Barotropic seiches in a perennially ice-covered lake, East Antarctica

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Scientific Significance Statement

This work contributes to a growing body of observations on currents and seiches in ice-covered lakes. Under-ice currents play an important role in the biology of ice-covered lakes, and are especially important for redistributing nutrients in perennially ice-covered, polar lakes. This manuscript provides evidence of barotropic seiches below a 4-m-thick ice cover with consistent 10.5-min periods in Lake Hoare in the McMurdo Dry Valleys of East Antarctica. The period of the seiche seasonally lengthened to 13 min following the arrival of summer melt. During winter, there is a strong relationship between surface winds >5 m s⁻¹ and seiche activity, indicating that seiches are caused by flexural vibrations of the permanent ice cover. Our manuscript provides new information that will benefit those studying under-ice water movements. Firstly, Lake Hoare is much smaller and has a much thicker ice cover than previous studies. Secondly, our data include a much longer time-series. Lastly, our data cover an important period when the lake transitions from winter fast ice to summer floating ice.

Abstract

Water movement in ice-covered lakes is known to be driven by wind, sediment heat flux, solar radiation, saline density flows, and advective stream discharge. In large ice-covered lakes, wind-induced oscillations have been found to play a major role in horizontal flows. Here, we report recurrent, wind-driven, barotropic seiches in a small lake with a thick (~4 m) permanent ice-cover. Between 2010 and 2016, we recorded 10.5- to 13-min

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Author Contribution Statement: Devin Castendyk collected CTD profiles and performed initial field work leading to the investigation of seiche in Lake Hoare. Hilary Dugan installed and collected pressure transducer data in the field. Devin Castendyk, Hilary Dugan, Hugh Gallagher and Nimish Pujara performed data analysis, modeling, and writing. Peter Doran, John Priscu, and Berry Lyons provided field logistic support and contributed to the final manuscript.

Data Availability Statement: All CastAway CTD data presented in this study are archived in the Environmental Data Initiative (EDI) Data Repository (Castendyk and McKnight 2021). Raw pressure sensor data from Lake Hoare are available in the Environmental Data Initiative (EDI) Data Repository (Dugan and Doran 2020). Bathymetry data from Lake Hoare used to generate Fig. 5 are available in the Environmental Data Initiative (EDI) Data Repository (Priscu and Schmok 2006). Water quality data from Lake Hoare used to calculate total dissolved solids concentrations are available in the Environmental Data Initiative (EDI) Data Repository (Lyons and Welch 2014). Annual SeaBird CTD profiles collected from Lake Hoare are available in the Environmental Data Initiative (EDI) Data Repository (Priscu 2019). Additional Supporting Information may be found in the online version of this article.

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oscillations of the hydrostatic water level in Lake Hoare, McMurdo Dry Valleys, East Antarctica, using pressure transducers moored to the lake bottom and suspended from the ice cover. Theoretical calculations showed a barotropic seiche should have a period of 12.6 min. Barotropic seiches were most frequent during high wind events (> 5 m s\(^{-1}\)) in winter months (February–November). The period increased during summer months (December-January) when fast ice thinned and melted along the shoreline.

Many lakes on the Earth form an ice cover each year, the highest concentration of these being at boreal and arctic latitudes (Sharma et al. 2019). Because these lakes are vitally important habitats for sustaining life during winter months, there is renewed interest in understanding the physical limnology of ice-covered lakes (Kirillin et al. 2012) and implications for under-ice ecology (Hampton et al. 2015). While ice covers on lakes dampen wind-driven mixing, there are still subice currents in high-latitude lakes that sustain or modify the structure of the water column and impact biological productivity (Foreman et al. 2004; Doran et al. 2008; Vincent et al. 2008; Spigel et al. 2018). Among these, seiches are recognized as a principal mechanism driving horizontal subice motion (Bengtsson 1996; Malm 1999; Zyryanov 2011; Kirillin et al. 2012), and have recently been shown to contribute to seasonal ice melt through turbulence (Kirillin et al. 2018).

Two types of seiche are recognized: barotropic or surface seiches, and baroclinic or internal seiches (Fig. 1). In ice-free lakes, barotropic seiches occur in response to wind acting on a lake surface, which momentarily increases the water surface elevation at the downwind end of the lake and subsequently causes the water surface to oscillate after the wind stress ends. Oscillatory flow associated with barotropic seiches is typically nearly depth-uniform and has a period on the order of minutes. In contrast, baroclinic seiches occur in both stratified lakes where water layers of different density oscillate relative to one another (Fig. 1), as well as in continuously stratified lakes. Baroclinic seiches have larger amplitudes than barotropic seiches, and periods on the order of hours. In ice-covered lakes, barotropic seiches can form in response to disruptions in the horizontal pressure gradient below the ice generated by flexural vibrations of the ice cover caused by wind (Kiviniemi 1975; Squire 1986; Crocker and Wadhams 1988) and other mechanisms. Seiche motion either oscillates the maximum level of liquid water within a porous ice cover (called the hydrostatic water level), flexes the ice cover, and/or raises and lowers the ice cover where fast ice is detached from the shoreline. Previous researchers have measured barotropic seiches in ice-covered lakes by recording changes in ice surface elevation (Kiviniemi 1975), changes in water depth in ice holes (Heine 1971; Bengtsson 1996), and changes in both water level and temperature (Kirillin et al. 2018). Seiches have been observed to crack the ice surface (Mukai 1932; Eggleton 1955; Heine 1971) and to generate horizontal currents (Bengtsson 1996).

We report on the presence and driving factors of barotropic seiches in Lake Hoare, a perennially ice-covered, proglacial lake in the McMurdo Dry Valleys, East Antarctica (Appendix S1). Lake Hoare provides a natural laboratory to study under-ice seiches because the water column is covered year-round by thick ice and stream inflow is relatively low and limited in duration to 1–2 months per year (December and January).

**Study site**

Lake Hoare (77°38’S, 162°55’E) occupies a narrow, northeast-southwest trending basin impounded at one end by Canada Glacier (Supplemental Information Map in Appendix S1). In 1996, the lake was 4.2 km long, 1.0 km wide, with a surface area of 1.94 km\(^2\), an average depth of 15 m, and a maximum depth of 34 m. Rising lake levels (~2 m; Doran et al. 2008) have merged lakes Hoare and Chad into a single water body and increased the surface area to 2.3 km\(^2\). During the study period from 2012 to 2016, inflow only occurred during the austral summer (December to January) and included glacial runoff, stream discharge from Andersen Creek, and overflow from Lake Chad. A narrow band of ice typically melts along the shoreline in late December creating...
a narrow open-water perimeter called a “moat” that occupies ~3% of the lake surface area. Water is lost by ice ablation, and evaporation of moat water and water pooled on the surface of the permanent ice. Permanent lake ice thickness varies between 3.1 and 5.5 m (Dugan et al. 2013).

The physical limnology of Lake Hoare has been monitored for three decades as part of the McMurdo Long Term Ecological Research (MCM-LTER) program (Spigel and Priscu 1998; Vincent et al. 2008; Green and Lyons 2009; Priscu 2016). Each season, MCM-LTER melts a ~30-cm diameter “Limno Hole” at roughly the same location, approximately 200 m west of the Canada Glacier and 500 m south of Andersen Creek (Appendix S1) for water sample collection and in situ Conductivity-Temperature-Depth (CTD) probe measurements using a SeaBird CTD (Priscu 2019). Water samples are analyzed for major ion concentrations. Among the neighboring lakes in Taylor Valley, Lake Hoare is unique in that it is freshwater (TDS < 1 g L−1). Total dissolved solids in the water column, as calculated from the sum of ion concentrations (Na+, K+, Mg2+, Ca2+, Cl−, SO42−, Si, and DIC) collected by the MCM-LTER from 1993 to 2013 (Lyons and Welch 2014), range from 0 to 250 mg L−1 in the epilimnion to ~700 mg L−1 in the hypolimnion, with TDS being dominated by Na+ and Cl−.

Temperature profiles made in the lake between 1995 and 2018 show that summer water column temperatures are never above 1.2°C (Priscu 2019). Previous density calculations using EOS-80 (the International Equation of State for sea water, Fofonoff and Millard 1983), showed an abrupt density transition 13 m below the hydrostatic water level which marked a change from an upper layer (epilimnion) with a gradual density gradient to a lower layer (hypolimnion) with a relatively uniform density (Spigel and Priscu 1998). As such, the stability and location of this pycnocline is more strongly influenced by vertical changes in the concentration of TDS rather than temperature as warmer water with a lower TDS concentration and a lower specific conductance (SpC) generally overlies colder water with a higher TDS concentration and a higher SpC.

Although the water column does not routinely mix, the presence of tritium and CFC’s in the hypolimnion indicates circulation in recent decades (Tyler et al. 1998; Dowling et al. 2014). A tracer study in December 2012 showed that discharge from Andersen Creek flowed West, parallel to the shoreline, below moat ice, at 2.6 cm s−1, and generated diel horizontal pressure gradients (Castendyk et al. 2015).

Methods

CTD profiles and density calculations

We deployed a rugged, handheld, CastAway CTD (YSI 2010) through the Limno Hole approximately every week for 8 weeks between 25 November 2012 and 21 January 2013 (Castendyk and McKnight 2021). The device measured temperature, electrical conductivity, and pressure at 5 Hz during both downward and upward casts, and averaged the data from a given depth into a single profile. To initiate the downward cast, the CTD was suspended 10 cm below the hydrostatic water level for approximately 10 s and then was allowed to free fall through the water column at a design rate of approximately 1 m s−1. On the upward cast, the CTD was raised at a steady rate of approximately 0.3 m s−1 using a dive reel. The device calculated salinity and density from temperature and conductivity data using EOS-80. For our application, the use of EOS-80 for density calculations was acceptable even though the ion composition deviated from that of sea water, as deviations from true density would be very small in comparison to the density gradient observed in Lake Hoare (Spigel and Priscu 1998).

Pressure transducers

Two pressure sensors (Campbell Scientific, CS-455) were moored beneath the ice cover above a deep region of the lake approximately 50 m from the routine sampling site (Limno Hole). The pressure sensors have been part of the MCM-LTER lake monitoring program for over a decade. One sensor was moored on a buoy weighted to the bottom of the lake (B-Sensor) and measured lake level (stage), whereas the other sensor had its cable frozen into the ice cover and measured ice ablation (S-Sensor) (Fig. 1, Dugan et al. 2013, Winslow et al. 2014). Between 2014 and 2016, the S-Sensor was between 5 and 6 m deep and the B-Sensor was approximately 11 m deep. The position of each sensor relative to theoretical barotropic and baroclinic seiche modes is illustrated in Fig. 1. In 2012, we programmed the datalogger (Campbell Scientific, CR1000) to record high frequency pressure changes at 1-min intervals. Data were recorded from November 2012 to April 2013, November 2013 to February 2014, and November 2014 to October 2016 (Dugan and Doran 2020).

Spectra and fast Fourier transform analysis

For pressure transducer data, a 20-min running average of the 1-min data was subtracted from the raw data to isolate high frequency stage oscillations. To observe any periodicity, a continuous wavelet transform was applied to the normalized, detrended pressure data (see methods by Torrence and Compo 1998; Gouhier et al. 2016). For ice-free lakes, the duration of the first-mode period (T) of the unimodal barotropic (surface) seiche for a rectangular basin of length (L) and uniform depth (H) is given by the Merian formula:

$$T = \frac{2L}{\sqrt{gH}}$$

where g is acceleration due to gravity. The Merian formula is only strictly applicable to a rectangular basin of uniform depth. For more complex basin geometries, such as Lake Hoare, undamped free oscillations of the hydrostatic water
level may be more accurately modeled by the reduced wave equation (Carter and Lane 1996):

\[
\frac{\partial}{\partial x} \left( H(x,y) \frac{\partial \xi}{\partial x} \right) + \frac{\partial}{\partial y} \left( H(x,y) \frac{\partial \xi}{\partial y} \right) + \frac{\omega^2 g}{g'} \xi = 0,
\]

(2)

where \(H(x,y)\) is the spatially varying depth, \(g\) is the acceleration due to gravity, \(\omega\) is the angular frequency of the admitted seiche mode, and \(\xi\) is the spatially varying amplitude of the mode. \(H(x,y)\) was obtained by manually discretizing bathymetric observations of Lake Hoare (Priscu and Schmok 2006) to generate a finite element triangular mesh with 103 nodes. For this computational grid, Eq. 2, subject to the boundary condition that the gradient in the surface height normal to the boundary is zero, was solved using the Galerkin-weighted residual formulation of the finite element method to obtain the period and spatial distribution of the admitted modes (Rueda and Schladow 2002). The finite element analysis of Rueda and Schladow (2002) used here was specifically developed to address the challenges posed by spatial variations in the shape and depth of small to mid-sized lakes. Internal waves (among other mechanisms) could also be contributing to the pressure fluctuations, but are not addressed in the modeling approach here and likely have minimal impact on measured signals since the observed pressure fluctuations of the order of 5 mm are far larger in magnitude than those expected from internal waves (Gill 1982).

Baroclinic seiche modes are oscillations of the interface between layers of constant density (Fig. 1). The period of the first mode of a unimodal baroclinic seiche is given by (Gill 1982):

\[
T = \frac{2L}{\sqrt{g' H_1 H_2 / (H_1 + H_2)}},
\]

(3)

where \(g' = g (\rho_2 - \rho_1) / \rho_2\) is the reduced gravity, \(H_1\) is the depth of the upper layer and \(H_2\) is the depth of the lower layer. Like the Merian formula for barotropic seiche, Eq. 3 is only strictly applicable to a rectangular basin of uniform depth.

**Results**

**Vertical profiles**

Figure 2 shows four profiles of density, buoyancy frequency, temperature and specific conductance collected between December 2012 and January 2013. The density transition is 15 m below the hydrostatic water level, 2 m deeper than in 1996, due to the input of freshwater to the lake over time and the rising surface elevation. The water temperature was 0.1 °C just beneath the ice, increased to a maximum of 0.6 °C at 7 m depth, slightly decreased to 0.5 °C between 7 and 15 m depth, was relatively constant at 0.3 °C from 15 to 23 m, and then decreased to 0.2 °C at 30 m depth. The specific conductance gradually increased from the base of the lake ice to 15 m, and remained relatively constant from 15 m to the bottom of the lake. As a result, Lake Hoare exhibited a small (<0.6 kg m⁻³) change in density and weak stratification across the water column with a weak pycnocline at 15 m (Fig. 2).

**Seiche periods from pressure data**

A relationship is observed between strong wind events and disruptions in the hydrostatic water level over time...
(Figs. 3 and 4). While both pressure sensors recorded significant oscillations in the hydrostatic water level coincident with wind speeds > 5 m s\(^{-1}\), periodicity was more strongly recorded by Sensor-B moored from the lake bottom as it was not influenced by ice movement (Fig. 3d). This strongly suggests that the observed periodicity is associated with oscillations of the hydrostatic water level. Winter months are windier at Lake Hoare (Figs. 3a and 4a), yielding frequent barotropic seiches during the winter months (February to October) and relatively infrequent barotropic seiches during summer months (December to January) (Fig. 3d). Wavelet analyses show that the hydrostatic water level oscillates with approximately a 10.5- to 13-min period (Figs. 3d and 4b). The seiche period is the longest (~13 min) in January, coincident with ice melt around the edge of the lake and open-water moat formation, and declines to a minimum of ~10.5 min in early November (Fig. 3e).

### Theoretical seiche periods

If applied to Lake Hoare, the Merian formula (Eq. 1) predicts the East–West longitudinal axis should exhibit a 10- to 14-min barotropic seiche period. This period range is based on lake length \(L\) of 4200 m and lake depth \(H\) in the range 10–20 m. Applying the finite element analysis of Rueda and Schladow (2002) to solve the reduced wave equation (Eq. 2) for the discretized bathymetric observations of Lake Hoare (from MCM-LTER), we predict a 12.6-min period for the first harmonic of the longitudinal seiche mode, and a 6-min period for the second harmonic. The spatial distribution of the first harmonic on a normalized scale, shows that we expect the oscillation in the surface elevation at the West end of the lake to be larger than at the East end of the lake (Fig. 5). Because the East end of the lake is deeper and has greater surface area, the node of the first harmonic is shifted toward the East and the amplitude of the oscillation is
relatively small when compared to the West end of the lake (Fig. 5).

In contrast, Eq. 3 predicts the East–West longitudinal axis should exhibit a baroclinic seiche period of 16 h. This estimate is based on lake length $L = 4000$ m, density of the upper layer $\rho_1 = 1000.2$ kg m$^{-3}$, density of the lower layer $\rho_2 = 1000.5$ kg m$^{-3}$, depth of the upper layer $H_1 = 10$ m, and depth of the lower layer $H_2 = 15$ m. Varying the density and depths of the upper and lower layers within the data shown in Fig. 2 does not change the baroclinic seiche period too far from an approximate value of 10 h.

**Discussion**

Our results reveal that pressure oscillations in Lake Hoare represent a barotropic seiche with a 10.5- to 13-min period. Evidence comes from (i) the large time difference between the theoretical barotropic (12.6 min, Fig. 5) and baroclinic (16 h) seiches and (ii) the match between the observed barotropic seiche period (10.5 to 13 min) and the theoretical barotropic seiche period. Further evidence comes from the difference in the signal strength recorded by the bottom-moored Sensor-B and the ice-suspended Sensor-S (Fig. 3c,d). In response to a passing barotropic seiche, Sensor-B records the displacement of the height of the entire water column producing a stronger signal, whereas Sensor-S remains at a relatively constant depth below the ice cover as the cover rises and falls producing a weaker signal, consistent with our observations. A baroclinic seiche, in contrast, would produce a similar signal response in both sensors (Fig. 1).

Pressure data show a strong relationship between wind speed and stage variability during winter conditions (February to November) in Lake Hoare before the arrival of summer melt and stream discharge (Fig. 4). This indicates that wind-driven, flexural oscillations of the lake ice are responsible for seiches during winter conditions in Lake Hoare similar to ice surface motions observed elsewhere (Kiviniemi 1975; Squire 1986; Crocker and Wadhams 1988). Based on winter winds speeds that are often in excess of 5 m s$^{-1}$ in Taylor Valley (Obryk et al. 2020), seiches likely occur year-round in Lake Hoare.
Theoretical modeling of barotropic seiches under lake ice reveals distinct differences in seiche dynamics between an ice-covered lake where ice is frozen to the shore (fast ice) and an ice-covered lake with a moat where ice is separated from the shore. If an ice cover is present on a lake and is fixed to the shore, the Merian formula (Eq. 1) does not strictly apply because the hydrostatic water level at the boundary remains zero (Zyryanov 2011). While in the derivation of the Merian formula the boundaries are assumed to be antinodes, the presence of a fixed ice-cover forces the boundaries to be nodes. Consequently, a single-node barotropic seiche is not possible beneath a fixed ice cover because two nodes must be on the shores. However, a three-node barotropic seiche beneath an ice-cover fixed to the shoreline (fast ice) closely resembles a single-node seiche, and therefore, the observed periods of under-ice barotropic seiches are often similar to those predicted by the Merian formula (Zyryanov 2011), which our results corroborate.

Overall, compared to the influence of basin geometry on seiche periodicity (Fig. 5), the presence of a 4-m-thick ice cover appears to have minimal effect on seiche period. Although ice cover is expected to dampen the seiche amplitude (Kirillin et al. 2012), we observe oscillations of the hydrostatic water level between 5 and 10 mm (Fig. 3b) near the Limno Hole, which is near the expected location of an antinode in ice-free conditions (Fig. 5). Finite element modeling also indicates that the highest amplitude seiche may occur at the West end of Lake Hoare near the inlet from Lake Chad (Fig. 5). We hypothesize that this end of the lake has greater potential for sub-ice turbulence as a result of the amplitude of the barotropic seiche.

At the onset of summer in November, an increasing seiche period from 10.5 to 13 min was recorded in the pressure observations (Fig. 3e). We suspect this lengthening is driven by the preferential melting and thinning of near-shore, moat ice with respect to interior, permanent ice. Theoretical analysis of Zyryanov (2011) does not reach a general conclusion on how fast ice vs. moat ice changes the seiche period. Relative to ice-free conditions, fast ice can increase or decrease the seiche period based on the lake depth and geometry, whereas moat ice is always expected to increase the seiche period relative to ice-free conditions. However, since the theoretical analysis also shows that the first mode in fast ice conditions has a compressed effective lake length, an increase in seiche period is consistent with an increase in effective lake length that is expected with moat ice. Our observed annual pattern is most likely not driven by lake-level fluctuations because increasing lake level in the summer and decreasing lake level during the winter would show the opposite pattern in barotropic seiche period.

Our data reveal that wind-driven barotropic seiches are a common phenomenon under the perennial ice-cover of Lake Hoare, and show a recurrent annual pattern in periodicity. Barotropic seiches in Lake Hoare, and potentially other Antarctic lakes, may be an important overlooked source of under-ice horizontal fluid motion and should be considered in future investigations of mixing, turbulence, nutrient distribution, and ice dynamics.

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