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Lake ice phenology from AVHRR data for European lakes: An automated two-step extraction method

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ABSTRACT

Several lake ice phenology studies from satellite data have been undertaken. However, the availability of long-term lake freeze-thaw-cycles, required to understand this proxy for climate variability and change, is scarce for European lakes. Long time series from space observations are limited to few satellite sensors. Data of the Advanced Very High Resolution Radiometer (AVHRR) are used in account of their unique potential as they offer each day global coverage from the early 1980s expectedly until 2022. An automatic two-step extraction was developed, which makes use of near-infrared reflectance values and thermal infrared derived lake surface water temperatures to extract lake ice phenology dates. In contrast to other studies utilizing thermal infrared, the thresholds are derived from the data itself, making it unnecessary to define arbitrary or lake specific thresholds. Two lakes in the Baltic region and a steppe lake on the Austrian–Hungarian border were selected. The later one was used to test the applicability of the approach to another climatic region for the time period 1990 to 2012. A comparison of the extracted event dates with in situ data provided good agreements of about 10 d mean absolute error. The two-step extraction was found to be applicable for European lakes in different climate regions and could fill existing data gaps in future applications. The extension of the time series to the full AVHRR record length (early 1980 until today) with adequate length for trend estimations would be of interest to assess climate variability and change. Furthermore, the two-step extraction itself is not sensor-specific and could be applied to other sensors with equivalent near- and thermal infrared spectral bands.

1. Introduction

Lake ice phenology (i.e. freeze-up and break-up dates/ice cover duration) is a sensitive but robust climate indicator to assess short- and long-term variability (Robertson, Ragotzkie, & Magnuson, 1992; Weyhenmeyer, Meili, & Livingstone, 2004; Duguay et al., 2006). While short-term variability has its source in atmospheric conditions, oceanic oscillations, and volcanic eruptions, the ongoing global warming trend is apparent in the long-term variability (Latifovic & Pouliot, 2007). As observed for oceans, lakes integrate these physical parameters through their high temperature and heat absorption capacity (Schneider & Hook, 2010). Lake ice dynamics show a coherent response to climate signals within geographical districts and even at intercontinental scale, as a result of large-scale climate forcing, which drives the lake's inter-annual to inter-decadal variability (e.g. Livingstone, 2001; Magnuson, Benson, & Kratz, 2004; Blenckner et al., 2007; Livingstone et al., 2010). The potential of lakes as sentinels of current climate change is strong and thus their contribution to understand global climate effects (Adrian et al., 2009).

Several studies have determined impacts of atmospheric variables (e.g. solar radiation, air temperature, wind, and precipitation) as well as physical non-climate variables, which influence the formation and decay of lake ice (e.g. Edinger, Duttweiler, & Geyer, 1968; Williams, Layman, & Stefan, 2004; Magnuson, Benson, Lenters, & Robertson, 2006; Brown & Duguay, 2010). The correlation between lake ice phenology and air temperature is particularly high (e.g. Williams, 1971; Livingstone, 1997). Long-term lake ice phenology records were found to provide an early indicator of climate warming due to the sensitivity of ice cover to small changes in air temperature and the integration of climate conditions, which is possibly better than the weather records themselves (Assel & Robertson, 1995). Physical non-climate variables, like lake morphology and surroundings, affect foremost the freeze-up (Palecki & Barry, 1986). Changes in spatial and temporal distribution of all these variables can alter the lake ice and affect local climate factors and regional weather events (Rouse et al., 2005; Brown & Duguay, 2010). Furthermore, changes in lake ice influence heat storage and lake mixing regimes with secondary effects on the sensitive aquatic ecosystem and biochemical cycles (e.g. Nõges, Nõges, Jolma, & Kaitaranta, 2009; Laugaste, Haberman, & Blank, 2010).

Shifts in timing of freeze-thaw cycles of freshwater lakes towards shorter ice cover seasons are significant for the Northern Hemisphere

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(NH), but merely break-up dates for Europe. For the NH, Magnuson et al. (2000) yielded break-up trends of 6.3 d/100 a ($p < 0.05$) with records spanning at least 150 a. Compared to Europe, these are slightly less with 5.7 d/100 a over 100 a period, but fast accelerating to 2.93 d/10 a over the last 30 a period (Benson et al., 2012). Despite that, modelling outcomes for break-up showed a lack of trends for western Europe and probable, insignificant trends (same confidence level) for eastern Europe from 1960 to 1999 (Dibike, Prowse, Saloranta, & Ahmed, 2011).

In situ data, which assess these changes and the high variability in ice cover extent and duration (Hendricks Franssen & Scherrer, 2008), are mainly restricted to northern areas of Europe (i.e. Sweden and Finland). Monitoring of ice cover is generally scarce in central Europe (Livingstone, 1997). Long-term ice cover series are even lacking for Norway (Kvambekk & Melvold, 2010) and the alpine area as well as the lowlands of Switzerland (Livingstone, 1997). Few studies of lake ice cover exist for Germany (e.g. Bernhardt, Engelhardt, Kirillin, & Matschullat, 2012), Austria and Hungary (e.g. Soja, Kutics, Maracek, Molnár, & Soja, 2014), as well as Spain (Sánchez-López, Hernández, Pla-Rabes, & Toro, 2015). Traditionally, on-shore observers collected the information of lake ice recording the visible ice-edge. Within the past two decades due to lacks of budget and/or human resources, the number of field stations declined (Lenormand, Duguay, & Gauthier, 2002). Climate studies are further aggravated by inconsistent observations and inhomogeneous data assessment due to divergent definitions of lake ice phenology (Hendricks Franssen & Scherrer, 2008; Brown & Duguay, 2010; Kang, Duguay, & Howell, 2012).

The interest in ice season in combination with the lakes' response to changing climate is substantially increasing for mid- and high-latitude lakes between 45 and 80°N (Kirillin et al., 2012). Ecosystems of lakes in regions, where air temperature is periodically falling below 0 °C, are particular vulnerable to global warming in the NH (De Jong & Kamenik, 2011). Weyhenmeyer et al. (2010) suggest that the ice cover season of lakes below 61°N is highly sensitive to predicted rising air temperature and these lakes are at high risk to transition into open-water systems.

The potential of remote sensing sensors with different temporal and spatial resolution to measure the occurrence of lake ice was demonstrated by several authors (e.g. Palecki & Barry, 1986; Maslanik & Barry, 1987; Wynne & Lillesand, 1993). A comprehensive overview on remote sensing techniques, systems, and applications for lake ice monitoring is presented in Jeffries, Morris, and Kozlenko (2005); Latifovic and Pouliot (2007) and more recently in Duguay, Bernier, Gauthier, and Kouraev (2015). Optical sensors with medium-spatial resolution like the Moderate Resolution Imaging Spectroradiometer (MODIS), the Geostationary Operational Environmental Satellite Visible Infrared Spin-Scan Radiometer (GOES-VISSR), the Advanced Very High Resolution Radiometer (AVHRR), or the high resolution sensor Système Pour l'Observation de la Terre (SPOT-VEGETATION) have been used to estimate break-up mostly based on visual image interpretation with an accuracy of 1.75 to 3.2 d (Jeffries et al., 2005; Latifovic & Pouliot, 2007).

Few automatic extraction approaches have been developed for these sensors. For MODIS/Terra and MODIS/Aqua (launched 1999 and 2002), two products are mainly used for lake ice detection. The MODIS snow product (Snowmap; Hall, Riggs, Salomonson, DiGirolamo, & Bayr, 2002) provides information on snow-covered land and ice on inland water, which was found useful for detecting ice-on and ice-off (Brown & Duguay, 2012). Nevertheless, a full investigation of the products performance over lake ice in particular lake ice covered by patchy snow is missing so far (Duguay et al., 2015). MODIS derived lake surface temperature (LST) data were used for example by Kheyrollah Pour, Duguay, Martynov, and Brown (2012) to evaluate lake snow and ice temperature model outputs. This study was found helpful to identify current model limitations (Duguay et al., 2015). However, MODIS derived lake-ice products are limited in their temporal extend.

A standardized, homogeneous data set is essential for a consistent retrieval of short-term variability as well as scarce long-term lake ice cycles by means of remote sensing. If accurately pre-processed, data of the AVHRR can meet these requirements and can provide time series of lake ice phenology since the early 1980s. The across-track scanner senses the earth's outgoing radiation at medium-spatial resolution of 1.1 km^2 at nadir which decreases towards the edges of the 2700 km wide swath. The asset of daily global coverage is essential to overcome constraints due to cloud covered areas, especially during winter time. The AVHRR instruments are carried on the National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Environmental Satellites (POES) and on the Meteorological Operational Satellite System (MetOp) from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). The mission is expected to end in 2022, which will finally lead to a unique time series of AVHRR data for at least 40 years. Using AVHRR data, Semovski, Mogilev, and Sherstyankin (2000) analysed ice cover and simulated under-ice plankton; Bussières, Verseghy, and MacPherson (2002) derived water temperatures of boreal lakes to estimate freeze-up; Latifovic and Pouliot (2007) developed an automated extraction technique for the retrieval of lake ice phenology using these historical long-term satellite records.

As has been shown for MODIS, the detection of lake ice phenology with optical sensors has been done either by utilizing the reflected solar or the emitted terrestrial radiation to determine freeze-up and break-up events (Latifovic & Pouliot, 2007). So far, only one study tried to overcome the problematic definition of thermal infrared (TIR) derived water temperature thresholds in combination with near-infrared (NIR) values. Nonaka, Matsunaga, and Hoyano (2007) estimated break-up dates based on water temperature trends and threshold surface temperature for MODIS data using reflectance of the NIR in conjunction with sea surface temperature (SST) data.

This study focuses on the derivation and potential of long-term time series of lake ice phenology based on AVHRR. Here, we describe in detail the developed automatic two-step extraction method applicable for European lakes in different climatic regions. This approach uses the NIR and TIR spectral bands of the AVHRR, but avoids for the latter the definition of arbitrary or lake specific thresholds. Three lakes are selected for the development, validation, and to test the transfer of the approach to another climatic region.

2. Data

About 2174 lakes within Europe are larger than 10 km^2 (according to the European Environment Agency; EEA, 1995) and of potential interest where ice forms seasonally. The lake selection is determined by the spatial resolution of 1 km^2 per pixel of the AVHRR data, which dictates a minimum lake size. A lake's area has to be at least 9 km^2 to avoid noise introduced by mixing pixels at the shore line by using the centre pixel. The global, self-consistent, hierarchical, high resolution, shoreline database product (GSHHS database; Wessel & Smith, 1996) is applied to mask the selected lakes. For validation, the AVHRR retrieved lake ice phenology dates were compared with corresponding long-term in situ observations.

2.1. In situ data

On-shore observations of lakes with distinct seasonality were chosen for two northern European lakes: Lake Peipsi and Lake Võrtsjärv. To test the two-step extraction method for lakes which irregularly form ice cover, in situ data from a central European steppe lake, Lake Neusiedl, was selected. The locations and aspects of the lakes' morphology are shown in Fig. 1.

Lake Peipsi or Lake Peipsi sensu lato (58.14°N/27.29°E) is a large, lowland lake (3555 km^2) in the eastern part of Estonia forming the border to Russia in the area (Blank, Haberman, Haldna, & Laugaste, 2009). The fourth largest lake of Europe has a mean depth of 7.1 m (maximum depth of 15 m) and consists of three parts: The northern part Lake Peipsi sensu strictu (s.s.), the river-like Lake Lämmijärv and Lake Pihkva in the