes peak days and potential peak days. In this thesis peak days are used in the determination of the high slip risk. The results from combining of the increased slip risk and weather are presented in Section 4.1.

3.2 METEOROLOGICAL DATA

3.2.1 WEATHER OBSERVATIONS

The weather on days with increased slip risk (peak days including potential peak days) are studied in this thesis. As the slip injury data is in daily level, the daily weather parameters are used as well. The studied parameters were temperature (mean, minimum, maximum), precipitation, and snow amount. The days with zero crossing situations were also studied. The zero degree crossing occurs if the daily minimum temperature is lower than 0 °C and the maximum above 0 °C. The daily weather observations have the following limitations:

- Precipitation form is not available
- The timing of the weather phenomena is not available (for example when the lowest temperature was measured or when precipitation occurred)
- Daily precipitation sum is recorded between 6 UTC on the date of the observation and 6 UTC on the following day
- The snow depth is recorded at 6 UTC
- The daily minimum and maximum temperatures are measured between 18 UTC on the previous day and at 18 UTC on the data of the observations.

Meteorological data was obtained using gridded datasets which are stored on 10 km X 10 km spatial resolution covering whole Finland. The gridded data was used because synoptic weather observations were not available from all cities. The point data for all cities was picked up using nearest grid point. The data is produced operationally at the FMI from the station-wise temperature observations by Kriging interpolation system that also takes into account the topography and the effects of water bodies (Aalto et al. 2016; Venäläinen et al. 2005).

3.2.2 CLIMATE DATA

The climate change impacts on future roads and sidewalks were explored in this study as described in **Paper IV**. The studied area covered Finland, Norway and Sweden and the predictions were done for mid- and end century. For this purpose, RoadSurf and RoadSurf-Pedestrian models were run by data from a regional climate model, the cycle 38 of HARMONIE-Climate (HCLIM38) (Belušić et al. 2020), at a 12 km horizontal grid resolution and ALADIN physics. HCLIM38, in turn, was driven by two global climate models, EC-Earth, hereafter called ECE (Hazeleger et al. 2011; Hazeleger et al. 2010) and GFDL (Donner et al. 2011; Griffies et al. 2011), from the Coupled Model Intercomparison Project–Phase 5 (CMIP5) (Taylor et al. 2012). These models were selected as they considerably differ in their climate change predictions over the Nordic countries. The Representative Concentration Pathway (RCP) 8.5 was utilized for the study. For model evaluation purposes, the output of the global ERA-Interim reanalysis dataset (ERAI) (Dee et al. 2011) driven HCLIM38 was used as a forcing data in RoadSurf.

RCP means a scenario that describes a possible greenhouse gas concentration trajectory. The high emission scenario RCP8.5 was chosen for this study to present the future greenhouse gas emissions. The RCP8.5 scenario is a "business as usual" or "worst case" scenario assuming that global greenhouse gas emissions will continue to increase throughout the 21st century. According to RCP8.5 scenario, the increase of radiative forcing is expected to be 8.5 Wm^{-2} and atmospheric CO_2 concentration about 936 ppm year 2100 (IPCC 2013). This climate change scenario estimates a global temperature increase of +1.8°C (ECE) and +2.6°C (GFDL) by mid-century (2046–2065) and up to +3.5°C (ECE) and +4.7°C (GFDL) by the end of the century (2081–2100), relative to temperatures in the historical period (1986–2005) (IPCC 2013).

A study by Toivonen et al. (2019) confirmed that the RoadSurf model produces accurate historical road temperature estimates for Finnish area when driven with the cycle 38 of the regional climate model HCLIM38. Now, the study was expanded by exploring future road weather under a climate change scenario. Future road weather simulations were run for area covering Finland, Sweden and Norway.

Model evaluation against observations (surface temperature, road surface condition in Finland and Sweden) were done by combining historical RoadSurf simulations forced with (ECE-historical, GFDL-historical and ERAI reanalysis data) to the road weather observations. In case of other parameters, where observations were not available (road surface condition in Norway, traffic index and and pedestrian index), RoadSurf and RoadSurf-Pedestrian simulations were forced by HCLIM38 with ECE-historical and GFDL-historical and compared to runs forced by ERAI.

3.3 FMI ROAD WEATHER MODEL AND PEDESTRIANS' SIDEWALK CONDITION MODEL

3.3.1 DESCRIPTION OF THE ROADSURF MODEL

FMI has developed a road weather model, RoadSurf, to predict what happens on the road surface and below it due to weather (**Paper I**). The model has been running operationally since 2000. RoadSurf is a one dimensional energy balance model calculating the heat transfer in the ground and at the ground-atmosphere interface (Figure 4). The special road surface conditions on the surface and beneath it, as well as traffic are considered in the model. Traffic is causing increased turbulence and mechanical wear of snow, ice, frost, or water on the surfaces. There are several road weather models in use also in many other countries (Chapman et al. 2001; Crevier and Delage 2001; Fujimoto et al. 2012; Jacobs and Raatz 2007; Rayer 1987; Yang et al. 2012).

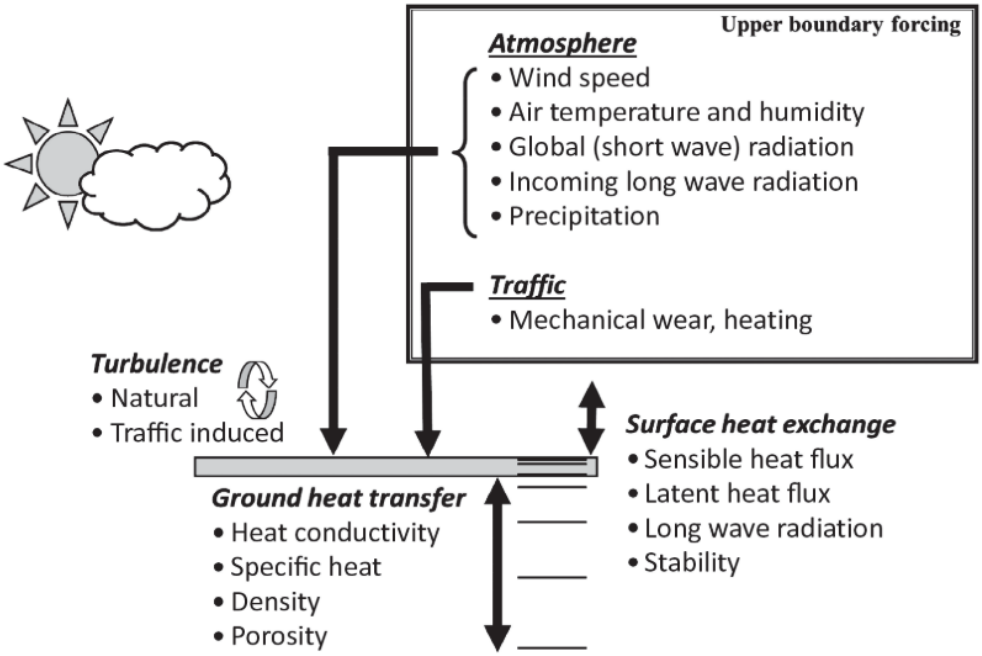

Figure 4 *Description of RoadSurf energy fluxes. Figure from* ***Paper I*** *©2015 Royal Meteorological Society.*

The input parameters of the model are:

- Ambient temperature
- Relative humidity or dew point
- Wind speed
- Short wave solar radiation
- Long wave solar radiation
- Precipitation
- Precipitation phase (optional)

The model run consists of two phases: initialization phase and forecast phase. In the initialization phase atmospheric parameters are obtained from observations excluding short wave and long wave radiation parameters which are taken from numerical weather prediction (NWP) data due to the lack of radiation observations. Observations are taken from synoptic or road weather stations and radar measurement network. Mobile vehicular data has also been used as a source of observations (Karsisto et al. 2017). The purpose of the initialization phase is to determine a good starting state for the temperature profile in the ground and initialize the storages for the forecast part. A coupling method of iterating the radiation adjustment can be used to adjust the road surface temperature at the end of the initialization phase (Karsisto et al. 2016). After the initialization phase there is a forecast phase, where atmospheric values are taken from an NWP model data. The length of both phases is 48 hours, but especially forecast run can be longer depending on the input data.

Output parameters of the model are road surface temperature, road surface condition, driving conditions and so-called storage terms, which describe the amount of water, snow, ice or frost on the surface. Also, the road surface friction is calculated based on a statistical friction model (Juga et al. 2012).

Storage terms are the main element of the model. There are own storages for water, snow, ice and frost describing the amount of water (in water equivalent mm) for each phase. The model tracks changes in the storages caused by physical phenomena like melting, freezing, evaporation, and condensation. Also, mechanical wear, caused by traffic (cars or pedestrians), are accounted for. Storages interacts with each other; for example, the size of the water storage is increased by precipitation as well as by melting of snow or ice.

According to storage terms RoadSurf classifies a road surface condition into eight classes:

- Dry
- Damp
- Wet
- Frost
- Dry snow
- Wet snow
- Partly icy
- Icy

RoadSurf also classifies the overall driving conditions by combining the information about surface class with certain weather parameters. The classification is a three step scale from normal driving conditions to hazardous; **(i)** Normal, **(ii)** Difficult and **(iii)** Very difficult.

The outputs of the RoadSurf model are used as tools when meteorologists are issuing road weather warnings or road maintenance personnel is scheduling road maintenance actions, like salting and snow ploughing. The model is also used in many road weather and intelligent traffic related projects when developing tailored or impact based road weather products for different purposes, like in CARLINK, WiSafeCar, FOTsis, 5G-Safe and 5G-Safe+ projects (Nurmi et al. 2008; Nurmi et al. 2013; Ojanperä et al. 2019; Sukuvaara et al. 2019; Sukuvaara and Nurmi 2012). A more detailed description of the RoadSurf model with physical principles is presented in **Paper I**.

3.3.2 DESCRIPTION OF THE ROADSURF-PEDESTRIAN MODEL

The RoadSurf model has been further developed to predict the level of slipperiness on the sidewalks from pedestrians' point of view, described in **Paper II**. A special pedestrians' sidewalk condition model is needed as the most slippery days from pedestrians' point of view are not necessarily the same as the days with high amount of traffic accidents (Anttila 2001). The pedestrian sidewalk condition model, RoadSurf-Pedestrian, is physically the same as the RoadSurf model. The appropriate mode (RoadSurf or RoadSurf-Pedestrian) can be chosen when running the model. The input data is same in both modes. However, there are four main differences between RoadSurf and RoadSurf-Pedestrian modes:

1. The effect of traffic (pedestrians, cars) is much lighter in RoadSurf-Pedestrian than in RoadSurf model.
2. The length of initialization phase is 96 hours in RoadSurf-Pedestrian and 48 hours in RoadSurf.
3. With RoadSurf-Pedestrian, two consecutive runs are performed: Initialization with ice (30 mm) and no ice.
4. Warning classification and slipperiness indices.

The length of the initialization phase is longer in RoadSurf-Pedestrian model than in original RoadSurf model because the initial state, meaning the amount of snow or ice on the sidewalk surface can be expected to originate from a longer time period than on road surface because of smaller wear and lighter maintenance activities. Sometimes even 96 hours is not enough to initialize the storages if the ice or snow layer have formed earlier, which is the reason why two model runs with different initial states are performed: one with a small original layer of ice and another with no ice. Based on the prevailing situation, a meteorologist on duty can choose the run that better represents the current state of sidewalks.

SLIPPERINESS CLASSIFICATION IN ROADSURF-PEDESTRIAN MODEL

Slipperiness is classified into different indices based on weather and sidewalk condition. Physical processes like freezing, melting, condensation, and precipitation in all forms can cause slipperiness. Slipperiness can also be formed by mechanical ways, when snow is compressed into a hard snow layer. Also, temperature and humidity has an impact on sidewalk slipperiness.

The RoadSurf-Pedestrian classifies modelled sidewalk slipperiness into three classes; **(i)** Normal, **(ii)** Slippery and **(iii)** Very slippery. Index "Normal" means a normal sidewalk condition. There can be ice or snow on the surface, but the slipperiness is not increasing slip risk or causing challenges when walking. Index "Slippery" means typical normal winter weather conditions when slipperiness may occur here and there, but not on the majority of sidewalks. In case of "Very slippery" sidewalk condition, slipperiness is expected to occur on most sidewalks, the slip risk has been increased, and extra care must be taken when walking. The warning about pedestrians' sidewalk slipperiness is issued when very slippery sidewalk condition is expected.

There are four different cases of sidewalk surface condition leading to class "Very slippery". Those are **(i)** frozen ice layer, **(ii)** compressed (foot-packed) snow, **(iii)** snow above the ice layer, and **(iv)** water above the ice layer. The cases are illustrated on Figs. 5a - 5d with a more detailed description below.

Figure 5 *Very slippery sidewalk condition indices; a) frozen ice layer, b) compressed snow, c) snow above the ice layer and d) water above the ice layer. ©Marjo Hippi.*

FROZEN ICE LAYER

When temperature drops below zero degrees, moist surfaces freeze. This is very typical situation especially at the beginning of the winter season when first slippery cases exist. Also, increased solar radiation causes the ice to melt during sunny spring days, but when the temperature drops at night the water freezes again. During mid-winter the temperature can vary above and below zero degrees, causing cycles of freezing and melting if there is snow or ice on the ground. These are typically cases for warning. In some cases there can be small scale slipperiness, like frozen puddles after cold night or ice in the places where melting water is running from roofs. However, warnings are not typically issued in those cases.

COMPRESSED SNOW

Compressed, or foot-packed, snow is causing slipperiness especially when temperature is slightly below zero degrees and there are enough pedestrians to compress the snow layer by walking on it. It typically happens during or right after snowfall when temperature is between -5 and 0 degrees. Pedestrians or cars can compress the snow or plough machines can polish the snowy surface into a dense, almost ice-like surface (FinnRA 1993).

SNOW ABOVE THE ICE LAYER

A light and loose snow cover above hard and smooth ice layer can be very slippery and hazardous. Pedestrians don't necessarily notice the risk of slipperiness as ice cover is not visible due to light snow.

WATER ABOVE THE ICE LAYER

Water on the top of ice layer makes surfaces extremely slippery. Water on ice occur in case of rain when there is a ice layer on the ground, or when icy surfaces are melting or melting water is running from the snow banks around the sidewalks.

The slipperiness classification and slipperiness index have been developed by combining slip injury data and weather data. The connection between high number of slips and weather phenomena have been studied. Also, there have been several measurement campaigns together with the Finnish Institute of Occupational Health (FIOH) where FIOH's slipmeter has been used as an instrument measuring friction between shoe sole and sidewalk surface in different weather conditions (Ruotsalainen et al. 2004). After collecting all available data about weather and slipperiness and taking into account the best professional knowledge, an empirical deduction chain code was developed and included into RoadSurf-Pedestrian model. The deduction chain contains information about storages, precipitation, humidity, and temperature from the current time and from the previous days. In many cases, the weather on the previous days (1–3) can play a significant role in the slipperiness of the following days.

Non-meteorological factors, like sidewalk maintenance practices, are not included in the model. Also, the RoadSurf-Pedestrian doesn't take into account surrounding trees or buildings obscuring radiation. The volume of pedestrians causing wear and interacting with the storages is assumed to be constant everywhere. These limitations can affect the results of the model.

4 SUMMARY OF THE RESULTS

4.1 RESULTS OF SLIP INJURY STATISTICS STUDIES

Figure 6 presents an example of the daily slip injury amounts compared to daily mean temperature. The bars in Figure 6a present daily amounts of slip injuries that have occurred while commuting (on the way from home to work or vice versa) on Uusimaa region on year 2010 based on TVK's data. The slip amounts are weekday corrected (explanation in **Paper II**) so weekends are comparable to weekdays although, people are not working and commuting on weekends as much as on weekdays. Figure 6b presents the daily mean air temperature measured at Helsinki Kumpula weather station.

Slipping injuries (including fall and trip injuries) use to happen through the year but the level of slips is much higher in the wintertime compared to summer. Winter season (blue background color) with increased slip rate can be clearly seen from the Figure 6a as the daily bars of slipping injuries are several times higher compared to summertime (green background color). Daily mean temperature (Figure 6b) correlates very well with the daily number of slipping injuries; high number of daily slipping injuries occurs at the same time when daily mean temperature is below zero degrees. Also, the end and beginning of the winter season is very visible in this case as the level of daily slip amounts increase or decrease

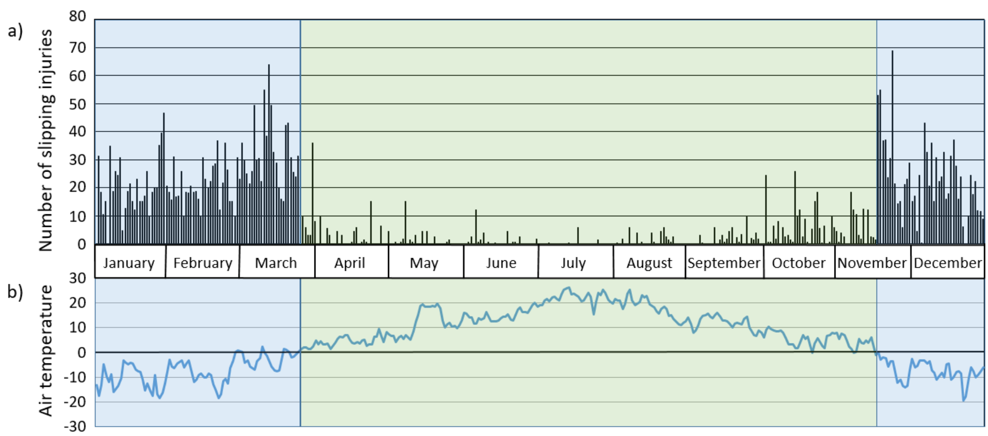

***Figure 6** a) Daily number of pedestrian slipping injuries (weekday corrected) on the way from home to work or vice versa in the Uusimaa region on year 2010. Data from Finnish Workers' Compensation Center. b) Daily mean 2m temperature observed in Helsinki Kumpula weather station on year 2010. Figure from **Paper II** ©2020 Royal Meteorological Society.*

at the same time when the daily mean temperature rises above or falls below zero degrees. There are also days when the daily number of slipping injuries is significantly higher than the average. Those days are called peak days of slipping injuries. The single higher peaks outside the winter season can be due to random variation, or, especially in the spring and autumn, daily minimum temperature might has been below zero degrees.

Typically there are 5-20 days per region during a winter when when the risk of slips is increased and warning would be appropriate. The amount of peak days varies a lot between winters, however, as can be seen in Figure 8 in the next Section.

4.1.1 SPATIO-TEMPORAL VARIATION OF SLIP RISK

The total amount of slip injuries is much higher in wintertime than in summertime, as could be expected. Based on TVK's slip injury data the winter months (January, February, March) cover about half or the yearly slip injuries expect in the eastern and northern part of Finland where the percentages for the mid-winter are slightly smaller (Figure 2 in **Paper III**). When taking into account all winter months from October to April, those months cover 80-90 percents of yearly slip injuries (Figure 2 and Table 1 in **Paper III**). However, it should be kept in mind that during the summer months (from June to August) the slip injury amounts are affected by the summer holiday season that reduces the number of commuting injuries.

Figure 7 presents temporal distribution of the peak days of slipping injuries in different cities for winter season. The beginning of the winter season with the first peak days occur typically in October, and the end of the season is in April. South coastal cities (Helsinki, Espoo and Turku) have many peak days in January-February. Cities located in the east or north (Joensuu, Oulu and Rovaniemi) seem to have more slips (thicker band) in the beginning and at the end of winter compared to mid-winter. This is probably due to the climate because near zero temperatures are not frequent in the eastern and northern part of Finland in the mid-winter. In Rovaniemi there are more slips at the beginning of the winter season than in other cities. The holiday season, especially Christmas time and the New Year period are visible in the data with lower amounts of slips (narrower band).

There can be a huge differences in the number of slip injuries between years and areas as can be seen in Figure 8. Naturally the number of peak days is highest in the cities where the number of citizens is high. The harshness of the winters correlates typically very well with the total number of slip injuries per winter. Especially in the cities with high population the amount of snow and long snowy season means typically high number of slip injuries (for example Helsinki in winter season 2010-2011), whereas mild and short winter season means obviously low number

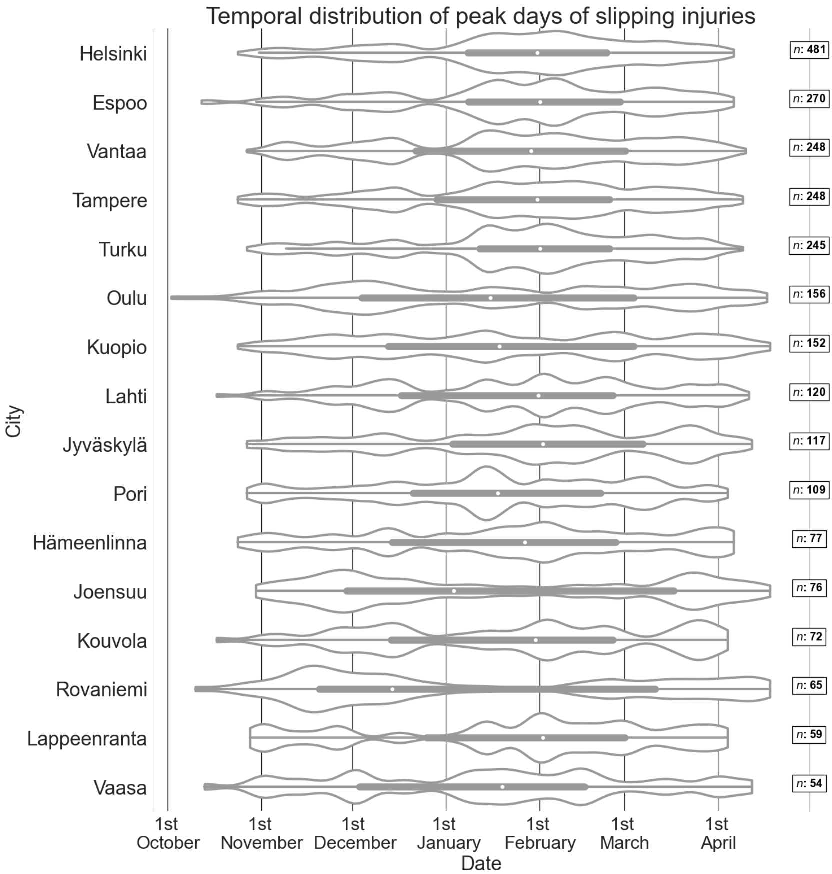

Figure 7 *Violin plot presenting the temporal frequency distribution of peak days of slipping injuries in different cities in winters 2005-2019. The width of the span corresponds to the frequency of slipping injuries. The white dot within each box represents the median dates of the winter season slips. The grey box spans the 0.25 and 0.75 quantiles, and the whiskers represent the minimum and the maximum dates. Outliers are within the violin plot area. The number of peak days (n) for each city is presented on the right. Figure from* ***Paper III*** *©2022 International Journal of Environmental Research and Public Health.*

of slipping injuries (for example Helsinki on winter season 2013-2014). Figure 8 reveals that the slip injury rate can differ greatly in different parts of Finland during the same winter season as can be seen when comparing the bars of Helsinki and Rovaniemi on winter seasons 2010-2011 and 2013-2014.

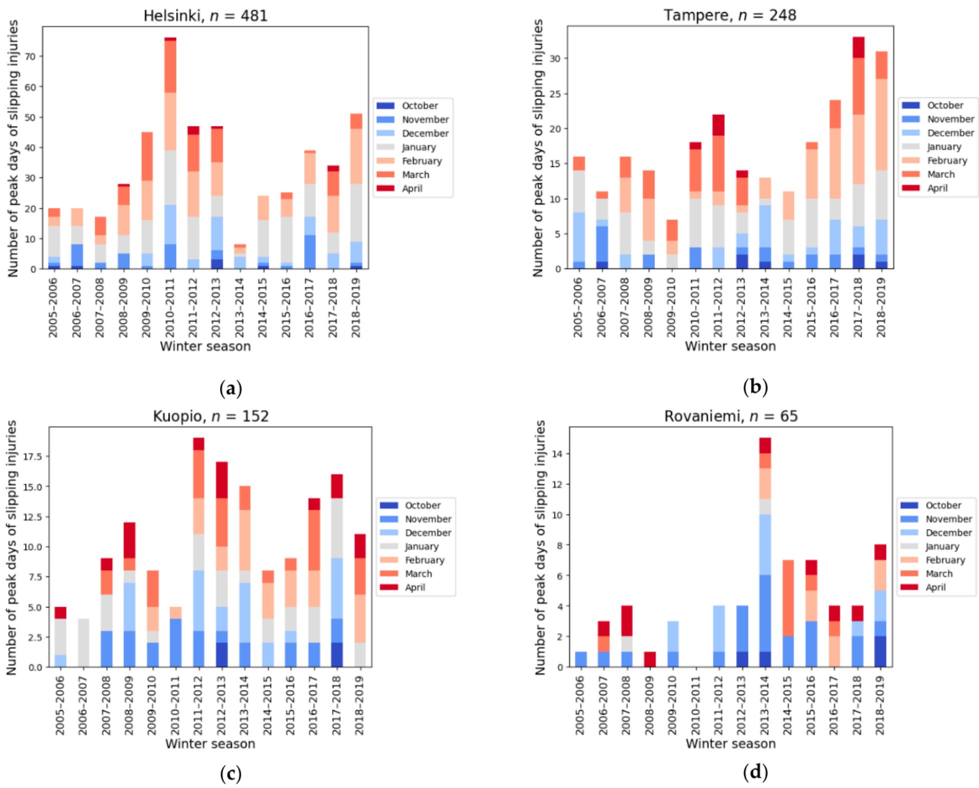

*Figure 8 The monthly and yearly distributions of the peak days for Helsinki (a), Tampere (b), Kuopio (c) and Rovaniemi (d) in winters 2005-2019. The number of peak days (n) is presented for each city. Figure from **Paper III** ©2022 International Journal of Environmental Research and Public Health.*

4.1.2 WEATHER CONDITIONS WITH HIGH SLIP RISK

Paper III studies the weather conditions when high slip risk occur. According to the results, near zero temperatures or temperature just below 0 °C are very typical conditions for high number of slipping injuries. The statistics of daily mean temperature on peak days of slip injuries are presented in Figure 9 for different cities. The mean temperature on peak days varies between -3.3 °C (Helsinki) and

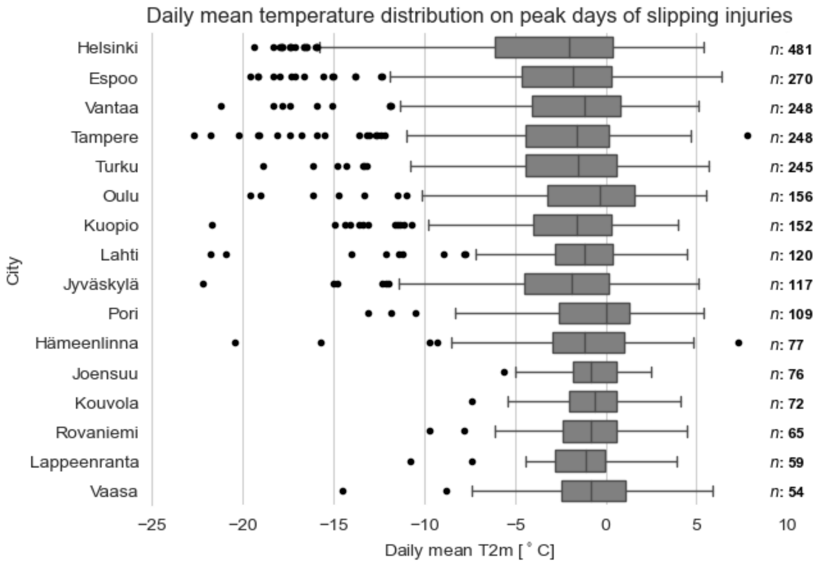

Figure 9 *Box plot distribution of daily mean temperature on peak days in different cities in winters 2005-2019. Boxes correspond to upper and lower quartiles of the data, with the median presented on vertical line. Whiskers indicate variability outside the quartiles and outliers are presented as black points. The number of peak days (n) for each city is presented on the right. Figure from* ***Paper III*** *©2022 International Journal of Environmental Research and Public Health.*

-0.7 °C (Joensuu). It is notable that the total temperature scale is quite large, and there are several peak days also when the daily mean temperature is very low, even below -20 °C. The temperature scale for peak days seems to be wider in bigger cities compared to smaller ones.

Temperature passed zero degrees on about half of the peak days. Precipitation (daily precipitation sum 0.3 mm or more) occur in more than half of the cases, varying between 50.7 percent (Helsinki) and 72.3 percent (Joensuu). In case of daily precipitation of 2 mm or more the on the peak days, the percentages are between 30.1 (Helsinki) and 49.2 (Rovaniemi).

Snowy situations were compared to no-snow situations. The day is defined snowy, if the observed snow amount has been 1 cm or more (measurement done at 6 UTC). Snow cover seems to increase the slip injury risk over three-fold, but there are differences between the cities. The ratio varies between 3.2 (Helsinki) and 5.5 (Kouvola) when examining the number of slip injuries between a snowy and no-snowy situations. However, it should be noted that a measured snow cover doesn't necessarily mean ice or snow on the sidewalk surface (or vice versa).

In some cases the weather on previous days (1-3 before) can have a significant role for upcoming slipperiness. For example freezing can occur days before and later light snowfall makes sidewalks very slippery. On the other hand, there are also some cases when a relationship between high slip amounts and weather cannot be found. It is possible that the main reason for the slipperiness occurred more than three days before.

The case with the highest number of slip injuries occurred in Helsinki, Espoo, and Vantaa on 24 November 2008 (**Paper III**). The snow accumulation was almost 30 cm in two days and the temperature was slightly below zero degrees. The weather situation was suitable for the foot-packed snow. Also, there was so much new snow that road maintenance service was not able to keep sidewalks properly maintained. In addition to that, the case was one of the first slippery days for that winter season. All of these factors together created extreme difficult sidewalk condition from pedestrians point of view.

4.1.3 SLIP RISK IN FUTURE CLIMATE

Paper IV explored the climate change impacts on roads by assessing possible future regional and temporal developments of average road surface temperatures, road surface conditions and driving and walking conditions, as well as zero-degree-crossings under climate change in reference to the historical period (1986–2005). Simulations were done using ECE and GFDL global climate model driven by HCLIM38 as an input data of RoadSurf and RoadSurf-Pedestrian. Generally, GFDL data yielded more extreme under and overestimations than ECE. This thesis focuses on surface temperature and pedestrians' sidewalk conditions. The slipperiness classification is the same as presented earlier in Section 3.3.2 except that "Very slippery" index "frozen surface" was not in use when running these simulations.

According to the results, the slip season will clearly change in the future due to warmer wintertime temperatures. The number of days when temperature is below zero degrees are decreasing. Also, the number of days with snow or ice on the surface are decreasing even though RoadSurf simulations by ECE and GFDL both overestimate the occurrence of icy surfaces. In the southern and western part of Finland winter season as well as slip season will become shorter, but probably more intensive. In the eastern and northern part of Finland near zero temperatures and slipperiness are becoming more frequent in the mid-winter.

Figure 10 shows how the number of zero-degree-crossing days will change in the future, in the mid-century (2041-2060) compared to the historical period (1986-2005). The results are presented separately for different seasons; autumn months September, October, November (SON), winter months December, January,

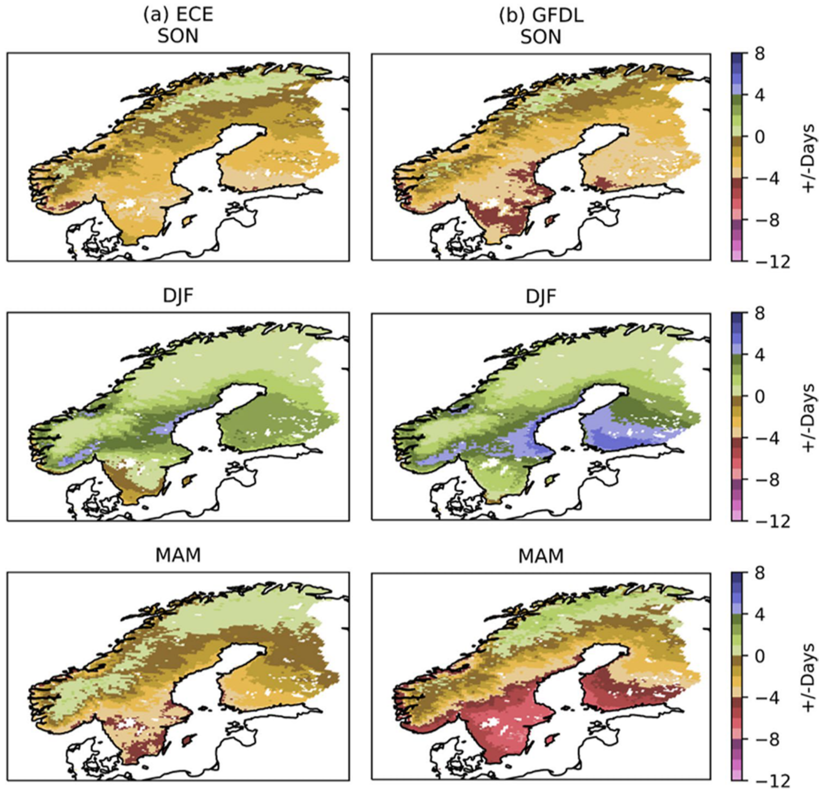

__Figure 10__ Change in the average seasonal number of zero-degree-crossing days in the mid-century (2041–2060) compared to the historical period (1986-2005) during autumn (SON, top row), winter (DJF, middle row) and spring (MAM, bottom row) estimated by a) ECE (left column) and b) GFDL (right column) under the RCP8.5 scenario. Figure from __Paper IV__ ©2022 Springer.

February (DJF), and spring months March, April, May (MAM). The number of zero-degree-crossing days were estimated to decrease in autumn and spring (apart from a minor increase in the northern part of Finland), but to increase in winter. The most significant changes will occur in southern part of Finland.

Figure 11 presents how the pedestrian walking conditions will change in the future (mid-century 2041-2060 and end-century 2081-2100) compared to historical period (1986-2005). The results are presented as projected changes in the occurrence, in Percentage points (PPs). The results reveal strong seasonality and regional differences. When looking at the results for the whole simulated area (Finland, Sweden, Norway) the strongest changes can be seen in autumn when the occurrence of index "normal" will increase (+7.8/11.5 PPs for mid-century and 14.3/17.5 PPs for end-century) while the occurrence of other indices will decrease. In the mid-winter the occurrence of "normal" index will decrease whereas index "very slippery II" (water above the ice layer) will increase (+2.9/4.1 PPs in mid-century and +6.8/10.6 PPs in end-century). In the springtime the strongest change is that the index "normal" will increase. In Finland the strongest increase of slipperiness can be seen in the eastern and northern part of the country in mid-winter where the "normal" conditions are shifted towards "slippery" and "very slippery" classes (**Paper IV**, supplementary material Figure F6).

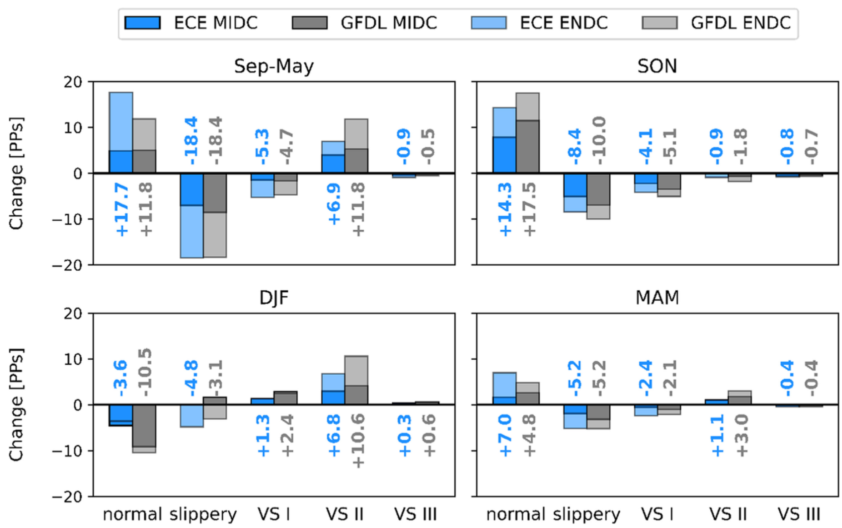

Figure 11 *Projected changes in the occurrences of pedestrian conditions (PPs) in the cold season from September to May (Sep–May), autumn (SON), winter (DJF) and spring (MAM) during mid-century (MIDC, 2041–2060) and end-century (ENDC, 2081–2100) compared to the historical period (1986–2005) as estimated by ECE (blue bars) and GFDL (grey bars) in the RCP8.5 scenario for the pedestrian indices normal, slippery, very slippery due to foot-packed snow (VS I), very slippery due to water above ice layer (VS II) and very slippery due to snow above ice layer (VS III). The results are presented over the whole domain (Finland, Sweden, Norway), where the bar labels show the resulting change by the end of the century compared to the historical period. Figure from* ***Paper IV*** *©2022 Springer.*

4.2 ROADSURF AND ROADSURF-PEDESTRIAN MODEL VERIFICATIONS

The verification of RoadSurf and RoadSurf-Pedestrian is challenging because the models represents a what-if-nothing-is-done scenario, meaning that models don't take into account road maintenance measures. Also, it is difficult, or even impossible, to determine how many accidents or injuries have been prevented by weather services, including weather forecasts and warnings. Some verification results are presented in **Paper I** and **Paper II**. Other RoadSurf model related verifications are presented by Karsisto et al. (2017), Karsisto and Lovén (2019) and Toivonen et al. (2019).

The RoadSurf model seems to overestimate snow and ice storages on the surface and underestimates the occurrence of water on the surface (Toivonen et al. 2019). The absence of road maintenance measures most definitely has an impact for the verification results. The lack of road maintenance measures may have an effect not only for the storages but road surface temperature as well.

The RoadSurf-Pedestrian model overestimates slipperiness and gives many false alarms. On the other hand, there are also days when the slip risk has been increased but the slipperiness is not predicted by the model (see Fig. 9 and Table 3 in **Paper II**). The model does not issue warnings automatically, but the meteorologist on duty issues warnings, combining the results given by the model with own professional skills and experience. In some cases warnings given by the model need to be ignored but on the other hand, there are cases when the warning is issued even though model is not predicting slipperiness. In addition, there are cases where the modelled slipperiness is correctly predicted but a warning is omitted. This illustrates the challenge of the phenomena. Duty forecasters should find a balance when giving warnings. Warnings should be issued always when hazardous sidewalk conditions are expected, but too many false alarms can decrease the value of the information.

4.3 ROADSURF-PEDESTRIAN MODEL APPLICATIONS

RoadSurf-Pedestrian model is running operationally at FMI once per hour alternating between two different initialization states (ice and no ice). Visualizations of the results are produced automatically for meteorologists. Figure 12 shows an example of RoadSurf-Pedestrian slipperiness index visualization. The forecast maps are color-coded to introduce the reason for the sidewalk slipperiness. In addition to the forecast maps, special meteograms are produced, including different weather parameters and pedestrian index for 27 pre-defined locations around Finland. Meteograms also include a 4 day history to help the meteorologist to get a better understanding of the weather development leading to the prevailing and upcoming slipperiness.

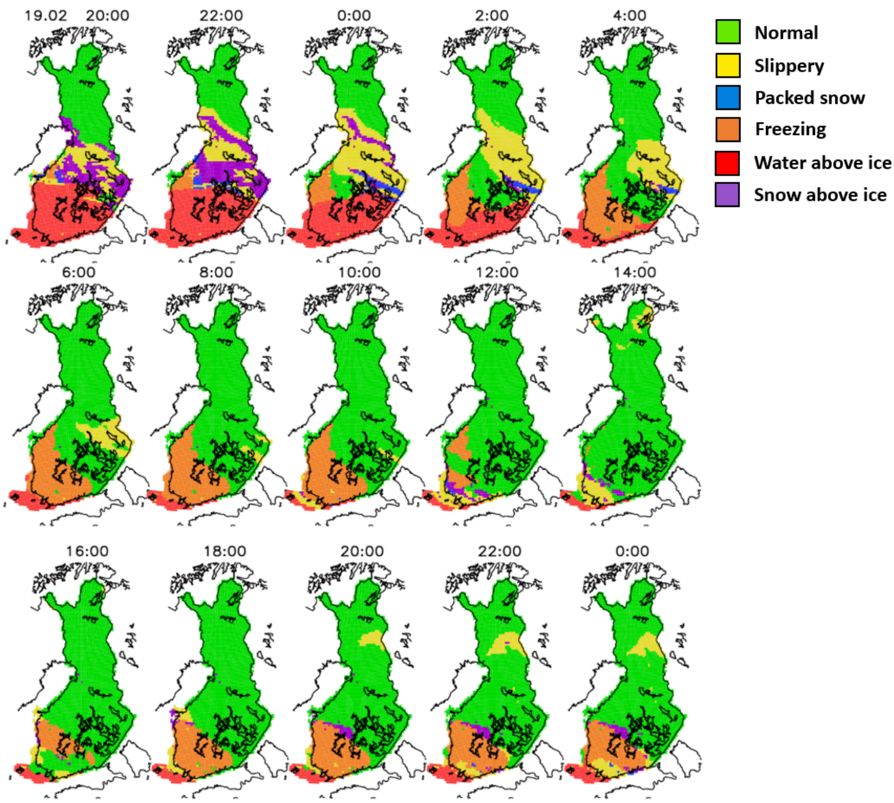

Figure 12 *An example of the pedestrian slipperiness index visualization produced by RoadSurf-Pedestrian model. Figure from* ***Paper II*** *©2020 Royal Meteorological Society.*

5 DISCUSSION

Slips can be considered a major public health and economic problem (Penttinen et al. 1999). There is a lot of potential to reduce the number of weather related slipping injuries. According to surveys, pedestrians could prevent slips with their own actions, like caution and the choice of footwear with a good grip. Also, the importance of winter maintenance has been highlighted in several studies (Mannola et al. 2021; Sundfør and Bjørnskau 2017).

Helsinki seems to have more non-weather related issues affecting the slip injury rate compared to the other cities. The reason might be that people are using sustainable transport modes, including walking, more in Helsinki than in smaller cities (Pastinen 2018).

RoadSurf-Pedestrian model forecasts and warnings given by the meteorologists could be verified in more detail to assess their accuracy. However, it is challenging, or even impossible, to approximate how many slips have been avoided by issued warnings or well performed sidewalk maintenance actions.

The lack of slipperiness observations is a major problem when determining the sidewalk slipperiness. It causes challenges also for duty meteorologists when issuing warnings. New techniques, like detecting changes in the way of walking (Immonen et al. 2019) or microslips (DiDomenico et al. 2005) or some other crowdsourcing techniques, like citizens' observations (Karjalainen and Jokinen 2019) or the accelerometer observations detected by smart phones (Saida et al. 2019), could be used to detect the potential of slipperiness in the future.

Also, machine learning methods could offer more detailed information about the slip risk. Spatio-temporal prediction could consider the differences between areas, like climatology and number of citizens, and improve the prediction of high slip risk.

6 CONCLUSIONS

Road weather as well as the slipperiness from pedestrians' point of view are important issues especially in countries located in the northern latitudes. Road safety can never be overemphasised. Pedestrians are a vulnerable group of road users not only because of other traffic but also because of the slipperiness caused by the weather. This thesis yields tools and background information to improve pedestrians' traffic safety in case of adverse slippery weather conditions.

The focus of this thesis was to describe the weather model, RoadSurf-Pedestrian, that predicts the state of the slipperiness due to the weather. RoadSurf-Pedestrian is a tool for meteorologists when estimating the the level of slipperiness and issuing warnings about slippery sidewalk condition. Another focus was to give information about the weather situations when slipperiness and high slip risk occur based on the slip injury statistics. Also, the effects of climate change on slipperiness are studied in this thesis.

The aim of this thesis was to answer following questions:

CAN WEATHER PHENOMENA LEADING TO SLIPPERY SIDEWALK CONDITIONS BE NUMERICALLY MODELLED?

Papers I and **II** present the numerical road weather prediction models RoadSurf and RoadSurf-Pedestrian. RoadSurf is a one dimensional energy balance model that has been developed to produce road surface specific forecasts. It calculates, for example, road surface temperature, road condition (surface dry, damp, wet, icy, snowy, etc) and driving conditions (normal, difficult, very difficult). Also, the model calculates the amount of water, snow, ice and frost on the surface.

RoadSurf has been developed further to predict the slipperiness condition on the pedestrians' sidewalks. RoadSurf-Pedestrian is physically the same as RoadSurf model having a couple of differences. RoadSurf-Pedestrian classifies the slipperiness from pedestrians' point of view and there are three classes for slipperiness; normal, slippery and very slippery. The most slippery class, very slippery, is divided into four different indices; freezing, compressed snow, snow above the ice layer and water above the ice layer. The slipperiness classification is strongly related on the i.e. the amount of water, snow, ice or frost on the surface, and weather.

The operative use of RoadSurf-Pedestrian has shown that the model is an important tool for meteorologists to support the decision making when issuing warnings about slippery sidewalk condition. The warning classification is developed to take into account all possible weather situations leading to slippery sidewalk condition.

WHAT ARE THE WEATHER PHENOMENA LEADING TO SLIPPERY SIDEWALK CONDITIONS?

Paper III presents information of slip injuries based on TVK's slip data. Slip injury statistics are used as an indirect information about slipperiness as real slipperiness observations (for example friction measurements) are not available from pedestrians' sidewalks. It is assumed that the days with a high number of slipping injuries have been caused by slipperiness due to weather.

Slip injury statistics were collected from 16 cities around Finland with the time range from 1st October 2005 to 30th September 2019. As expected, there is a clear seasonal variation as slip injuries use to occur much more in wintertime compared to summer. Months from January to March cover nearly half of the yearly slipping injuries.

Wintertime weather conditions with ice and snow increase the slip injury rate. Also, temperature plays a significant role on most of the days when the number of slip injuries are high. Near zero temperatures and daily zero-degrees-crossings are very typical on the peak days of slipping injuries. According to the results snow on the ground increases the injury rate more than three times compared to no-snow situation. New snow in suitable temperature conditions can make the sidewalk surface very slippery, large amount of new snow can make the situation even worse if the snow is not removed. However, there are also days when the high amount of slip injuries cannot be explained by the weather. Non-meteorological factors can affect to slipperiness in some cases.

FACTORS AFFECTING PEDESTRIANS' SIDEWALK SLIPPERINESS - DO THEY CHANGE IN THE FUTURE WHEN CLIMATE IS CHANGING?

In **Paper IV** the RoadSurf and RoadSurf-Pedestrian models are run using climate model data as input. According to the results, days with surface temperature below zero degrees will be decreasing. In addition, the occurrence of ice and snow on the sidewalk will decrease and consequently, the time with slippery sidewalk conditions will be shorter. Also, the occurrence of surface temperature fluctuating across zero degree will mostly decrease in spring and autumn but increase in winter. However, in the mid-winter there might be more cases when ice layer is covered by water in the future. As conclusion, winter season with increased slip risk might become shorter but more intensive, and mostly confined to mid-winter.

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RoadSurf: a modelling system for predicting road-weather and road-surface conditions

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ABSTRACT: Forecasting of road-surface and traffic conditions is an important aspect of traffic safety and winter road maintenance, especially in the harsh northern climate. The weather conditions can change quickly, for example, with the onset of snowfall or during rapid temperature variations. A prior knowledge of road weather is important from a public road-safety standpoint. Proper consideration of upcoming weather events also helps the road-maintenance authorities to attend the roads in an effective and economical manner. In Finland, the Finnish Meteorological Institute (FMI) is duty bound to issue warnings of hazardous traffic conditions to the general public. To strengthen these services towards more efficient estimation of rapidly varying conditions of the road surface at a national scale, a simulation model, RoadSurf, has been developed. As input, the model employs numerical weather forecasts, either directly or after modifications made by meteorologists, as well as observations from synoptic or road-weather stations and radar precipitation measurement network. As output, the model produces not only road-surface temperature, but also road-surface condition classification and a traffic index describing the driving conditions in more general terms, as well as road-surface friction. The model has been in operational use since 2000. In addition to the original goal of providing road-weather forecasts for the national road network, the model has been used in several other applications, for example, in predicting pedestrian sidewalk conditions and in numerous intelligent traffic applications. The present study describes the road-weather model RoadSurf and its main applications.

KEY WORDS road-weather forecasting; intelligent traffic; road-surface condition; road-surface friction; road-weather observations; road-weather stations; forecast models

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1. Introduction

Services providing tailored information describing the hydro-meteorological state of the road surface are required by a number of user groups such as drivers, duty meteorologists and road-maintenance units (Vajda *et al.*, 2014a). Benefits to the society have proven to be manyfold greater compared to the investments and running costs of such services. For example, Leviäkangas and Hautala (2009) found that each Euro put into the Finnish Meteorological Institute (FMI) weather services produces a socioeconomic benefit of a minimum of €5 to society.

The objective of a dedicated road-weather service is to deliver timely and localized forecasts of hydro-meteorological conditions near or at the road surface as well as to issue warnings about adverse road conditions with a lead time from a few hours up to 1 or 2 days, or even longer. In an operational framework, these services rely on an integrated system employing extensive observational information from meteorological and/or roadside observations networks, numerical weather prediction data and interpretation tools for the meteorologists to qualify and control the information used for issuing warnings and delivering customer products.

For a more general use, safety related road-weather information obtained from this kind of integrated system along with other weather forecasts can be delivered in a more compact form, such as road-weather alerts and warnings as well as an index indicating the severity (risk level) of driving conditions. Such risk indices are also useful for general assessment of the role of weather in traffic accidents. A survey covering the period from 1997 to 2007 indicated that on an average ∼35% of all accidents during the winter season (November to March) in Finland occurred when weather was rated into difficult or very difficult driving condition categories (Sihvola *et al.*, 2008).

Road-weather services operating in Finland since the late 1970s (Nysten, 1980) have helped to plan and optimize road maintenance and to improve safety on roads during the winter season. To strengthen these services towards a more efficient estimation of rapidly varying conditions of the road surface at a national scale, a simulation model known as RoadSurf has been developed at the FMI during the late 1990s and has been in operation since 2000 (Heikinheimo *et al.*, 2000; Kangas *et al.*, 2006, 2012). Similar models based on physical formulation of the hydro-meteorological processes at the road surface have been introduced by several authors (e.g. Rayer, 1987; Alexandersson *et al.*, 1990; Sass, 1992; Jacobs and Raatz, 1996; Shao and Lister, 1996; Crevier and Delage, 2001).

The primary task of RoadSurf is to provide estimates of the road-surface temperature and guidance for the assessment of the road hydro-meteorological state and slipperiness along the main road network, at a scale representative of the horizontal grid size of the weather prediction system. As a novel feature, the model produces road-surface condition classification as well as a traffic index describing the driving conditions in more

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general terms. A road-surface friction forecast is also included (Juga *et al.*, 2012).

A special feature of RoadSurf is that in addition to the more traditional way of running the model in individual road-weather station (RWS) locations, it can be run on a network of points. This network can consist of a gridded set of points covering, for example, the whole of Finland, or individual points on stretches of road. With appropriate surface and traffic description, the model can be applied to different types of road and traffic.

Through the years the model has undergone several modifications in different projects for specific purposes, for example, for simulation of pavement conditions from the view point of pedestrians (Ruotsalainen *et al.*, 2004; Ruuhela *et al.*, 2005) and for optimizing ploughing or use of salt (Hippi, 2004; Hellinen, 2007). The model has also been employed in various intelligent traffic research projects, like CARLINK (Nurmi *et al.*, 2008), WiSafeCar (Sukuvaara and Nurmi, 2012) and FOTsis (Nurmi *et al.*, 2013).

The present study first describes the basic physical principles of the FMI road-weather model RoadSurf (Section 2). Numerical solution as well as the input and output data and the post-processing scheme for road-weather services are described briefly in Section 3. Section 4 depicts verification tests of the model. Section 5 provides a description of the operational environment. Conclusions and an outlook for the future are presented in Section 6.

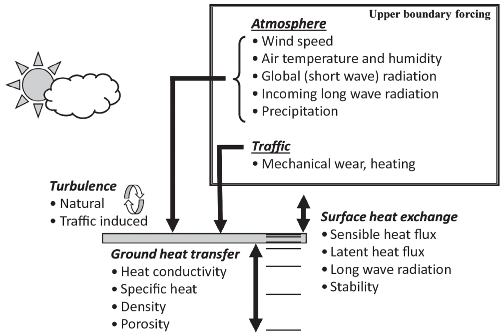

Figure 1. Energy balance schematic of the RoadSurf model.

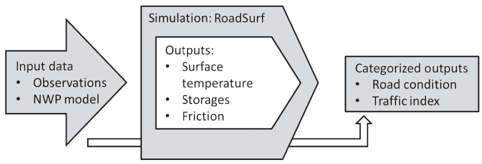

Figure 2. Conceptual process chart of RoadSurf.

2. Model description

2.1. General principles

RoadSurf is a 1D energy balance model based on the formulation of energy fluxes at the ground surface. The model calculates vertical heat transfer in the ground and at the ground–atmosphere interface, taking into account the special conditions prevailing at the road surface and in the ground below it (Figure 1). In order to quantify the hydrological state of the surface, the surface layer parameterization includes hydrological processes such as accumulation of rain and snow, run-off of surface water, sublimation, freezing, melting and evaporation. The effect of traffic is also accounted for.

For input, forecasts from a numerical weather prediction (NWP) model, either directly or after being edited by duty meteorologists, is used as forcing at the upper boundary. The initial conditions are determined based on a retroactive 2 day road-model run using observational weather data. For observations, spatially interpolated observational data (either synoptic or from RWSs) as well as weather radar data (precipitation) are used.

As output, the model provides not only road-surface temperature but also surface friction and categorized variables describing detailed road conditions as well as traffic conditions in a more general level. The amount of water, snow, ice and frost are also made available in the form of storage terms (Figure 2).

The gridded data set used for the upper boundary forcing in the present operational road-weather model provides the horizontal coupling between individual grid points. At the lower boundary, the climatological ground temperature is used as the boundary condition. The model is, however, in no way limited to using gridded data for boundary forcing. Being 1D, it can be run for individual data points or for any set points, for example for specific RWSs or a set of points on specified stretches of a road. For research purposes, the model can be run using observed meteorological data only.

The model physics closely follows the methods used in other models (e.g. the Metro model of Crevier and Delage, 2001), so it is described only briefly here, with the stress being more on the unique features of RoadSurf, such as the surface condition interpretation and the operational setup with gridded data.

The operational scheme discussed in the present study is limited in the sense that all parameters describing the simulated environment are site-independent, thus assuming a fixed environment at all simulation points. These simulations in fact represent an average ‘ideal’ site characterized by a flat horizontal surface, without shading elements such as nearby trees. The thermodynamic properties of the road surface and the road bed beneath are the same for all simulated points. The operational scheme does not necessarily require access to RWS data. However, these were used for model verification in the present study.

2.2. Calculation of the surface temperature

Physically, the model is based on solving the energy balance at the ground surface, which can be written as (e.g. Brutsaert, 1984), *cf.* Figure 1:

$$G = I_{\mathrm{NET}} - H - \mathrm{LE} + \mathrm{PC} \qquad (1)$$

where G is the heat flux into the ground, I_{NET} the net radiation on the surface, H the sensible and LE the latent turbulent heat flux from the ground surface, and PC describes heat flow due to phase change (freezing/melting).

The radiation term I_{NET} describes atmospheric forcing and is calculated as:

$$I_{\mathrm{NET}} = \left(1 - \alpha_{\mathrm{s}}\right) I_{\mathrm{g}} + \varepsilon_{\mathrm{s}} I_{\mathrm{L}} - \varepsilon_{\mathrm{s}} \sigma T_{\mathrm{s}}^{4} \qquad (2)$$

where α_{s} is the surface albedo, ε_{s} its emittance and T_{s} surface temperature. The model gets global (I_{g}) and long wave radiation (I_{L}) as input from a weather forecast or from measurements. Albedo is represented with a simple two-value approach,

Table 1. Surface properties.

Parameter	Value	Units
Surface albedo (bare ground/road)	0.10	–
Surface albedo (snow)	0.60	–
Surface albedo (ice)	0.10–0.60[a]	–
Emittance	0.95	–
Roughness length for momentum	0.4	m
Roughness length for heat	0.1	m
Temperature reference height	2	m
Wind reference height	10	m

[a]Linear dependence on ice thickness.

Table 2. Ground properties.

Parameter	Upper layers (asphalt)	Lower layers (soil)	Units
Dry soil heat capacity	1.9×10^6	1.3×10^6	$\mathrm{J\,m^{-3}\,K^{-1}}$
Dry soil bulk density	2.11	1.60	$\mathrm{kg\,m^{-3}}$
Soil heat conductivity	0.5	1.4	$\mathrm{W\,K^{-1}\,m^{-1}}$
Porosity	0.10	0.40	–

one for bare surface and one for snow (Table 1); for ice, the albedo varies linearly between these two values depending on ice thickness.

Sensible (H) and latent heat (LE) fluxes between the surface and the atmosphere are calculated using the concepts of boundary layer conductance and aerodynamic resistance (Campbell, 1986; Monteith and Unsworth, 1990; *cf* Table 1). Atmospheric stability is also accounted for when calculating the heat transfer co-efficients. As to saturation vapour pressures, different formulations over the water and icy surface are used (Calder, 1990). The temperature dependence of the various physical parameters (e.g. the latent heat of fusion and the psychrometric constant) is also accounted for. Table 1 lists the surface parameter values used in the model.

The heat transfer in the ground is assumed to take place through 1D heat conduction only, and temperature (T) can thus be calculated from (e.g. Carslaw and Jaeger, 1986):

$$\frac{\partial T(z,t)}{\partial t} = \kappa_g \frac{\partial^2 T(z,t)}{\partial z^2}, \qquad \kappa_g = \frac{k_g}{\rho_g c_g} \tag{3}$$

where z denotes the vertical distance in the ground, t the time, and κ_g the thermal diffusivity, k_g heat conductivity, ρ_g density and c_g specific heat capacity of the ground. The porosity of the ground is also accounted for. The ground is assumed to consist of two types of soil, the uppermost layers being asphalt and the lower ones consisting of 'standard' soil. Table 2 lists the ground properties and parameter values used in the model. The heat capacity, heat conductivity and density of the dry ground are taken to be constant; temperature dependency is introduced because of the water in the soil pores. For example, the conductivity of saturated soil (k_g) can be written as (Bear, 1988):

$$k_g = (1-n)\,k_d + nk_w \tag{4}$$

where k_d and k_w are the heat conductivity of dry ground and water, respectively, and n is the porosity. Below freezing point, constant values are used for icy conditions (Oke, 1987).

In the model, the vertical heat transfer and temperature distribution are calculated down to a depth of about 4 m. At the lower boundary ($z = z_b$), a sinusoidally variable climatologic temperature is assumed (Campbell, 1986):

$$T(z_b, t) = \overline{T} + A \sin\left(\omega\, t - \frac{z_b}{d}\right) \tag{5}$$

where A is the amplitude of the variations, ω the angular frequency of the oscillation, t time in days and d the so-called damping depth. The numerical values of these parameters are based on measurements taken at the FMI observatory in Jokioinen, southern Finland (60.8 °N, 23.5 °E), with (Fougstedt, 1992):

$$\overline{T} = 6.4\,^\circ\mathrm{C}, \quad A = 0.6, \quad \omega = 2\pi/365, \quad d = 2.7\,\mathrm{m}$$

Various tests with different values of these parameters were performed but yielded only small effects. Thus, same values were used throughout the calculation area (Finland).

2.3. Hydrological surface condition

The road condition interpretation is based on various storage terms that describe the amount of water, snow, ice and frost on the surface. The model constantly tracks the changes occurring in these storage terms caused by precipitation, evaporation, condensation, melting and freezing, as well as by traffic wear. The storages may also interact with each other, for example, the size of the water storage is increased by precipitation as well as by melting of snow or ice.

The storage sizes for water (S_w), ice (S_i), track ice (S_{ii}), snow (S_s) and frost (S_f) are controlled by conservation equations:

$$\frac{dS_w}{dt} = \Phi_{PR} - \Phi_E + \Phi_M - \Phi_F - W_w \tag{6}$$

$$\frac{dS_i}{dt} = \Phi_F - \Phi_M + \Phi_S + K_{rf} W_S - W_i, \quad K_{rf} = 0.5 \tag{7a}$$

$$\frac{dS_{ii}}{dt} = \Phi_F - \Phi_M + \Phi_S + K_{rf} W_S - W_{ii}, \quad K_{rf} = 0.5 \tag{7b}$$

$$\frac{dS_s}{dt} = \Phi_{PS} - \Phi_M - \Phi_F - W_s \tag{8}$$

$$\frac{dS_f}{dt} = \Phi_D - \Phi_M - W_f \tag{9}$$

where the Φ terms indicate source/sink terms with the subscripts PR, PS, E, F, M, S and D denoting precipitation (rain and snow), evaporation, freezing, melting, sublimation and desublimation, respectively. The W terms represent the wear (or actual rate of wear) of the substance in question caused by the traffic. In addition to decreasing the size of these storages, the traffic is also assumed to pack part of snow into ice, represented by factor K_{rf} in the above equations; the remaining part of the snow wear is thought to be blown away from the road. In addition to wear, or blow-off by traffic, the water wear term describes the run-off of water caused by road surface cross slope.

As to ice, two separate storage terms are used to describe the different rate of traffic wear on the different parts of the road, that is, in the tracks of the traffic or elsewhere. For the other storage terms, a single term for each was considered adequate.

The mechanical rate of wear caused by the traffic (W_j, in $\mathrm{mm\,h^{-1}}$ water equivalent) is described in the model as simple linear function of storage size:

$$W_j = A_j S_j \; (j = \mathrm{w, i, ii, s, f} \text{ for water, ice, track ice, snow and frost, respectively}) \tag{10}$$

Table 3. Storage interactions.

Storage term	Increased by	Decreased by
Snow	Snowing	Packing to ice Traffic 'blow off' Melting to water Sublimation
Ice	Packing from snow Freezing of water Freezing of wet snow	Traffic wear Melting to water Sublimation
Frost	Desublimation	Traffic wear Melting to water Sublimation
Water	Rain Condensation Melting of snow/ice/frost	Traffic wear Run-off Evaporation

where the co-efficients A_j are empirical constants. Track ice refers to the track area on the road where the traffic is concentrated, and thus wears the ice quicker. This type of relationship was chosen so that the rate of wear decreases together with the decreasing amount of the substance in question on the road surface as shown by observations. The empirical values in Equation (10) were determined by experimentation and discussions with road engineering and maintenance experts.

Traffic also affects the road-surface temperature by turbulent heat transfer caused by the moving vehicles. It is approximated in the model by using a non-zero minimum value of wind speed. During night-time, a smaller minimum value is used. The model also includes a term describing the heating effect of traffic on the surface. Reliable information about this effect and especially about traffic densities it depends on is, however, currently not available, so this term is presently set to zero and thought to be included in the turbulent heat transfer effect described above.

Table 3 summarizes the different factors that can affect the various storage sizes by increasing or decreasing them.

2.4. Surface friction

An explicit method to estimate surface friction has been included in the model. The statistical friction model (Hippi *et al.*, 2010; Juga *et al.*, 2012) is based on observations from four Finnish RWSs during the winters of 2007/2008 and 2008/2009. The equations have been validated with independent data from the winter of 2009/2010.

The underlying idea of the methodology (so-called Perfect Prog method) is that the friction model uses the road-weather model output as predictor variables (assuming them to represent perfect forecasts) in the regression equations of the friction model. The resulting statistical friction model equations are:

$$\text{Snowy and/or icy roads}: \ \mathrm{CF_{si}} = a_1 f\left(X_\mathrm{S}\right) + b_1 f\left(X_\mathrm{I}\right) + c_1 f\left(T_\mathrm{r}\right) + d_1 \qquad (11)$$

$$\text{Wet road surface}: \ \mathrm{CF_w} = a_2 f\left(X_\mathrm{W}\right) + d_2 \qquad (12)$$

$$\text{Dry road surface}: \ \mathrm{CF_d} = 0.82 \ \text{(constant)} \qquad (13)$$

where a_i, b_i, c_i and d_i ($i = 1,2$) are regression co-efficients and T_r is the road-surface temperature. X_S, X_I and X_W represent the thickness of snow, ice and water layers (in equivalent water mm), respectively.

2.5. Road condition interpretation and the traffic index

Based on the sizes of the different storage terms and on the calculated road-surface temperature, RoadSurf makes a road condition interpretation, that is, it determines the status of the road surface. At present, eight road surface classes are used:

1. Dry ($W_\mathrm{p} < 0.1\%$, $S_\mathrm{s} = S_\mathrm{i} = S_\mathrm{ii} = S_\mathrm{f} = 0$ mm)
2. Damp ($0.1\% \le W_\mathrm{p} \le 0.5\%$, $S_\mathrm{s} = S_\mathrm{i} = S_\mathrm{ii} = S_\mathrm{f} = 0$ mm)
3. Wet ($W_\mathrm{p} > 0.5\%$, $S_\mathrm{s} = S_\mathrm{i} = S_\mathrm{ii} = S_\mathrm{f} = 0$ mm)
4. Wet snow ($S_\mathrm{w} > 0$ mm, $S_\mathrm{s} > 0$ mm, $R_\mathrm{ws} \ge 10\%$)
5. Frost ($S_\mathrm{f} > 0$ mm)
6. Partly ice ($S_\mathrm{i} > 0$ mm, $S_\mathrm{ii} = 0$ mm)
7. Ice ($S_\mathrm{i} > 0$ mm, $S_\mathrm{ii} > 0$ mm)
8. Dry snow ($S_\mathrm{s} > 0$ mm, $R_\mathrm{ws} < 10\%$)

where W_p is ground soil/asphalt pore saturation (relative amount of water in the pores), R_ws is the ratio of water to snow in precipitation or on the ground, and S_w, S_s, S_i, S_ii, S_f are the amount of water, snow, ice, track ice and frost on the surface, respectively.

Damp and wet classes thus differ only by the amount of water on the surface. In the damp class, only part of the ground pores are filled with water, whereas in the wet class the pores are filled with water and there may also be a layer of water on the surface. The 'partly ice' case means conditions in which only part of the road surface is covered by ice, with tyre tracks or whole lanes with more traffic already ice-free. The two ice storage terms with different rates of wear are used to describe this case. When 'partly ice' condition exists, a secondary road class is determined in addition to the main road-surface class in order to indicate the condition of the ice-free parts of the road. A same type of two-valued road-surface classification is used to describe a situation where snow or water exists on top of ice.

The model further combines information about road condition, storage sizes and certain weather parameters (at present wind speed, precipitation type and intensity) to produce a three-valued traffic index describing the weather related traffic conditions in more general terms:

1. Normal
2. Difficult
3. Very difficult

These indices are the same as used by FMI when issuing road-weather warnings. This type of tripartite warning status is also used by many European weather services, although the thresholds differ (Vajda *et al.*, 2014a).

Traffic index is determined by first defining a basic numerical value using the information about the road condition, and then adding a correction factor based on wind speed, precipitation intensity and phase. For this purpose, wind speed and precipitation intensity have been divided into three categories. The division as well as the whole procedure has been designed to correspond to the instructions and decision logic used by the FMI duty meteorologists when issuing road-weather warning. The warning criteria of the meteorologists are calibrated regularly using road-accident statistics (e.g. Sihvola *et al.*, 2008).

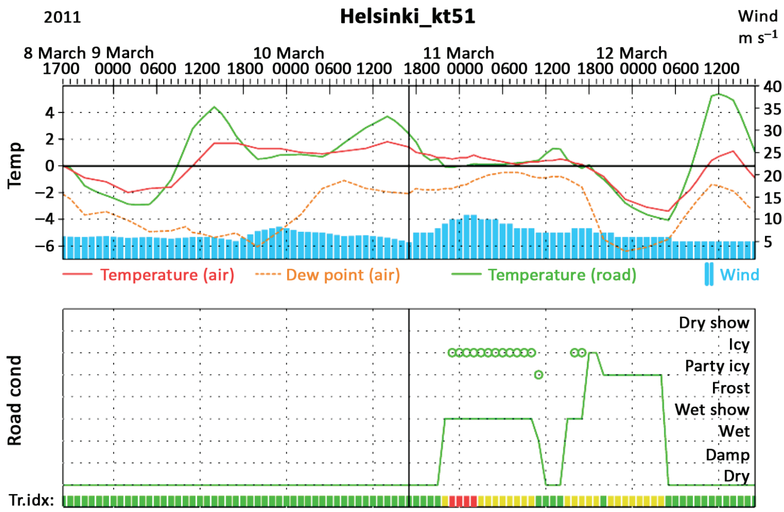

Figure 3. Example of RoadSurf graphic output showing road-surface temperature ('Temp', green solid line), road condition ('Road cond', green solid line) and traffic index ('Tr.idx'). Traffic index value is indicated by the small coloured bars at the bottom of the plot (green for normal, yellow for difficult and red for very difficult conditions). Vertical line in the middle of the plots denotes the start of the NWP model output based forecast, with plot to the left showing initialization run based on observations input. Air temperature (red solid line), dew point temperature (orange dotted line) and wind (blue bars) in the upper plot are input parameters for the model.

3. The numerical model

3.1. Numerical solution

In the numerical model, the ground domain is divided vertically into 15 layers with varying thickness with the top of each layer given by the expression (in metres)

$$Z(k+1) = Z(k) + 0.0103 \cdot 1.4^{(k-1)},$$
$$k = 1, 2, \ldots, 15,\ Z(1) = 0\ \text{m} \qquad (14)$$

with the thinnest layers being next to the ground surface, where the temperature changes are the largest and swiftest. The lowest layer (top at about 3.5 m) is in the climatological temperature zone, which is used as the lower boundary condition. The first two layers below the ground are assumed to consist of asphalt or related material, while the rest of the layers are described as porous ground.

The heat transfer equations are written numerically using a time-centred Crank–Nicholson scheme. The resulting tridiagonal matrix system is then solved iteratively using the Thomas Algorithm (Campbell, 1988).

3.2. Model inputs and outputs

Model input consists of time series data from observations and weather forecasts, the latter either directly from an NWP model or from a forecast edited by the duty meteorologists. The input parameters include:

- ambient temperature (T_{2m});
- relative humidity (Rh_{2m});
- wind speed (V_{10m});
- short-wave radiation (I_g, global radiation);
- long-wave radiation (I_L, mostly from clouds);
- precipitation;
- precipitation phase (optional).

The precipitation and radiation inputs can consist of either cumulative or instantaneous values. The precipitation phase information can be provided either directly as a phase or as the amount of water/snow precipitation. Weather radar precipitation is used whenever possible. If no phase information is available, the model makes a phase interpretation simply by using a correlation based on temperature and humidity (Koistinen and Saltikoff, 1999).

The values of the input variables can be taken from observations or from a forecast, the model making no distinction as to the source of the data. In case both observations and forecasts are used as input (as is presently done in the operational runs), smoothing of the leap from the observations to the forecast caused by forecast errors can be used.

The forecasted output parameters of the model include:

- road-surface temperature;
- road condition (primary and secondary);
- traffic index;
- road-surface friction;
- storage terms.

both in plain ASCII format and a binary file for the GrADS (Grid Analysis and Display System, http://grads.iges.org/grads/head.html) visualization programme. The plain ASCII files can be used for further post-processing, whereas GrADS is used to produce special graphical web pages (Figures 3 and 4) for forecast monitoring, model development and to be used as a forecasting aid.

4. Model verification

Road-weather model verification is a complicated task because the model represents a what-if-nothing-is-done scenario, that is, it does not take into account road-maintenance measures.

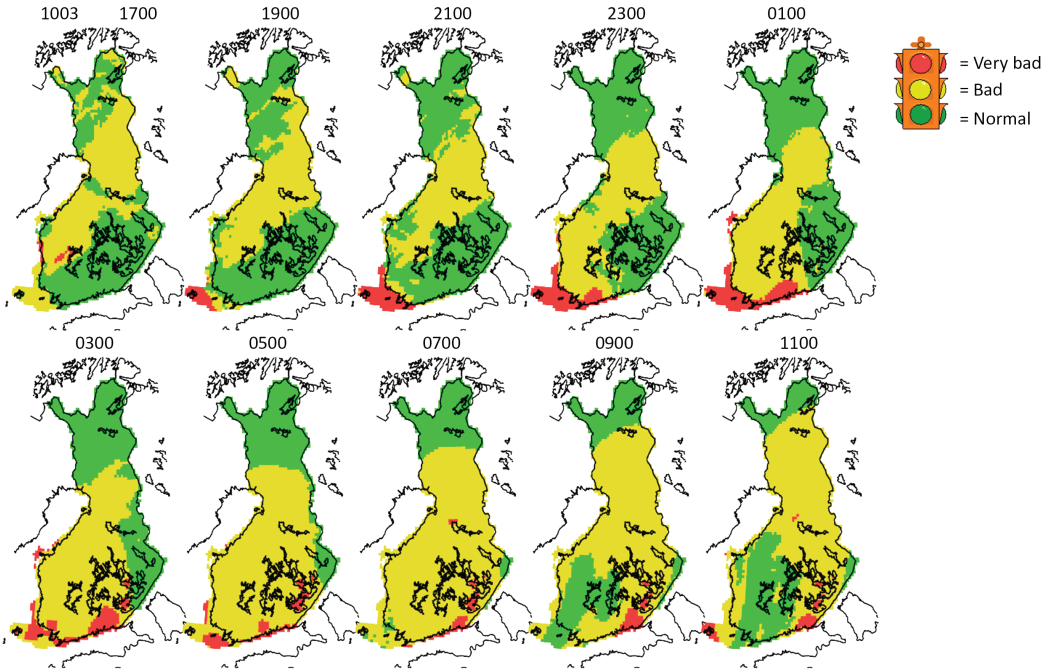

Figure 4. Exemplary traffic index map time series as produced by the RoadSurf for 3 March. Time indicated as hhmm on top of each map.

In practice, some road maintenance (snow ploughing, salting) is bound to take place, especially in cases where hazardous conditions are encountered or expected; in Finland it is common practice to keep the highways as clean as possible always. This must be borne in mind when choosing the verification cases and when interpreting the verification results.

RoadSurf performance assessment has been carried out earlier using data from RWSs administered by the Finnish Transport Agency (Heikinheimo *et al.*, 2000). The test data covered the winter of 1997/1998 from October to April and the winter of 1998/1999 from October to February. Periods of a few days duration were selected to represent contrasting winter weather types. Test runs were performed as hindcasts using measurements at the RWSs complemented by solar radiation data based on the nearest SYNOP weather stations as model input. The mean error between simulated and measured road-surface temperature was 0.3 °C with a root mean square error of 1.35 °C under conditions in which severe icing could be expected, that is, rapid air temperature rise towards zero or wet surface freezing with temperature dropping below zero. The correspondence between periods when icing was detected by the Vaisala road sensor and when ice was predicted by the model was qualitatively good. The timing of icing could be predicted to within a few hours compared to the road sensors. Accurate determination of the night-time minimum (to within 1 °C) was observed, but with slight underestimation of the daytime maximum surface temperature.

A more detailed model performance assessment has now been done for two 7 day periods at two RWS locations in southern Finland: Anjala (60.70 °N, 26.81 °E) and Utti (60.90 °N, 26.94 °E). These specific cases were chosen to represent precipitation events connected with rapidly rising temperature, which have been found to cause hazardous traffic conditions (Juga *et al.*, 2005). One reason to choose relatively cold cases was to keep the air temperature at least most of the time below −7 to −10 °C, which in Finland is the limit below which road salting is not performed. Above these temperatures possible salting complicates the analysis.

In addition to surface temperature, simulated storage sizes, road condition and friction values were also compared. This is very challenging, as these parameters are very sensitive to possible road-maintenance measures (mostly snow ploughing in this case) which are not accounted for in the model. The results of the verification of these parameters are therefore more or less qualitative and must be considered with care.

The input for the model runs was taken from the RWS in question as completely as possible. Because precipitation measurements were considered unreliable and solar radiation measurements were not at all available from the stations, they were obtained by other means, precipitation from weather radar measurements and radiation from a NWP model, using data from the closest grid point in the operational grid.

The results are shown in Figure 5 (Anjala) and Figure 6 (Utti). Each figure consists of four panes (a–d). Time is given as UTC. Panel a shows measured and modelled road-surface temperatures. Panel b consists of three parts, the upper and lower parts showing the modelled and measured storage terms (frost was not available from measurements) as stacked area charts, while the centre part shows the modelled traffic index. For the cases studied here, very difficult traffic conditions were not encountered. Panel c shows precipitation as measured by radar (used as model input) as well as that measured at the RWS. Finally, panel d shows measured and modelled road-surface friction co-efficient.

The modelled temperature can be seen to follow measurements quite closely, especially when approaching zero. It appears,

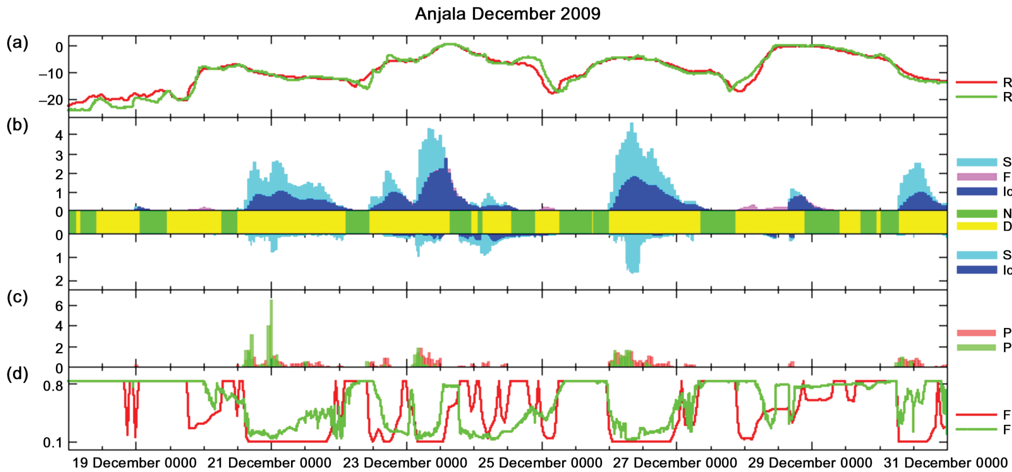

Figure 5. Model verification case for Anjala (RST = road-surface temperature, RWS = road-weather station, Mod = modelled). Temperatures in °C, friction in relative units (0 … 1), traffic index categorized, all other units mm water equivalent.

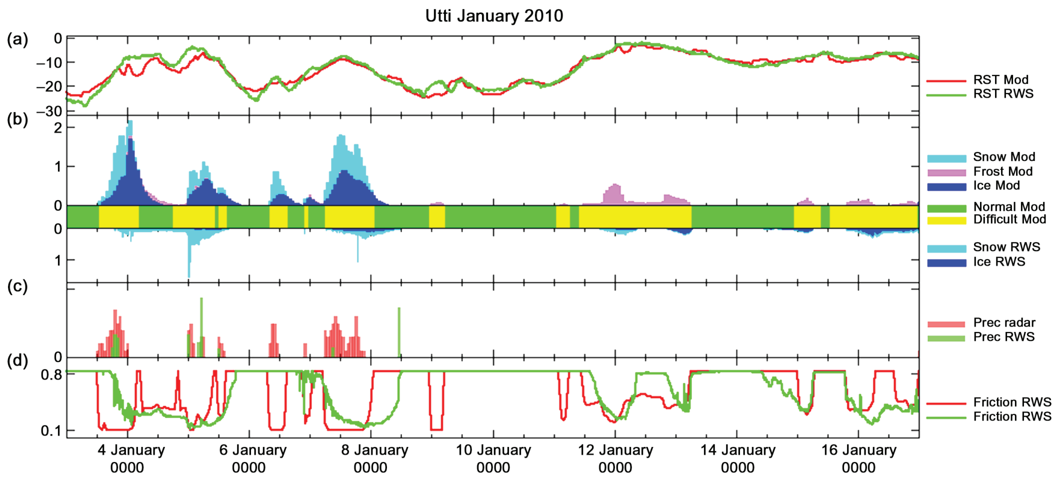

Figure 6. Model verification case for Utti (RST = road-surface temperature, RWS = road-weather station, Mod = modelled). Temperatures in °C, friction in relative units (0 … 1), traffic index categorized, all other units mm water equivalent.

though, that the model forecast is a bit too cold with low (−15 °C or lower) temperatures, but this is not a significant problem, as the road condition is not very sensitive to temperature changes in such cold weather conditions. There are also some larger differences in warmer cases which in Utti on 4 January 2010 can probably be attributed to road maintenance during and after the snowfall. Information about possible road-maintenance measures was unfortunately not available.

As to storage sizes (panel b), the differences between the modelled and measured values are much bigger. This can probably at least partly be attributed to road maintenance (ploughing) that is not included in the model. In general, the duration of the snow/ice cover is about the same, which is also reflected in the traffic condition that quite closely follows the measured existence of snow and/or ice. One can also see that in some cases the frost predicted by the model is seen as ice in the measurements (e.g. Utti, 12 and 16 January 2010).

The difference in storage sizes can also be attributed to precipitation differences (panel c). One reason for this is the different measurement method: model precipitation input is based on areal (10 km × 10 km) weather radar signal averages, whereas road-station measurement is a point measurement. Especially during winter, some low cloud precipitation can escape radar observation; on the other hand, beyond the horizon some radar detected precipitation can evaporate before reaching the ground. Judging from the figures it also seems apparent that there are some problems with the road-station measurements. In Utti, for instance, there seems to be one high measured precipitation peak with no measured storage growth (8 January 2010 at about 1200 UTC).

The road friction (panel d) also shows the same general structure for the model and the measurements. Friction is a very sensitive and rapidly varying parameter, whereby even small discrepancies in the model are reflected in seemingly large differences in the friction co-efficient. Generally, however, the friction model is on the 'safe side', that is, gives lower than measured values. One larger exception to this rule occurs at the end of the Utti comparison period, where the measured low friction is not reflected in the modelled value, another at Anjala at about 24 December 2009. A more detailed analysis is needed here to see whether the problem is with the model or with the measurements. One possible explanation is that the road-friction measurement is a point measurement (which may or may not be in the track) whereas the model value is an area averaged and based purely on the track storage value.

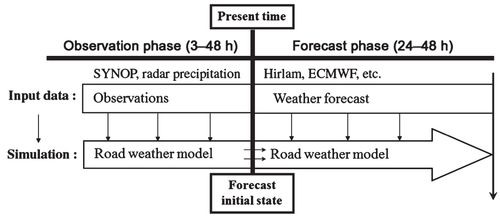

Figure 7. Schematic flow chart of the operational RoadSurf model run.

5. Operational usage

The model is presently run operationally once an hour. The modelled area covers Finland between latitudes 60 and 70 °N on a 10 km × 10 km grid. This specific grid was chosen because of synergy with other FMI operational products. Observational and forecast data are interpolated into this grid using the Kriging method (Bigg, 1991). The same grid and method is used at FMI also, for example, for forest fire warning calculations (Vajda *et al.*, 2014b).

To counter the problem of initial state definition, the operational model run consists of two parts, the first one based on observations and the second one on a forecast. The purpose of the observation-based run is to set the initial state of the forecast-based run that follows immediately, continuing from the final state of the observation-based run (Figure 7). The length of both runs is 24–48 h depending on the amount of available input data. Technically, there is just one computer run, where the input source changes from observations to forecast when the end of the observations is reached.

At present, the observation run is based on meteorological SYNOP observations from the regular meteorological observation network maintained by FMI and on weather radar precipitation data. The weather radar data are used wherever they are available. If there is no radar data, synoptic precipitation observations are used instead. In Finland, the radar network is very comprehensive and covers practically the whole country.

Because of scarceness of radiation measurements they were originally supplemented with radiation calculated from cloudiness observations using formulae based on a method by Lind and Katsaros (1982) and Iqbal (1983), which was further modified for Finnish conditions (Venäläinen and Heikinheimo, 1997, 2002; Venäläinen *et al.*, 1999; Venäläinen and Kangas, 2003). The number of synoptic stations reporting cloudiness reduced recently, however, with the consequence that interpolated radiation fields based on synoptic observations are no longer usable. Thence, the solar radiation components for the observation-based runs must now be estimated using short-term weather model forecasts.

The forecast-based part of the run (Figure 7) uses output from a NWP model. The data are fed in from a quality controlled database edited by the duty meteorologists with an interactive editing tool called SmartMet developed at FMI. The edited forecast data have proven to contain a very small bias in 2 m temperature resulting in a practically seamless shift from the hindcast to the forecast so that no coupling phase or smoothing is required. A second operational suite with input directly from the HIRLAM NWP model (http://hirlam.org/) is provided for comparison and as a backup. It is run at synoptic hours, that is, at 3 h intervals. The SmartMet-based forecasts are run operationally every hour.

Separate data acquisition routines take care of collecting the input data from various sources and providing the model with the latest information that is available. Excluding post-processing to produce graphics, a typical 2 day forecast run (with a 2 day observation run) covering mainland Finland with 3551 grid points on an SGI single-processor main frame computer takes about 1–2 min real wall-clock time (40–60 CPU seconds). The runtime scales linearly with the number of grid points.

6. Conclusions and outlook

The Finnish Meteorological Institute (FMI) road-weather model RoadSurf has been operational since 2000 and, with all its versions (including, e.g. pedestrian condition and road-maintenance guidance versions of the model), a total of over 100 model runs are now performed daily. The model has been found to be very robust and reliable and it has performed well.

The current main operational model is limited to one road type, the Finnish main road network, with no maintenance information included. It provides a generic forecast forming the basis of road-weather forecasting and decision-making. The degree of localness of model forecasts can be improved by including observations from road-weather stations (RWS). With proper environmental and weather information, the model can be applied in other environments as well. One must, however, ensure the reliability and meteorological representativeness of the RWS measurements. The environment can also change (e.g. cutting of trees) and a system providing up-to-date information to the model must be built. RoadSurf includes structures for providing RWS measurements as well as location-dependent information into the model.

Planned future enhancements of the model include steps to better account for locally and temporally varying traffic and environmental conditions. Road-maintenance measures could also be included in the model if they were made available. The use of real time analyses from FMI's LAPS (Local Analysis and Prediction System, http://laps.noaa.gov/) system to replace the presently used synoptic and weather radar precipitation observations is already in trial use with some RoadSurf products.

During the past few years, interest in road-weather modelling has increased significantly. RoadSurf has proven to be versatile, and versions for various applications have been developed. These include models for:

- pedestrian sidewalk conditions;
- road-maintenance guidance;
- VARO road condition alert;
- road station based forecasting.

The model for pedestrian sidewalk conditions is a version of the model predicting slipperiness conditions from the viewpoint of the pedestrians. The model is used operationally as an aid for the meteorologist when considering the need to issue slipperiness warnings to pedestrians during winter (Ruotsalainen *et al.*, 2004). The road-maintenance guidance system employs an enhanced version of RoadSurf to produce tailored, advance information about upcoming needs for road maintenance (Hippi, 2004; Hellinen, 2007). Within the VARO Alert system for drivers, developed within the AINO programme, RoadSurf predictions were used as the basis for a system issuing automatic localized warnings to vehicles entering areas where dangerous traffic conditions were predicted to develop (Miles and Broeders, 2007).

Within the road station based forecasting routine, RoadSurf is run at a set of actual road station locations instead of an evenly distributed grid used in the main operational system. Lately, this form of model use has grown in importance as RoadSurf has been adapted for piloting in various recent intelligent traffic system (ITS) projects, for example, CARLINK, WiSafeCar and FOTsis.

The objective of the international CARLINK (Wireless Traffic Service Platform for Linking Cars, Nurmi *et al.*, 2008) was to develop an intelligent wireless traffic service platform between cars, supported with wireless transceivers along the roads. RoadSurf was integrated in the system to provide up-to-date road-weather data along with data from traffic management infrastructure.

As a pilot study of the international WiSafeCar project (Sukuvaara and Nurmi, 2012), a platform for data transfer between vehicles and infrastructure was developed. The data provided for the system included road weather and emergency information. Data were transferred wirelessly between cars or between cars and infrastructure to enable the most urgent data to be delivered to drivers in real-time. The vehicles themselves could also act as an active part in the system and provide data to the infrastructure.

Route planning is another ITS application in which weather information can be successfully used. FMI is a partner in a EU FP7 project FOTsis (http://www.fotsis.com), where FMI road-weather know-how and road-weather forecasts are applied in a widespread European context (Nurmi *et al.*, 2013).

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RESEARCH ARTICLE

Meteorological Applications RMetS

RoadSurf-Pedestrian: a sidewalk condition model to predict risk for wintertime slipping injuries

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Abstract

Icy and snowy sidewalks are typical wintertime phenomena in Finland. Wintertime slipping injuries are common and lead to substantial economic costs to health care as well as losses to society due to long sick leaves. In Finland, almost every second person slips and falls outdoors annually, and around 70,000 persons are injured needing medical attention. Typically, the most slippery conditions are encountered when the daily average temperature is slightly below 0°C or temperature crosses 0°C and there is precipitation in some form. The Finnish Meteorological Institute (FMI) has developed a numerical weather model that simulates the level of slipperiness on the sidewalks. The model classifies the sidewalk slipperiness into three classes; normal, slippery and very slippery. The FMI issues warnings of hazardous sidewalk conditions to the general public. Pedestrians' road safety can be increased with sidewalk condition forecasts and warnings. When warned, people can choose proper footwear or use anti-slip devices, change the route or mode of transport, postpone the journey or cancel it altogether. Precise and reliable weather and sidewalk condition forecasts enable targeted and more effective sidewalk maintenance activities that can improve the grip of sidewalks and thus reduce the risk of accidents and injuries. This study presents the sidewalk condition model RoadSurf-Pedestrian, its physical principles and examples of model runs. There are some challenges in the modelling of the slipperiness but the model gives valuable information on the slipperiness for duty forecasters. Slipping injury statistics are also presented and used as verification data.

KEYWORDS

pedestrians, road safety, road weather forecasting, slipperiness, walking, weather warnings

1 | INTRODUCTION

Health impacts of weather and climate are of increasing concern due to the ongoing climate change and demographic changes such as ageing of the population that may increase vulnerability of people to weather related hazards. A hazard that has not been widely recognized is weather induced slippery sidewalk conditions in wintertime leading to pedestrian slipping injuries. The number of yearly slipping injuries of pedestrians and cyclists needing medical attention is around 70,000; two-thirds of these occur in wintertime when the surface is icy or snowy (Grönqvist, 1995; Vuoriainen *et al.*, 2000). Typical slip and fall injuries include bruises, sprains and fractures causing, at worst, long sick leaves and human suffering (Andersson and Lagerlöf, 1983; Lund, 1984; Strandberg, 1985; Björnstig *et al.*, 1997; Eilert-Peterson and Schelp, 1998; Kemmlert and Lundholm, 2001; Flinkkilä *et al.*, 2011). The annual costs of slip and fall injuries are estimated to be about €2.4 billion (2006 value) including the costs of medical care, loss of work input and reduced well-being (Hautala and Leviäkangas, 2007). Reduced well-being is estimated to account for 95% of the total costs. Slippery sidewalks can be hazardous also among tourists coming from places where they rarely, if ever, encounter snow, being thus unfamiliar and unprepared to face the Nordic winter environment (Lépy *et al.*, 2016). In national risk and weather and climate risk assessments, wintertime pedestrian slipping injuries were recognized as a significant health risk in Finland (Tuomenvirta *et al.*, 2018; MoI, 2019).

Northern high latitude countries have a distinct winter season or at least shorter cold periods with ice and snow. In Finland, the winter season is quite long, about 6 months, depending on the geological area. During this time ice and snow may exist on the ground, and the temperature is below or near 0°C. Coastal areas (about 10–20 km from the sea) may be substantially warmer and more humid than the inner part of the mainland (Pentti and Rovaniemi, 1994). Wintry conditions cause slipperiness and raise the risk of slip and fall among the people.

There is an evident causal relation between weather and pedestrians' slip injuries. People can slip or fall throughout the year, but there is a clear seasonal variation; in wintertime the falls are more frequent and injuries more serious than during summertime. For instance, the number of fall related distal radius fractures is 2.5 times higher on slippery winter days compared to non-winter days (Flinkkilä *et al.*, 2011). Similarly, a Russian study found that non-fatal accidental outdoor fall injuries were 1.7 times higher in the cold season compared to the warm season (Unguryanu *et al.*, 2020). During winter, there are typically 5–20 days when the sidewalk conditions are very slippery with the number of slip injuries much higher than on average. Consequently, the workload in emergency rooms increases, especially due to leg and hand fractures. Previous studies have revealed that the number of slip injuries increases when the daily average temperature is slightly below 0°C, temperature crosses 0°C and/or there is precipitation in some form (Eskelinen, 1999).

When the significance of slipping injuries as a national health risk was realized, it was suggested that, with the help of a special weather service for pedestrians including warnings of slippery sidewalk conditions, the number of slipping injuries might be reduced (MTCF, 2005). During the winter 1998–1999, the Finnish Meteorological Institute (FMI) started a pilot service to warn pedestrians about slippery sidewalk conditions in the Helsinki metropolitan area. Later, starting from 2004, the service was expanded to cover the whole of Finland (Ruuhela *et al.*, 2005). Evaluation of the service clearly indicated a need for new tools and education for forecasters as well as for further research on the dependence between slipping injuries and weather conditions.

In addition to the FMI, SVA-Konsultointi supplies warnings about slippery sidewalk conditions for several cities in Finland (http://liukastumisvaroitus.fi/index.php/en/home; Bezemer, 2014). This service is based on observations. Worldwide, also, a couple of cities in other countries are, or have been, providing warnings of slippery sidewalk conditions for citizens. The city of Winnipeg launched a fall alert notification system to prevent wintertime falls in 2012 (Sylvestre, 2016). The service, called SureFoot, rated sidewalk condition into four classes from easy to hazardous. Another city with an information system for citizens about slippery sidewalk conditions is Sapporo in Japan. The service, called Walk Smart, provides tips for safe walking on snowy and icy roads as well as sidewalk slipperiness forecasts on the webpage http://www.tsurutsuru.jp/english/index_e.html (Kawamura *et al.*, 2019). The service has been running since 2006 and it evaluates the expected slipperiness into three classes: "not slippery," "slippery" and "extremely slippery."

At the FMI, a road weather model RoadSurf has been developed to predict the road surface temperature, road condition and traffic index on roads (Kangas *et al.*, 2015). As a tool for pedestrian warning, it has been further developed to predict the level of slipperiness on pedestrian sidewalks. Assisted by the modelled and forecasted slipperiness, FMI is issuing warnings when very slippery pedestrian sidewalk conditions are expected. The main aim of the present paper is to provide information on the RoadSurf-Pedestrian sidewalk condition model and its physical details with some examples of model runs. Furthermore, the needs for a targeted weather service for pedestrians and use of the model in an operational pedestrian warning service are discussed. Information about slipperiness and slipping injuries is also introduced as background information for the study.

2 | SLIPPERINESS AND SLIPPING INJURIES

2.1 | Slipperiness and friction

In this study, slipperiness means the friction, or grip, between surface and shoe sole. Physically, the friction coefficient is the ratio of the force required to move one surface over another to the total force pressing the two surfaces together (Weast, 1971). The friction coefficient C_f is defined as the ratio of the horizontal friction force F_μ to the vertical (normal) force F_n (Aschan *et al.*, 2005):

$$C_f = F_\mu / F_n = (ma)/(mg) = a/g \quad (1)$$

where m is the mass, a the acceleration and g the acceleration due to gravity. There are two types of friction coefficients: the coefficient of static friction is the ratio of the maximum static friction force between the surfaces in contact before movement commences, and the coefficient of kinetic friction is the ratio of the kinetic friction force between the surfaces in contact during movement.

Friction is a dimensionless coefficient which varies from 0 to 1, surfaces with lower values being more slippery than those with higher values, as presented in Table 1 (Grönqvist, 1995). Bare and dry asphalt has a good grip; water on the surface reduces friction a bit, snow and ice more. Most slippery sidewalk conditions during the winter develop when the temperature varies around 0°C, with melting and freezing cycles forming smooth icy surfaces, thus increasing the risk of slipping (Jylhä *et al.*, 2009). Walking can be assumed to be safe if the friction coefficient is 0.2 or more (Ruuhela *et al.*, 2005). In the case of running or when carrying load, a higher friction value is required.

Friction can be measured or estimated using several different instruments and methods. One type is a mechanical device based on braking and deceleration (Wallman and Åström, 2001) or on rotation of wheels (Malmivuo, 2016). Another type is an optical sensor that estimates the surface friction based on measured water/snow/ice layer information using spectroscopic measuring principles (Bridge, 2008; Vaisala, 2017). In addition to measuring devices, there are numerical models that use meteorological information (Juga *et al.*, 2012) or neural networks and historical friction data (Pu *et al.*, 2019) to predict the road surface friction. The sensors and devices listed above have been developed to measure or estimate the friction between the road surface and vehicle tyre (Aschan *et al.*, 2004). Unfortunately, most devices are not suitable for assessing slipperiness from the pedestrians' point of view due to the fact that the parameters used differ too much from human biomechanical parameters (Chang *et al.*, 2001a; 2001b). At present, there are no devices available that could measure operationally the slipperiness of sidewalks (Hippi, 2012).

The Finnish Institute of Health has developed a special portable slip simulator to measure the friction between road surface and shoe sole (Aschan *et al.*, 2004; 2005). The portable slipmeter simulates stepping using the known force and step movement with different shoes attached to it. As a result, the instrument gives information about the prevailing friction between the shoe sole and the surface. The grip of the shoe is influenced by several sole properties, like sole material, hardness, roughness, wear, tread (geometry) design, centre of gravity and anti-slip devices (Grönqvist *et al.*, 2001). The slipmeter gives a reliable estimate of the prevailing friction, but the device is intended for case studies and not for operational sidewalk slipperiness monitoring (Hippi, 2012).

TABLE 1 The connection between the coefficient of kinetic friction and subjective evaluations (Grönqvist, 1995)

Class	Explanation	Coefficient of kinetic friction
1	Very slip-resistant	≥0.30
2	Slip-resistant	0.20–0.29
3	Unsure	0.15–0.19
4	Slippery	0.05–0.14
5	Very slippery	<0.05

2.2 | Data and statistics on slipping injuries

There are no complete statistics available about slip and fall accidents or injuries in Finland. There do exist some sources, however, from which slipping and falling accident and injury statistics can be collected, like the Finnish care register, ambulance transport, injury claim data or the injury databases of individual companies (Karlsson, 2013; Hippi *et al.*, 2017). Accidents and injuries occurring to pedestrians and cyclists are typically single accidents (thus, without a collision with another party) and are not included in traffic accident statistics (Utriainen, 2020). Single accidents of these vulnerable road users are highly underreported (Airaksinen, 2018).

Slipping and falling injuries occur both indoors and outdoors throughout the year. In Finland, about 70,000 people are injured annually due to slipping or falling outdoors leading to serious consequences (Vuoriainen *et al.*, 2000). Two-thirds of these injuries occur when the surface is covered by ice or snow (Grönqvist, 1995), which means about 50,000 slipping injuries during wintertime affecting about 1% of the Finnish population.

Slips and falls occur on icy, snowy, slushy or frosty surfaces for both outdoor workers and the general public (Gao and Abeysekera, 2004). The winter months from November to March cover about 70% of the annual slipping and falling injuries, as will be presented later in the present study. The importance of choosing the right footwear is emphasized in slippery weather conditions. In very slippery sidewalk conditions, it is difficult to achieve adequate grip with footwear using a conventional sole structure. Therefore, in such conditions, it would be a good idea to use anti-slip devices or stud shoes (Hippi *et al.*, 2017).

Slipping injuries can occur for everybody regardless of age and young people tend to slip more often than older people (Figure 1), but people between the ages of 35 and 65 are the ones who are most often injured and need medical attention (Figure 2) (Rantala and Pöysti, 2015). Slipping injuries are most harmful for elderly people because they may easily get hip or other fractures, and the consequences of the injuries are often more severe than among young people. Women over 50 years have the highest risk to slip and hurt themselves (Björnstig *et al.*, 1997; Vuoriainen *et al.*, 2000). According to a Swedish study, hospital stays caused by slipping are, on average, longer than for road traffic accidents (Björnstig *et al.*, 1997).

Slips and falls often occur in familiar places, like on a sidewalk, outdoor path, courtyard or in parking places (Vuoriainen *et al.*, 2000; Hautala and Leviäkangas, 2007; Rantala and Pöysti, 2015). Quite often slipping occurs as an unexpected sudden loss of grip when unexpected slipperiness is encountered (Grönqvist *et al.*, 2001).

According to Pilli-Sihvola *et al.* (2019) the overall cost of slipping injuries is difficult to assess, as the injuries are not systematically recorded. In order to establish the overall harm, the patients and their recovery should be monitored for a long time after the incident. Assessing the decrease in work productivity is difficult, and various estimates are used in assessing the costs of lost well-being. Based on assessments used in the health sector, the annual direct and indirect costs amount to €420 million at national level (Vuoriainen *et al.*, 2000). On the other hand, using the traffic sector's figures, the same number of slipping injuries results in annual direct and indirect costs of €2.4 billion, including the costs of medical care (∼€800 per fall), loss of work input (∼€1,400 per fall) and reduced well-being (∼€46,600 per fall) (Hautala and Leviäkangas, 2007). As can be seen, the major cost factor in this analysis is reduced well-being, accounting for about 95% of the total costs.

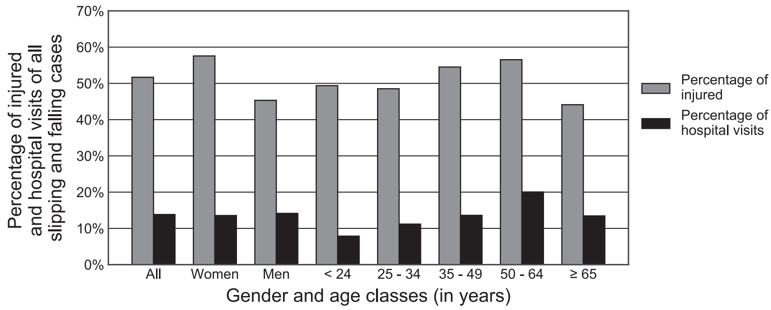
2.3 | Commuting accidents

Most commuting accidents occur to pedestrians. In 2018, 57% of commuting accidents compensated to employees occurred to pedestrians, 23% to cyclists and 16% to car drivers or passengers (TVK, 2018). The driver or passenger of a car is interpreted as a pedestrian in the case of slipping or falling after leaving the car. 33% of commuting accidents occurred to men and 67% to women. According to surveys, women use cars less than men while commuting, which affects their risk of accidents (TVK, 2018).

In the present study, the slipping injury data in the Uusimaa region and in the whole of Finland in 2005–2018 obtained from the Finnish Workers' Compensation Center (TVK) was used as an indicator for slippery conditions on sidewalks due to weather. The TVK coordinates the practical application of workers' compensation. In Finland, the employers are obliged to insure their employees against work related accidents and injuries. The analysed data include injuries that have occurred while commuting and for which the insurance company has paid compensation from the occupational accident insurance. The TVK's injury data are based on self-reported crashes that have been handled by the insurance companies, which have paid the compensation. Injury

FIGURE 1 Share of people having slipped during 12 months by different gender and age classes based on a survey made by the Finnish Road Safety Council. Number of answers 1,656 (Rantala and Pöysti, 2015). See also Figure 2

FIGURE 2 Share of injured and those who needed hospital visits as a result of slipping and falling during 12 months by different gender and age classes based on a survey made by the Finnish Road Safety Council. Number of answers 644 (Rantala and Pöysti, 2015). See also Figure 1



descriptions have been written by the injured person, the supervisor, another employee or the claims handler in the insurance company (Utriainen, 2020). In this paper, a single-pedestrian injury is determined as an event when a pedestrian has slipped, fallen or stumbled. Henceforth, slipping includes fallings and stumblings when examining TVK's slipping, falling and stumbling injuries.

Figure 3a presents daily numbers of slipping injuries on the way from home to work or vice versa in the Uusimaa region in 2010, based on TVK's data, and Figure 3b shows the daily average air temperature measured at Helsinki Kumpula weather station. The Uusimaa region and Helsinki are presented on the map in Figure 4a,b. To get a more accurate estimation of the slippery days, some corrections have been made to TVK's data (Karlsson, 2013). First, there is a clear day-of-the-week effect in the number of slipping injuries data because most people do not work and commute during weekends. The day-of-the-week effect is controlled by multiplying the number of slip injuries for each day by the weekday correction coefficient (Table 2). Second, since this study only concerns the injuries that occurred due to slippery sidewalk conditions, the injuries that occurred for other reasons are eliminated statistically. This is done by subtracting the average summertime (from May to October) daily injury amount (6.4) from all daily injury values. Occasional negative values produced by this correction method are set to zero. The temperature in Figure 3b is for Helsinki, but it serves as a good assumption for exposure because the population of Uusimaa is concentrated in Helsinki and especially the Helsinki metropolitan area.

The winter season, when the temperature is mainly below 0°C (blue background colour), can be clearly distinguished in Figure 3 with the number of daily slipping injuries being typically higher compared to the summer season (green background colour). There are 15–20 days each winter when the number of injuries is clearly higher than normal. The peak day of pedestrians' slipping injuries is determined as a day when the number of

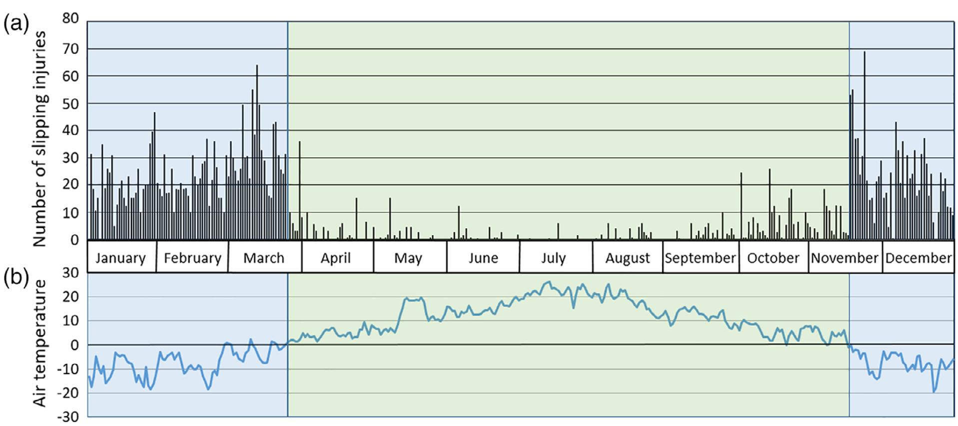


FIGURE 3 (a) Daily number of pedestrian slipping injuries on the way from home to work or vice versa in the Uusimaa region between January 1, 2010, and December 31, 2010. (b) Daily average air temperature observed in Helsinki Kumpula weather station in the same time period. Source of data: Finnish Workers' Compensation Center (a), Finnish Meteorological Institute (b)

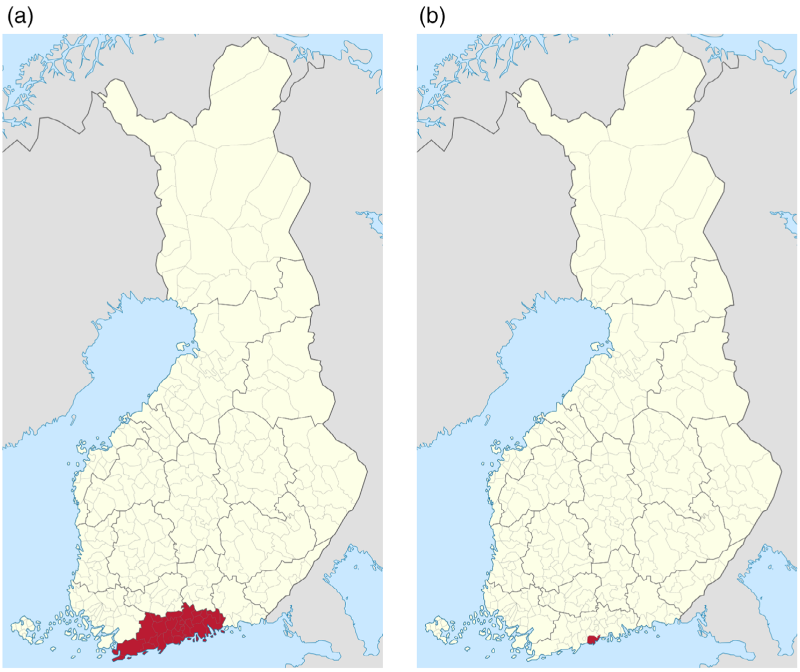


FIGURE 4 Map of Finland, with the Uusimaa region marked as red (a) and the city of Helsinki marked as red (b) (Wikipedia, 2020a; 2020b)

TABLE 2 The correction coefficients for daily injury amounts when using the Finnish Workers' Compensation Center data for each weekday in 2010 (Karlsson, 2013)

Weekday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Coefficient	0.6	0.8	0.8	0.9	0.9	5.4	6.2

slipping injuries exceeds the threshold of the number with probability less than 0.01% in a Poisson distribution (Penttinen *et al.*, 1998; Ruuhela *et al.*, 2005). It can be assumed that the peak days are those with very slippery sidewalks.

According to TVK's statistics there is a clear seasonality in the data, and the winter months from November to March cover 70% of the yearly slips (Figure 5). Summer months from June to August are underrepresented in TVK's data due to the summer holiday season. There is also a substantial interannual variation in the injuries, as can be seen in Figure 6. This variation between the years is strongly related to slipperiness conditions during the years (TVK, 2018).

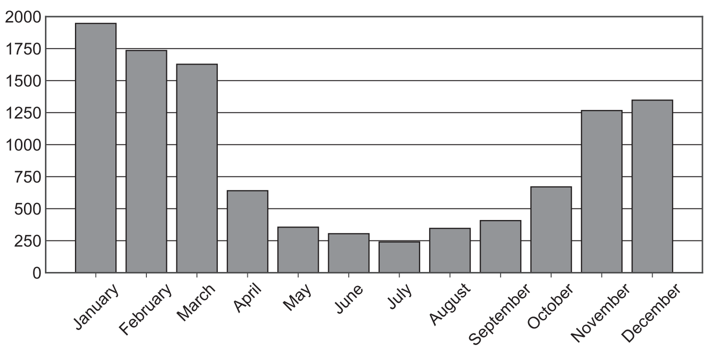


FIGURE 5 The number of average monthly commuting accidents when the injured were walking. Data cover the whole of Finland, years 2005–2018 (TVK, 2020)

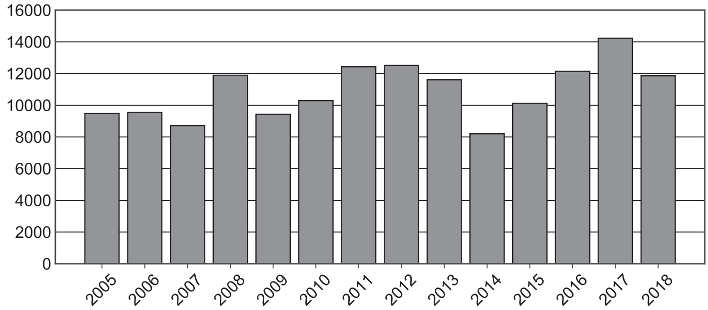


FIGURE 6 The number of yearly commuting accidents when the injured were walking. Data cover the whole of Finland, years 2005–2018 (TVK, 2020)

3 | MODEL DESCRIPTION AND WEATHER WARNINGS

3.1 | Road weather model RoadSurf

At the FMI, a road weather model RoadSurf has been developed (Kangas *et al.*, 2015). Starting from 2000, RoadSurf has been used operationally to produce road weather forecasts and warnings for the Finnish road network. From 2004, an enhanced version of the model has been used to produce adverse weather warnings also for pedestrians on sidewalks (Ruuhela *et al.*, 2005).

RoadSurf is a 1D energy balance model that calculates vertical heat transfer in the ground and at the ground–atmosphere interface, taking into account the special conditions prevailing at road or sidewalk surface. The effect of traffic is also accounted for. In order to quantify the hydrological state of the surface, the surface layer parameterization includes hydrological processes, such as accumulation of rain and snow, run-off of surface water, sublimation, freezing, melting and evaporation.

Depending on the nature of the surface, the model can be run in different modes, the main modes being car traffic and pedestrian sidewalk condition modes. A special mode for providing road surface maintenance advice has also been developed.

In all modes, in addition to calculating ground and surface temperature, RoadSurf makes a surface condition interpretation, describing the surface status using eight classes:

- dry
- damp
- wet
- frost (deposit)
- dry snow
- wet snow
- partly icy
- icy

The "partly icy" case means conditions in which only part of the surface, for example lanes with less traffic, is covered by ice. In this case the model also makes a secondary surface condition interpretation, which describes the surface in places where no ice is present. Similarly, the secondary surface condition class is used in cases with snow or water on top of ice.

The surface condition interpretation is based on various storage terms, which describe the amount of water, snow, ice and frost (deposit) on the surface. The model constantly tracks changes in the storages caused by melting, freezing, evaporation, condensation and mechanical wear. The storages may also interact with each other; for example, the size of the water storage is increased by precipitation as well as by melting of snow or ice.

RoadSurf also makes an overall classification describing the surface conditions in more general terms, telling whether the driving or walking conditions are normal or hazardous. This is done by combining the information about surface class with certain weather parameters (Kangas *et al.*, 2015). This process is mode dependent, as for example difficult conditions for car traffic are not necessarily difficult for pedestrians, and vice versa (Ruuhela *et al.*, 2005). A different classification is thus used in different RoadSurf modes (hereafter called RoadSurf-Traffic and RoadSurf-Pedestrian).

As input, output from a numerical weather forecast prediction model, either directly or with duty meteorologist's corrections, is used as a forcing at the upper boundary in RoadSurf. This input also provides the horizontal coupling between individual points. The input variables include:

- ambient temperature
- relative humidity or dew point
- wind speed
- short wave solar radiation
- long wave solar radiation
- precipitation
- precipitation phase (optional)

The values of these variables can be taken from observations or from a forecast; the model does not make any distinction as to the source of the data. This makes it possible to run RoadSurf also for climatological research purposes. An additional forcing at the surface is the traffic, which causes not only increased turbulence (in the case of car traffic) but also mechanical wear of, for example, snow, ice or frost that is present on the surface. The details of the traffic influence are run mode dependent.

At the lower boundary, sinusoidally varying climatological ground temperature is used as the boundary condition.

Starting from the forcing variables, the heat balance at the ground surface is then solved, taking into account such factors as sensible and latent heat flux as well as atmospheric stability. The effect of melting or freezing is also included in the energy balance. A more detailed description can be found in Kangas *et al*. (2015). Surface friction is also calculated using a statistical friction model that is based on observations from four Finnish road weather stations (Hippi *et al*., 2010; Juga *et al*., 2012).

As output, the model produces

- road (sidewalk) surface temperature,
- road (sidewalk) condition (primary and secondary),
- traffic (pedestrian) index,
- storage terms (amounts of water, ice, snow and frost on the surface),
- road surface friction (RoadSurf-Traffic only),

both in plain ASCII format and as a binary file for the GrADS (Grid Analysis and Display System) visualization program. The plain ASCII files can be used for further postprocessing, whereas GrADS is used to produce special graphical web pages.

In operational use, the initial state for the forecast is produced by running the model first for a few days using observations (initialization phase) and then continuing directly to forecast by changing the input from observations to forecast.

3.2 | Pedestrians' sidewalk condition model

The pedestrian sidewalk condition model (RoadSurf-Pedestrian) that is used to predict the level of slipperiness on the pedestrian sidewalk is physically the same as the RoadSurf-Traffic for car traffic, and is included as a separate mode in the same RoadSurf code base. The same data input is used in both modes. However, there are four main differences between RoadSurf-Traffic and RoadSurf-Pedestrian modes:

1. Traffic (pedestrians *versus* cars) and its effect on the road surface and storages are much lighter in RoadSurf-Pedestrian than in RoadSurf-Traffic.
2. Warning classification: circumstances producing hazardous conditions are not the same for car traffic and pedestrians.
3. Initialization phase: 96 hr in RoadSurf-Pedestrian *versus* 48 hr in RoadSurf-Traffic.
4. Because there is no information about the real initial state of the sidewalk surface conditions, two optional versions of the pedestrian forecasts are calculated, starting from different initial states: one with a layer of ice (30 mm) and another with no ice. Based on the expert judgement on the prevailing slipperiness situation, a user (meteorologist on duty) chooses the better initial state and thus the forecast version. Typically, during the winter season when there is snow and ice on the ground the initial state with ice is suitable, whereas in autumn or early winter it is better to use the model run with no ice.

The model predicts the expected sidewalk status taking into account the past (initialization phase) and the forecasted weather. The model calculates a slipperiness index and classifies the level of slipperiness on the sidewalks into three classes: normal, slippery and very slippery. During very slippery sidewalk conditions, normal walking is challenging for everyone and extra care must be taken when walking.

The most slippery cases for pedestrians with low friction occur when there is dry, loose snow or a thin water layer on an icy surface. The layer of water on ice may originate directly from rain or from melted ice or snow on and around the sidewalk. Snow on the icy surface can be hazardous, because pedestrians do not necessarily notice the ice below the snow. In certain circumstances, foot-packed (compressed) snow as well as freezing conditions can result in a very slippery surface.

Slipperiness categorization in the RoadSurf-Pedestrian has six different indices and three different warning classes:

1. No slipperiness → normal sidewalk condition
2. Slippery → typical normal winter weather when slipperiness may occur here and there
3. Foot-packed snow → very slippery and warning is suggested by the model
4. Freezing → very slippery and warning is suggested by the model
5. Snow above ice layer → very slippery and warning is suggested by the model
6. Water above ice layer → very slippery and warning is suggested by the model

The slipperiness index and slipperiness classification have been developed using slipping injury data gathered from different sources. Weather conditions especially on peak days of the slipping injuries have been analysed in detail and the reasons for the slipperiness have been examined. There have also been several measurement campaigns in cooperation with the Finnish Institute of Occupational Health, and their slipmeter observations have been used in the model development (Ruotsalainen *et al*., 2004). Then, using all the collected slip injury data, slip measurement and weather observation data, an empirical deduction chain leading from weather parameters, surface condition and surface temperature to slipperiness index has been developed for the model. The deduction chain is based strongly on storages, precipitation and temperature values. Previous weather up to 3–4 days back often has a strong impact on prevailing and upcoming slipperiness, and has been accounted for in the model. Non-meteorological factors, such as sidewalk maintenance practices and local small scale conditions, are not included in the model and may induce incorrect results. The RoadSurf-Pedestrian expects open areas and it does not take into account, for example, surrounding trees or buildings obscuring radiation, which can play a crucial role affecting the surface temperature especially within urban areas. The volume of pedestrians causing wearing and interacting with the storages is assumed to be constant everywhere. The model warns about slipperiness if it is predicted to occur generally and widely. Slipperiness may occur locally (e.g. frozen puddles) also when the model does not give information about slipperiness.

The numerical model is a tool for meteorologists when determining the need for warnings about slippery sidewalk conditions during wintertime. RoadSurf-Pedestrian is running operationally once an hour alternating between two different initialization states (ice and no ice). For the meteorologists, colour coded maps of the pedestrian index are provided (Figure 7). Furthermore, meteograms including different weather parameters and pedestrian index are available for 27 pre-defined locations around Finland. Meteograms also include a 4 day history to help the meteorologist get a better picture of the weather development leading to the prevailing and upcoming slipperiness.

3.3 | FMI weather warnings

The FMI's Weather and Safety Centre produces weather services important to public safety. The operational Weather and Safety Centre is run 24/7/365. Its key services are to provide nationwide 10 day weather forecasts as well as weather or weather related warnings up to 5 days ahead. The warnings are routinely updated every 3 hr and, if necessary, updated also at other times.

Figure 8 gives an example of a weather warning map provided by the FMI. Up-to-date warning maps are

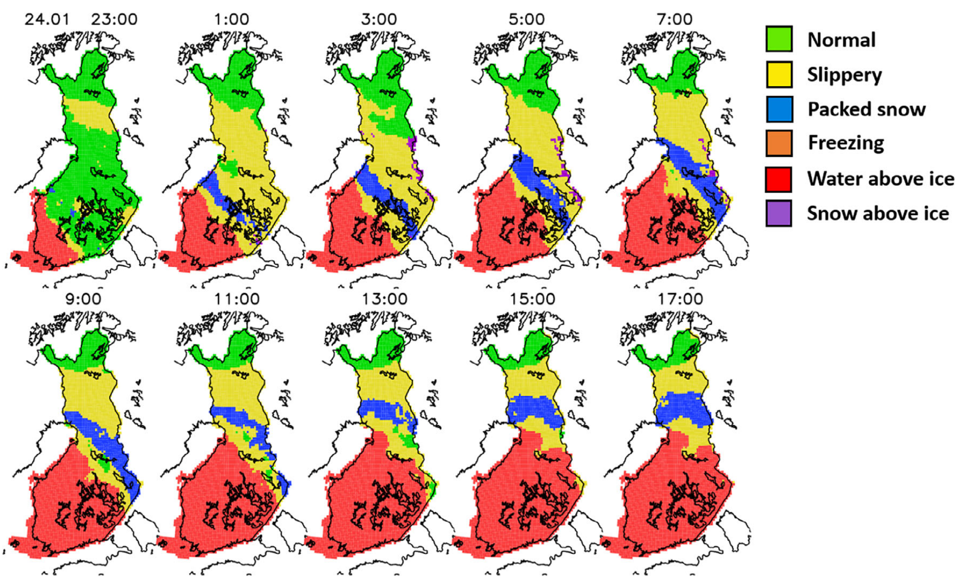


FIGURE 7 An example of the pedestrian slipperiness index produced by RoadSurf-Pedestrian, visualized by the Grid Analysis and Display System

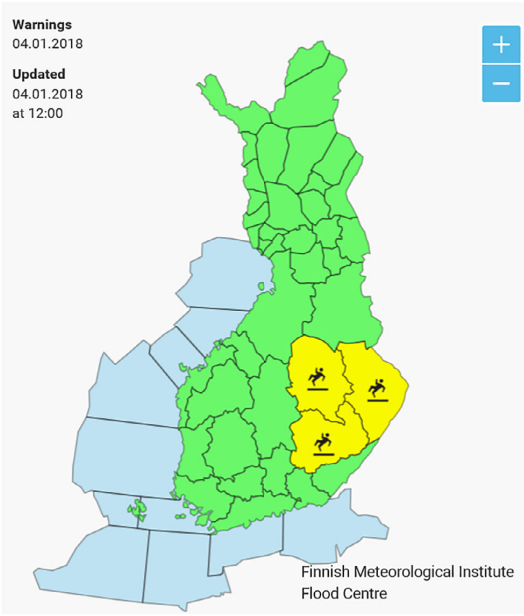


FIGURE 8 An example of a weather warning map provided by Finnish Meteorological Institute. Warning about slippery sidewalk conditions is issued to the eastern regions in Finland

available online on the FMI's internet site and on the FMI's weather application on mobile phones. Yle, the Finnish Broadcasting Company, presents the warnings issued by the FMI in their weather forecasts on TV and radio. Warnings are issued, for example, when heavy rain, strong wind, cold or heat waves, or hazardous driving or slippery sidewalk conditions are to be expected. Warnings are issued to targeted regions (sea areas, regions or municipalities in Lapland); nowadays, also freely defined areas determined by duty meteorologists can be used. The severity of the awareness level is shown by a colour-coded map to represent four levels of warning: red to indicate exceptional risk from hazardous weather conditions, down through orange and yellow to green, indicating that severe weather is not expected. The level of awareness is the same as that provided by the European Meteorological Network at the MeteoAlarm website (www.meteoalarm.eu/) which gives information on potential meteorological risk and awareness over the European geographical domain.

One of the FMI warnings is the slipperiness level on pedestrian sidewalks. Meteorologists decide about warnings by combining available weather observations and forecasts and using their own expert judgement and knowhow. The warning specifies the cause and duration of slippery conditions. During the winter, there are typically 5–20 days per region when slippery sidewalk warnings are issued. In these circumstances, extra care should be exercised when walking by carefully choosing footwear and using slip guards, if possible. In addition to the FMI's warning map, slipperiness warnings can be delivered via SMS or different online services. For example, cities and companies can also purchase tailored services and inform their citizens or employees about slippery sidewalk conditions (Hippi *et al*., 2017).

One criterion for issuing warnings is that slipperiness should occur generally and widely in the region. In practice, it is not possible to issue warnings with very high spatial resolution, and locally slipperiness may thus occur also when no warning has been issued. In the beginning of the winter season, the threshold for issuing the warnings is kept somewhat lower, because people tend to have difficulties in adapting even to milder slippery conditions after the summer season.

4 | MODEL VERIFICATION EXAMPLES

For verification purposes, the slipperiness index produced by the RoadSurf-Pedestrian model and the warnings issued were compared to slip injury statistics which were collected from commuting accidents by the TVK. Section 4.1 presents the reported daily number of slipping injuries compared to the modelled pedestrian index and warnings as well as to some modelled and observed weather parameters for winter 2011–2012 in the Uusimaa region. Section 4.2 presents a case study with a model run for one very hazardous day for pedestrians, February 20, 2017, with a high amount of slipping injuries based on TVK's slip injury data.

4.1 | Winter season 2011–2012

The RoadSurf-Pedestrian model was run for the winter season 2011–2012 from November to April for the Uusimaa region. Winter 2011–2012 was chosen for the verification case because it was very challenging due to the high amount of snow, and the Uusimaa region covers about 30% of the Finnish population. Meteorological observations were used as input data, so the uncertainty of the forecast data was eliminated from the results. Observations were obtained from a 10 km × 10 km grid, and the closest grid point was selected to obtain the data. Solar radiation measurements were not available and they were obtained from a numerical weather prediction model, using data from the closest grid point in the operational grid. The injury statistics were from the Uusimaa region but weather observations were from Helsinki Kumpula weather station and modelled data were the closest point from Helsinki, Kumpula.

Figure 9 presents the results for the verification with weather observations, modelled data, issued warnings about very slippery sidewalks and slipping injury statistics. The figure consists of four panels (a)–(d). Panel (a) presents modelled hourly road surface temperature (T_surf), observed daily maximum temperature (T_max) and observed daily minimum temperature (T_min). Panel (b) presents daily snow cover measured daily at 6000 UTC and daily precipitation amount. Panel (c) shows modelled pedestrian index value (1–6; see the definitions of the values in Section 3.2) as red columns (PedIdx) and issued warnings as blue markers (Warning). Finally, panel (d) shows the daily numbers of slipping and falling injuries from the Uusimaa region. TVK's injury data were corrected as in Section 2.3. The red horizontal line shows the peak day limit for slipping injuries (36). It was defined using a Poisson distribution when the number of injuries exceeds the number with probability 0.01.

The beginning of the winter season in November and December was quite mild; temperature dropped only occasionally below 0°C. However, there are quite a few false alarms of hazardous slipperiness during November and December when the pedestrian index (PedIdx) gets values of 3, 4, 5 or 6 but the slipping injury columns are relatively low. The snowy season started at the beginning of January when the first high columns can be seen in the slipping injury data; also the model indicates slipperiness and a couple of warnings have been issued. In the middle of January it was snowing for many days and the snow cover quickly reached 40 cm. Lots of injuries occurred during those days with snowfall; also the model gives slippery conditions and several warnings were issued by the duty forecaster. From the end of January until the middle of February, when there was a real winter season with temperature continuously below 0°C, slipperiness did not occur and the number of injuries was quite low. After that, in the second half of February, there were a couple of very snowy days; warnings were issued and suggested by the model. Starting from the end of February, the temperature was around 0°C and slippery conditions existed every now and then. In March the temperature varied around 0°C and snow melted quite fast, and also short wave radiation became effective causing a large variation in the road surface temperature. At the beginning of April there was a short snowy season and a peak is also evident in the injury data, but no warnings were issued although the model gives information about slipperiness.

The number of peak days (daily injuries ≥36) was 24 in total, which is a rather high number, most probably due to the very snowy winter season. As can be seen from Figure 9, the model overestimates slipperiness; on the other hand, there are also days with lots of slipping injuries with no indication of slipperiness predicted by the model. In contrast, the number of issued warnings (13) is lower than the number of peak days and the issued warnings are not always the same as the detected peak days of slipping injuries. This illustrates the challenge of

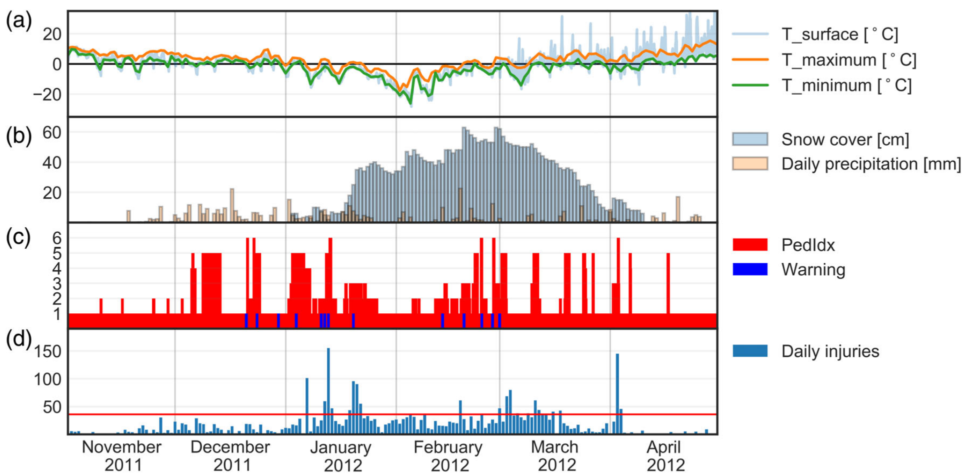


FIGURE 9 Model verification case for Helsinki/Uusimaa for winter 2011–2012. Weather observations (T_maximum, T_minumum, snow cover and daily precipitation), modelled data (T_surface, PedIdx is the pedestrian index), issued warnings and daily pedestrian slipping injuries based on the Finnish Workers' Compensation Center data. More detailed information about panels (a)–(d) can be found in the text

modelling and predicting slipperiness. Duty forecasters should find a balance when giving warnings. Warnings should be issued always when hazardous sidewalk conditions are expected, but too many warnings when slipperiness does not occur can decrease the value of the information.

Table 3 presents the hits and false alarms for the winter 2011–2012 data. The daily slipping injury data were divided into three categories using a Poisson distribution:

- Peak days of slipping injuries, when the number of daily slips is equal to or greater than 36 ($p < .01$).
- Potential peak days of slipping injuries, when the number of daily slips is equal to or greater than 28 but less than 36 ($0.1 < p \leq .01$).
- Days that are not peak days or the potential of peak days of slipping injuries ($p \geq .1$).

Slipping injury categories were compared to issued warning data (on/off) and modelled pedestrian index data (warning suggested on/off). In this study a warning was suggested by the model if a PedIdx value of 3–6 exists for 6 hr or more per day. The results show that the modelled data correlate better with the peak days of slipping injuries than with issued warnings. On the other hand, the modelled data give more false alarms on non-slippery days than warnings that were issued.

One must bear in mind that the RoadSurf model has not been developed for this kind of long run for one point so the results are more or less indicative. The parameter development (especially storages) during the long run may be problematic and is not working quite properly. Also, weather observations and modelled data are in this case from Helsinki which is not always a good assumption because the slipping statistics cover the whole Uusimaa region. Furthermore, a point forecast, although being a reasonable approximation of the region, gives limited information about the situation in the whole area.

4.2 | Case study February 20, 2017

According to TVK's data February 20, 2017, was the most slippery and hazardous day for pedestrians during 2017, especially in the southern and western parts of Finland. A total of 921 pedestrian slipping injuries occurred on that day for the whole of Finland (485 in the Uusimaa region), whereas the average daily value for slipping injuries for the winter months from November 2016 to April 2017 in the whole of Finland was 66.9 (28.3 in the Uusimaa region). Nine hundred and twenty-one pedestrian slipping injuries per day is a very high number, the highest number per day typically being between 200 and 450 per winter except for November 24, 2008, when the number of slipping injuries was slightly over 1,000.

Figure 10 presents the weather development during February 18–20, 2017. On the first few days, February 18–19, 2017, the weather was quite mild in the southern and western parts of Finland, air temperature was between 0°C and 5°C, there was a small amount of precipitation in different forms in many places, and snow cover was 0–10 cm. In the eastern and northern parts of Finland the temperature was lower and there was more snow on the ground. On February 20 the temperature started to drop due to a cold front pass and surfaces froze. Also, there was light snowfall on February 20 so surfaces turned very slippery, not only due to freezing but also because of snowfall.

RoadSurf-Pedestrian was run the way it is used operatively. There was a 96 hr long initialization phase and after that a 48 hr long forecast part. The visualization reproduces the slipperiness forecast the way the duty forecaster would have seen it on the previous evening

TABLE 3 Verification for the different peak day definitions (peak day, potential peak day and not a peak day or potential peak day), issued warnings and the warning suggestion by RoadSurf-Pedestrian for the winter season 2011–2012

	Warning on $N = 13$	Warning off $N = 169$	Warning suggested by the model $N = 35$	Warning not suggested by the model $N = 147$
Peak day (injuries ≥ 36) $N = 24$	5	19	10	14
Potential peak day (28 ≤ injuries < 36) $N = 13$	0	13	3	10
Not a peak day or potential peak day (injuries < 28) $N = 145$	8	137	22	123

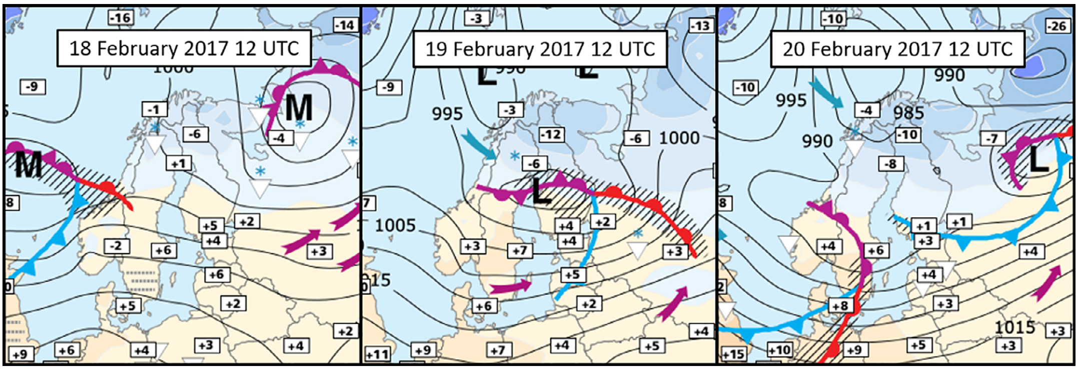


FIGURE 10 Weather development on February 18–20, 2017, based on the Finnish Meteorological Institute (FMI) weather analysis for each day, made by FMI's duty forecaster

(February 19, 2017). The pedestrian index calculated by RoadSurf-Pedestrian for the case starting from the 19 February evening with 2 hr intervals is presented in Figure 11. Different values of the pedestrian index can be seen, revealing that the weather was changing from a melting situation (water on ice and temperature above

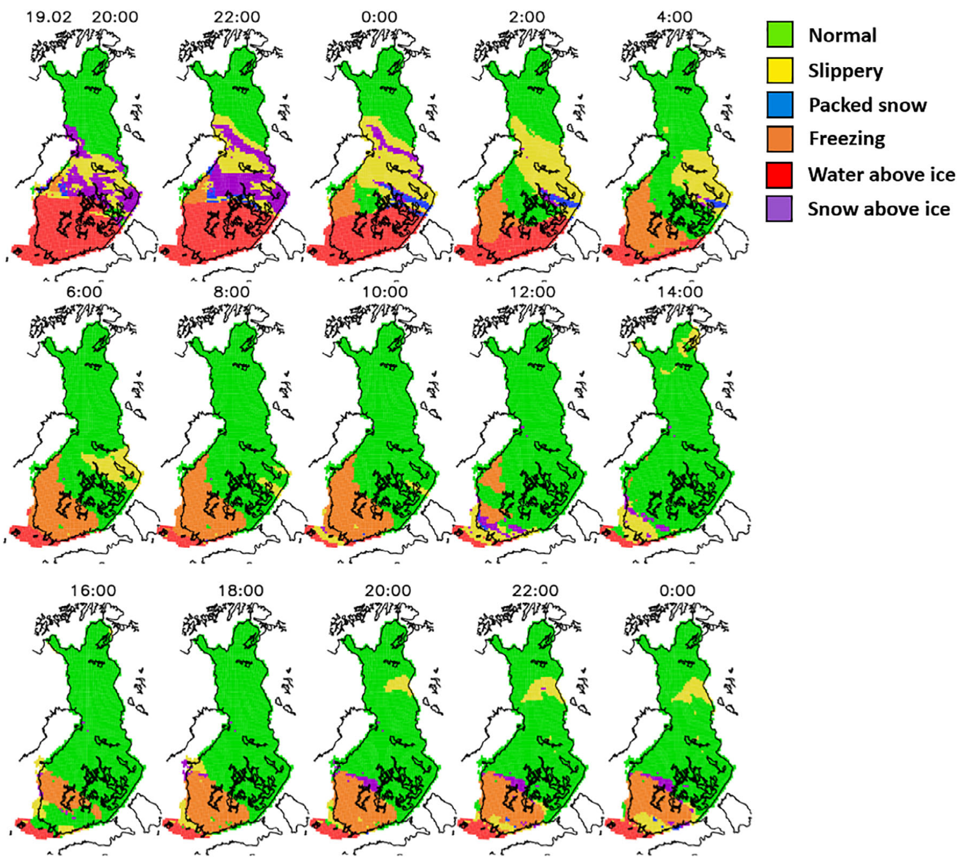


FIGURE 11 Modelled pedestrian index run by RoadSurf-Pedestrian for the February 20, 2017, case

0°C) (red) to freezing temperatures (orange) and light snowfall (violet) with foot-packed snow (blue). On that day a warning was issued to the southern regions of Finland.

5 | DISCUSSION

An operative system to observe the slipperiness on pedestrian sidewalks is lacking, so far. On the Finnish road network, the road weather observation network is quite dense. However, road weather conditions and pedestrian sidewalk conditions are not always the same and there is a need for specific slipperiness observations for sidewalks. Furthermore, severe road weather conditions and slippery sidewalk conditions often occur on different days (Ruuhela *et al.*, 2005). Because of this, road weather observations cannot directly be used to replace pedestrian sidewalk observations. Car traffic typically has problems and there are a lot of accidents in the case of snow due to reduced friction and visibility (Juga *et al.*, 2010). New snow is not necessarily slippery from the pedestrians' point of view. However, if the surface were already icy, even a light snowfall might be hazardous for pedestrians (Penttinen *et al.*, 1998; Anttila, 2001). Also, in certain weather and pedestrian volume conditions new snow may be packed into a slippery layer.

The level of slipperiness on the sidewalks can be detected also by foot and eye. Recent developments in citizen science provide new possibilities to increase the number of observations. The FMI has developed a weather application (FMI Weather app) that is available for mobile phones (Android and iOS) (Karjalainen and Jokinen, 2019). The application includes a tool to report citizen observations (My observations), with slipperiness from a pedestrian's point of view being one of them. Citizen observations are a valuable new source for getting more observations of different weather or weather related phenomena. This has a real impact on the weather forecaster's decision-making when making weather forecasts and issuing weather warnings (Karjalainen and Jokinen, 2019). However, citizen observations need strict quality control procedures to filter out unreliable measurements (Nipen *et al.*, 2019). Another new innovation to determine the risk of slippery sidewalks is the accelerometer on smartphones which can estimate slipperiness based on walking acceleration (Saida *et al.*, 2019). When widely used, it could also provide reliable information on local slipperiness. Real time observations about prevailing slipperiness could give valuable input to improve model development and help decision-making when duty forecasters are issuing warnings about slippery sidewalk conditions.

Elderly people and people with decreased locomotion balance are more fragile for injuries than younger people. Slipping injuries are expected to become more common in Finland in the future as the population is ageing (Statistics Finland, 2018). In contrast to the young, older people have a higher risk of fractures as a result of falls, with slow healing and a high risk of serious consequences (Mänty *et al.*, 2006). In the older age groups, falls and slips are clearly more common for women than for men (Haikonen *et al.*, 2010). The use of anti-slip devices has become more common, especially among some professional groups (e.g. in mail delivery and in rail yard work) and among the elderly and joggers (Juntunen *et al.*, 2005; Vartiainen *et al.*, 2009). In Finland, several cities provide free shoe grips or shoe studdings for elderly residents. It has been said that "Even one fall fewer and this project has paid for itself" if elderly people are kept out of hospitals and helped to avoid fractures (BBC, 2016). This is a good example of an injury protection campaign provided by society.

As a result of global warming the climate will change, and wintertime temperatures are predicted to rise leading to a situation where freezing-point days will become more frequent throughout the whole country (Jylhä *et al.*, 2009). However, in the longer run the winter season in the southern part of Finland is expected to become shorter, which may decrease the number of slip injuries (Saranko, 2019). The importance of the topic will become more important in the future, because walking and cycling are increasing rapidly in several urban areas. There could be collaboration between different countries to exchange methods and results.

6 | CONCLUSIONS

The weather service for pedestrians in Finland is a good example of a service that has been developed for a need identified by decision-makers. Wintertime slipping injuries are common and lead to substantial economic costs to health care and losses to the society due to long sick leaves. In this paper, the service and related slipperiness warnings as well as the RoadSurf-Pedestrian model in its current state, after a gradual development over a period of two decades, have been described. During the development phase, there have been several challenges that still limit the accuracy of the operational modelling and forecasting of pedestrians' sidewalk conditions: lack of slipperiness observations, different rules and practices of sidewalk winter maintenance, and the varying number of pedestrians in different areas. All these can cause big differences in local slipperiness within short distances and make the estimation of slipperiness difficult. As the verifications reveal, there are still some challenges in the modelling of slipperiness but the model already gives now valuable information on slipperiness for the duty forecasters. More complete verification should be done to get information on the limitations and bottlenecks of the model. Verification results would also be beneficial for further model development.

There exists considerable potential to reduce the level of slipping risk and thus decrease economic losses and human suffering. Better awareness of slippery sidewalk conditions can be expected to impact the safety of wintertime walking. Reliable weather and sidewalk condition forecasts can improve pedestrians' road safety by reducing the risk of accidents in several ways. People can choose proper footwear or use of anti-slip devices, choose the route, change the mode of transport, postpone the journey or cancel it altogether. Also, precise and reliable weather and sidewalk condition forecasts enable targeted and more effective sidewalk maintenance activities to improve the grip of sidewalks as well as to reduce the risk of accidents and injuries (Hautala and Leviäkangas, 2007).

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III

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Article

Impact of Weather on Pedestrians' Slip Risk

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Abstract: Pedestrians' slipping injuries are a very typical problem in the Nordic countries, causing varying degrees of injuries and in the worst case, long sick leaves. There is a clear seasonal variation in the number of slips. Sidewalk slipperiness and the risk of slips is a complex combination of weather, winter maintenance activities, number of walkers, and the grip between shoes and surface, as well as human behavioral and physical factors. In this study, the effect of weather on pedestrians' slipping injuries is studied. Daily weather observations are compared to the slip statistics that have been collected from commuting accident statistics in cases where the way of commuting has been walking. A total of 16 cities from Finland for 14 winters are included in this study. The results reveal that snow on the ground increases the slip risk more than three times compared to no-snow situations. Near zero temperatures and precipitation are very typical on days when slip injuries occur more than usual. However, there are also days when high amounts of slips cannot be explained with the weather. The study also shows that there are significant differences as to the number and timing of slips between different parts of the country.

Keywords: pedestrians; weather; road safety; slipperiness; slip; walking; commuting accident

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1. Introduction

The Ministry of Transport and Communications has set a programme to promote sustainable transport modes in Finnish municipalities [1]. The aim is to increase trips made on foot or by bicycle, promote public health, improve traffic safety, and decrease the greenhouse gas emissions from transport as well as emissions harmful to air quality [1,2]. The goal is to replace private motoring with sustainable transport modes, especially in urban areas within short distances [3]. The key idea is to make walking and cycling safe, fluent, and attractive as well as to invest in winter maintenance and infrastructure of sidewalks [3]. Similar sustainable transport promotion plans have been made also in many other countries [4].

Pedestrians' wintertime slipping and falling injuries are a very typical problem for the Nordic society, causing at worst long sick leaves and varying degrees of injuries, like bruises, sprains, and fractures [5–12]. The most common injuries due to falls and slipping are fractures of the wrists and ankles, concussions, and other head injuries [13,14]. However, there seem to be some differences between the age and gender as fractures resulting from slipping among females aged 50 and older seem to be significantly more frequent than among males in the same age range [9]. Slips can be considered a major public health and economic problem [15].

Slips are due to fairly complex causal pathways, involving both environmental and human factors [16]. Sidewalk slipperiness and risk of slips is a combination of weather, winter maintenance activities, number of walkers, and grip between shoes and surface as well as human behavioral and physical factors. Many of these factors are difficult, or even impossible, to consider when studying the slipping risk. Weather is the only factor studied in this article. Other factors can cause uncertainty to the results.

There is a clear seasonal variation in the number of slips, as more slips occur in the wintertime compared to summertime. Weather has a significant effect on the amount of slipping, as snow and ice increase the risk of slipping. Slipping and falling accidents and injuries occurring when there is snow or ice on the ground have been reported in the Nordic and European countries and in Japan [8,12,17–21]. Slips cause congestion for rescue centers and healthcare especially on the most slippery days. The emergency clinics of the hospitals can be crowded, and surgery queues grow due to high slip rates.

Accidents and injuries occurring to pedestrians and cyclists are typically highly underreported as they are often single accidents (thus, without a collision with another party) and are not included in traffic accident statistics [22,23]. This is a problem not only in Finland but also in many other countries [24,25]. No complete statistics about slips and falls exist. However, the information about pedestrians' slip and fall amounts can be estimated from other data sources, like the Finnish care register for Health Care (HILMO), ambulance transport, injury claim data, or from other injury databases of individual companies [26,27].

In Finland, almost every second person slips or falls outdoors annually, and around 70,000 persons (including pedestrians and cyclists) are injured needing medical attention [13]. Slip and fall injuries cause high financial costs each year, with an estimated annual cost of more than 2 billion euros (2006 value) including the costs of medical care, loss of work input and reduced well-being [28]. Reduced well-being is the largest part of the sum covering about 95% of the total costs.

Weather phenomena like freezing, melting, condensation, and precipitation in all forms can cause slipperiness. Slipperiness can also be formed by mechanical ways, when pedestrians or cars compress the snow or plough machines polish the snowy surface into a dense, almost ice-like surface [29,30].

In a previous study [15], three explanatory factors were found for the increased risk of slipping:

1. The daily average temperature was between −2 and 0 °C;
2. The temperature crossed zero degrees during the day;
3. There was at least some precipitation during the day.

Also, a rapid drop in temperature appeared to increase the number of slips.

Finnish Meteorological Institute (FMI) has developed a numerical model, RoadSurf-Pedestrian, that predicts the state of slipperiness on the sidewalks due to weather [30]. FMI also issues warnings for the public in case when very slippery sidewalk conditions are forecasted. RoadSurf-Pedestrian classifies the expected sidewalk slipperiness into three classes: normal, slippery, and very slippery. Very slippery cases are divided into four categories: slipperiness due to packed snow, freezing, snow above ice and water above ice. RoadSurf-Pedestrian is used by meteorologists when issuing the warning of challenging or dangerous sidewalk conditions.

This study presents the temporal and spatial statistics of slip amounts and weather parameters when the daily number of slips is high. Also, the number of injuries on winter days and non-winter days are compared. The slip injury data is based on insurance data covering the injuries occurring to people while commuting. Data is provided by the Finnish Workers' Compensation Center (TVK). A total of 16 cities around Finland are selected for this study. The analyses are performed using the TVK's slip injury data (people on the working age) regardless of age and sex. Weather data is based on daily weather observations of daily temperature (mean, minimum, maximum), precipitation, and snow amount. Time period for the study is between 1 October 2005, and 30 September 2019.

The results of this study yield more detailed information and better understanding about the weather phenomena causing slipperiness and days with a high number of slips and falls. The global warming and its effect on slip risk are speculated as well. The findings can also be used to improve the RoadSurf-Pedestrian sidewalk condition model.

2. Materials and Methods

In the present study, the slipping injury data is analyzed and compared to weather data. This data, obtained from the TVK, is used as an indicator of slippery conditions on sidewalks. TVK coordinates the practical application of workers' compensation. In Finland, the employers are obliged to insure their employees against work related accidents and injuries. The analyzed data include injuries that have occurred while commuting and for which the insurance company has paid compensation from the occupational accident insurance. TVK's injury data are based on self-reported crashes handled by the insurance companies that have paid the compensation [23]. In this paper, a single-pedestrian injury is determined as an event when a pedestrian has slipped, fallen, or stumbled. Henceforth, slipping includes falls and trips when examining the TVK's slipping, falling, and stumbling injuries.

The data includes slips on daily and municipal level; there is no specific information available of the time or area the slip occurred. In this study, TVK's data doesn't include information about the type or severity of the injury or the socio-demographic characteristics of the victims. Even though the TVK's slip injury data doesn't cover all of the slip injuries that occur in Finland, it gives enough information about the daily slip amounts, especially when the daily number of slip injuries have been high. Also, variation on slip amounts between the days can be seen. If the number of the daily slips is high, it is assumed here that the weather will affect slipperiness and slip amounts.

Nine percent of all commuting trips in Finland are made entirely on foot [31]. Walking is more common in bigger cities than in smaller cities [31]. However, all road users are pedestrians at some point of their journey [32], as the driver or passenger of a vehicle is interpreted as a pedestrian in the case of slipping or falling after leaving the vehicle. The slip-related injuries occur typically on the sidewalk, outdoor path, courtyard or in a parking lot [13,28,33]. Slipping occurs often when unexpected sudden loss of grip is encountered [34].

Accidents are typically assumed to be Poisson-distributed as they typically occur randomly and independently [35]. The peak day of pedestrians' slipping injuries is determined as a day when the number of slipping injuries exceeds the threshold of the number with probability less than 0.01% in a Poisson distribution [15,36]. Similarly, a potential peak day with increased risk of slipping is defined with a probability less than 1%. It can be assumed that the slipping risk is higher when sidewalks are slippery due to weather.

The thresholds for a peak day and a potential peak day are defined separately for all cities in this study. Typically, the more citizens with a high number of total slips, the higher the peak day definition threshold. The daily peak day threshold varies between 6 and 25, and potential peak day between 4 and 18, as presented in Table 1. The daily peak day threshold for a specific city is the same for all winter seasons, thus revealing the changes in slip amounts between the years and months. Threshold values are calculated using the total slip amount values for the whole period between 2005 and 2019.

The daily weather observations are studied and compared to the daily slipping injury amounts. Of special interest are days when the number of slipping injuries is high (the so-called peak days of slipping injuries). Weather observations on the days preceding the peak days of slipping injuries are also studied. The focus of this study is to find the weather situations that are dominant and that use to occur when the daily slip amount is high. Mean temperatures, zero crossings, precipitation and snow amount are studied as well as temporal and areal differences. Other factors, like the amount of public transport, the mode of transport while commuting, and the length of the work trip are not considered in this study.

A total of 16 cities have been selected for this study (see Figure 1 and Table 1). According to the TVK's data, the selected cities are among the 16 cities in Finland with the highest yearly slip amounts. In terms of population, the cities are the 15 largest ones in Finland, with Rovaniemi being the 17th largest. Places are located around Finland, thus representing different climatological areas from coastal areas to inland and from south to north. Helsinki, Espoo, Vantaa, Turku, Pori, Vaasa, and Oulu are located in the coastal area and the sea has a strong impact on the weather. Oulu is located further north and due to its northern location, it is colder and there is more sea ice in winter than in other coastal cities. Joensuu and Kuopio are the most continental sites having the longest distance to the sea, whereas Rovaniemi is located in the northernmost and climatologically coldest place. Other cities, Lahti, Kouvola, Hämeenlinna, Tampere, Jyväskylä and Lappeenranta, are located inland.

Table 1. Information of the cities including the number of employees [37], amounts of slips, injury rate in winter, number of days with high slip rate and thresholds for peak day and potential peak day during 2005–2019 based on the TVK's slip injury data.

City	Number of Employees	Total Amount of Slip Injuries	Total Amount of Slip Injuries in Winter	Injuries per Winter (%)	Injury Rate in Winter per 1000 Employees	Number of Days with High Slip Risk	Peak Day/Potential Peak Day Limit
Helsinki	413,677	38,627	30,658	79.4%	5.3	481	25/18
Espoo	126,820	10,376	8635	83.2%	4.9	270	12/8
Vantaa	122,871	10,014	8405	83.9%	4.9	248	12/8
Tampere	126,687	8878	7433	83.7%	4.2	248	11/7
Turku	105,364	8148	6898	84.7%	4.7	245	9/6
Oulu	92,267	5513	4887	88.6%	3.8	156	11/7
Kuopio	53,394	4148	3576	86.2%	4.8	152	8/5
Lahti	51,485	3533	3049	86.3%	4.2	120	7/5
Jyväskylä	64,937	3916	3417	87.3%	3.8	117	8/5
Pori	34,375	2408	2122	88.1%	4.4	109	6/4
Hämeenlinna	28,520	1829	1598	87.4%	4.0	77	6/4
Joensuu	34,321	1943	1738	89.4%	3.6	76	6/4
Kouvola	30,500	1797	1628	90.6%	3.8	72	6/4
Rovaniemi	27,311	1885	1694	89.9%	4.4	65	6/4
Lappeenranta	31,700	1799	1591	88.4%	3.6	59	6/4
Vaasa	37,070	1682	1491	88.6%	2.9	54	6/4

The number of slips differs much between the cities and is strongly related to the number of citizens or employees (see Table 1). The results are statistically more reliable for bigger cities compared to smaller cities where the amount of daily slipping injuries can be quite low. Forms of transportation to work (car, biking, walking, or the use of public transportation), the amount of public transportation, the number of pedestrians, and the winter maintenance rules may vary between the cities, but that information has not been considered in this study. Table 1 also presents the total and wintertime slip amounts, slip injury rate per 1000 employees, number of peak days (including potential peak days), and the calculated thresholds for peak and potential peak day, separately for each city.

Slips occurring on weekends and public holidays are highly underestimated in the TVK's slip injury data as people during these days work less than on normal weekdays. Also, days around public holidays, like Christmas, New Year and Easter as well as the typical winter holiday season in the end of February and early March cause slight uncertainty to the results with reduced amounts of daily slipping amounts, as people are not working, and community accidents don't occur that much compared to normal weekdays.

As meteorological data, daily observations that were calculated as spatial averages for the study areas from the gridded temperature data set on the spatial resolution of 10 km × 10 km, were used. Daily weather observations include information of temperature (daily mean, minimum, maximum), daily precipitation sum, and snow depth. The daily mean temperature is calculated as the mean of the eight daily synoptic measurements. The daily minimum and maximum temperatures are measured between 18 UTC on the previous day and at 18 UTC on the date of the observation. Daily precipitation sum is recorded between 6 UTC on the date of the observation and 6 UTC on the following day, snow depth is recorded on 6 UTC. The data is produced operationally at the FMI from the station-wise temperature observations by Kriging interpolation that also takes into account the elevation and the share of water bodies [38,39].

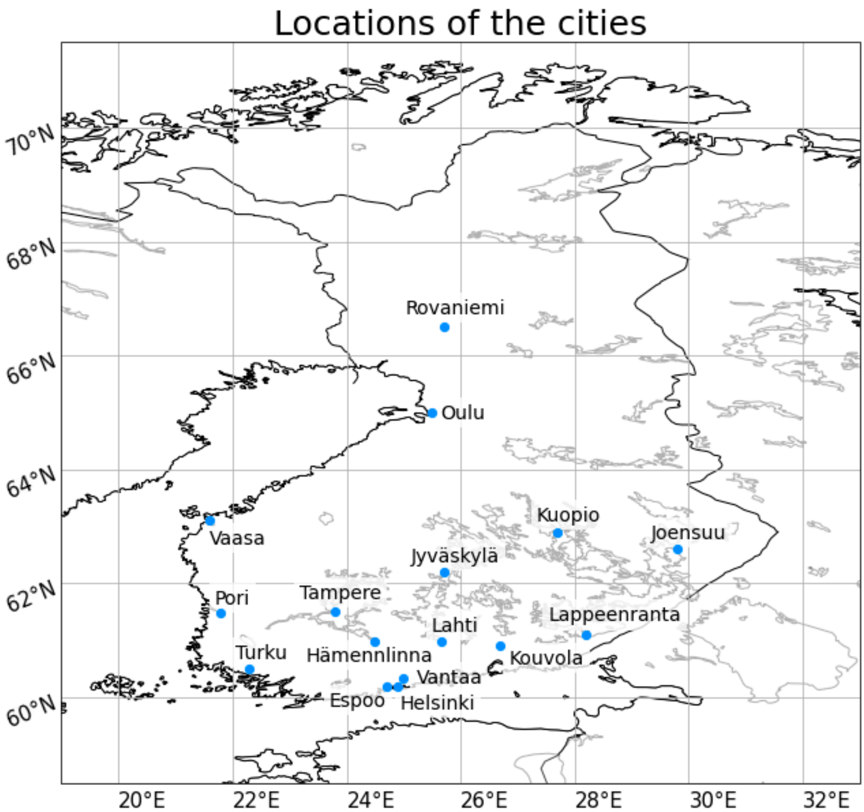

Figure 1. Location of the cities presented on the map.

As weather observations are available only on a daily level, there is no information for example about the timing of weather phenomena, like zero crossings, temperature variation or precipitation. Also, the precipitation form is not available. In addition, it is not known whether the sidewalk surface is covered by ice or snow or not. Thus, the snow amount measurements are the best available estimation for the potential icy and snowy sidewalk condition, even though it does not necessarily correlate with the slipperiness for example at the end of the winter season when snow has melted but there is still ice on the sidewalks.

3. Results

3.1. General Information about Data and Slips

Data between 1 October 2005, and 30 September 2019, is included in this study, covering a total 14 winter seasons. Months from October to April have been defined as winter months. Weather differs a lot during this time, with winters ranging from those with mild temperatures and low snowfall to colder and snowy ones. Also, during a specific winter there can be huge differences between the cities: weather on the coastal areas can be mild with small amounts of snow whereas at the same time, northern and eastern parts of Finland are colder and snowy.

As Table 1 shows, the number of slip injuries varies a lot between the cities: the more citizens (or employees in this table), the more slip injuries. The slip injury rate per 1000 employees is highest in Helsinki (5.3) and lowest in Vaasa (2.9).

Days with increased risk of slipping are considered in this study. They are defined as days when the daily number of slip injuries is equal or greater than the potential peak day threshold. The thresholds of the daily peak days and potential peak days are presented on Table 1. Hereafter, when mentioning peak days, the potential peak days are included as well. The data from all 16 cities include a total of 2549 peak days.

3.2. Temporal Distribution of Peak Days of Slipping Injuries

As can be expected, the total amount of slips is much higher during winter than summer. According to the TVK's data, winter months January, February, and March cover about half of the yearly slip injuries except in eastern and northern part of Finland where the percentages for mid-winter months are slightly smaller (see Figure 2, the full set of the figures can be found from the Supplementary Material Figure S1).

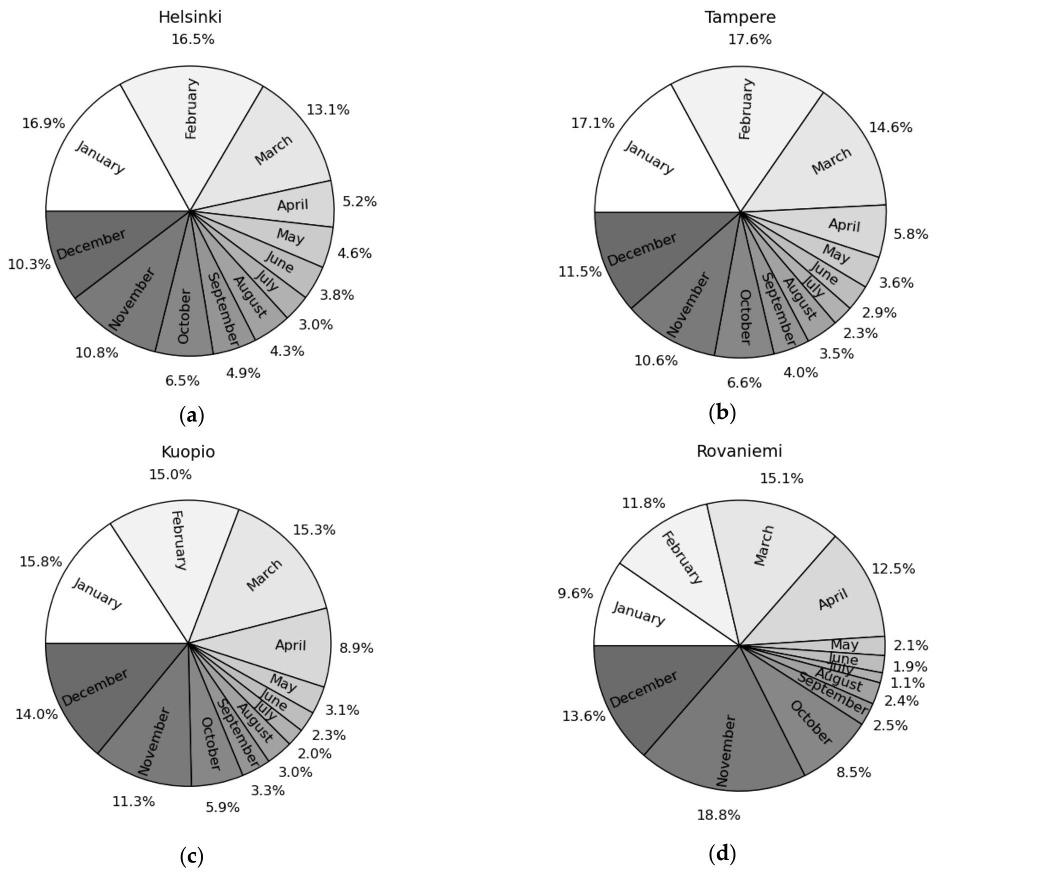

Figure 2. Pie charts showing the portion of each month's slip injuries based on the TVK's data for Helsinki (**a**), Tampere (**b**), Kuopio (**c**) and Rovaniemi (**d**) with a time range between 1 October 2005, and 30 September 2019. Different shades of gray present different months from January (white) to December (dark gray). Figures for all cities are presented in the Supplementary Material (Figure S1).

When also considering the other winter months (April, October, November, and December) the percentage is between 80 and 90 (Table 1 and Figure 2). However, the total number of slips and falls in summer months (June–August) is affected by the summer holiday season that reduces the number of commuting accidents.

Figure 3 presents the temporal distribution of the peak days of slipping injuries in different cities. The peak days are presented as a function of sequential numbering of days starting from October 1. To make the figure easier to read, the sequential numbering of days has been changed to calendar days (i.e., 1st is October 1, 31st is November 1, and so on). In the case of leap years (2008, 2012 and 2016) there is a one-day shift on peak days occurring in March and April.

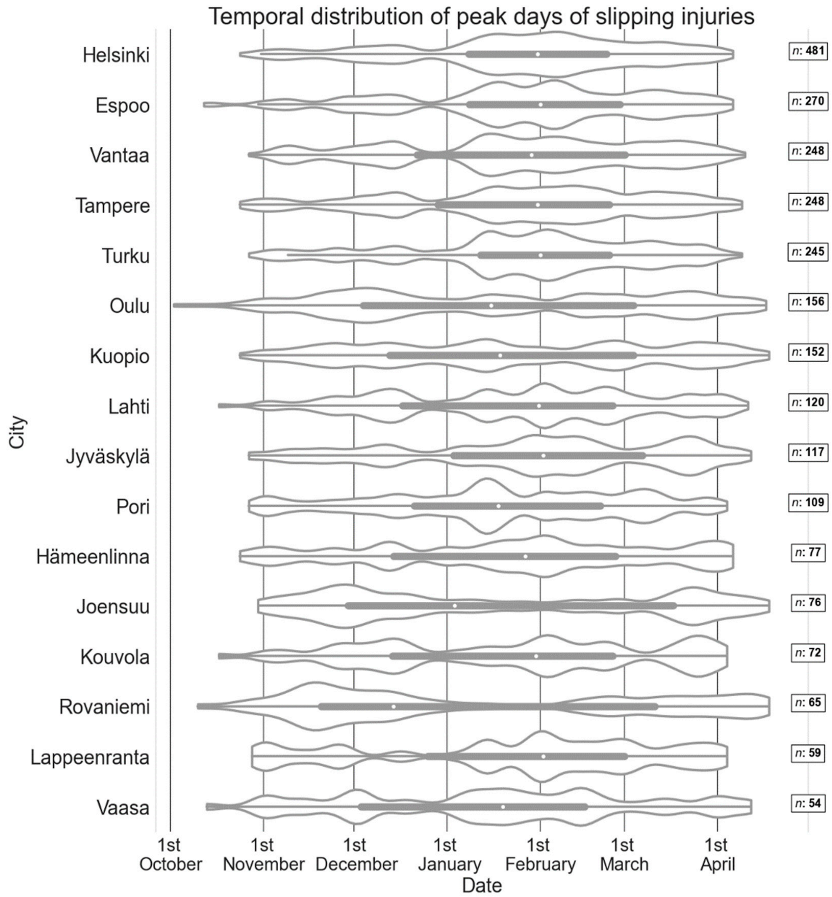

Figure 3. The temporal frequency distribution of peak days of slipping injuries in different cities in winters 2005–2019 presented on a violin plot. The width of the span corresponds to the frequency of slip injuries, the wider the distribution is the more slip injuries happen. The white dot within each box represents the median dates of the winter season slips. The box spans the 0.25 and 0.75 quantiles, and the whiskers represent the minimum and the maximum dates. Outliers are within the violin plot area. The number of peak days (*n*) is presented for each city on the right.

The beginning of the slip season and the first peak days of slip injuries occur typically in October, and the end of the season is in April. In south coastal cities, Helsinki, Espoo and Turku, the peak days are concentrated in the middle of the winter, with 50% of the peak days occurring within a shorter time period than elsewhere. Cities located in the east or north (Joensuu, Oulu and Rovaniemi) have more slips in the beginning and at the end of winter compared to mid-winter. This is strongly related to the climate because near zero temperatures are not frequent in the eastern and northern part of Finland in the middle of the winter, as can be seen in Figure S4 on Supplementary Material. In places where the slip season is usually short, the median of the slips is typically dated at the turn of January–February, whereas in other places the median is reached earlier. In Rovaniemi, the beginning of the slip season seems to be somehow more intensive with more slips than in other places. The holiday season, especially Christmas time and the New Year period are visible in the data with lower amounts of slips.

The monthly distribution of peak days for four of the cities is presented for all winter seasons (2005–2019) in Figure 4a–d (the full set of the figures can be found from the Supplementary Material Figure S2). The number of peak days per winter is the highest in Helsinki. The difference between winter seasons can be large but there can also be large differences within one winter season. For example, during winter season 2010–2011, there was a high number of peak days in Helsinki whereas during the same winter Rovaniemi recorded zero peak days. On the contrary, during the winter season 2013–2014, Helsinki had only a few peak days, while Rovaniemi during the same time had the largest number of peak days (see Figure 4a,d). The winter of 2010–2011 was very snowy already from the beginning of winter season, and high snow amounts were measured also in the southern part of Finland during the winter. The temperature was below average. In the winter of 2013–2014, the temperature was 2–4 degrees warmer than the average. In the southern part of Finland, the snowy season was very short, and sidewalks were not covered by ice and snow for a long time. Meanwhile, the northern part of Finland had more zero degree temperatures and icy surfaces than normally [40].

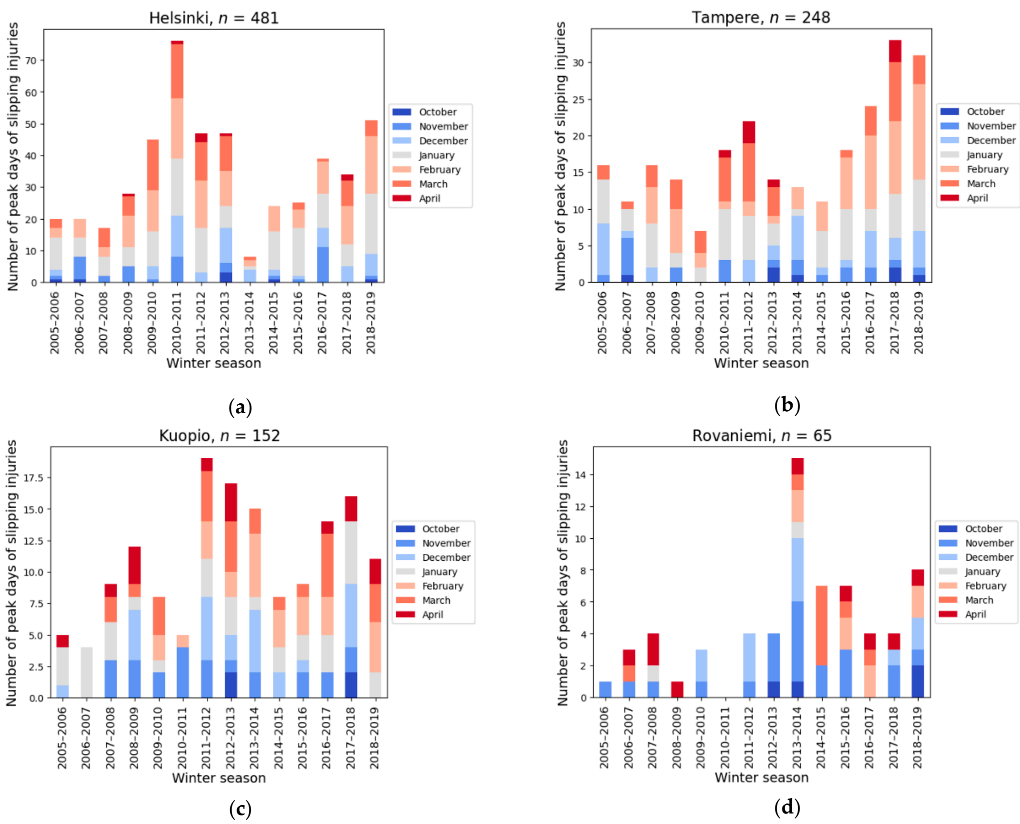

Figure 4. The monthly distributions of the peak days on different winters for Helsinki (**a**), Tampere (**b**), Kuopio (**c**) and Rovaniemi (**d**) between the years 2005 and 2019. The number of peak days (n) is shown for each city. Figures for all cities are presented in the Supplementary Material (Figure S2).

The beginning of the winter season and the first slippery days can be challenging for pedestrians. Wrong footwear, unexpected slipperiness, and the lack of preparedness for the slippery sidewalk condition easily increase the slip risk. Similarly, tourists may encounter snow and ice for the first time in their life and be in general unfamiliar and unprepared to the Nordic winter environment [41]. The beginning of the winter season with the first snow falls and temperatures below 0 °C is often very visible when looking up slip statistics [30]. The general level of slip rate increases rapidly when it snows for the first time and the temperature drops below zero degrees.

In the springtime, snowy and icy sidewalks begin to melt. Warm air masses and increased shortwave radiation can cause large temperature variations. Because of increased differences between daytime and nighttime temperatures, it is possible that snow and ice on the sidewalks melt during the day and freeze again during the night, so sidewalk slipperiness can be quite different in the morning compared to the afternoon. It must be remembered that even when the snow has already melted from the area, the sidewalks and paths may be icy, especially in places that are in the shade.

3.3. Temperature on Peak Days of Slipping Injuries

Near-zero temperatures or temperatures just below 0 °C can typically be seen to exist when peak days of slipping injuries occur. The statistics of the daily mean temperature on peak days of slip injuries are presented on box plots in Figure 5. The mean temperature of peak days varies between −3.3 °C (Helsinki) and −0.7 °C (Joensuu). The overall temperature scale of the peak days is quite large and there are several peak days when the daily mean temperature is very low, in some cases even below −20 °C. The temperature scale is larger in the bigger cities with a higher number of peak days compared to smaller cities with a lower number of peak days.

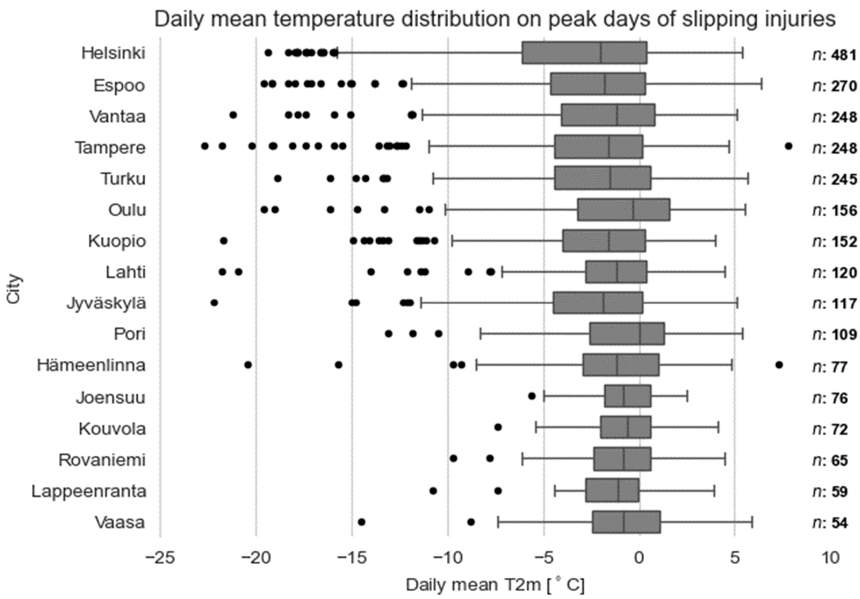

Figure 5. Box plot for daily mean temperature on peak days in different cities during the 14 winters between the years 2005 and 2019. Boxes correspond to upper and lower quartiles of the data, with the vertical line in each box showing the median. Whiskers indicate variability outside the quartiles and outliers are shown as individual black points. The number of peak days (n) for each city is shown on the right.

Figure 6a–d show the frequency histogram for the daily mean temperature on the peak days for four of the cities (the full set of figures is presented in the Supplementary Figure S3). Typical daily mean temperature on the peak days is around 0 °C, with the mean temperature above zero more frequently in cities located on the coast than inland.

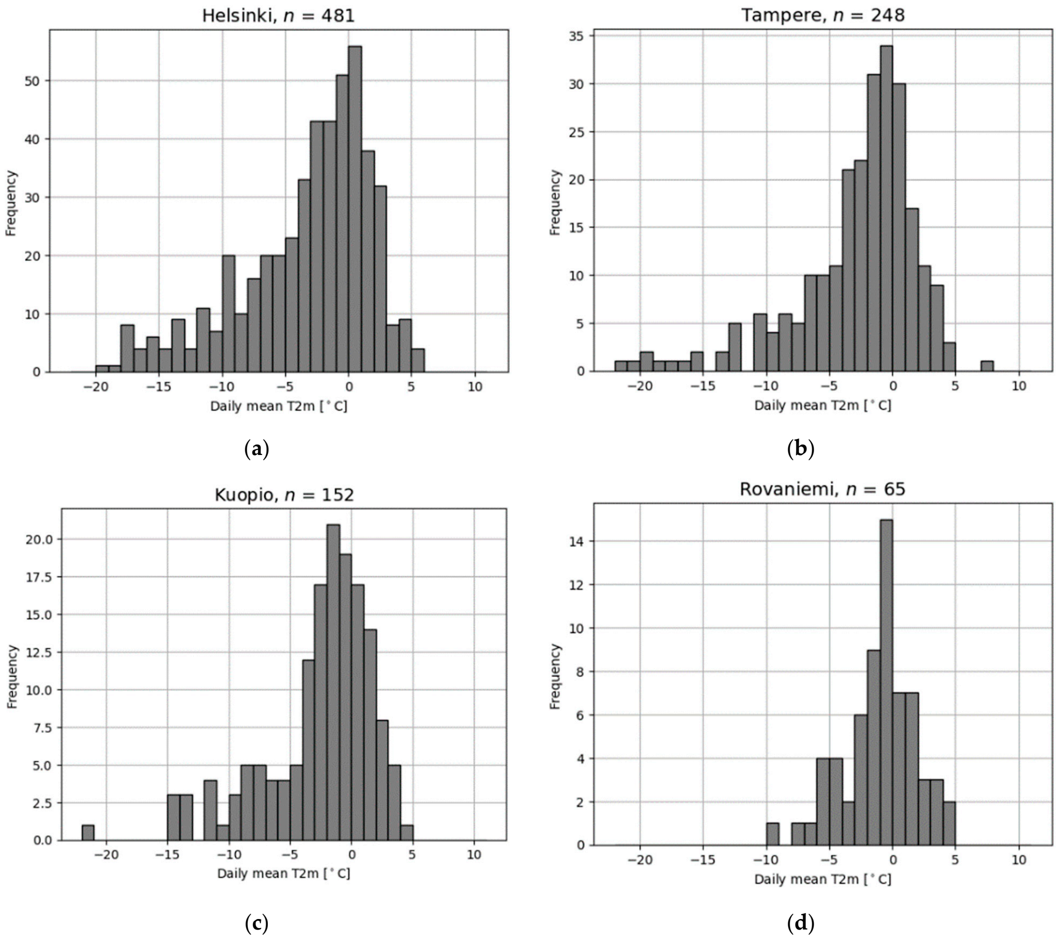

Figure 6. Frequency histograms of the daily mean temperature on peak days of slipping injuries for Helsinki (**a**), Tampere (**b**), Kuopio (**c**) and Rovaniemi (**d**) between the years 2005 and 2019. The number of peak days (n) is shown for each city. Figures for all cities are presented in the Supplementary Material (Figure S3).

Zero degree crossings cause slipperiness due to phase transition (from solid to liquid or vice versa) when moisture exists on the sidewalk surface. In this study, zero degree crossing cases are defined as days when daily maximum temperature is above 0 °C and minimum temperature below 0 °C. Temperature crossing 0 °C is most typical in springtime when the daily temperature fluctuation is at its largest (see Figure S4 on Supplementary Material). In the northern and eastern part of Finland zero crossings are not typical in mid-winter whereas in the other places, especially in the coastal cities, zero crossings happen throughout the winter. Similarly, in the northern and eastern part of the country zero crossings during peak days are not typical in mid-winter, but in many other cities they occur also in the mid-winter (Figure 7). The zero crossings on peak days are most typical in Kouvola (65.3%) and least typical in Helsinki (38.0%).

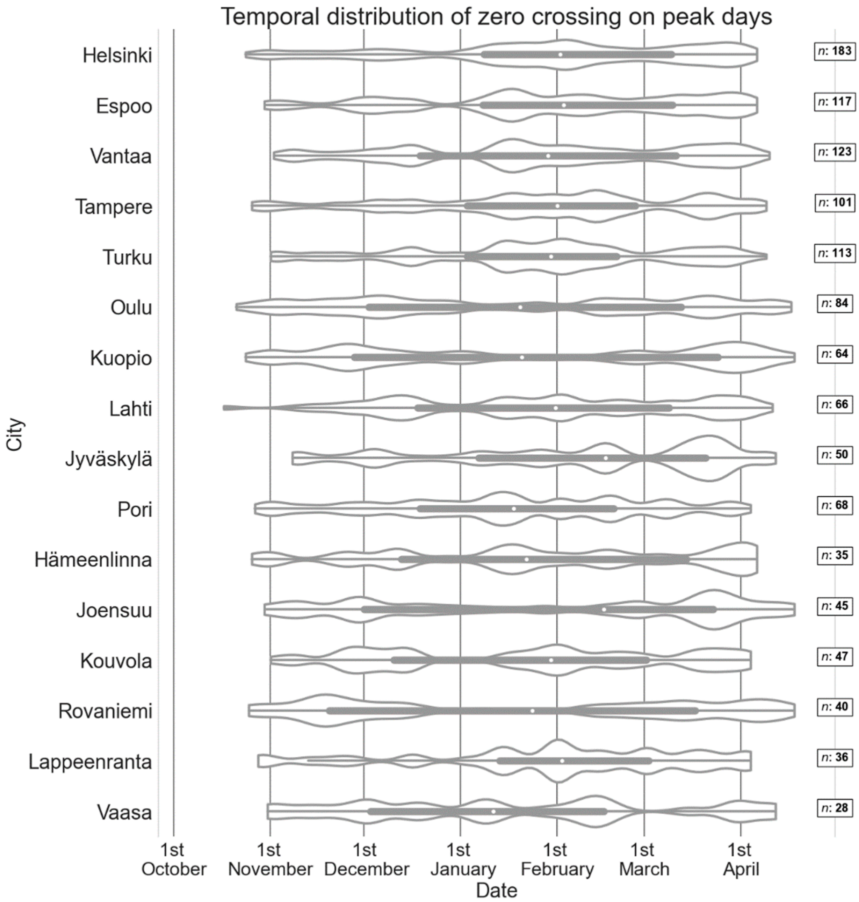

Figure 7. Temporal distribution of the wintertime zero crossings on peak days for all cities between October and April in winter 2005–2019 presented on a violin plot. The width of the span corresponds to the frequency of slip injuries, the wider the distribution is the more slip injuries happen. The white dot within each box represents the median dates of the zero crossings on the peak days. The box spans the 0.25 and 0.75 quantiles, and the whiskers represent the minimum and the maximum dates. Outliers are within the violin plot area. The number of zero crossing days during peak days (*n*) is presented for each city on the right.

3.4. Precipitation and Snow Amount on Peak Days of Slipping Injuries

It is expected that precipitation raises the slip risk. Daily precipitation sum is recorded between 6 UTC on the date of the observation and 6 UTC on the following day. This measuring method brings some uncertainty to the results as the data is not available on a daily level. The precipitation form is also not available. According to the results, precipitation (daily precipitation sum 0.3 mm or more) on peak days of slip injuries varies between 50.7% (Helsinki) and 72.3% (Joensuu). Similarly, the percentages for precipitation sums of at least 2 mm vary from 30.1 (Helsinki) to 49.2 (Rovaniemi).

The impact of snow on the slip amounts is also investigated in this study. According to the weather and slip injury data, snow cover raises the number of slip injuries over three-fold and there are differences between the cities. When comparing snowy situations to no-snow situations, the ratio is lowest in Helsinki (3.2), and highest in Kouvola (5.5). Snowy situations are defined as days when the observed snow amount has been 1 cm or more (measurement done at 6 UTC). Measured snow cover doesn't necessarily mean icy or snowy sidewalk conditions and vice versa but it is, nevertheless, the best data that is available to describe the snow and ice situation on the sidewalks.

It is found that in the case of bigger cities, the longer the snowy season, the higher the number of peak days per winter season. The correlation shows that the number of the peak days increases as a function of the length of the snowy season. In the case of smaller cities, however, the signal is weak or even opposite compared to bigger cities.

The day with the highest number of slip injuries was 24 November 2008, in Helsinki, Espoo and Vantaa. Snow accumulation was almost 30 cm during that day and on the day before, and temperature was about −1 °C. The reasons for the high slip injury numbers can only be speculated. The situation was favorable for the slipperiness due to packed snow that occurs when the temperature is just below 0 °C, it is snowing, and there are enough people walking to compress the snow. Most probably, the snow removal crew was busy because of continuous and long lasting snowfall and there were challenges to maintain the sidewalks properly. Large amounts of snow also create barriers on the walking routes which can raise the slip risk. In addition, the situation was one of the first actual slippery days for that winter season, so people weren't necessarily yet prepared for slippery sidewalk conditions. High slip amounts were also recorded over the next three days, maybe due to high snow amounts but also because the temperature rose above 0 °C.

3.5. Weather before Peak Days of Slipping Injuries

The weather on the previous days (1–3) can play a significant role in the slipperiness of the following days. If temperature drops below zero degrees, moist surfaces freezes. Frozen surfaces can be slippery themselves but even a light snowfall can make surfaces more slippery still if the light and loose snow covers the hard and smooth ice layer. Pedestrians don't necessarily notice the risk of slipperiness as the icy surface is covered by snow [30]. Also, lots of new snow may cause slipperiness for several days if the winter road maintenance is unable to reduce sidewalk slipperiness and remove the snow, as was noticed in case 28 November 2008.

In some cases, the slipperiness may also occur when the daily mean temperature is low, below −10 °C or even below −20 °C. Part of those cases can be explained by a notable temperature decrease during one or more days of continuing light snowfall. However, there are several cases with high slip rate also when precipitation has not been measured. In those cases, high slip rates can be due to hard ice layers or to other non-meteorological reasons. The number of these cases is quite small in the studied material, however, and the cases appear typically during mid-winter with high amounts of snow.

4. Discussion

Winters with ice, snow and near zero temperatures have a strong impact on sidewalk slipperiness and the findings of this research are consistent with the previous studies. According to the results, the mean temperature on peak days of slipping injuries is typically around zero or slightly below zero degrees. However, the temperature scale on peak days is large and there are also a few peak days when daily mean temperature is even below −20 °C. Also, zero-degree crossings are very typical on peak days and their occurrence is around 50% in all the cities studied here.

Precipitation (daily accumulation 0.3 mm or more) occurred on more than half of the peak days. Also, the length of the winter (snowy season) seems to correlate with the number of peak days of slips, especially in the bigger cities: the longer the snowy season is, the more peak days of slips seem to occur. In addition, lots of new snow in a short time period seems to increase the slip risk.

However, there are some cases when the high slip rate cannot be explained by weather. Non-meteorological factors, such as the lack of winter maintenance of sidewalks or the number of pedestrians making sidewalks slippery due to packed snow, can also influence slip rates. Also, weather on previous days may be the reason for slipperiness. Slipperiness is a very complex phenomenon, and further studies are needed to understand the role of non-meteorological factors affecting the risk of slips.

Helsinki, with the highest number of pedestrians, seems to have more non-weather-related issues affecting slip-injury rate than other cities. The use of sustainable transport modes, including walking, is more common in the Helsinki metropolitan area than in smaller cities [42]. This may explain at least partly why slips and slip-related injuries are more common especially in Helsinki compared to smaller cities.

It is expected that climate change will bring changes on slipperiness in Finland in the future. As wintertime temperatures are forecasted to rise, less icy and snowy sidewalk conditions in the beginning and at the end of the winter season can be expected because of increased occurrence of temperatures above or close to 0 °C. Season with ice and snow on the sidewalks will become shorter. However, the coldest places in Finland, especially Rovaniemi, Kuopio and Joensuu, may face the largest impacts due to global warming, because near-zero temperatures are becoming more frequent in the mid-winter [43], increasing slipperiness and risk of slips between January and March.

According to pedestrians themselves, the most important measures to prevent slips are the pedestrians' own actions, like caution and the choice of footwear with good grip, as well as improvement in the winter maintenance of sidewalks [15]. The importance of winter maintenance has been highlighted in several studies [3,24]. Pedestrians' awareness about slipperiness can be increased by warning about the expected slippery conditions. In addition to Finland, special warning services to inform citizens about slippery sidewalk conditions and the high risk of slips have been developed in Japan and Canada [30,44–46]. One method to improve safe walking is the use of anti-slip devices on a person's ordinary shoes [47–49].

Instead of daily values, more detailed weather observations, for example hourly or more frequent data and precipitation form, would be beneficial when determining the state of slipperiness. Daily mean temperature observations are not always the best parameter to be used, especially in cases when the daily maximum temperature reaches above zero degrees during a day and the mean temperature stays below zero degrees. There are similar problems also in case of large temperature fluctuations during a day, or if air is cooling or warming. Also, surface temperature and the knowledge about existence of ice or snow on the sidewalk surface could give valuable information about potential slipperiness.

At present, there does not exist a measurement device that could measure operationally the sidewalk condition or slipperiness [30]. With a proper observation system, the state of slipperiness could be detected, which would help to estimate the forthcoming slipperiness. A proper and dense observation network would also give valuable information for winter maintenance.

Machine learning methods could offer more detailed information about the level of slipperiness and slip risk. Spatio-temporal prediction could consider the differences between cities, like climatology and number of pedestrians, and improve the prediction of high slip risk. Further research could also take into account additional information about slip injuries, including the type and severity of the injury, as well as and socio-demographic characteristics. A more detailed analysis of the cause-consequence relationships of slip amounts and weather could also be performed.

5. Conclusions

The aim of this study was to find out how the pedestrian slip rates vary between different seasons and months, and what is the weather typically like when high slip rates occur. Wintertime slipperiness due to ice and snow together with near zero temperatures clearly increases the risk of slips. Although temperatures are forecasted to rise in the future, slipperiness will still occur. As sustainable transport modes, especially walking, are becoming more recommended, it is important to invest in safety. The slip risk can be reduced by effective and timely winter sidewalk maintenance, the awareness of slippery sidewalk condition and risks of slipping, as well as by the use of the right footwear with good grip or anti-slip devices. Also, improvements in the coverage of slip-and-fall accident statistics are recommended. Additionally, traffic safety work should be broadened to cover single pedestrian accidents [50].

The Finnish national transport policy targets include increasing the combined share of walking and cycling and decreasing total transport emissions [51]. The promotion of walking and cycling helps to obtain the national health objectives, too. As the aim in the future is to increase the amount of walking, sidewalk condition forecasting, pedestrian awareness as well as winter maintenance should be improved. This could help to decrease the number of slips that cause personal suffering and also significant costs to society. Because the risk of slipping is highest where there is a lot of walking, the greatest benefits could be achieved in big cities where the number of pedestrians is high.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijerph19053007/s1, Figure S1: Pie charts showing the portion of each month's slip injuries based on TVK's data. Data covers 16 cities with a time range between 1 October 2005, and 30 September 2019. Figure S2: The monthly distribution of the peak days on different winters for all cities between the years 2005 and 2019. Figure S3: Frequency histogram of the daily mean temperature on peak days of slipping injuries for all cities between the years 2005 and 2019. Figure S4: Temporal distribution of the zero-degree crossings in winter months between October and April in winter 2005–2019.

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ORIGINAL ARTICLE

Climate change impacts on future driving and walking conditions in Finland, Norway and Sweden

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Abstract

Road weather is a major concern for the public safety and health, industries and transport sectors. Half of the yearly 27,000 road and 50,000 pedestrian injuries in Finland, Norway and Sweden can be traced back to slippery road and walkway conditions. We simulated the climate change impacts on future roads and walkways for mid- and end-century in Finland, Norway and Sweden with the road weather model RoadSurf, driven by the regional climate model HCLIM38 with boundary data from two global climate models following the RCP8.5 scenario.

Our simulations for mid-century suggest strong road surface temperature increases, especially in southern Finland (+ 5.1 °C) and Sweden (+ 7.1 °C). Snowy and icy road surface conditions decreased by 23 percentage points, causing 18.5 percentage points less difficult driving conditions during the cold season. Zero-degree-crossing days mostly decreased in autumn and spring by up to 7 days and increased in winter by up to 5 days. Sidewalks mostly showed a decrease in slipperiness, but a five percentage point increase of water above ice layers on the sidewalks in winter, suggesting the slip-season might become shorter, but more slippery.

Our results are upper extreme estimates but can serve as a reference to help local decision-makers plan mitigation and adaptation measures ahead of time.

Keywords Road weather · Climate change impacts · Road safety · Pedestrian safety · Winter road maintenance · Climate modelling

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Introduction

Weather plays a crucial role for the transportation of passengers and goods (Norrman et al., 2000). Traffic accidents involving personal injury or death due to slippery conditions account for up to 50% of the over 27,000 injuries in recent years in Finland, Norway and Sweden (FNS). Medical costs and economic production losses arising from these accidents sum up to €16.2 billion yearly (European Commission Directorate-General for Mobility and Transport & CE Delft, 2019; International Traffic Safety Data and Analysis Group, 2020a, b, c, d; Statistics Finland, 2021; Statistics Sweden, 2019). An often-overlooked burden is posed by pedestrian slip injuries. A majority of the 50,000 slips that need medical attention yearly are caused by slippery conditions (Elvik et al., 2009; Elvik & Bjørnskau, 2019; Hippi et al., 2020; Port and Ocean Engineering under Arctic Conditions (POAC) (2009).

These accidents cannot be prevented even with full winter-time road maintenance (Norrman et al., 2000). Therefore, reducing accident numbers by informing the public about hazardous road weather is important for the public health sector. Road maintenance and transport sectors benefit from road weather forecasts as well, for planning ahead their actions and reducing costs (Juga et al., 2013; Keskinen, 1980; Nurmi et al., 2013).

Currently, public authorities are working with real-time road weather observations and short-term weather forecasts to issue warnings when the road weather is expected to worsen. Road weather models typically predict the road surface temperature and the amount of snow, ice or water on the surface, and in some cases also friction and driving condition (Juga et al., 2013; Kangas et al., 2015). Regional road weather models have been developed in several countries to improve the regional accuracy (Chapman et al., 2001; Crevier & Delage, 2001; Fujimoto et al., 2012; Jacobs & Raatz, 2007; Kangas et al., 2015; Yang et al., 2012).

As climate change has been posing far-reaching challenges on the transport sector worldwide (Forzieri et al., 2018; Hori et al., 2018; Matthews et al., 2017), road planners and maintenance operators are assessing the monetary funds needed to manage (either current or soon-arising) regional climate change impacts on the transport sector. Such challenges include shifts in more frequent extreme weather, safe transport routes, time and locality of accidents, shifts in tourism and agriculture and pavement material damage and road maintenance changes. (Andersson & Chapman, 2011a; Axelsen et al., 2016; Balston et al., 2017; Koetse & Rietveld, 2009). Particularly in high northern latitudes like Northern Europe or Canada, where winter road maintenance is both a necessity and a big cost point, climate change is estimated to have stronger impacts due to arctic amplification (Screen, 2014).

Whilst weather models produce road weather forecasts for the near future and help manage immediate risks, they are not capable of portraying long-term developments beyond a few weeks. Climate models on the other hand give estimates for many decades or even centuries ahead and can simulate different climate change scenarios. Driving road weather models with climate models therefore can help road management and authorities to better plan ahead for the arising challenges and opportunities of road management in the far future (Matthews et al., 2017; McSweeney et al., 2016). Our predecessor study by Toivonen et al. (2019) confirmed that the Finnish road weather model RoadSurf (Finnish Meteorological Institute, Kangas et al., 2015) produced accurate historical road temperature estimates for Finland when driven with the cycle 38 of the regional climate model HARMONIE-Climate (HCLIM38) and thereby set the grounds for this study.

We expand upon Toivonen et al. (2019) by exploring future road weather under a climate change scenario and adding the Norwegian and Swedish domains. We assess (1) whether forcing with the computationally more expensive high-resolution regional climate model HCLIM38-AROME configuration (3 km grid resolution) provides considerable benefits over the HCLIM38-ALADIN configuration (12 km grid) and, thereafter, we explore (2) the climate change impacts on roads in FNS by assessing possible future regional and temporal developments of average road surface temperatures, road surface conditions and driving and walking conditions, as well as zero-degree-crossings under climate change in reference to the historical period (1986–2005).

Data sources and models

Our main model was the road weather model RoadSurf (Kangas et al., 2015) driven by regional climate model simulations from the cycle 38 of HARMONIE-Climate (HCLIM38; Belušić et al., 2020). Since RoadSurf cannot produce its own climate scenario, it needs external data to provide the meteorological boundary data. To provide these data, we used three different sources: one reanalysis dataset and two CMIP5 global climate models, EC-Earth (ECE) and GFDL that considerably differed in their climate change predictions for the Nordics. See below for details about the models and data.

RoadSurf model and data

RoadSurf is an energy balance model that predicts driving conditions for the next 24 h. It estimates (1) the road surface temperature, (2) friction and (3) storages on the road (water, snow, ice, frost in water mm-equivalent), and from these (4) road surface condition and (5) driving conditions (driving difficulty derived from a combination of weather and road surface conditions) (Kangas et al., 2015).

The model calculates the vertical heat fluxes between the atmosphere and the road surface by means of turbulence (including traffic-induced), generalised soil material properties and meteorological input parameters. The meteorological input parameters, taken from HCLIM38 regional model output, include 2-m air temperature, precipitation, relative humidity, wind speed and downwelling shortwave and longwave radiation with a time resolution of 1 h. Hydrological processes, including freezing, melting, evaporation, sublimation, run-off from the surface and accumulation of rain and snow, are parameterized. RoadSurf assumes a flat horizontal paved surface over the whole domain with similar deep-ground properties, without elements shading the road, such as trees. Topography, water bodies or forests are implicitly accounted for through the HCLIM38 input data.

Traffic is simulated as a spatially constant atmospheric turbulence on the ground with a larger value for daytime and a smaller one for night. Traffic reduces and changes the storages, e.g. by compressing snow into ice, whilst unpacked snow is assumed to be partly blown away by the wind. The model assumes neither salting nor road maintenance and, therefore, overestimates snow and ice storages on the road (Toivonen et al., 2019). This is justified as RoadSurf is commonly used to warn about the possibility of hazardous driving conditions, as a call to action for the regional road management (Kangas et al., 2015). Despite these overestimations, however, Toivonen et al. (2019) showed that RoadSurf reproduced observed road weather conditions in Finland (2002–2014) well when driven by HCLIM38. Furthermore, RoadSurf has been further developed to predict pedestrian sidewalk conditions (walking difficulty) (Hippi et al., 2020).

This study expands upon Toivonen et al. (2019) by exploring a future scenario of driving as well as pedestrian conditions and additional countries. Our study employed version 6.60b of RoadSurf with a few minor adjustments made in this study. We focused on four output variables: (1) road surface temperature (T_{RS}) (from which zero-degree-crossing days were derived); (2) road surface condition: dry, damp, wet, snow, frost, icy and partly icy; (3) driving condition: normal, difficult and very difficult; (4) pedestrian condition: normal, slippery (slipperiness may occur), very slippery due to foot-packed snow (VS I), very slippery due to water above ice layer (VS II) and very slippery due to snow above ice layer (VS III).

HARMONIE-Climate data

We used the HARMONIE-Climate "cycle 38" model runs (HCLIM38) (Belušić et al., 2020; Lind et al., 2016; Lindstedt et al., 2015) recently performed by the NorCP project for Northern Europe (Lind et al., 2020; Médus et al., 2022) with the packages (1) HCLIM38-AROME (3 km grid resolution) (Bengtsson et al., 2017; Seity et al., 2011; Termonia et al., 2018) and (2) HCLIM38-ALADIN (12 km grid resolution) (Termonia et al., 2018). A detailed description of the model can be found in Belušić et al. (2020).

The boundary data for HCLIM38-ALADIN were taken from either the global ERA-Interim reanalysis dataset (ERAI, 80 km grid resolution) (Dee et al., 2011) or from two CMIP5 global climate models (GCMs) from the Coupled Model Intercomparison Project–Phase 5 (CMIP5) (Taylor et al., 2012): EC-Earth (Hazeleger et al., 2010, 2011) and GFDL-CM3 (Donner et al., 2011; Griffies et al., 2011) (Table 1). We chose ECE and GFDL as driving GCMs as they cover the full range of temperature and precipitation projections for northern Europe in the RCP8.5 scenario in CMIP5 (Lind et al., 2022, in preparation).

Table 1 RoadSurf simulations presented in this paper. Combinations of one global ERA-Interim reanalysis (ERAI), two different global climate models (ECE, GFDL), two different HCLIM38-Configurations (AROME, ALADIN), two road-user modes (car, pedestrian) and four different time frames (historic 1986–2005, present 1998–2018, mid-century 2041–2060, end-century 2081–2100) were used

Boundary data	HCLIM38 configuration	Traffic mode	Time frame	Scenario	Purpose
ERAI	AROME	Car	1998–2018	Reanalysis	Evaluation
ECE	AROME	Car	1986–2005	Historical	Reference period
ERAI	ALADIN	Car and pedestrian	1998–2018	Reanalysis	Evaluation
ECE	ALADIN	Car and pedestrian	1986–2005	Historical	Reference period
ECE	ALADIN	Car and pedestrian	2081–2100	RCP 8.5	Future projection
GFDL	ALADIN	Car and pedestrian	1986–2005	Historical	Reference period
GFDL	ALADIN	Car and pedestrian	2041–2060 2081–2100	RCP 8.5	Future projection

The reanalysis-driven simulation was used for model evaluation purposes, whilst the GCM–driven runs were used to estimate the impacts of climate change.

Representative concentration pathway 8.5

The two global climate model simulations for HCLIM38 boundary data followed the representative concentration pathway (RCP) 8.5, which assumes continuing rising global greenhouse gas emissions, resulting in an expected increase of radiative forcing of 8.5 Wm^{-2} by 2100. This climate change scenario entails an estimated global temperature increase of + 1.8 °C (ECE)/ + 2.6 °C (GFDL) by mid-century (2046–2065) and up to + 3.5 °C/ + 4.7 °C by the end of the century (2081–2100), relative to temperatures in the historical period (1986–2005) (Stocker et al., 2013).

RCP8.5 may be becoming increasingly unlikely due to the overestimation of future coal use (Ritchie & Dowlatabadi, 2017; Schwalm et al., 2020), but it remains valuable especially for mid-century projections, to assess policies or to account for higher-than-expected carbon cycle feedbacks (Schwalm et al., 2020).

Road weather observations

We collected observations of road surface temperature and road surface conditions from representative road weather stations in Finland (25 stations, 2002–2005), Sweden (5 stations, 2015–2018) and Norway (5 stations, 2015–2018) in hourly resolution (see details in Online Resource T1). Three of the Norwegian stations are located in mountainous regions near or above 1000-m elevation, which brings challenges to model evaluation as the terrain differences between the model and observations can be large. Swedish observations were from around the country, with one on a bridge. The Finnish observations were more numerous, because there were more reliable observation data available, and the same list of stations was used in the previous study by Toivonen et al. (2019).

Finnish road weather stations use the Vaisala ROSA road weather package equipped with asphalt-embedded DRS511 sensors. Swedish observation data was provided by the PT-100 resistance thermometer probe (Platina 100) embedded in the road and a DSC111 optical sensor (Vaisala). The Norwegian observations were recorded with weather stations from Scanmatic (sensors not communicated).

For the evaluation, we selected the modelled grid cell closest to the stations' coordinates. Thus, the observations were point measurements, whilst the modelled data were an average over one grid cell.

Methods

Henceforth, RoadSurf runs driven with ECE-HCLIM38-ALADIN and GFDL-HCLIM38-ALADIN will be referred to as ECE–driven and GFDL–driven runs, respectively.

Evaluation against observations

We compared historical RoadSurf simulations to the road weather observations in FNS for the years 2002–2005 to assess RoadSurf's predictive accuracy when driven with different combinations of HCLIM38 configurations (-ALADIN or -AROME) and global climate models (ECE or GFDL) as well as with ERAI reanalysis data.

Probability density functions (PDFs) of the regionally observed road surface temperatures (T_{RS}) were compared to HCLIM38-ALADIN simulations (ERAI, ECE-historical, GFDL-historical) over FNS. Norwegian and Swedish observations did not overlap with the modelled years, so we compared 2015–2018 with the years 2002–2005 from the model under the assumption that the climate did not considerably change during the gap. Thereafter, we calculated the monthly mean bias (MMB, model minus observations) and mean absolute error (MAE) of the modelled T_{RS}.

Road surface condition observations were only available for Finland and Sweden. We compared the observed time fractions of the occurrence of each road surface condition to HCLIM38-ALADIN runs (ERAI, ECE-historical, GFDL-historical). Road surface conditions in historical simulations in Norway were only compared to their corresponding ERAI run.

Modelled traffic and pedestrian indices could not be evaluated against observations as no such observation data existed to our best knowledge. However, we compared the historical simulations with the ERAI-HCLIM38-ALADIN runs.

Furthermore, we assessed whether there was an additional value of using the computationally heavier high-resolution HCLIM38-AROME configuration over HCLIM38-ALADIN in terms of road weather predictions with RoadSurf (three-fold longer run time with four-fold storage space needed for RoadSurf simulation with HCLIM38-AROME data) by repeating all abovementioned evaluation steps for HCLIM38-AROME and comparing them to HCLIM38-ALADIN and observations.

Projected future driving and walking conditions

We analysed T_{RS}, driving conditions, road surface conditions, pedestrian conditions and zero-degree-crossing (ZDC) days for their temporal development and change in the mid-century (2041–2060) and end-century (2081–2100) compared to the historical period (1986–2005) in the northern and southern parts of FNS. Traffic and pedestrian conditions depict the level of hazard due to road or walkway slipperiness and weather.

To analyse the changes in occurrence of road surface conditions, we counted the average seasonal time fraction for each condition (dry, damp, wet, snow, frost, icy, partly icy) and compared mid-century and end-century results to the historical period, as well as ECE-RoadSurf and GFDL-RoadSurf results against each other. For further analysis, we also assessed the spatial distributions of the changes.

We repeated the same analysis for the driving conditions (normal, difficult, very difficult) and pedestrian conditions (normal, slippery, very slippery I, II and III). The driving condition “very difficult” occurs rarely and only for short periods during extreme weather events, such as heavy snowfall. For this reason, the “difficult” and “very difficult” driving categories were grouped into one.

ZDC-days give valuable information as most traffic accidents happen when T_{RS} is close to 0 °C (Andersson & Chapman, 2011a). We defined a ZDC-day as a day on which the T_{RS} (at least once) drops from above + 0.5 °C to below − 0.5 °C (or vice versa) causing freezing of water (or melting of ice and snow) on the road surface. We calculated monthly averages of ZDC-days. Subsequently, we calculated the change in average seasonal ZDC-days over the century compared to the historical period and performed a Student’s *t*-test. We also compared the PDFs of historical and future ZDC-days estimates between GFDL-RoadSurf and ECE-RoadSurf.

Results

Evaluation against observations

We compared T_{RS}, PDFs, MMB and MAE of HCLIM38-ALADIN-RoadSurf and HCLIM38-AROME-RoadSurf driven by the ERAI reanalysis data to observations in FNS to quantify if the higher horizontal resolution of HCLIM38-AROME configuration brought benefits over HCLIM38-ALADIN when used as an input in RoadSurf. Means, temporal variation and seasonal patterns of modelled road surface temperature (T_{RS}) and road surface conditions agreed well with observations in Finland, Norway and Sweden (FNS).

The PDFs showed that both HCLIM38 configurations reproduced observations almost interchangeably well, with a small exception for spring in Finnish Lapland, where HCLIM38-AROME estimated stronger variability around 0 °C than observed (not shown).

The MAE showed that both HCLIM38 configurations reproduced observed T_{RS} accurately over flat inland regions. For Norway however, both HCLIM38 configurations became increasingly inaccurate. In the Norwegian mountains and northern Norwegian Fjords, HCLIM38-AROME showed better results. This may be attributed to the fact that HCLIM38-AROME can resolve topography-related features better than HCLIM38-ALADIN. However, considering all the above results, the improvement was not deemed sufficient to warrant the use of computationally more expensive HCLIM38-AROME simulations for the climate change analysis.

HCLIM38-ALADIN-RoadSurf driven by three different boundary data, the ERAI, ECE-historical and GFDL-historical, reproduced T_{RS} observations satisfyingly over Finland, but produced slightly lower autumn- and wintertime T_{RS} compared to observations in Sweden and Norway (Fig. 1). The inaccuracy in the simulated wintertime T_{RS} over Norway might stem from topography inaccuracies on the one hand, and sensors submerged in snow on the other. However, due to the lack of information which sensors were used (optical or asphalt-embedded, etc.), it is difficult to estimate the root cause for the negative bias.

ECE- and GFDL-RoadSurf both overestimated the occurrence of icy road surfaces whilst grossly underestimating frost (Online Resource F1a). Overestimation of icy surfaces was acceptable for the original near future (0–24 h) warning purposes of the model, but must be kept in mind when interpreting the future results in this study. GFDL-RoadSurf yielded more extreme under- and overestimations than ECE-RoadSurf.

The ECE- and GFDL-RoadSurf driving conditions agreed very well with the ERAI reanalysis (Online Resource F1b). GFDL-RoadSurf produced overall more frequent occurrence of difficult driving conditions, with the largest model differences in Finnish Lapland.

Despite the small discrepancies between the modelled and observed road weather parameters, we concluded that the overall performance of RoadSurf was satisfying for this study.

Projected future driving and walking conditions

Road surface temperature

We calculated the whole-period mean of T_{RS} for the historical period (1986–2005), mid-century (2041–2060) and end-century (2081–2100). Both ECE-RoadSurf and GFDL-RoadSurf estimated a clear increase in T_{RS} for all parts of FNS (Fig. 2). Whilst 46.9%/43.5% (ECE-RoadSurf/GFDL-RoadSurf) of historical monthly T_{RS} means over the whole domain were below 0 °C, in the mid-century this dropped to 39.8%/36.4% and even further to only 29.7%/23.9% in the end-century period.

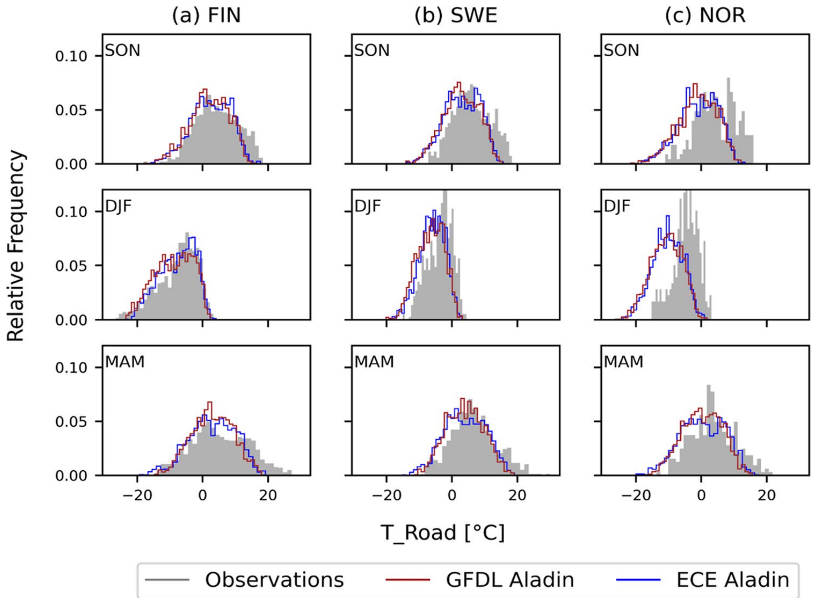

Fig. 1 Comparison of daily road surface temperature observations and simulations for **a** Finland (FIN, left column), **b** Sweden (SWE, middle column) and **c** Norway (NOR, right column) in autumn (September–October–November; SON, top row), winter (December–January–February; DJF, middle row) and spring (March–April–May; MAM, bottom row) driven by ECE-HCLIM38-ALADIN (ECE Aladin) and GFDL-HCLIM38-ALADIN (GFDL Aladin). The simulations covered the historical period 2002–2005 and the observations covered 2002–2005 over Finland and 2015–2018 over Sweden and Norway

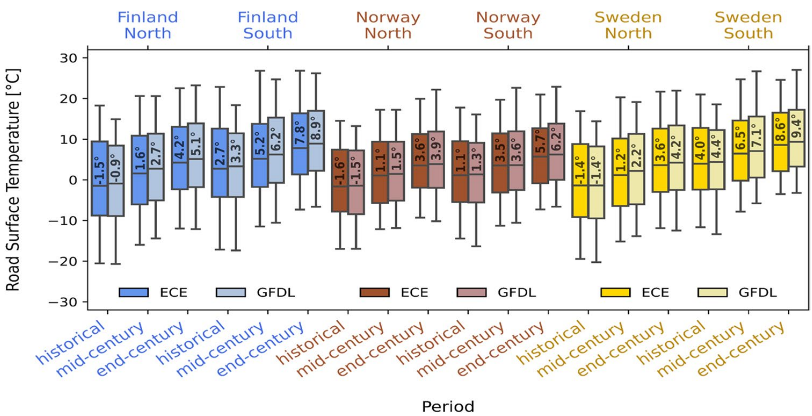

Fig. 2 Average regional road surface temperatures over the whole historical (1986–2005), mid-century (2041–2060) and end-century (2081–2100) periods in the northern and southern halves of Finland (blue), Norway (brown) and Sweden (yellow). The boxes enclose the first and third quartile. The numbers inside the boxes represent the region's median road surface temperature in the given period in °C. The whiskers represent the minimum and maximum simulated temperatures simulated by ECE-HCLIM38-ALADIN-RoadSurf (ECE, dark shades) and GFDL-HCLIM38-ALADIN-RoadSurf (GFDL, light shades) following the RCP8.5 scenario

During autumn (September to November, SON), T_{RS} increased 2.5 °C/3.7 °C on average in the mid-century period and 4.9 °C/6.8 °C in the end-century, compared to historical values (Fig. 3 and Online Resource F3). A slight north–south gradient in T_{RS} increase was simulated to intensify over the course of the century for autumn as well.

The strongest T_{RS} warming was simulated for meteorological winters (December to February, DJF), with an average increase of 2.7 °C/3.9 °C in the mid-century and a 6.2 °C/7.2 °C increase in the end-century.

GFDL-RoadSurf simulations showed an extreme T_{RS} increase of > 4.5 °C regionally in Finland (especially south-eastern Finland) during the mid-century, which intensified and extended into the Norwegian mountain range and its entire piedmont with > 8 °C increase in the end-century period.

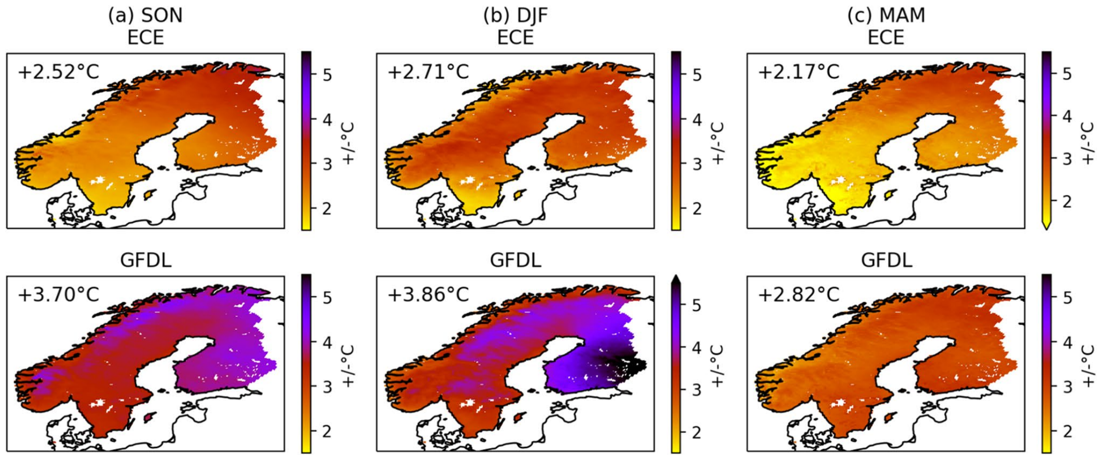

Fig. 3 Projected seasonal road surface temperature change in Finland, Norway and Sweden in the mid-century period (2041–2060) compared to the historical period (1986–2005) **a** autumn (SON, left column), **b** winter (DJF, middle column) and **c** spring (MAM, right column), as estimated by ECE-HCLIM38-ALADIN-RoadSurf (ECE, top row) and GFDL-HCLIM38-ALADIN-RoadSurf (GFDL, bottom row) in the RCP8.5 scenario. Displayed in the top left corners are the road surface temperature changes averaged over the whole region for the corresponding season (for the end-century see Online Resource F3)

ECE-RoadSurf, on the other hand, simulated an almost uniform T_{RS} increase across the three countries in mid-century winter, except for weaker T_{RS} increase in the southern tip of Sweden. A strong acceleration in T_{RS} warming occurred in end-century with > 7.5 °C regional T_{RS} increase in the northern parts of FNS. This roughly agreed with the estimated warming from the GFDL-RoadSurf simulations.

Springtime T_{RS} values (March to May, MAM) warmed 2.2 °C/2.8 °C in the mid-century and 4.6 °C/5.0 °C in the end-century. Whilst GFDL-RoadSurf showed a spatially uniform T_{RS} increase, ECE-RoadSurf estimated a noticeably weaker T_{RS} warming for southern Norway and Sweden, with partially < 1.5 °C T_{RS} increase (compared to > 2.5 °C in more northern latitudes) in the mid-century and < 4 °C (compared to > 5 °C in more northern latitudes) in the end-century period during spring.

Road surface conditions

We calculated the change in occurrence of road surface conditions (dry, damp, wet, snow, frost, icy, partly icy) in the mid-century and end-century compared to the historical period.

The simulations for the cold season from September to May showed an overall decline in snowy and icy road surfaces with up to 17.3/23.0 percentage points (PPs) less in the mid-century and up to 39.6/47.0 PPs less in the end-century (Fig. 4). Autumn and spring showed large changes during the mid-century and a decelerated change until the end-century. The strongest changes were indicated for autumn with a combined average decrease of 9.5/14.7 PPs in snow and ice storages on roads in the mid-century and a decrease of 17.4/22.5 PPs in the end-century. Hence, dry roads were simulated to be 7.7/10.1 PPs more frequent in mid-century autumn and 13.4/15.6 PPs more frequent in end-century autumn, compared to historical ones. Spring showed 3.0/4.4 PPs more frequent dry road surface conditions for mid-century and 7.5/7.0 PPs more frequent for end-century.

The net change in the occurrence of road surface conditions in DJF in Fig. 4 seems to be small compared to the change seen in SON, especially in the mid-century, which might leave the illusion that mid-century winters were simulated to expect as much snow and ice on roads as in the historical period. Further investigation however showed that the small net change was attributed to strongly contrasting, region-dependent developments.

Whilst northern parts of FNS showed a 1–9/9–15 PPs shift towards icy road surface conditions in winter, southern Finland and the southern tip of Sweden showed a 3–11/0–21 PPs increase in dry winter road surface conditions. Snowy road surfaces in the Norwegian mountain range, central Sweden and elevated parts of Lapland increased by up to 6.4/6.4 PPs in the mid-century estimates, but decreased by the same amount for southern Sweden, southern Finland and the Norwegian fjords. In autumn and spring, almost all regions showed drier road surface conditions, possibly due to earlier snow melt, except for the glacial regions of Norway, where the earlier onset of spring caused an increase of 0–5/0–5 PPs in wet road surface conditions as well as slight increases

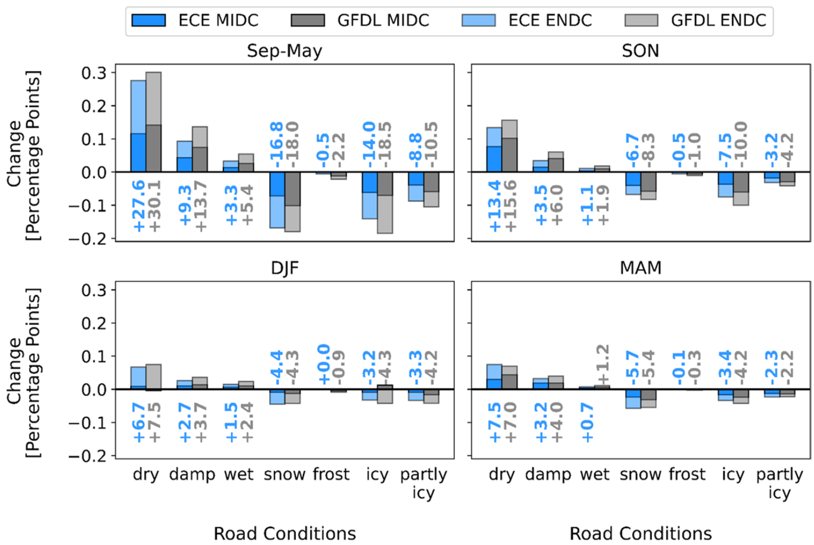

Fig. 4 Projected changes in occurrences of road surface conditions in the cold season from September to May (September until May), autumn (SON), winter (DJF) and spring (MAM) during mid-century (MIDC, 2041–2060, dark bars) and end-century (ENDC, 2081–2100, light bars) compared to the historical period (1986–2005) in Finland, Norway and Sweden as estimated by ECE-HCLIM38-ALADIN-RoadSurf (ECE, blue bars) and GFDL-HCLIM38-ALADIN-RoadSurf (GFDL, grey bars) under the RCP8.5 scenario. The bar labels show the resulting change by the end of the century compared to the historical period in gained or lost percentage points

Table 2 Average historic ratio of road surface conditions (HIST) in percent and change in road surface condition occurrences for the mid-century (MIDC) and end-century (ENDC) in percentage points compared to the historic period in the northern and southern halves of Finland, Norway and Sweden. Results are shown in the format "ECE-RoadSurf estimates/GFDL-RoadSurf estimates" with increases in green and decreases in red

Region	Period	dry [±PPs]	damp [±PPs]	wet [±PPs]	snow [±PPs]	frost [±PPs]	icy [±PPs]	partly icy [±PPs]
Finland North	HIST	57.9% / 54.8%	3.6% / 3.9%	0.7% / 0.9%	9.7% / 11.1%	1.7% / 1.5%	16.6% / 17.6%	7.0% / 7.4%
	MIDC	+2.2 / +3.2	+0.8 / +1.5	+0.3 / +0.5	-1.5 / -2.5	0.0 / -0.4	-0.7 / -0.6	-1.1 / -1.8
	ENDC	+6.1 / +6.6	+1.8 / +2.9	+0.7 / +1.2	-3.4 / -3.9	**-0.2 / -0.6**	-2.6 / -3.0	-2.4 / -3.2
Finland South	HIST	63.1% / 60.9%	4.8% / 5.1%	1.2% / 1.4%	7.7% / 8.1%	1.4% / 1.4%	13.4% / 14.8%	5.2% / 5.2%
	MIDC	+ 3.9 / +4.0	+0.9 / +1.9	+0.2 / +0.6	-1.8 / -2.1	0.0 / -0.4	-1.8 / -2.3	-1.4 / -1.7
	ENDC	**+9.5 / +9.6**	+1.9 / +3.6	+0.6 / +1.1	-3.9 / -4.2	**-0.2 / -0.6**	**-5.0 / -6.3**	**-2.9 / -3.2**
Norway North	HIST	51.7% / 48.1%	5.0% / 4.0%	1.4% / 1.1%	15.6% / 17.1%	1.2% / 1.4%	14.3% / 17.2%	6.4% / 7.1%
	MIDC	+3.2 / +2.5	+1.6 / +2.3	+0.7 / +0.9	-3.7 / -3.9	+0.2 / -0.2	-0.7 / -0.4	-1.2 / -1.3
	ENDC	+6.6 / +4.9	**+4.2 / +4.6**	**+1.8 / +2.0**	**-7.5 / -6.4**	+0.1 / -0.4	-2.7 / -2.2	-2.5 / -2.5
Norway South	HIST	57.2% / 53.8%	6.4% / 6.4%	2.4% / 2.5%	12.8% / 14.6%	1.5% / 1.2%	12.4% / 13.3%	4.9% / 5.3%
	MIDC	+2.2 / +2.3	+1.3 / +2.6	+0.7 / +1.4	-1.9 / -3.5	-0.1 / -0.2	-1.6 / -1.5	-0.7 / -1.1
	ENDC	+4.5 / +5.1	+2.7 / +4.3	**+1.5 / +2.6**	-4.5 / -5.9	-0.2 / -0.4	-2.4 / -3.7	-1.6 / -2.0
Sweden North	HIST	55.5% / 51.1%	3.7% / 3.5%	0.7% / 0.8%	11.3% / 13.8%	1.9% / 1.7%	17.6% / 18.3%	6.3% / 7.2%
	MIDC	+1.9 / +2.4	+0.7 / +1.4	+0.3 / +0.5	-1.2 / -2.1	0.0 / -0.3	-1.1 / -0.6	-0.6 / -1.4
	ENDC	+4.7 / +4.4	+1.7 / +2.9	+0.8 / +1.3	-3.2 / -3.5	-0.1 / -0.5	-2.1 / -2.2	-1.7 / -2.3
Sweden South	HIST	67.6% / 62.8%	5.3% / 5.4%	1.4% / 1.5%	6.3% / 8.0%	1.7% / 1.4%	12.4% / 14.6%	3.3% / 4.2%
	MIDC	+3.9 / +5.0	+0.9 / +1.7	+0.1 / +0.5	-1.5 / -2.5	-0.1 / -0.3	-2.5 / -2.9	-0.8 / -1.4
	ENDC	**+8.2 / +9.9**	+1.6 / +2.5	+0.4 / +0.9	-3.5 / -4.2	-0.2 / -0.5	-4.6 / -6.1	-1.9 / -2.5

(< 5 PPs) in icy and partly icy road surface conditions in the mid-century, which is most probably connected to the simultaneous increase in ZDC days (see section "Zero-degree-crossing days") in these regions. Changes in road surface condition occurrences of the regions are listed in Table 2.

Driving conditions

We calculated the change in driving condition occurrences (normal, difficult, very difficult) from historical to mid- and end-century.

"Normal" driving conditions increased strongly in all parts of FNS. The mid-century cold season (September until May) showed a 12.2/18.5 PP increase of normal driving conditions, which increased to + 28.5/33.2 PPs for the end-century compared to the historical period (Fig. 5a). The strongest increase of easier driving conditions was seen in autumn with + 6.3/9.8 PPs in the mid-century and + 11.2/14.3 PPs by the end-century, followed by spring with + 3.7/5.0 PPs in the mid-century and + 8.6/8.6 PPs in the end-century.

Winter showed a moderate change at first with only + 2.2/3.6 PPs in mid-century, but a strong acceleration of change for end-century with an + 8.7/10.3 PPs increase in normal driving conditions.

ECE-RoadSurf simulated the strongest increases in normal driving conditions along the Norwegian coasts and the southern half of Finland (Fig. 5b and Online Resource F4). GFDL-RoadSurf estimated an overall stronger change with the largest changes in southern Norway, southern Finnish Lapland and the valleys of the Scandinavian mountains.

Pedestrian conditions

We calculated the occurrence of pedestrian conditions normal, slippery and very slippery (VS) I, II and III in the historical, mid-century and end-century periods.

The projected walking conditions showed strong seasonality as well as regional differences. Generally, in the cold season between September and May, the pedestrian condition "slippery" was estimated to decrease by 7.0/8.5 PPs in the mid-century and 18.4/18.4 PPs in the end-century, compared to the historical period. An increase was simulated for "normal" (+ 4.9/5.0 PPs mid-century and + 17.7/11.8 PPs end-century) and "VS II" (+ 3.9/5.3 PPs mid-century and + 6.9/11.8 PPs end-century) (Fig. 6).

Similarly, to the changes in driving conditions, the strongest changes in pedestrian conditions were seen for autumn, during which "normal" walking conditions increased by an average 7.8/11.5 PPs for mid-century and 14.3/17.5 PPs for end-century. The most strongly affected regions were the Norwegian fjords and the piedmont of the Scandinavian mountains (Online Resource F6). Estimates for winter showed a clear shift from "normal" conditions towards "slippery" pedestrian indices with the strongest increase in "VS II" (+ 2.9/4.1 PPs in mid-century and + 6.8/10.6 PPs in end-century).

Almost all regions show this increase, except for the southern tip of Sweden and in the south-western coastline of Norway, where the "slippery" indices decreased. Spring

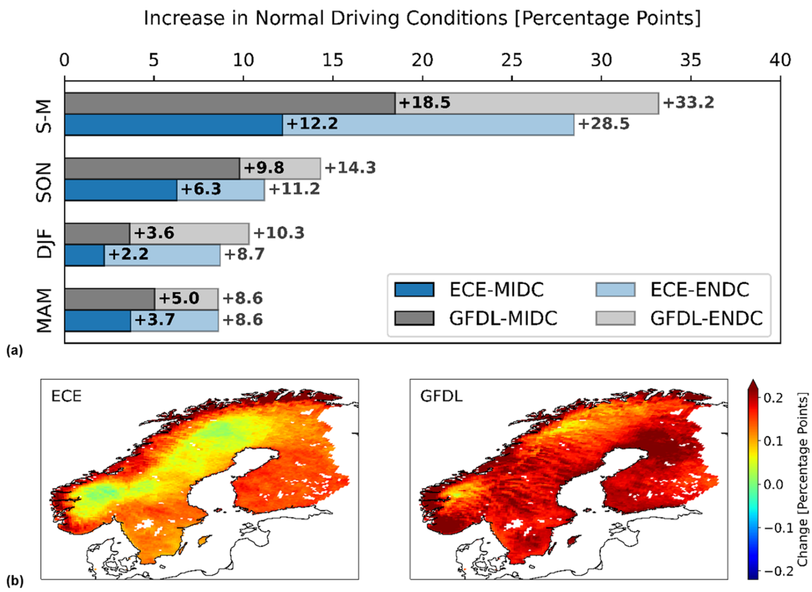

Fig. 5 **a** Increase in "normal" (less dangerous) driving conditions in percentage points for autumn (SON), winter (DJF) and spring (MAM) and the cold season from September to May (S-M) in the mid-century (MIDC, 2041–2060, dark bars) and end-century (ENDC, 2081–2100, light bars) compared to the historical period (1986–2005) in Finland, Norway and Sweden. **b** Changes in "normal" driving conditions during the mid-century cold season from Septemeber to May (275 days in total) compared to the historical period in Finland, Norway and Sweden (for the end-century see Online Resource F4). Estimates by ECE-HCLIM38-ALADIN-RoadSurf (ECE, **a** blue bars/**b** left side) and GFDL-HCLIM38-ALADIN-RoadSurf (GFDL **a** grey bars/**b** right side) with the RCP8.5 scenario

showed a slight increase in "VS II" condition too, with a 1.0/1.8 PP increase for mid-century and 1.1/3.0 PP increase for end-century. However, the "normal" condition increased simultaneously by 1.6/2.6 PPs mid-century and 7.0/4.8 PPs end-century. These changes affected mostly the Norwegian fjords and the Scandinavian mountain range.

Zero-degree-crossing days

We calculated the seasonal average number of ZDC-days, i.e. days when T_{RS} decreased from minimum + 0.5 °C to − 0.5 °C (or vice versa). ECE-RoadSurf and GFDL-RoadSurf estimated a mostly steady increase in winter ZDC-days and decrease in autumn and spring (attributed to the later onset and earlier end of cold winter temperatures), however with strong regional differences (Fig. 7).

Regions above the Arctic Circle and around the Norwegian mountain range showed minor changes (max. ± 2 ZDC-days) in all seasons during the mid-century (Fig. 7). Finnish regions south of the Arctic Circle showed 2–3/3–6 additional ZDC-days on average in mid-century winter, with the strongest increase in south and south-west Finland. The same regions showed an estimated decrease of 2–4/4–5 ZDC-days in autumn and a decrease of 1–5/3–7 ZDC-days in spring.

Other considerable changes in mid-century ZDC-days were simulated for the Norwegian fjords, southern Sweden and Swedish regions around the Bothnian sea. Mid-century winters showed 1–4/0–1 fewer ZDC-days to regions around the Kattegat strait and 3–5/4–6 more ZDC-days to regions around the Bothnian sea. Autumns of southern Sweden and the Norwegian fjords showed 3–5/3–5 fewer ZDC-days, whilst spring showed 2–5/4–8 more ZDC-days compared to the historical period.

The number of ZDC-days increased even more in wintertime by the end of the century (Online Resource F7). End-century simulations for regions north of the Arctic Circle showed 1–5/2–5 more wintertime ZDC-days, as well as 0–3/1–4 fewer autumn and 0–4/0–5 fewer spring ZDC-days. An increase of 4–10/4–10 wintertime ZDC-days was simulated for almost all regions in FNS below the Arctic Circle (with exception of the southern tip of Sweden with 0–5/0–5 fewer winter ZDC-days). The same regions showed 3–6/4–7 fewer autumn and 3–8/5–13 fewer spring ZDC-days.

The Student's *t*-test concluded all the above shown results of changes in ZDC-days to be statistically significant on a 5% level compared to the historical ZDC-days.

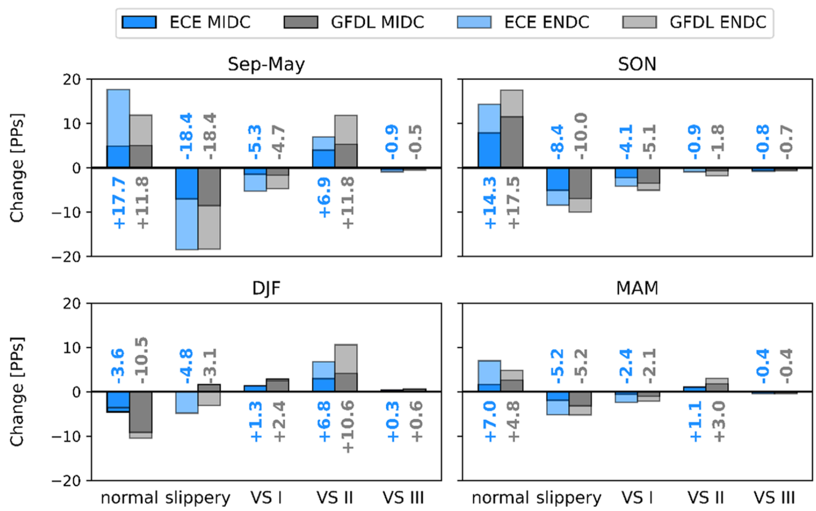

Fig. 6 Projected changes in the occurrences of pedestrian conditions (in percentage points (PPs)) in the cold season from September to May (Sep–May), autumn (SON), winter (DJF) and spring (MAM) during mid-century (MIDC, 2041–2060) and end-century (ENDC, 2081–2100) compared to the historical period (1986–2005) in Finland, Norway and Sweden as estimated by ECE-HCLIM38-ALADIN-RoadSurf (ECE, blue bars) and GFDL-HCLIM38-ALADIN-RoadSurf (GFDL, grey bars) in the RCP8.5 scenario for the pedestrian indices normal, slippery, very slippery due to foot-packed snow (VS I), very slippery due to water above ice layer (VS II) and very slippery due to snow above ice layer (VS III) over the whole domain, where the bar labels show the resulting change by the end of the century compared to the historical period (for the map view see Online Resource F6)

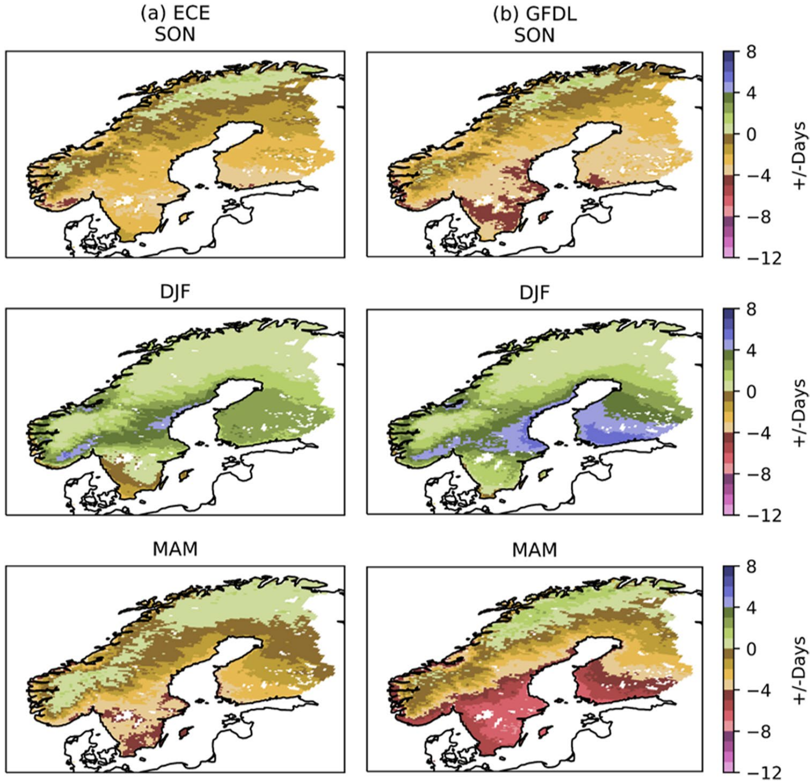

Fig. 7 Change in the average seasonal number of zero-degree-crossing days in the mid-century (2041–2060) compared to the historical period (1986–2005) during autumn (SON, top row), winter (DJF, middle row) and spring (MAM, bottom row) estimated by **a** ECE-HCLIM38-ALADIN-RoadSurf (ECE, left column) and **b** GFDL-HCLIM38-ALADIN-RoadSurf (GFDL, right column) under the RCP8.5 scenario. For the end-century (2081–2100) results see Online Resource F7

Discussion and conclusions

In this study, we assessed the climate change impacts on driving and walking conditions in Finland, Norway and Sweden (FNS) based on simulations carried out with FMI's road weather model RoadSurf driven by ECE-HCLIM38-ALADIN and GFDL-HCLIM38-ALADIN (ECE-RoadSurf and GFDL-RoadSurf, respectively). Our results are based on the RCP8.5 scenario, a worst-case climate change scenario that anticipates an unprecedented increase in greenhouse gas emissions. Therefore, our simulations are upper extreme estimates, but can serve as a reference of locality and seasonality of the expected changes, and thus help local decision-makers to plan for mitigation and adaptation measures ahead of time.

We concluded that the model performance was accurate enough to carry out the climate change projections for this study, albeit RoadSurf was shown to overestimate dry and icy road surface conditions. The considerably lower computational expense of the HCLIM38-ALADIN configuration allows a wider set of modelled road weather scenarios and is generally preferable, however at the cost of losing topographical features compared to the HCLIM38-AROME configuration, which should be considered for studying regions with large elevation differences.

Our simulations suggested a strong increase in the average annual road surface temperatures (T_{RS}), with the strongest regional T_{RS} increases in southern Finland and southern Sweden. Winters showed an increase in water above ice on walkways (except for the southern tip of Sweden). Autumn and spring, however, showed a decrease in slippery pedestrian conditions. Hence, the future pedestrian slip-injury season might be shorter, mostly confined to winter, but with an exacerbated risk for slipping. Zero-degree-crossing days (ZDCs-days) were estimated to decrease in autumn and spring (apart from an increase north of the Arctic Circle), but to increase in winter. An increasing number of ZDC-days is a major hazard for pedestrians, as temperatures near 0 °C pose one of the greatest risks for pedestrian slip accidents (Hippi et al., 2020).

The results also showed a decrease in snowy, frosty and icy road surface conditions and an increase in dry, damp and wet road surface conditions. As a result, there was a strong decrease in difficult driving conditions during the cold season between September and May.

This is congruent with studies of countries with comparable climates like Canada, where 43% less slippery-related accidents and less road maintenance costs were estimated due to the easier driving conditions (Andersson & Chapman, 2011b). Intuitively, one could expect less traffic accidents due to slippery roads based on our results (Norrman et al., 2000). However, in different studies, the number of accidents did not change in less slippery road conditions, as they evened out with drivers paying less attention in less dangerous driving conditions (Andersson & Chapman, 2011a; Bernard et al., 2001). The combination of more frequently wet roads and more ZDC-occurrences observed in our study could still be exacerbating the risk for traffic accidents, as slippery conditions near 0 °C might be less apparent to drivers (than e.g. snow-covered roads); thereby, drivers could be at risk of underestimating the immediate slip risk and not adjust their level of attention.

As climate change progresses, it is important to understand and be ready for the changes to come. Our results motivate us to recommend road managers and authorities in Nordic countries—amongst others, Destia, Traficom and Fintraffic in Finland, Trafikverket in Sweden and Statens vegvesen in Norway—to plan actions and secure necessary budgets for managing the shorter, but more intense, slippery roads and walkways in the future successfully.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-022-01920-4.

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Data availability The data analysed in this paper can be accessed through the https://doi.org/10.23728/fmi-b2share.8be17e3ebccf4ff f869fd5ddaab7361d.

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