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Standing waves during ice breakup in a polar lake

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Strong wind events play a crucial role in breaking the seasonal ice sheet in lakes and marginal seas. Still, the mechanism of ice break-up is poorly investigated. We demonstrate that, apart from the obvious effect of horizontal drift, wind produces basin-scale standing waves (seiches) under ice, which, in turn, may essentially contribute to breaking the ice sheet and accelerate ice melting. An extensive dataset on lake physical properties during the ice breakup has been aquired in spring 2013 in polar Lake Kilpisjarvi, Finland. The high-resolution records of pressure, current velocities and water temperature revealed continuous oscillatory motions with periods of 10 to 25 min. The spectral energy peaks resided on frequencies corresponding to the first three eigenfrequencies of the lake indicating the oscillations are produced by the seiche movements at the lake surface. In agreement with previous studies, seiches persisted under ice cover. During the period preceding the breakup, amplitudes of the lake surface oscilations under ice did not exceeded 1mm. The ice breakup was associated with a strong wind event and a 10 times increase of seiche amplitudes under ice. We suggest that vertical motions of the soft ice sheet significantrly accelerated its melting, so that at the lake surface covered by ice to 80 per cent, the ice completely melted within 10-15 hours.

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Introduction

There is evidence that strong wind events play a critical role in seasonal ice breakup in lakes and marginal seas (Kirillin et al., 2012). However, the process of ice breakup, i.e. breaking of the ice sheet and of the stable boundary layer beneath with subsequent fast melting remains poorly investigated. There are two apparent mechanisms associated with wind that accelerate the ice breakup: the drag force moving and disjointing the ice sheet, and wind-produced shear turbulence destroying the strongly stratified boundary layer in the warm atmosphere above the cold ice surface and intensifying the downward heat flow.

We demonstrate that, apart from these mechanisms, wind drag also produces strong basin-scale standing waves (seiches) under ice, whose amplitudes under breaking ice exceed those in the open water conditions. We hypothesize that seiches contribute to the acceleration of the breaking and melting of the seasonal ice cover.

1. Study Site and Methods

An extensive dataset on the lake physical properties during the ice breakup was acquired in spring 2013 in polar Lake Kilpisjärvi, Finland (69°01'N 20°49'E; Fig. 1). Kilpisjärvi is a mid-size (surface area 37 km^2, max. depth 57 m) polar lake with the longest ice-covered period among the West-European lakes (Lei et al. 2012). Various hydrophysical parameters were sampled from May 25 to June 6, 2013, including high-frequency pressure variations in the water column recorded by the pressure logger 'RBR Duo Wave'. The pressure variations were recorded at sampling interval of 10 s with accuracy of 0.01 dBar. The latter dataset is discussed below.

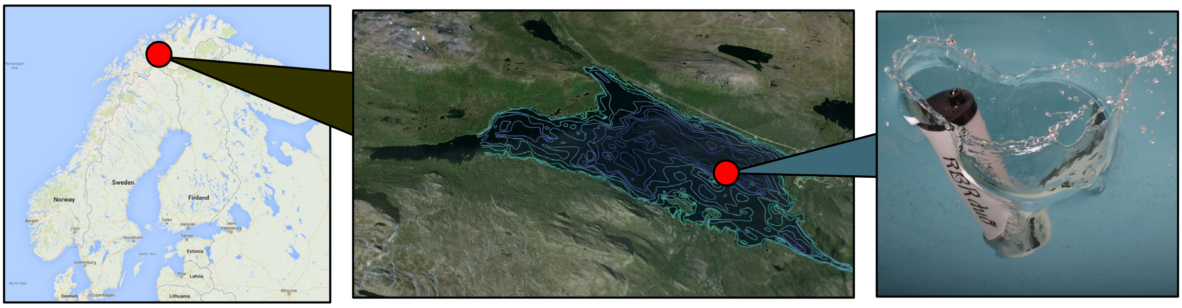

Figure 1. Study site: (left) geographical location, (center) bathymetry and pressure sampling position, (right) the pressure logger RBR DUO wave.

2. Results and discussion

Ice breakup: During the campaign period, the lake area was exposed to sunlight for nearly 24 hours a day, with no observed clouds and wind speeds < 5 m s^{-1} during the first six days of the study. These conditions followed a cold winter (the ice cover in winter 2012 to 2013 was ~10 cm thicker than the long-term mean, Finnish Environmental Service, pers. comm.), with a relatively low snow pack: at the start of the campaign, no measurable snow layer persisted on the 60 cm thick ice cover. Despite a strong radiation flux and maximum air temperatures above 30° C, approximately 90% of the lake surface remained covered with 40-50 cm of ice, which underwent internal melting and reduced its thickness at the rate of 1-2 cm day^{-1}. On late June 1, 2013 the wind speeds increased to ~7-10 m s^{-1} and on June 3, 2013 the lake was completely ice-free.

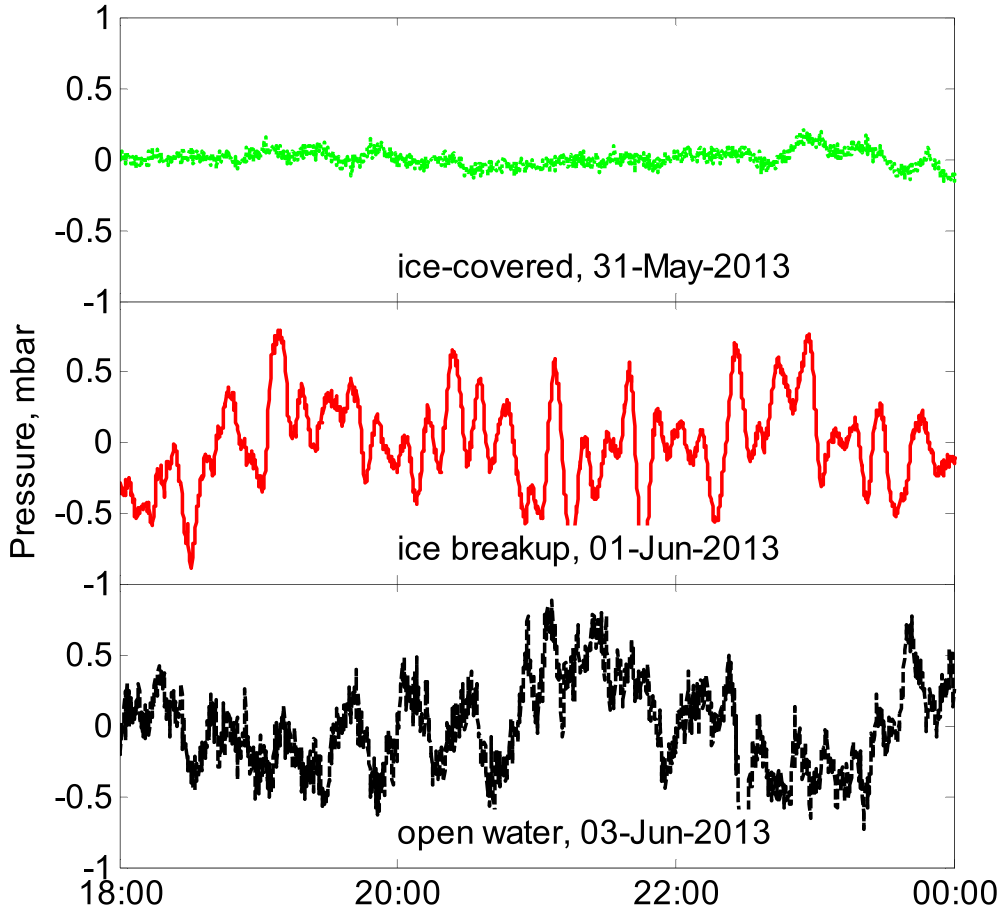

Figure 2. 4-hour outtakes from the pressure oscillation records at different stages of the ice break-up.

Pressure oscillations: The high-resolution records of pressure, current velocities and water temperature revealed continuous oscillatory motions with periods of 10 to 25 min (Figure 2). The spectral energy peaks resided on frequencies corresponding to the first three eigenfrequencies of the lake indicating the oscillations are produced by the seiche movements at the lake surface. In agreement with previous studies, seiches persisted under the ice cover. During the period preceding the breakup, amplitudes of the lake surface oscillations under ice did not exceed 1mm. The ice breakup was associated with a strong wind event and a 10-fold increase of seiche amplitudes under ice. Despite the wind speed not changing significantly after the ice cover melting, the seiche amplitudes decreased, indicating a redistribution of the wind energy towards the surface waves and drift currents. We suggest that vertical motions of the soft ice sheet significantly accelerated ice melting, so that, from the point the lake surface was covered by up to 90% ice to completely ice-free was approximate 10-15 hours.

At the final stage of the ice-covered period, the ice sheet is detached from the shoreline, allowing wind to produce deflection of the free surface. Simultaneously, ice prevents the formation of wind waves and drift currents. Hence, most of the wind energy entering the lake is transformed into surface seiches, which appear to increase the rate of ice melting. One important seiche effect consists of destroying the stable water-ice boundary layer and bringing ice in contact with lake water at temperatures exceeding 0°C and strongly increases the melting rate. This mechanism provides a plausible explanation for the disappearance of ice cover within 1-2 windy days as observed in many temperate lakes worldwide.

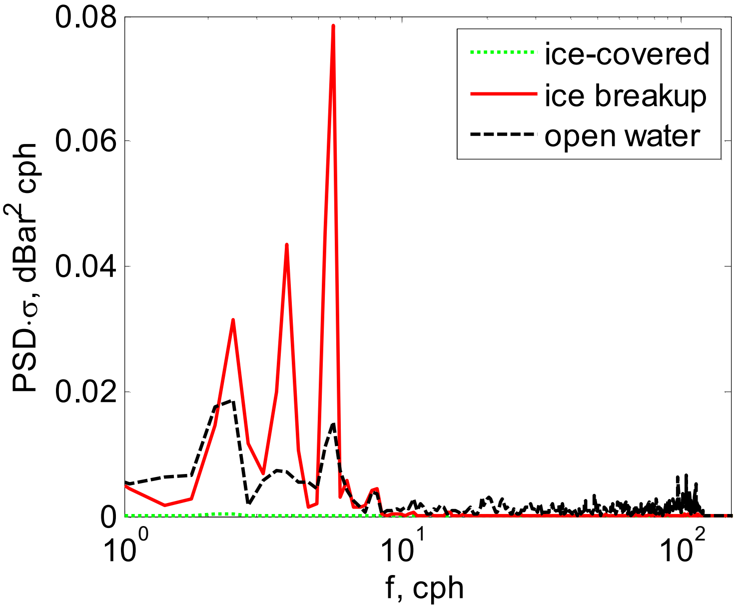

Figure 3. Spectra of pressure oscillations for the three periods from Fig. 2.

Acknowledgments

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