HYDROLOGY OF BRAGANZAVÅGEN UNDER ICE-COVERED CONDITIONS

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ABSTRACT
The hydrology regime of Braganzavågen, the bay in the Van Mijen Fjord, Spitsbergen, has been studied during several winter seasons. Hydrological characteristics of the bay are determined by the local bathymetry, influx from the river Kjellstromelva, semidiurnal tide and land fast ice covering Braganzavågen during 6-7 months of the year. Tidal elevations of the water level in the Van Mijen Fjord are varied from 1 in neap tide to 2 m in spring tide. During the ice season significant part of sea ice in Braganzavågen sits at the bottom continuously, some part of the ice floats in high tide only, and some part of the ice is always afloat. There is no information about river water influx during the ice season. The mining company Store Norske Spitsbergen Kulkompani AS has an interest in the development of coal deposit on the southern shore of Braganzavågen, for which construction of a road crossing from the northern to southern shore of the bay is necessary. Hydrological information is useful for the road design.

Visual observation of ice surface, mechanical drilling together with CTD measurements of sea water and temperature and salinity measurements of sea ice along the bay were performed. The river channel was clearly visible due to ice cracks going around the channel. CTD measurement performed in the channel demonstrated significant deformations of tidal curves showing the dependence of the water level from the time with approaching to the river mouth. Variations of the water salinity over the channel were insignificant.

INTRODUCTION
This work presents the results of field studies of hydrology regime in the bay Braganzavågen in the Van Mijen Fjord of Spitsbergen (Figure 1) performed in the March 2014. The fjord is about 50 km long and spreads into Spitsbergen from the West to the East at about 77.8°N (Figure 1b). At the mouth, the fjord has a width of about 10 km, while the width of Braganzavågen bay is about 5 km. At the mouth of the fjord Akseløya island almost completely blocks the fjord. This facilitates the process of stable land-fast ice formation. Usually in Braganzavågen and Svea bay stable ice conditions prevail from January until June and thickness of sea ice usually reaches value about 1 m.

Location of coal mining settlement Svea is shown in Figure 1b. The University Centre in Svalbard (UNIS) is located in Longyearbyen (Figure 1a). The distance between Svea and Longyearbyen is 60km and in wintertime its easily be travelled by bulldozers, snow groomers, snowmobiles ect. Stable ice conditions, easy transportation access and established infrastructure in Svea made Van Mijen Fjord a favourite field laboratory of Arctic

Technology department at UNIS. Beside the possibilities to study fundamental properties of shallow sea waters covered by ice, physical and mechanical properties of sea ice, there are scenes where ice-structure or ice-shore interactions can be study on real structures or medium scale models.

At Van Mijen Fjord at different time ice ridges and sea bed gouging were studied by Løset et al. (1998), Høyland and Løset (1999), Liferov and Høyland (2004), Høyland and Liferov (2005) and Strub-Klein and Høyland (2012). Physical and mechanical properties of level sea ice were studied by Moslet (2007), Strub-Klein and Høyland (2012), Marchenko et al. (2011a), Karulin et al. (2011). Moslet (2008) performed medium scale ice-structure interaction experiment in Van Mijen Fjord. Full scale tidal ice action on the coastal infrastructure in Svea was studied by Løset and Marchenko (2009), Caline and Barrault (2008), Marchenko et al. (2011b), Wrangborg et al. (2013) and Wrangborg and Marchenko (2014). Hydrology regime of the fjord was studied by Marchenko et al. (2009), Morozov et al. (2011) and Marchenko and Morozov (2013). This work is a contribution to the previous hydrology studies of Van Mijen Fjord and Braganzavågen bay in particular. Hydrology regime of the bay is of interest for potential future mining activities in Svea.

The mine in Svea is operated by Store Norske Spitsbergen Kulkompani AS (SNSK). SNSK is the northernmost mining company in the world. Store Norske was established in 1916 and currently operates three coal mines on Spitsbergen: Svea Nord and Lunckefjell by Svea and the Gruve 7 mine, in the valley of Adventdalen outside Longyearbyen. Mines Svea Nord and Lunckefjell are SNSK's principal operations (Figure 1c). Lunckefjell mine was open in February 2014 with plan to start main production in 2015. The Lunckefjell Mountain lies northeast of the Svea Nord mine and contains an estimated 8.4 million tonnes of saleable coal. After Lunckefjell, the remaining coal reserves are in Svea Øst, the Svea Nord rim zone and Ispallen. All of these will be operated from the infrastructure in Svea. The current situation in the coal market is not in favour to the mining industry, but according to the production profile of previous years, SNSK, potentially, could continue mining in Svea until about 2030. (www.snsk.no, 2012).

To be able to run a mine in the mountain Ispallen, it will be necessary to transport the coal across the tidal inlet Sveasundet (Figure 1c). The design of the road crossing the tidal inlet of the fjord covered by ice for 5-6 months would become a challenge. That is why both, action of sea ice on the coastal structures and hydrology regime of Braganzavågen potentially interrupted by the road, are of interest and importance for research. Extensive research on the ice actions on the coastal zone was carried out by Caline (2010) during his PhD work at UNIS, which was partly founded by SNSK. In Sveasundet Caline designed and supervised the construction of a breakwater, equipped with thermistor strings, stress gauges, tide sensors and photo cameras, where he afterwards conducted several seasons of monitoring of costal-ice processes. After this work studies on hydrology regime of Sveasundet and Van Mijen Fjord were continued by Arctic Technology department at UNIS and results are presented in papers mentioned above. But until now there was no understanding on the influx to Braganzavågen from river Kjellstromelva, which, if exists, we believe, would become an affecting parameter in road design crossing and blocking the Sveasundet. Thus the aim for these studies was to allocate the riverbed and find out whether there is a water flux during the winter, and, if so, whether water from the fjord is able to penetrate to the river mouth at the high tide. That would mean that even during the winter there is an active hydrology processes in Braganzavågen through the Sveasundet, where the potential road crossing is considered.

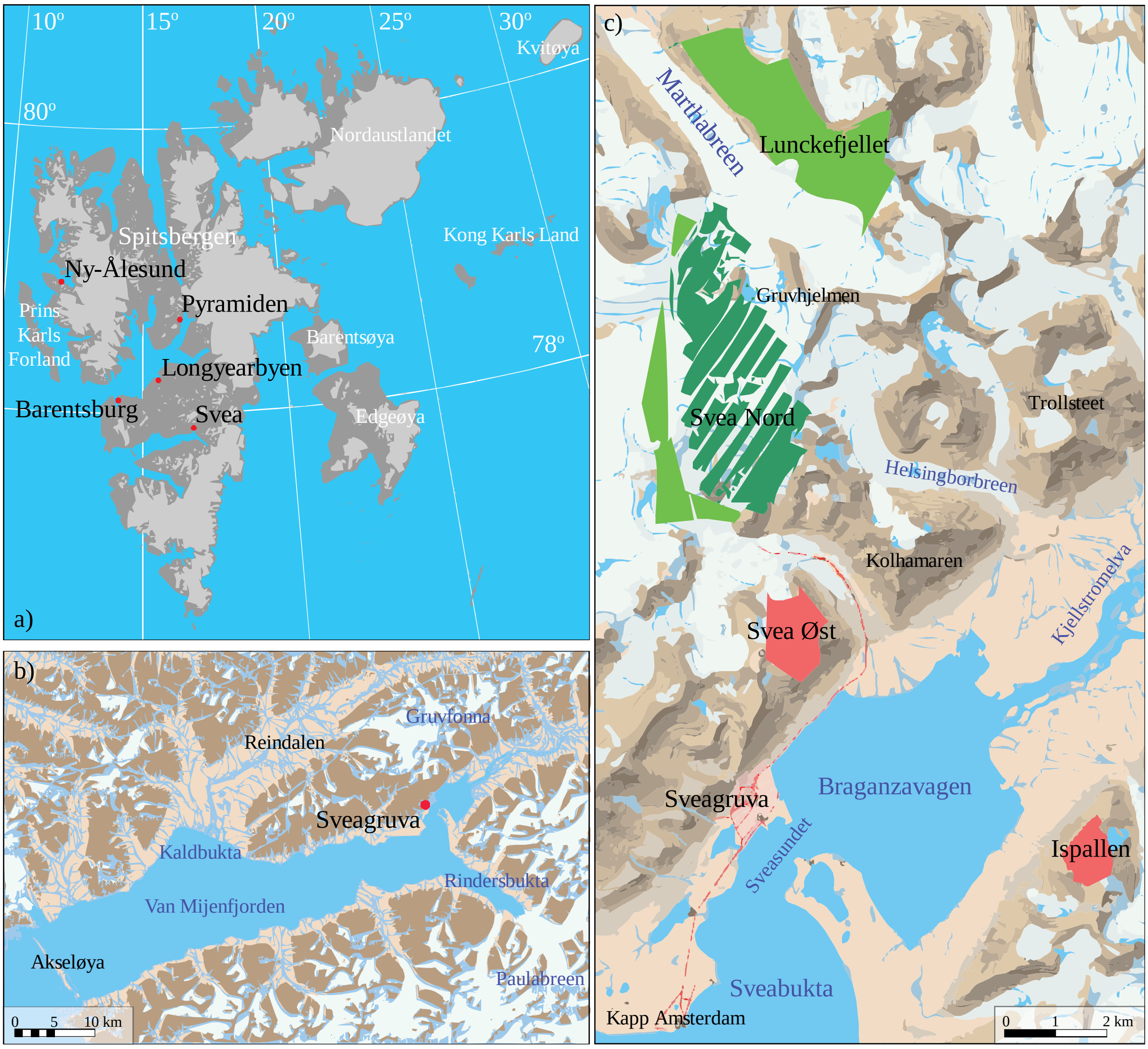

Figure 1. Spitsbergen is the largest and the only permanently populated island of the Svalbard archipelago (a). Van Mijen Fjord is the third-longest fjord in Svalbard archipelago. Sveagruva settlement is located at the head of the fjord (b). Braganzavågen bay with flowing in Kjellstromelva River. Coal deposits of Store Norske Spitsbergen Kulkompani AS in Sveagruva (dark green: almost worked out Svea Nord mine; light green: new Lunckefjell mine and rim zone in Svea Nord mine; red: coal deposits for potential development) Kapp Amsterdam is the location of coal loading terminal on the transporting ships (c).

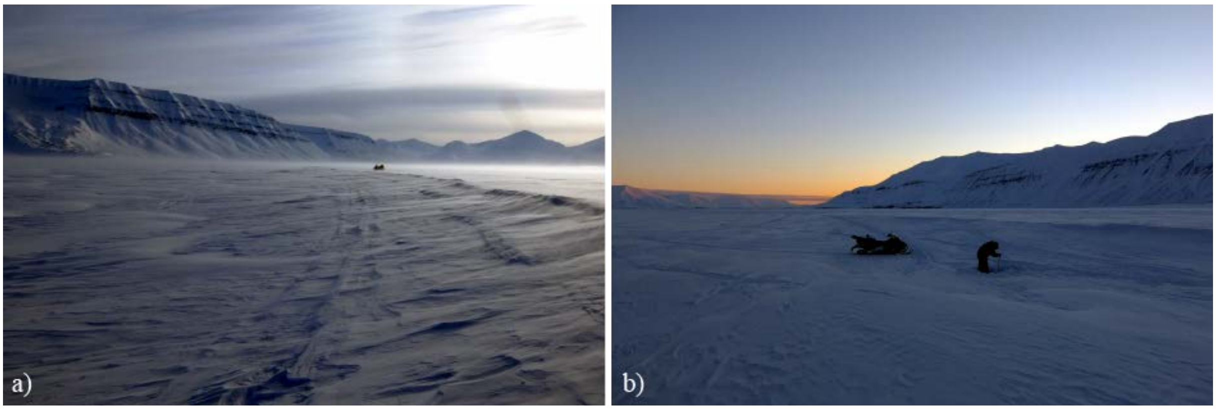

Figure 2. Visible cracks on surface of sea ice in Braganzavågen. Double crack going along the Kjellstromelva river (a). Deploying conductivity, temperature and pressure recorder at the mouth of the river in one of the measurement points (b).

FIELD STUDIES AND RESULTS

This paper includes results of tidal observation in Sveasundet during period from February 20 to May 11, 2014 and results of observation in Braganzavågen during a shorter field campaign carried out from March 25 to April 3, 2014. Three temperature and pressure recorders SBE 39 and one conductivity, temperature and pressure recorder SBE 37-SM (Sea-Bird Electronics) were used for measurements. Visual observation of the tidal cracks along the river banks were performed and tracked by GPS (Montana 600, Garmin). Qualitative drilling of sea ice with 2 inch auger (Kovacs Enterprise, Ice drilling and coring equipment) was performed in some representative areas in Braganzavågen to determine whether sea ice was grounded or not.

Figure 2 shows visible cracks on the surface of sea ice in Braganzavågen. Often there were two cracks going along the river bank (Figure 2a). Level of sea ice in the river was lower compare to the level outside riverbed area. Difference between those two at low tide could exceed 1 m at the mouth of the river (Figure 2b). Drilling at several points laying on the straight line perpendicular to the crack, we determined, that sea ice is grounded on one side of the crack and that there is water beneath the ice on the other side of the crack. From here we concluded that dealing with a riverbed path.

Once all visible cracks have been determined and tracked, four points of measurements were chosen along the river from its mouth to the Sveasundet. Figure 3 shows the scene of studies, GPS tracks of spotted cracks and points BV-0, BV-1, BV-2 and BV-3, where measurements with conductivity temperature and pressure recorders were performed. Geographical coordinates of these four points are listed in Table 1. Thicknesses of snow, sea ice and water column below the ice at the low tide are presented in Table 2.

Table 1. Points of measurements with conductivity, temperature and pressure recorders

Point	Coordinates	
BV-0	77.8941°N	16.7517°E
BV-1	77.8988°N	16.8184°E
BV-2	77.9070°N	16.8506°E
BV-3	77.9150°N	16.9250°E

Table 2. Thickness of snow, sea ice and column of water below the ice at the low tide.

	BV-0	BV-1	BV-2	BV-3
Snow, cm	n/a	37	n/a	35
Sea ice, cm	n/a	90	n/a	94
Water below ice at low tide, cm	n/a	60	n/a	61

Since we had only one recorder SBE 37-SM, able to measure conductivity, all four recorders were moved between four points in a certain way. During period of the field campaign March 25 - April 3, 2014, temperature and pressure at the sea bed were measured all the time in all points, while conductivity was measured consequently in each point during the time of few tidal cycles (see Figures 4, 5). Figure 4 shows tidal records of pressure and temperature in points BV0, BV1, BV2 and BV3. Figure 5 presents salinity measurements in these four points. Measurement in point BV1 during March 28-29 failed due to impurity in the conductivity cell, as we think, caused either by soil mud or ice crystals. The measurement was repeated during April 1-2.

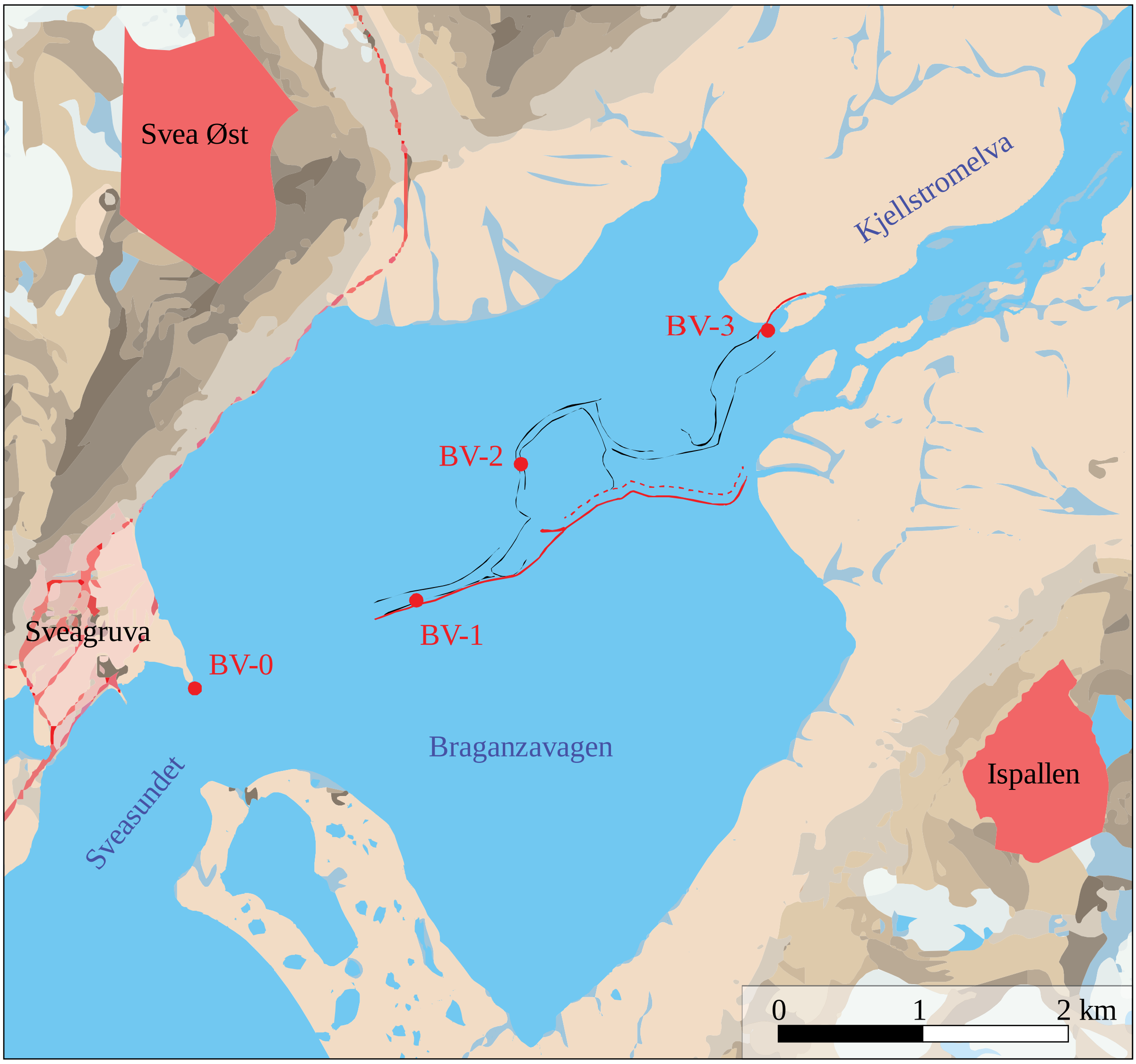

Figure 3. GPS tracks (solid lines) of observed cracks in sea ice along the river banks in Braganzavågen (in black, cracks logged in March 2014; in red, ones in February 2015). Red dashed line show visually observed crack, but not logged with GPS. BV-0, BV-1, BV-2, BV-3 are points of measurements with conductivity, temperature and pressure recorders.

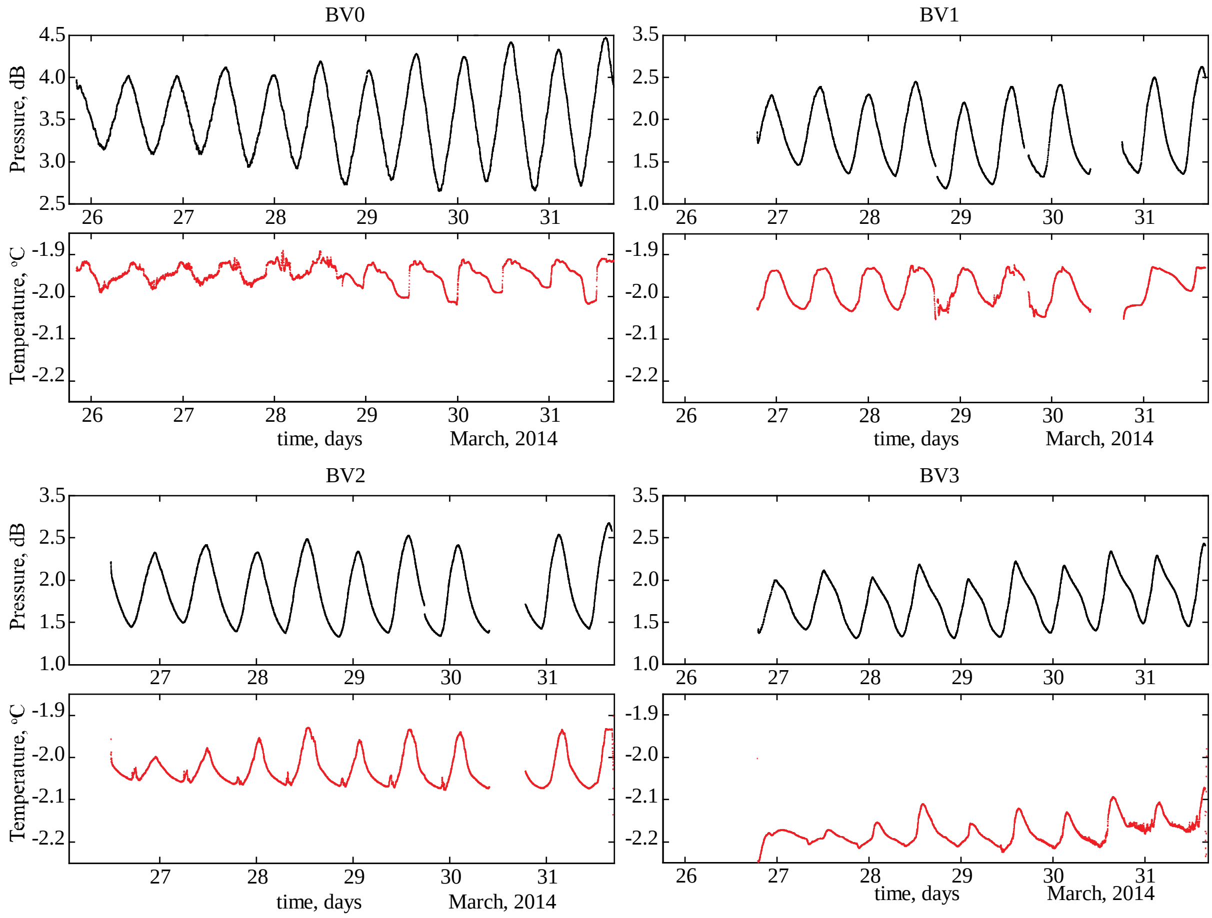

Figure 4. Pressure and temperature at the bottom of seabed measured in points BV0, BV1, BV2 and BV3.

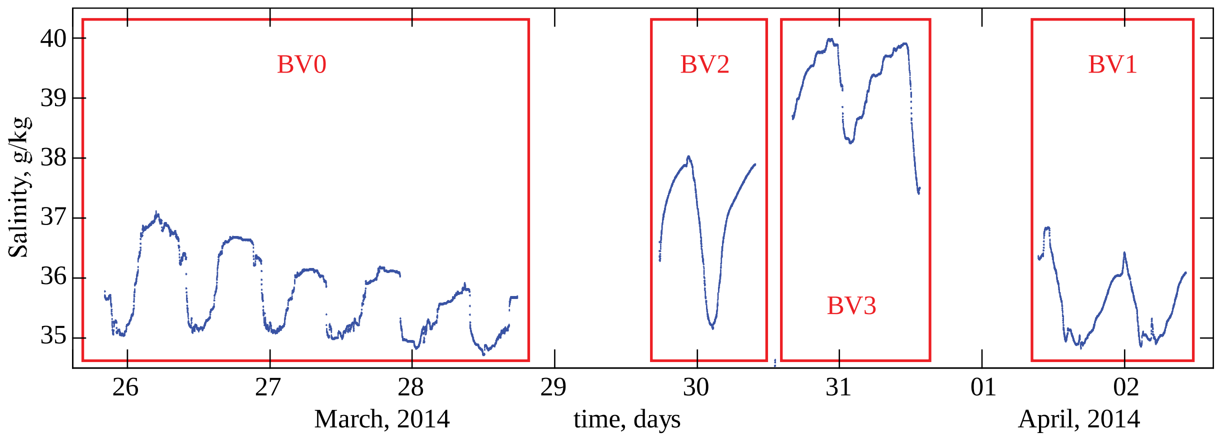

Figure 5. Salinity of water measured in points BV0, BV2, BV3 and BV1.

The entire tidal records over period of accessible sea ice in Sveasundet are presented in Figure 6, as measured in point BV0. Data of water column pressure (Figure 6a) and water temperature (Figure 6b) are available. Rectangles indicate the time period of field campaign during March 25th – April 3rd. Plot in Figure 6b includes also air temperature in Van Mijen Fjord over the period. Data for air temperature are provided through the service eklima.met.no from the meteorological station "Sveagruva" (#99760, N77.8833 E16.7167) located at the head? of the fjord.

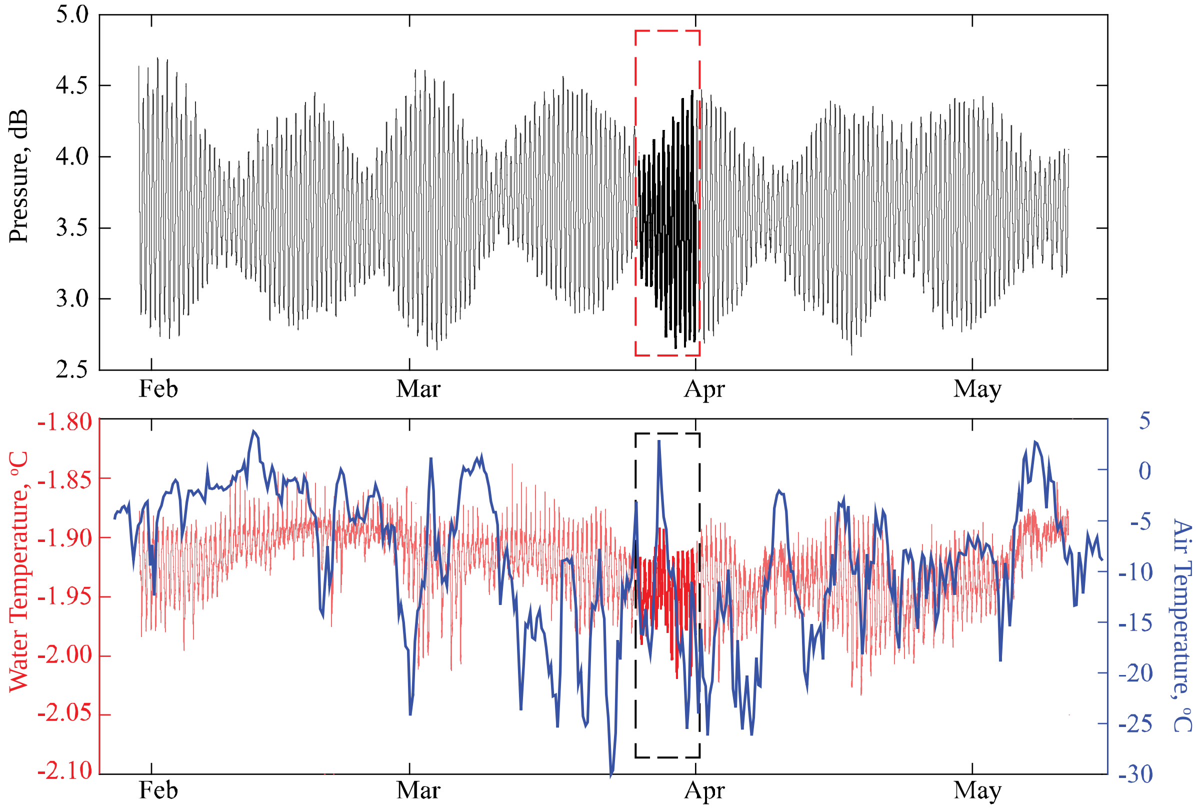

Figure 6. Tidal course at the point BV0 through the winter season 2014 (a). Temperature of sea water at the seabed in point BV0 and air temperature in Van Mijen Fjord (b). Air temperature is taken from eklima.met.no and measured at meteorological station Sveagruva (#99760, N77.8833 E16.7167) at the head of the fjord.

DISCUSSION

The tide in Braganzavågen has a clearly visible semidiurnal component. The amplitude of the tide is varying between 0.5 to 1.0 m. The measurements, we have done, were performed during the increasing stage of tide amplitude. During March 25th – April 3rd, tidal records were registered almost all the time in all four points (see Figure 4). Figure 7 shows pressure readings from all points plotted together with offset to zero. One can see that there is a phase shift of semidiurnal tide between Sveasundet (BV0) and mouth of Kjellstromelva River (BV3). The amplitude of the tide is reducing as well. At the flood the phase shift between points BV0 and BV3 reaches 50-55 min, while at the ebb it achieves values about 140 min. This means water floods the Braganzavågen faster than leaves it.

Average temperature of the water correlates with the air temperature. During the winter season, average value of water temperature is not subjected to high changes and is governed by changes in air temperature. In the second half of April there was a rise in air temperature and as a consequence continuous increasing of water temperature, which we interpret, as the beginning of the melting season. Though during the tidal cycle water temperature oscillates and is governed by the water coming from the fjord.

During the field campaign March 25th – April 3rd we found a clear trend of decreasing of water temperature and increasing salinity of water while propagating along the line BV0, BV1, BV2, BV3 (see Figures 4, 5). Figure 8 shows readings of water temperature by SBE 37-SM conductivity, temperature and pressure recorder, measured in all four points BV0-BV3

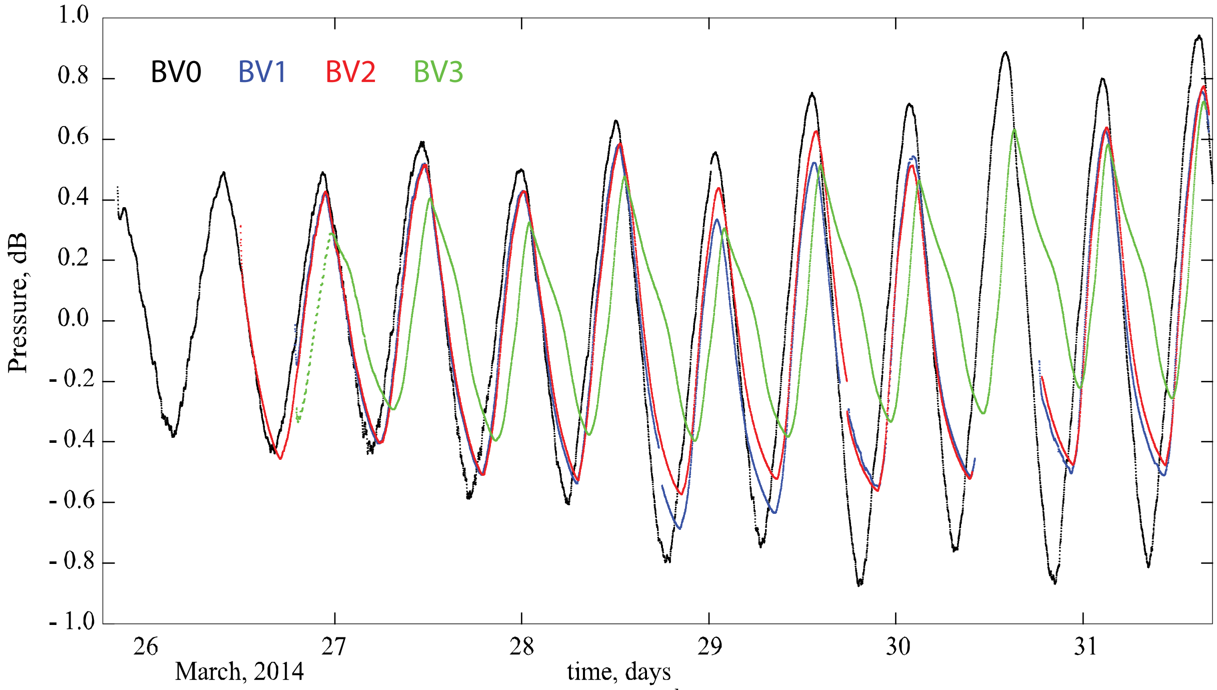

Figure 7. Pressure tidal readings during March 25th – April 1st in points BV0 (black), BV1 (blue), BV2 (red) and BV3 (green) with offset set to zero.

and freezing point temperature of water calculated based on measured conductivity. Calculations were performed using Thermodynamic Equation of Seawater – 2010 (TEOS-10) and its toolbox (McDougall and Barker, 2011). Combining views of Figures 4-6, one can see that, in all points BV0-BV3, temperature of water is higher at the high tide, while salinity of water is higher at the low tide. This is observed the same in all points. It means water from the sea, which coming to the fjord is warmer and less saline. At the same time Figure 8 shows that during high tide water is at its freezing point in all points, while during the low tide it is clearly above its corresponding freezing point in points BV0 and BV3. This means that ice growing process in Sveasundet can happen only during the high tide.

The deviation from the freezing point is higher at the Sveasundet (BV0) compared to the mouth of the Kjellstromelva River (BV3) and in the points BV1 and BV2 water is always at the freezing points. Therefore there should be some source of salt in Braganzavågen which

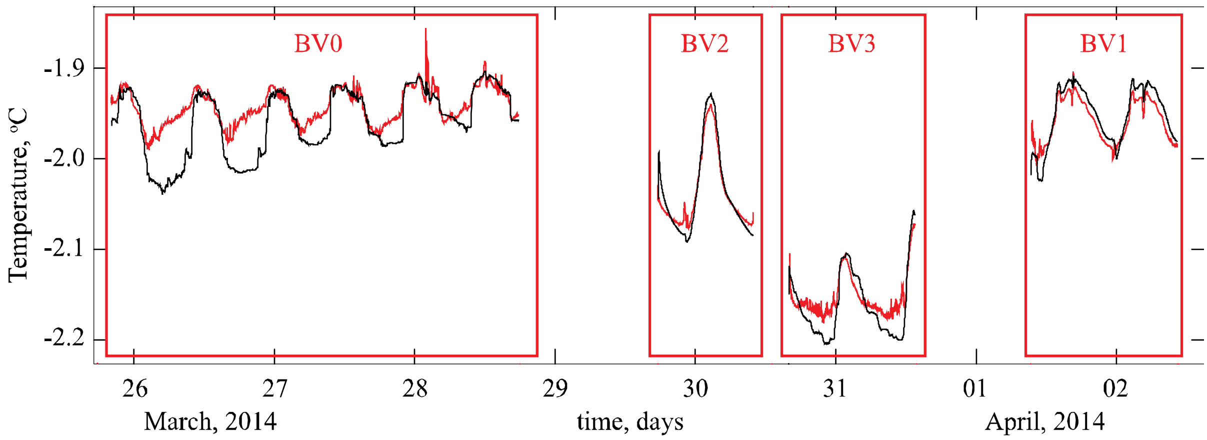

Figure 8. Sea water temperature (red) measured by SBE 37-SM in four different points and calculated (using TEOS-10) freezing point of this water based on conductivity measurements at the same points.

provides salt to be flushed out by the tide and increase the salinity of water in the Sveasundet at the low tide. It is observed also that average level of salinity over the tidal cycle is increasing from 35.5 g kg^{-1} at BV0 to 39 g kg^{-1} at BV3 point (Figure 5). The possibilities are either brine solution drains itself from the ice, or the brine is flushed from the ice by some current and income from the Kjellstromelva river. Samples of sea ice have not been taken yet, to find their salinity. We expect salinity to be high, as sea ice is grounded over the most of Braganzavågen, and therefore rejected salt beneath the ice either should be frozen into lower layers of sea ice or stay below the ice as highly concentrated brine solution at the freezing point, as we observe for example in the river. The fact that the salinity in the river is not going down is in favour of some process feeding the river with salt, though the process were registered for a relatively short time compare to the entire ice season .

Difference in the BV3 point compare to BV1 and BV2 in relation to the freezing point temperature aspect (see Figure 8) indicates that potentially this might be counted as a sign of river activity. For example increase of salinity at the low tide in BV3 is explained by the fact that sea water going away and the present brine solution is considerably higher. But the fact that temperature of water in BV3 is above the freezing point, at the low tide, not as in BV2 and BV1, where it is at the level of freezing point, might be explained by the influx of fresh "warm" water.

CONCLUSIONS

During the winter season 2014 measurements of tide were performed in Sveasundet the tidal inlet to the Braganzavågen Bay in the head of Van Mijen Fjord, Spitsbergen. During the field campaign March 25th – April 3rd visual observations of tidal cracks along the Kjellstromelva river flowing into the Braganzavågen were performed and conductivity, temperature and pressure measurements were performed in four points from Sveasundet to the mouth of the river. The main findings, results and conclusions are listed below.

- There is a tidal process through the Sveasundet, with water penetrating up to the mouth of the Kjellstromelva River at the high tide.
- The river bed path in Braganzavågen was detected visually by spotting tidal cracks along the banks of the river. The path was further proven by mechanical drilling, while most of the sea ice in the bay was grounded there was water beneath the ice in the river bed. At least two branches of the river path were found and logged by GPS.
- The tide amplitude decreases from Sveasundet (BV0) to the river mouth (BV3). Varying with the moon phase, amplitude in Sveasundet is between 0.5 – 1 m, while at the mouth of the river it is 0.2 – 0.4 m.
- There is phase shift of semidiurnal tide between Sveasundet and the river mouth. In flood the phase shift is about 50 min, while at ebb it is about 140 min.
- Average level of water salinity over the tidal cycle is 35.5 g kg^{-1} at Sveasundet and 39 g kg^{-1} at the mouth of river.
- In Sveasundet and in the mouth of the river temperature of water is at its freezing point during flood, while it is above it during ebb. In points between Sveasundet and mouth of the river (BV1 and BV2) the water temperature is at the freezing point all the time.
- We conclude that Braganzavågen is acting as a salt storage for the complicated tidal and hydrology processes in the area. No obvious signs were found to report that there is fresh water influx from the river.

In the perspective of the industrial use of this area to build a road across the Sveasundet, by the mining company Store Norske Spitsbergen Kulkompani AS, the study in hydrology of the Braganzavågen remains relevant and definitely should be taken under account when designing the crossing. For the further work a study on physical properties of ice in the bay, registering of velocity in the river path and repeating the conductivity, temperature and pressure measurements are planned.

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