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Effects of recent temperature variability and warming on the Oulu-Hailuoto ice road season in the northern Baltic Sea

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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 ($p < .05$) 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.

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 from 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

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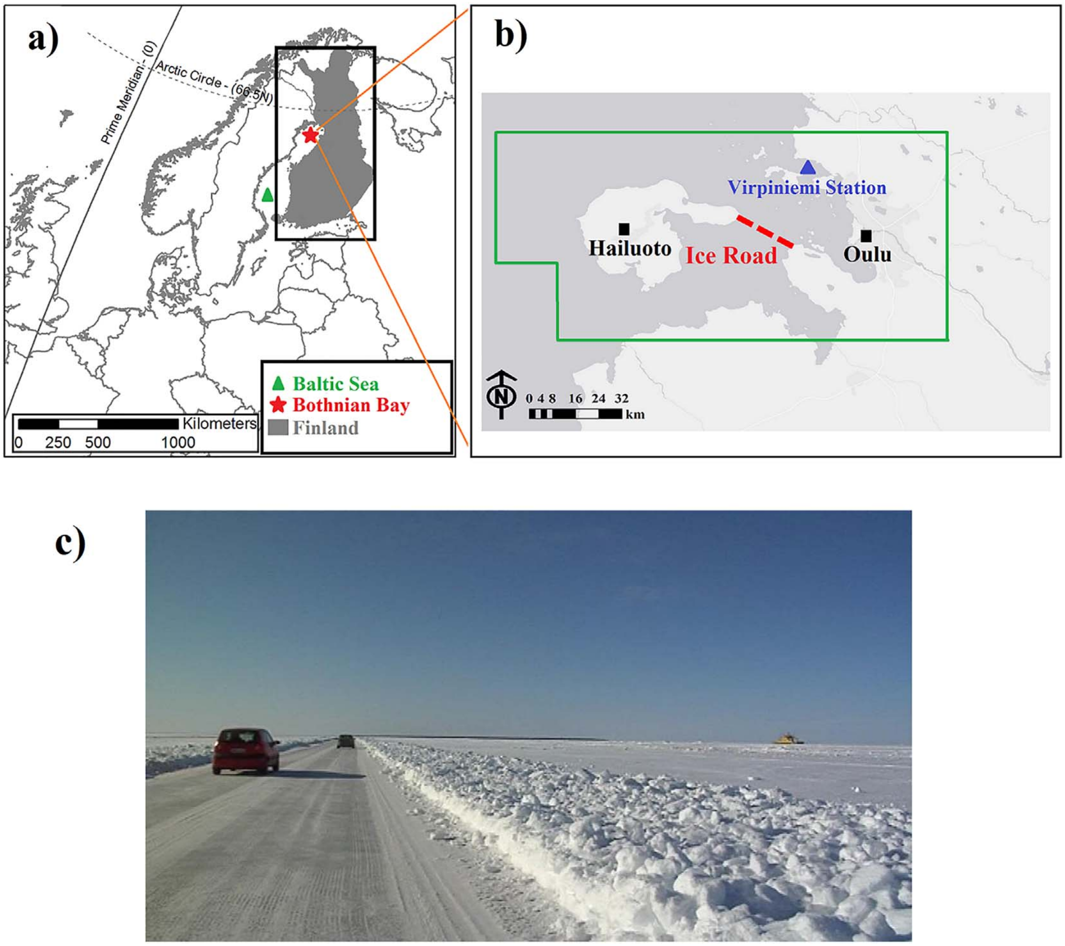

Fig. 1. (a) Geographical location of Finland, the Baltic Sea and the Bay of Bothnia, (b) the Oulu-Hailuoto ice road, Virpiniemi Station, and the selected area for calculating daily mean surface air temperature (SAT) at the ice road, and (c) A photo of Oulu-Hailuoto ice road, taken by Timo Sipola (Yle,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

(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 Loon, 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; Jevrejeva 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; Jevrejeva 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