Effects of Recent Temperature Variability and Warming on the Oulu-Hailuoto Ice Road Season in the Northern Baltic Sea

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Highlights

- Oulu-Hailuoto ice road season shortened in 1974-2009, due mainly to later start days
- Ice road season (IRS) started later due to declines in freezing degree-days of Oct-Jan
- Increase in thawing degree-days of Feb-Apr caused IRS to end earlier
- Arctic Oscillation affected both freezing degree-days (Oct-Jan) and IRS start days
- East Atlantic influenced both thawing degree-days (Feb-Apr) and IRS end days

Abstract

In cold climate regions, ice roads are engineered as temporary winter transportation routes on frozen lakes, rivers and seas. The ice road season start, end and duration principally depend upon ice thickness, which is controlled by surface air temperature (SAT) in terms of freezing and thawing degree-days (FDD and TDD, respectively). Both FDD and TDD are indicators of climate variability and change, and are naturally
influenced by large-scale atmospheric circulation patterns (ACPs). This study examined the role of ACPs in interannual variations in the operating season of the Oulu-Hailuoto ice road in the Bay of Bothnia, northern Baltic Sea, during 1974-2009. Significant (p<0.05) shortening in duration of the ice road season, mainly attributable to later start and earlier end days, was observed. In the Oulu-Hailuoto area, maximum ice thickness showed significant declines over time. This sea ice thinning was associated with SAT warming in cold months, manifested by statistically significant decreases in cumulative FDD during October-January within the water year (September-August). Significant increases in cumulative TDD during February-April, reflecting warmer SAT in mild months, resulted in earlier end day for the Oulu-Hailuoto ice road season. The Arctic Oscillation (AO) was the most influential ACP for variations in cumulative FDD (October-January), and accordingly for sea ice thickness and start day of the Oulu-Hailuoto ice road season. However, cumulative TDD (February-April) showed significant positive correlations with the East Atlantic (EA) pattern, which also controlled the end day of the Oulu-Hailuoto ice road season.

Key words: Ice road season; atmospheric circulation pattern; ice thickness; Baltic Sea.

1 Introduction

In cold climate zones, roads generally cross the frozen land, lakes, rivers and seas during every winter. Such wintertime routes over land are commonly known as winter roads, while over water bodies as ice roads (e.g. ACIA, 2005). Both winter and ice roads are mainly engineered for linking the remote communities and the different industry (e.g. mining, oil and gas) to all-season gravel and/or paved roads. These winter transportation corridors also facilitate bringing in heavy machinery, supplies and fuel that might contrarily be shipped only by air cargo services that seems very expensive option (Hinzman et al., 2005). Hence, it is very important for both communities and industries that the winter/ice roads open as soon as possible, if weather allows efficient and safe road construction phases.

Establishment of ice roads is fundamentally dependent on the ice thickness, which must be sufficient to support safe public and commercial traffic (Masterson, 2009; Mesher et al., 2008; Rawlings et al., 2009). The ice dynamics naturally responds to variations and changes in surface air temperature (SAT),
precipitation amount and type (rainfall and snowfall), wind speed, convection, insolation and evaporation (Williams and Stefan, 2006). In northern Europe, the Baltic Sea ice growth is largely sensitive to the exchange of heat between sea water and air, the ice/snow surface radiative and turbulent heat transfers, the effects of precipitation, and the ice bottom heat flux (Launiainen and Cheng, 1998; Cheng et al., 2003). Controlling both freezing and thawing of water, SAT principally influences the Baltic Sea ice thickness and extent (Lafrance, 2007; USACE, 2002; Williams et al., 2004). Likewise, it plays a critical role in the shifting of precipitation falling form liquid (rain) to solid (snow) (Räisänen, 2008), although relative humidity is also influential (Matsuo et al., 1981; Motoyama, 1990). The interaction between snow and ice is complicated because of two dissimilar effects of snow on ice dynamics: i) the ice thickness increases due to the transformation of snow into ice, and ii) the ice thickness decreases due to the thermal insulation ability of snow (Cheng et al., 2003, 2014). In fact, SAT and precipitation are the most influential thermodynamic factors for the Baltic Sea ice growth on seasonal scale. Hence, the Baltic Sea ice forms in early November, reaches its annual maximum thickness during February, starts melting in April, and usually disappears in May (e.g. Drusch, 2006; Merkouriadi and Leppäranta, 2015).

Variations in regional SAT and precipitation are generally influenced by atmospheric circulation patterns (ACPs), e.g. the North Atlantic Oscillation (Hoy et al., 2013; Omstedt et al., 2004; Trigo et al. 2002). These patterns principally reveal the long-term behaviour in natural incidence of chaotic deviations in the atmospheric characteristics of the Earth (e.g. Moron et al., 1998; Thompson and Wallace, 2000). Reflecting shifts in atmospheric waves and jet streams (Hurrell and Van Lonn, 1997; Thompson and Wallace, 2001), ACPs also affect the global climate system (Nicholls et al., 1996). The ACPs are periodic, insistent and large modes of pressure anomalies, commonly expressed by numerical indices that describe the strength and effects of airflow circulation across a wide geographical area during a specific period of the year (Chen and Chen, 2003; Hurrell, 1995). Glantz et al. (2009) provides a comprehensive review of the main features of large-scale ACPs and their natural influences on variations in climate conditions, particularly SAT and precipitation, in different parts of the world.

Strong relationships have been reported between ACPs and ice cover formation (e.g. Bonsal et al., 2006; Comiso, 2012; Ghanbari et al., 2009; Jervejeva et al., 2003), providing an opportunity to improve knowledge
of interannual variability in the winter/ice road season in cold regions. Affecting SAT and precipitation, in fact, ACPs can significantly control ice thickness and extent, and consequently all construction phases, usability and seasonality of winter/ice roads. Knowland et al. (2010) concluded that extremely late opening years of the Tulita-Norman Wells ice road across the Northwest Territories in Canada were significantly correlated with strong El Niño seasons. In addition, Zell (2014) reported that the shorter season of the Tibbitt-Contwoyto winter road in the Northwest Territories in 1998 was strongly connected to the El Niño/Southern Oscillation (ENSO; e.g. Moritz et al., 2002). Moreover, ENSO was the most influential atmospheric driver of substantially shorter (26 days below normal) Tibbitt-Contwoyto winter road season in 2006 (e.g. Macumber et al., 2012). In the Baltic Sea, ACPs influencing the ice cover extent and season (e.g. Karpechko et al., 2015; Jervejeva and Moore, 2001; Omstedt and Chen, 2001; Uotila et al., 2015; Vihma and Haapala, 2009) have received much more attention than those influential ACPs for the ice thickness variability (e.g. Koslowski and Loewe, 1994; Vihma et al., 2014; Merkouriadi and Leppäranta, 2015). However, information on the role of ACPs in the interannual variability of winter/ice roads season in the Fenno-scandinavian region, particularly the Baltic Sea, is still lacking.

The overall aim of this study was to identify ACPs explaining interannual variations in the documented seasonality of an ice road between the Hailuoto Island in the Bay of Bothnia (northern Baltic Sea) and mainland (the bay offshore of Oulu) during recent decades. This ice road is located in the land-fast ice zone, where the thickness of sea ice is largely controlled by thermodynamics (Leppäranta, 2013). Vihma et al. (2014) concluded that precipitation amount and type (rainfall and snowfall) have a weak or no effect on sea ice thickness growth in the vicinity of Oulu-Hailuoto ice road due to their compensating positive and negative contributions. They also reported no clear relationships between wind speed and the sea ice thickness in the Bay of Bothnia. Besides, there is not much information about the ice drift and the effects of autumn sea heat content on the ice dynamics in the Bay of Bothnia. Hence, this study only focused on ACPs significantly associated with the Oulu-Hailuoto operating season by influencing recent SAT variability and warming. Specific objectives were to: 1) evaluate variability and trends in Oulu-Hailuoto ice road season parameters (in terms of start, end and duration) over the period 1974-2009; 2) investigate variations in annual maximum ice thickness and the corresponding day in the northern Baltic Sea; 3) determine historical changes
in SAT over the Oulu-Hailuoto region; and 4) measure the correlations between road season parameters, SAT, annual maximum ice thickness and date, and well-known ACPs. The results can be used as perquisite knowledge to forecast the ice dynamics (e.g. Omstedt and Chen, 2001; Chen and Li, 2004; Luomaranta et al., 2014) for efficient construction planning of winter/ice roads, particularly in the northern Baltic Sea. This study also intended to improve understanding of natural climate variability effects on cold environments and societies.

2 Material and methods

2.1 Study area and data used

Hailuoto is the largest island in the Bay of Bothnia, the northern Baltic Sea, with the shortest distance of 8 km from the northeastern part of the bay offshore Oulu (Fig. 1) (Leppäranta, 2013). Traffic between Hailuoto and mainland is connected by ferry during most of the year, while by an ice road in wintertime. The Oulu-Hailuoto ice road is very unique in the world as it is entirely constructed on the frozen, very shallow (<10 m) sea between the mainland and the island (Leppäranta, 2013). Although ice is rigid when it reaches a thickness of 30 cm, the thickness must be more than 40 cm for public transportation, 70 cm for commercial traffic (up to 3 tons) and 120 cm for a fully loaded timber truck (Leppäranta, 2013). The width of safe ice roads must be between 45 and 60 m (Lafrance, 2007). To increase the thickness and width of ice, the technique of flooding water from below onto the ice surface usually forms part of the ice road construction process (Lafrance, 2007). To facilitate such techniques and reduce their costs, the construction of ice roads is generally started when the ice thickness naturally reaches about 40 cm. After using, the ice road is normally closed when the ice thickness naturally drops under 40 cm. For maintaining satisfactorily high albedo, a thin layer (~10 cm) of compacted snow is always required over the ice road (GNWT, 2007). However, a thick snow cover impairs safe ice conditions by insulating the underlying cryosphere, and thus needs to be cleared (Lafrance, 2007).

In the past, the Oulu-Hailuoto ice road was open for 4-5 months (November-April/May), while it has only been in operation for 4-5 weeks (late February-March/early April) during recent years. Such shortening in the seasonality of Oulu-Hailuoto ice road might be related to thinner sea ice due mainly to climate warming.
Shorter ice road season forces the operation of ferry once per hour during the winter, adding CO2 emissions to the vicinity of Hailuoto Island. Thinner sea ice makes more difficult to maintain the ice road. Before opening, the development of ice thickness is always and continuously checked, and the ice road is equipped with the necessary warning system and other road signs. During recent decades, the Oulu-Hailuoto ice road was sometimes closed down, mainly for maintenance, clearing excessive snow, and enhancing the ice bearing capacity by artificially increasing its thickness. Besides, no dramatic accident or event related to the Oulu-Hailuoto ice road has been reported, based on our knowledge.

Oulu-Hailuoto ice road opening and closing dates for the period 1974-2009 were obtained from the Centre for Economic Development, Transport and the Environment (ELY Centre) in Finland. Long-term (1974-2009) sea ice thickness records at the Virpiniemi station (65°07.4’N, 25°14.2’E) of the Finnish Meteorological Institute (FMI), close to the Oulu-Hailuoto ice road, were also included in the analysis (Fig. 1b). The PaITuli-Spatial Data for Research and Teaching provided data on daily mean SAT (10 × 10 km²) throughout Finland for the period 1961-2011. To create its gridded datasets, FMI used daily mean SAT records at 100-200 stations scattered fairly uniformly within Finland as input to a spatial model developed by Henttonen (1991) based on the Kriging spatial interpolation technique (Ripley, 1981). The temporal variations in number of such temperature measurement stations, their locations, and all grid cells throughout Finland are given in our previous studies (e.g. Irannezhad et al., 2016). Such gridded SAT time series have previously been used by Tietäväinen et al. (2010), Vajda (2007), Irannezhad and Kløve (2015) and Irannezhad et al. (2015). The present study used gridded daily mean SAT around the Oulu-Hailuoto ice road, covering the area shown in Fig. 1b.

To study climate variability effects on the ice road, six different large-scale ACPs influencing climate variability in Finland (e.g. Irannezhad et al., 2014; 2015) were considered in this study: the Arctic Oscillation (AO), East Atlantic (EA), East Atlantic/West Russia (EA/WR), North Atlantic Oscillation (NAO), Polar/Eurasian (POL) and Scandinavia (SCA) patterns. Action centres and natural signs of these ACPs are summarised in Table 1. The Climate Prediction Center (CPC) at the National Oceanic and Atmospheric Admission (NOAA), USA, calculates standardised monthly values of these well-known ACPs. These values
(since January 1950) are freely accessible online at:


2.2 Ice road-related variables

Ice road season was determined based on three ice road season parameters: start (IRSS), end (IRSE) and duration (IRSD), where IRSS and IRSE refer to the opening and closing dates of the ice road, respectively, within the water year from September to August and IRSD is the number of days between IRSS and IRSE. Two variables of maximum ice thickness (MIT) and the corresponding date throughout the water year were employed for investigating sea ice conditions in the Oulu-Hailuoto area. Freezing and thawing degree-days (FDD and TDD, respectively), which are SAT-based variables controlling MIT (Zubov, 1945; Leppäranta, 1993), were also used. FDD and TDD are defined, respectively, as the negative and positive deviation of SAT from freezing point, which was assumed to be 0°C for this study (Leppäranta, 2013). Thus cumulative FDD and TDD over a certain period show how cold and warm, respectively, the weather has been and for how long (e.g. Merkouriadi and Leppäranta, 2015).

Cumulative FDD and TDD principally influence ice growth and melting processes during winter and spring, respectively. In the Oulu-Hailuoto area, sea ice formation usually begins in October, when SAT progressively declines to below 0 °C. Accordingly, the ice road season generally starts in January (Leppäranta, 2013). For every water year between 1974 and 2009, this study calculated the cumulative FDD during October-January as the corresponding SAT time series for IRSS, MIT and its corresponding day. The earliest end of the ice road season was observed in February, while the latest was in early May (Fig. 2c). Hence, cumulative TDD during February-April were computed as the SAT dataset for the end of the ice road season. The influential ACPs for the start of the ice road season, cumulative FDD, MIT and its corresponding day were calculated as the average of ACP standardised monthly values over the period October-January. For the end of the ice road season and cumulative TDDs, the influential ACPs were also computed by averaging their standardised monthly values within February-April.
2.3 Trend and correlation analyses

The Mann-Kendall non-parametric test (Kendall, 1975; Mann, 1945) was used to detect statistically significant (p<0.05) trends in ice road season parameters (IRSS, IRSE and IRSD), cumulative FDD and TDD (hereafter FDD and TDD), MIT and its corresponding day during 1974-2009. For calculating the slope of determined significant trends, the Sen method (Sen, 1968) was used, considering 95% confidence interval to acknowledge uncertainties (Helsel and Hirsch, 1992). Spearman rank correlation (rho) was used to measure significant (p<0.05) relationships between ice road season parameters, FDD and TDD, MIT and its corresponding day. It (rho) was also used for determining significant (p<0.05) correlations between ice road-related variables and different large-scale ACPs considered in this study. However, the trend-free pre-whitening method developed by Yue et al. (2002) was applied for time series that were positively auto-correlated. To estimate the standard deviation of rho values, the residual bootstrap method (Park and Lee, 2001) with 5000 independent replications was used. All these statistical methods have widely been applied in previous studies evaluating climate variability and change (e.g. Tabari et al., 2012; Irannezhad and Kløve, 2015).

3 Results and discussion

During 1974-2009, there was a significant shortening in Oulu-Hailuoto ice road season duration (-0.22±0.86 days/year). Such shortening was mainly referred to a later start (1.83±0.67 days/year) rather than the earlier end (-0.44±0.40 days/year) (Fig. 2). This was also supported by a stronger correlation of IRSD with IRSS than IRSE (Table 2). Likewise, Knowland et al. (2010) concluded that later starts played a key role in shortening the Tulita-Norman Wells ice road season in the Northwest Territories, Canada, during 1982-2006. Strandberg et al. (2014) also reported that a significant shift toward later opening date of Prudhoe Bay-Tundra winter road in Alaska was the main cause of its shorter operating window. By influencing ice growth processes, cold season SAT was the most important climate factor controlling such later openings of both the Tulita-Norman Wells (Knowland et al., 2010) and Prudhoe Bay-Tundra ice roads (Strandberg et al., 2014). Similarly, later start days of the Oulu-Hailuoto ice road season were significantly (rho = -0.82) associated with lower FDD (warmer weather) in October-January, which significantly (rho = 0.77) decreased MIT in
the study area (Table 2). Previous studies have also reported warmer winters (e.g. Irannezhad et al., 2015) and thinner sea ice (e.g. Launiainen et al., 2002; Vihma and Haapala, 2009; Vihma et al., 2014) in the Bay of Bothnia in recent decades.

Earlier ends to the Oulu-Hailuoto ice road season showed no clear connection with MIT, but a moderate positive correlation (rho = 0.41) with its corresponding day (Table 2). This may reflect the significant weak (rho = -0.23) and moderate (rho = -0.53) relationships between MIT and its corresponding day, respectively, and TDD in mild months from February to April (Table 2). In fact, warming in such TDD was inadequate to cause thinner MIT resulting in earlier IRSE, but was sufficient to shift the MIT corresponding date, and consequently IRSE, toward earlier in the water year. This is possibly confirmed by the significant link between IRSE and TDD (February-April), with rho = -0.57 (Table 2). This negative correlation indicates that warmer TDD results in earlier IRSE, and consequently shorter IRSD. Irannezhad et al. (2015) reported significant increases in spring (March-May) SAT over the Oulu-Hailuoto area during 1961-2011, but with smaller magnitude than in wintertime (December-February) warming trends. This may indicate a stronger effect of later start days in cold months than earlier season end days in mild winter months in shortening the duration of the Oulu-Hailuoto ice road season. Similarly, earlier closing days have been previously reported for the Prudhoe Bay-Tundra winter road in Alaska and the Tuk-Inuvik winter road in Canada (e.g. Strandberg et al. 2014). Knowland et al. (2010) point out that closing dates of winter ice roads are often associated with non-climatological factors like economic losses.

The long-term (1974-2009) average value (hereafter ‘base value’) for the duration of the Oulu-Hailuoto ice road season was 73 days (Fig. 2a), starting 19 January (Fig. 2b) and ending 7 April (Fig. 2c) during the water year. The shortest duration was 10 days, from 20 to 29 March 2008 (Fig. 2a), and was associated with the lowest MIT (35 cm on 17 March 2008) (Fig. 3) and the warmest mean SAT of cold months (indicated by the lowest FDD of 321.5 °C) (Fig. 4a). The smallest difference between FDD (October-January) and TDD (February-April) was about 230.1 °C in 2008, which was the warmest year during 1974-2009 (Fig. 4).

Previous studies have also reported the smallest annual maximum ice cover extent in the Baltic Sea during 2008 (e.g. Luomaranta et al., 2014; Vihma and Haapala, 2009), in which the very mild winter (Uotila et al., 2015; Vainio, 2011) resulted in MIT in the Bay of Bothnia being 30-50 cm below its typical level of 65-80
cm (Vihma and Haapala, 2009; Vihma et al., 2014). The present study also showed that MIT in 2008 (35 cm) was about 36 cm less than its base value of 70.9 cm (Fig. 3a). On the other hand, the longest duration of the Oulu-Hailuoto ice road season was 129 days, from 23 December 1986 to 30 April 1987 (Fig. 2a). Likewise, Uotila et al. (2015) reported that the Baltic Sea was almost entirely covered by ice during the severely cold winter of 1986/1987 (Vainio, 2011).

During 1974-2009, the AO index in cold months (October-January) played a key role in interannual variability in Oulu-Hailuoto ice road season start days (rho = 0.36) by negatively influencing FDD of these months (rho = -0.34) and consequently controlling MIT (rho = -0.33) (Fig. 5a-c and Table 2). Based on such significant relationships, hence, observed increasing trends in the AO index (e.g. Thompson et al., 2000; Ostermeier and Wallace, 2003; Jaagus, 2006) can partially explain warmer winters, thinner MIT, and later ice road season start days in the Bay of Bothnia. On the other hand, wetter climatic conditions associated with the upward trend in the AO index can lead to more snowfall in Finland, and consequently earlier ice road start days. Over central Finland covering the Oulu-Hailuoto area, however, the effects of warmer temperature are stronger than wetter weather on snowfall variability (Irannezhad et al., 2016, 2017; Räisänen, 2008), which has no influence on the growth of sea ice thickness (Vihma et al., 2014). Previous studies also reported such effects of the AO on precipitation and SAT across the Oulu-Hailuoto area (e.g. Irannezhad et al., 2014, 2015) and the Baltic Sea ice conditions (e.g. Vihma and Haapala, 2009). The AO index describes the power of the circumpolar vortex (Thompson and Wallace, 1998), which generally controls the annular mode of atmospheric circulation and the variability of SAT over the northern hemisphere (Thompson et al., 2000). Its positive phase is naturally associated with a strong westerly circulation and predominantly mild airflow over northern Europe, particularly during cold months (Thompson and Wallace, 1998; 2000). The AO largely consists of the NAO index (Serreze et al., 2000), which expresses the strength of westerly airflow from the North Atlantic to the Atlantic European sector (e.g. Hurrell, 1995). This close relationship between the AO and the NAO led most previous studies to focus only on the responses of Baltic Sea ice cover to the effects of shifts in the main mode of the NAO index (e.g. Omstedt and Chen, 2001; Uotila et al., 2015; Vihma and Haapala, 2009; Vihma et al, 2014) or wintertime SAT over northern Europe (e.g. Chen and Hellström, 1999; Irannezhad et al., 2015; Omstedt et al., 2004).
The EA pattern significantly (p<0.05) influenced interannual variability in the end of the Oulu-Hailuoto ice road season (rho = -0.37) by moderately (rho = 0.47) controlling TDD of mild months from February to April during the water years 1974-2009 (Fig. 5d and e). This pattern was defined based on the normalised 500 hPa geopotential height anomalies at two high pressure centres in the south-western Canary Islands and between the Caspian Sea and Black Sea, and also two lesser pressure centres to the west of the British Isles and over the centre of Serbia (Wallace and Gutzler, 1981). In general, the EA pattern describes westerly airflow from east Canada to central and southern Europe (Panagiotopoulos et al., 2002; Sáenz et al., 2001). In mild months, the positive phase of the EA pattern is associated with prevailing anomalous winds from the south naturally bringing warm and humid airflow towards northern Europe (Irannezhad et al., 2015). Hence, earlier and later end days of the Oulu-Hailuoto ice road season can principally be expected during the positive and negative phases of the EA, respectively.

In cold months (October-January) of 2008, the positive AO phase resulted in the warmest airflow (FDD of 321.5 °C) over the Oulu-Hailuoto area, the lowest MIT (35 cm) in the Bay of Bothnia, the latest start to the Oulu-Hailuoto ice road season (20 March) and the shortest duration of the season (10 days, from 20 to 29 March). On the other hand, the negative phase of the AO in cold months of 1987 was associated with persistent very cold winter weather, which resulted in great MIT (87.4 cm) occurring in 28 April 1987 and consequently the longest duration of the Oulu-Hailuoto ice road season (129 days from 23 December 1986 to 30 April 1987). Similarly, previous studies have reported that the severely cold and very mild winters in 1987 and 2008, respectively, were significantly associated with the strong positive and negative phases of the NAO index, forcing the largest and smallest annual maximum ice cover extent, respectively (e.g. Luomaranta et al., 2014; Uotila et al., 2015; Vihma and Haapala, 2009).

4 Conclusions

This study investigated the relationships between the seasonality of the Oulu-Hailuoto ice road in the Bay of Bothnia and large-scale atmospheric circulation patterns (ACPs). Important conclusions were:
• During 1974-2009, a significant shortening trend in the duration of the Oulu-Hailuoto ice road season was largely associated with later start day, rather than earlier end day.

• Annual maximum ice thickness in the vicinity of the Oulu-Hailuoto ice road significantly declined in the period 1974-2009, while its corresponding day showed no clear trend.

• Statistically significant warming trends were found in surface air temperature of both cold (October-January) and mild (February-April) months in the Oulu-Hailuoto area during the study period (1974-2009), with a higher rate for the cold months.

• The Arctic Oscillation was the most significant atmospheric pattern affecting interannual variability in surface air temperature in cold months (October-January), maximum ice thickness and the start day of the Oulu-Hailuoto ice road season. However, the East Atlantic pattern was more influential for interannual variations in surface air temperature in mild months (February-April) and the end day of the Oulu-Hailuoto ice road season.

• In 1987, a strong negative phase of the Arctic Oscillation caused persistent severely cold weather in northern Europe and resulted in the latest maximum ice thickness day in the Bay of Bothnia and consequently the longest duration of the Oulu-Hailuoto ice road season. In 2008, a strong positive phase of this weather pattern gave a very mild winter, resulting in the lowest maximum ice thickness and the shortest ice road season duration.

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Figure 1. (a) Geographical location of Finland, the Baltic Sea and the Bay of Bothnia, (b) the Oulu-Hailuoto ice road, Virpiniemi Station, and the selected area for calculating daily mean surface air temperature (SAT) at the ice road, and (c) A photo of Oulu-Hailuoto ice road, taken by Timo Sipola (Yle, 2013).

Figure 2. Annual variability and statistically significant (p<0.05) trends in the Oulu-Hailuoto ice road season (a) duration (IRSD), (b) start (IRSS), and (c) end (IRSE), 1974-2009.

Figure 3. Annual variability and statistically significant (p<0.05) trends in (a) maximum ice thickness (MIT) and (b) its corresponding day (date) at the Virpiniemi station near the Oulu-Hailuoto ice road, 1974-2009.

Figure 4. Annual variability and statistically significant (p<0.05) trends in (a) freezing degree-days (FDD) of cold months (October-January) and (b) thawing degree-days (TDD) of mild months (February-April) in the Oulu-Hailuoto area, 1974-2009.

Figure 5. Correlations between Oulu-Hailuoto ice road-related variables and their most influential atmospheric circulation pattern (ACP), 1974-2009. For abbreviations, see text.
<table>
<thead>
<tr>
<th>Atmospheric circulation pattern (ACP)</th>
<th>Action centres</th>
<th>Natural sign over northern Europe during positive phase</th>
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<tbody>
<tr>
<td>Arctic Oscillation (AO)</td>
<td>A dipole between the adjacent zonal ring centred along 45°N and the polar cap area</td>
<td>Low and high pressures over the Arctic and at mid-latitudes, respectively, leading to wetter and warmer weather than normal&lt;sup&gt;a, b&lt;/sup&gt;</td>
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<tr>
<td>East Atlantic (EA)</td>
<td>South-North dipoles in the North Atlantic</td>
<td>Intensive westerly airflow, bringing wetter and warmer weather than normal&lt;sup&gt;b, c&lt;/sup&gt;</td>
</tr>
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<td>East Atlantic/West Russia (EA/WR)</td>
<td>Western Europe, north-west Europe and Portugal in spring and autumn, Caspian Sea in winter and Russia</td>
<td>Northerly and north-westerly circulation across the Baltic Sea, resulting in drier and milder weather than normal&lt;sup&gt;b, c, d&lt;/sup&gt;</td>
</tr>
<tr>
<td>North Atlantic Oscillation (NAO)</td>
<td>Ponta Delagada (Azores) and Stykkisholmur (Iceland)</td>
<td>Strong westerly circulation bringing wetter and warmer weather than normal&lt;sup&gt;b, c&lt;/sup&gt;</td>
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<tr>
<td>Polar/Eurasia (POL)</td>
<td>North Pole, Europe and north-eastern China,</td>
<td>Strong polar vortex resulting in drier and milder weather than normal&lt;sup&gt;b, e&lt;/sup&gt;</td>
</tr>
<tr>
<td>Scandinavia (SCA)</td>
<td>West of Europe, Mongolia and Scandinavia</td>
<td>High pressure over Scandinavia, bringing drier and milder weather than normal&lt;sup&gt;b, c, f&lt;/sup&gt;</td>
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<sup>a</sup>Thompson and Wallace (1998), <sup>b</sup>Irannejad et al. (2014, 2015), <sup>c</sup>Barnston and Livezey (1987), <sup>d</sup>Lim and Kim (2013), <sup>e</sup>CPC (2011), <sup>f</sup>Bueh and Nakamura (2007).
Table 2. Spearman’s rank correlation (rho) for different Oulu-Hailuoto ice road-related variables. For values in bold, p<0.05. For abbreviations, see text.

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<th>IRSS</th>
<th>IRSE</th>
<th>IRSD</th>
<th>FDD (October-January)</th>
<th>TDD (February-April)</th>
<th>MIT</th>
<th>Corresponding Day for MIT</th>
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<td>TDD (February-April)</td>
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<td></td>
<td></td>
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<td>-0.23</td>
<td>-0.53</td>
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<tr>
<td>Corresponding day for MIT</td>
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Table 3. Spearman’s rank correlation (rho) between Oulu-Hailuoto ice road-related variables and atmospheric circulation patterns (ACPs). For values in bold, \( p<0.05 \). For abbreviations, see text.

**ACPs (October-January)**

<table>
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<th>EA</th>
<th>EA/WR</th>
<th>SCA</th>
<th>POL</th>
<th>AO</th>
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<td>0.18</td>
<td>-0.25</td>
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**ACPs (February-April)**

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<th>EA</th>
<th>EA/WR</th>
<th>SCA</th>
<th>POL</th>
<th>AO</th>
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<td>-0.11</td>
<td>-0.12</td>
<td>0.20</td>
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<tr>
<td>(February-April)</td>
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Figure 1. (a) Geographical location of Finland, the Baltic Sea and the Bay of Bothnia, (b) the Oulu-Hailuoto ice road, Virpiśniemi Station, and the selected area for calculating daily mean surface air temperature (SAT) at the ice road, and (c) A photo of Oulu-Hailuoto ice road, taken by Timo Sipola (Yle, 2013).
Figure 2. Annual variability and statistically significant (p<0.05) trends in the Oulu-Hailuoto ice road season (a) duration (IRSD), (b) start (IRSS), and (c) end (IRSE), 1974-2009.
Figure 3. Annual variability and statistically significant (p<0.05) trends in (a) maximum ice thickness (MIT) and (b) its corresponding day (date) at the Virpiniemi station near the Oulu-Hailuoto ice road, 1974-2009.
Figure 4. Annual variability and statistically significant (p<0.05) trends in (a) freezing degree-days (FDD) of cold months (October-January) and (b) thawing degree-days (TDD) of mild months (February-April) in the Oulu-Hailuoto area, 1974-2009.
Figure 5. Correlations between Oulu-Hailuoto ice road-related variables and their most influential atmospheric circulation pattern (ACP), 1974-2009. For abbreviations, see text.