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Measurements of stresses in the coastal ice on both sides of a tidal crack

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Six stress sensors were frozen-in in two rosettes nearby a breakwater at 15 cm depth on each side of a tidal crack from 6 to 11 May 2007 in Van Mijenfjorden, Svalbard, Norway. An additional rosette was installed some distance from the shore in the level ice. The tidal movement of the ice was recorded with differential GPS equipment a week later. The tide is being recorded continuously in the area. Weekly visual observations of the sea ice were done as well.
This paper gives an order of magnitude of the stresses in the active zone and how they are affected by the tide.
The principal stresses next to the tidal crack during one cycle are presented. They are strongly influenced by the tide and are highest, around 150 kPa, at low tide and in the direction parallel to the crack. It is unknown whether these variations are local to the crack or take place in the whole active zone.

1. Introduction

The main coalmine in Svalbard is situated in Svea, by the inner bay of Van Mijenfjorden called Sveabukta. A coal deposit has been found under Mount Ispallen, on the opposite side of the bay. The mining company SNSG is considering building an access road across the fjord. In this context the University Centre in Svalbard (UNIS) has been looking into methods for protecting this causeway against seawater erosion. The study is relevant for a wide range of coastal structures built in shallow Arctic waters like breakwaters and quays. Due to the presence of seasonal sea ice the main challenge is to build an erosion protection system that sustains ice loads.

Few measurements of sea ice stresses close to the shore have been made. Apart from being the first step for evaluating loads on coastal structures, the study of stresses in the coastal ice is necessary for defining the boundary conditions of thermal and/or mechanical stresses in constrained first-year landfast sea ice. Investigations were done in connection with the construction of a coal loading pier in Svea (Instanes, 1979). Moslet (2001) measured in situ stresses in order to estimate sea-ice loads on this structure. Frederking et al. (1986) and Sayed et al. (1988) measured stresses in the area of Adams Island (Canada). Nikitin et al. (1992) studied the behaviour of the ice in the active zone (see definition in part 2) at a location in the Okhotsk Sea. Stander et al. (1988) also studied the coastal ice while Frederking and Nakawo (1984) studied the sea ice close to the piles of the Nanisivik wharf.

Researchers at UNIS have been investigating level ice stresses in Sveabukta for several years and found thermal expansion to have the most significant effect (Teigen et al., 2005, Barrault and Høyland, 2007). In addition, during the winter of 2007 coastal stresses were measured in one location. During the same period weekly observations of the coastal ice were done and its movement was recorded throughout one tidal cycle with differential GPS equipment. Sea level data were obtained from a tide recorder situated 100 m from land.

2. Proposed terminology

The *ice foot* is determined as the ice frozen to the shore when gradual freezing of sea water from tide and wave spray occurs early in the season. It is in effect a block of ice that is fixed to the ground and does not move with the tide (WMO, 1970). At a certain distance from shore the ice, which is unaffected by the shore, is called *level (floating) ice*. In between is a transition zone which Croasdale (1980) calls *active zone*. The active zone is composed of *coastal ice* which forms simultaneously with the sea ice and is subjected to tidal forces significant enough to create tidal cracks.

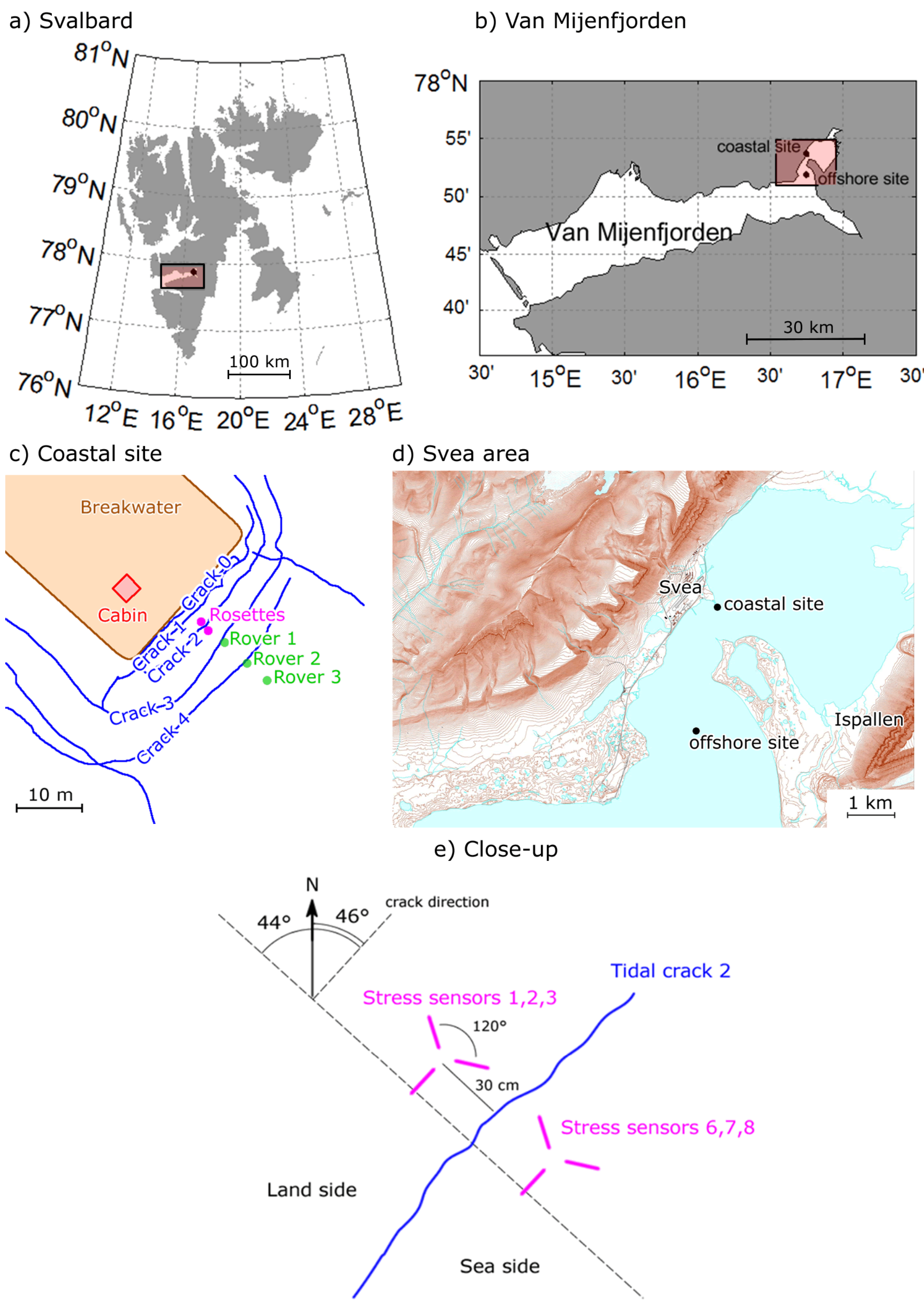

Figure 1. Map of the measurement site and instrument set-up in the innermost basin of Van Mijenfjorden

3. Site and experimental method

A breakwater was built in Sveabukta, the innermost bay of Van Mijenfjorden (Svalbard, Norway) for research purposes. It is 50 m long, 25 m wide and rises 2 m above the mean sea level (MSL), which is taken as the reference level. The depth at the toe is 3.5 m and the slope is 1V:2.5H. During the winter several cracks form in the ice parallel to the breakwater and up to 25 m away. The stress sensors were placed on each side of crack #2 (Figure 1c) which is oriented 46° to the North and runs through the whole 1.6 m thick ice cover.

The instruments are Amplified Solid State Pressure Sensors 242PC100G and they were deployed from 6 to 12 May 2007. These sensors consist of a disc of 10.5 cm in diameter filled with hydraulic oil and a transducer head measuring the voltage difference. Compressive stresses are obtained with ± 0.1 kPa resolution. Tensile stresses are not measured. They were connected to a CR10X Campbell Scientific datalogger. The sensors were deployed as two rosettes on each side of the crack at a depth of 0.18 m. The centre of the rosettes was at 30 cm from the crack. In both rosettes, one sensor measured stresses perpendicular to the crack (Figure 1e) and the angle between each sensor was 120 degrees. Another rosette of three BP stress sensors was frozen-in in the offshore ice 2.6 km away from the breakwater, in the middle of Sveabukta from 16 February to 17 April (Figure 1d). The site, the instrumentation set-up and the logging are described in (Barrault and Høyland 2007).

A Seabird SBE 26Plus tide and wave recorder is permanently placed at 2.5 m depth 100 m from the breakwater. The water level is recorded continuously and averaged every 20 minutes. The ice movement was surveyed with differential GPS equipment on 17 May. A base station was placed on land and three rovers were placed from 8 to 20 m from the shore (Figure 1c). The rover antennas were placed on 1 m-long poles stuck some 20 cm in the snow layer and the position was recorded with 2 cm accuracy every 30 seconds for 20 hours. In additional ice observations and profile measurements were made.

The air temperature of the Svea airport weather station situated at about 1 km west of the site is obtained from the open weather database of the Norwegian Meteorological Institute (http://eklima.met.no).

4. Results

As shown in Figure 2 stresses were identified as periodic events on both sides of the crack with higher pressure on the land side of the crack with a maximal value of 245 kPa compared with 139 kPa on the sea side. The stresses are strongly influenced by the tide and their tidal response is similar during the whole week. There are missing data for the sensor oriented at 46 degrees on the land side. The sensor in fact did not record data when stresses where lower than 24 kPa. During the 6 days of measurements the temperature increased almost linearly from -15 to 0°C. The wind was around 11 $m \cdot s^{-1}$ until 9 May then fell to 5 $m \cdot s^{-1}$. All the time it was blowing from the North-East, i.e. parallel to the tidal crack. The tidal range decreased from 1.26 m on 6 May to 0.56 m on 11 May.

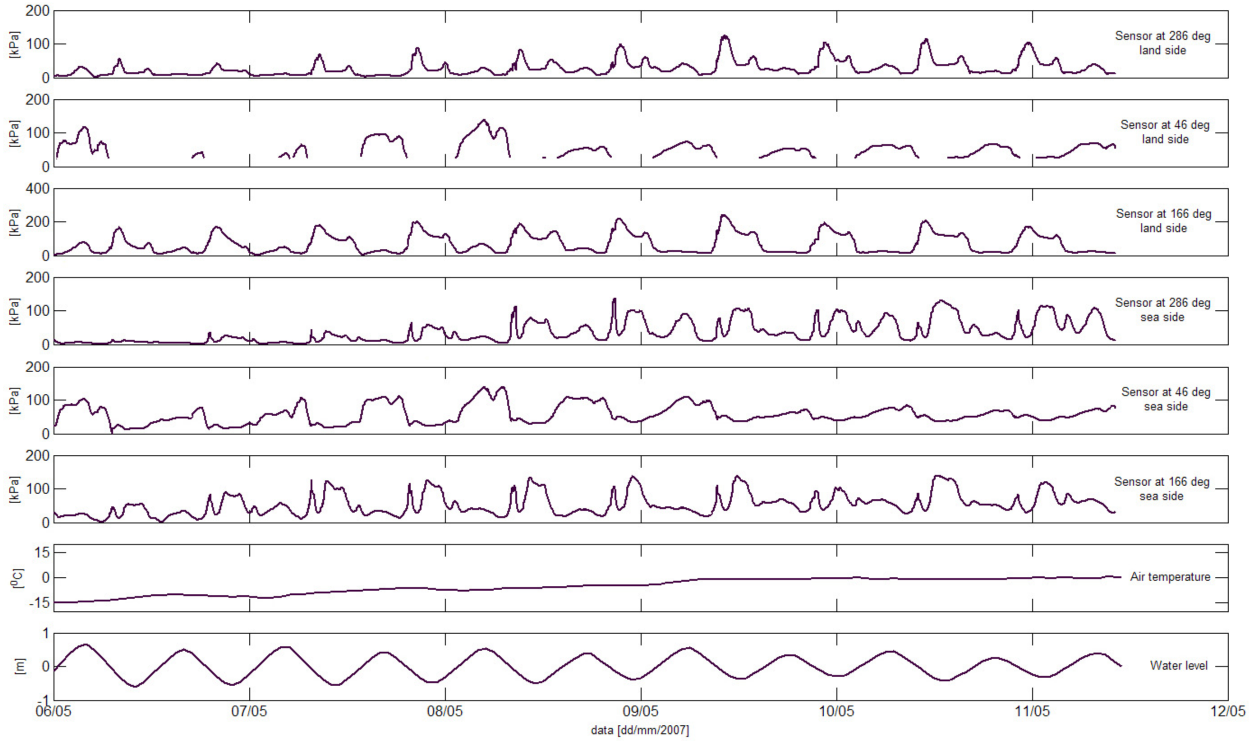

Figure 2. Stresses in the two rosettes on both sides of the crack, air temperature and sea level.

The plot of the calculated principal stresses during one tidal cycle on both sides of the tidal crack (Figure 3) shows they have the same pressure range and their curves have a relatively similar shape. The highest stresses, about 150 kPa, are reached at low tide last for about 3 hours and are oriented parallel with the crack. At high tide the major principal stress is about 70 kPa and oriented perpendicularly to the crack. Finally there is a short 100-150 kPa stress peak oriented parallel the crack when the tide is around mean sea level. This peak is more evident on the sea side.

The results of the DGPS measurements (Figure 4) show that the effect of the tide on the vertical movement of the ice decreases with the proximity to the shore: 20 m from shore, at the location of Rover 3, the ice is completely floating while 8 m from shore, at the location of Rover 1, the ice is moving vertically 60 % less than the sea. The difference in movement is highest at low tide where the sinusoidal curves of the vertical movement of Rover 1 and to a smaller extent Rover 2 are capped. The horizontal movement is perpendicular to the tidal cracks (Figure 4) and is highest at Rover 1 where it attained 22 cm during a tidal cycle.

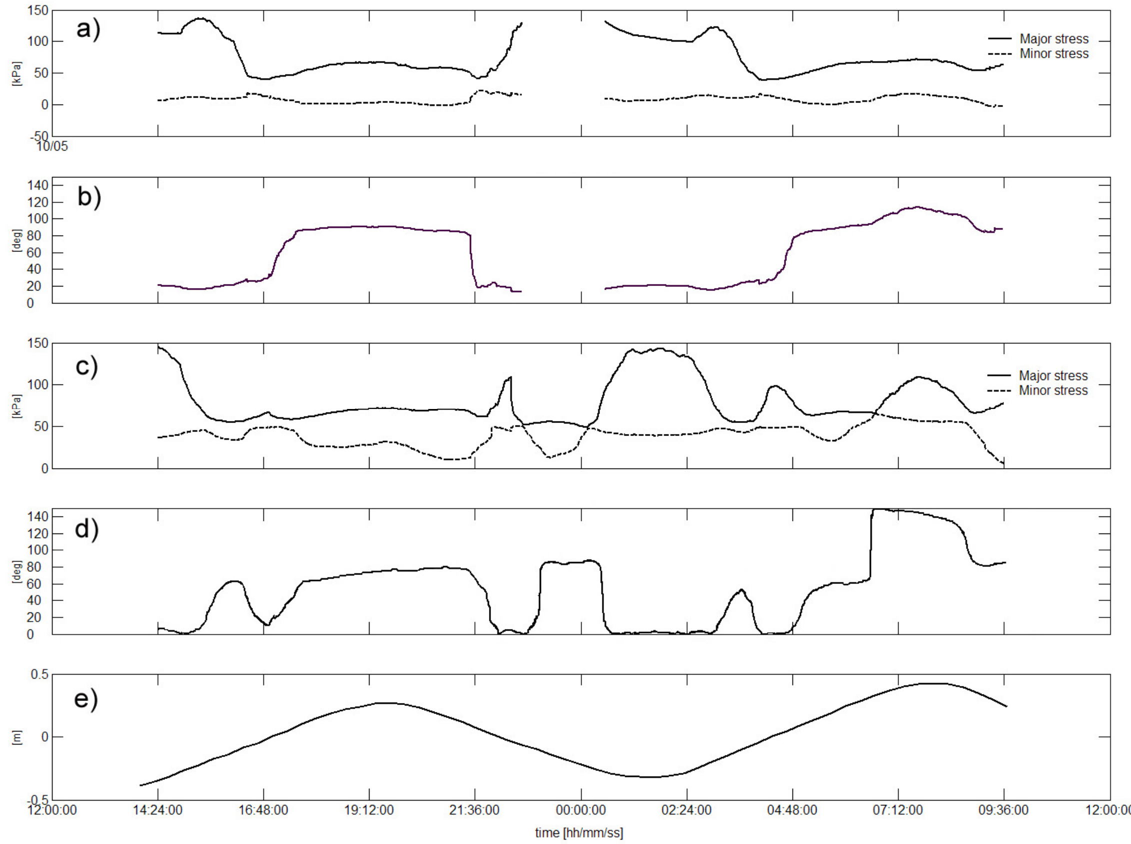

Figure 3. Principal stresses and direction on land side (a and b) and on sea side (c and d) from 10 to 11 May. The sea level is shown on e). The 0 degree reference direction is taken parallel to the tidal crack.

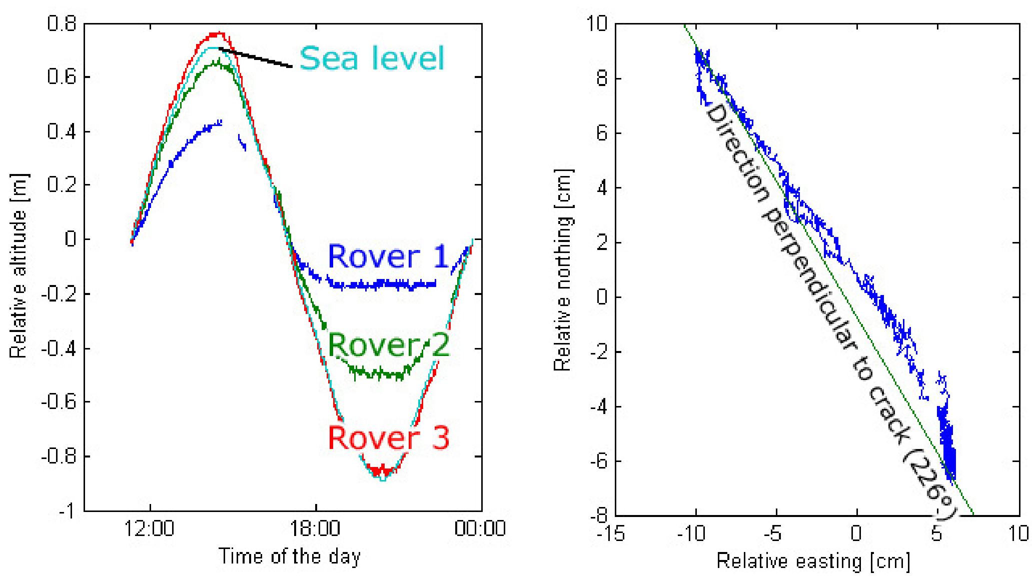

Figure 4. *Left*: DGPS measurement of the vertical movement of the ice top at three locations (Rover 1-3) and sea level during one tidal cycle — *Right*: horizontal movement of Rover 1 during that cycle. Measurements made on 17 May 2007.

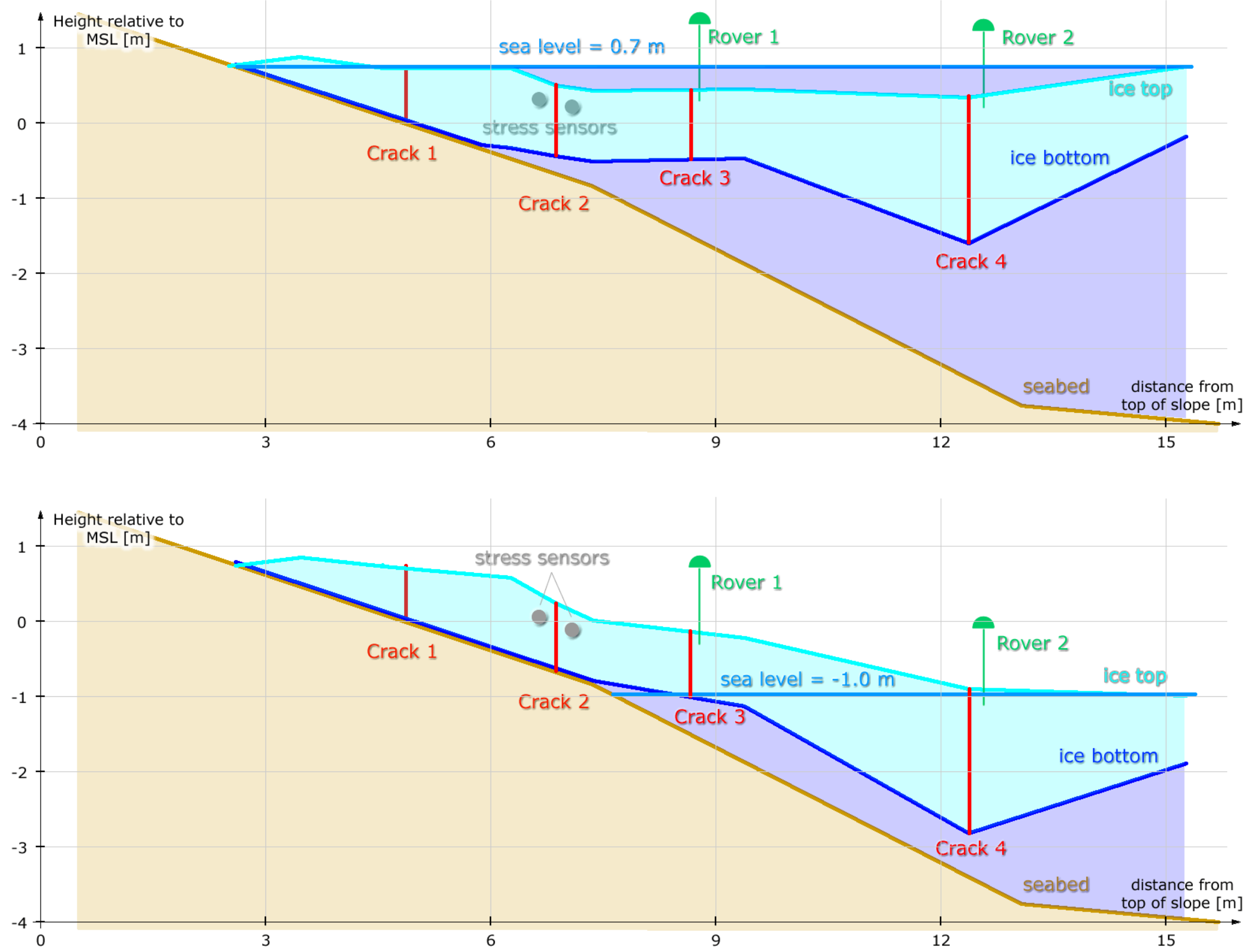

Figure 5. Cross-section of the active zone at high tide (above) and low tide (below)

5. Discussion

Stress data

Stresses in the area close to a coastal crack were measured but it is difficult to say if the stresses in the rest of the active zone vary in the same way. It is possible to give hypotheses of what could have caused the stress variations but testing them would require more measurements. It would be particularly instructive to record stresses at different depths in the 1.6 m-tick ice layer but the current instruments cannot be used because they do not resist to submersion.

Previous studies in Sveabukta (Teigen et al., 2005) showed that the wind does not affect ice stresses below 20 $m \cdot s^{-1}$. Early in the winter 2008, a survey conducted by UNIS researchers measured the tidal current close to the breakwater and found a maximum value of 30 $cm \cdot s^{-1}$. It is unlikely that such a small current would have a major effect on the stresses in the ice cover.

When it comes to thermal effects, the 40 cm-thick snow cover isolated the level ice and no thermal stresses were recorded during the first part of the season. On the coastal ice however the ice was in direct contact with the air through the crack openings. Figure 5 shows that the sea water filled the cracks at every tidal cycle and it is reasonable to suppose that the induced temperature variations would cause thermal stresses. It is expected that the grounding of the ice

(Figure 5) has an effect on the stress distribution in the ice but under a plane strain hypothesis the induced stress variations are expected to be perpendicular rather than parallel to the crack. The plane strain hypothesis might however not be valid since the breakwater is only 25 m wide and there is a rubble accumulation at its western corner which could cause bending in the direction normal to the plane of the cross-section in Figure 5 and hence stress variations in the direction parallel to the crack.

The 20 kPa peak of the stresses perpendicular to the cracks is almost certainly due to the opening and closing of the crack depending on the tide.

The observed stress variations are within the range of values found in the literature. Frederking et al. (1986) measured 70 kPa off the Coast of Adams Island where the tidal range is up to 2 m while Sayed (1988) measured 350 kPa there. Moslet (2001) had 25 kPa in Svea and Nikitin et al. (1992) 500 kPa in the active zone of the Okhotsk Sea with a tidal range of 1.25 m. As in this study they all found that the highest stresses were in antiphase with the tide. However the ice around the breakwater was not translating away from the shore as Frederking and Nakawo (1984) observed around the Nanisivik wharf piles where they measured horizontal displacements of several metres throughout the season. Stander et al. (1988) also recorded horizontal displacements, of several centimetres per day.

DGPS data

The plots of the vertical movement of the ice (Figure 4) show that the coastal ice is not in hydrostatic equilibrium with the sea water. The non-equilibrium is a consequence of friction forces along the cracks. The boundaries are on one side the ice foot which is fixed to the ground and on the other side the level ice which is completely floating. The horizontal movement data are exaggerated because the rover antennas were almost 1 m above the ice top and the vertical movement data reveal that the sections of ice between two cracks has a combined movement of translation and of rotation throughout the tidal cycle. The rotation takes place around a horizontal axis directed like the cracks. A numerical evaluation shows that the correct value of the horizontal movement of the ice at the Rover 1 location is 10 cm rather than 22 cm.

6. Conclusion

Stresses were measured close to a tidal crack in the active zone and showed a strong tidal dependency. The highest stresses were measured in the direction parallel to the tidal crack. The limited amount of stress data makes it difficult to propose more than hypotheses on the mechanical processes taking place in the active zone during a tidal cycle. Close to the tidal cracks the thermal variations caused by the cyclic sea water flooding might create stresses. A simple way to test this hypothesis would be to place a vertical thermistor cable in the ice close to a crack and another one at some distance. The tidal current is expected to have an insignificant effect. In order to measure stresses in more locations and depths in the ices, it is necessary to use a different type of sensors that resist to flooding. A numerical analysis would help optimise the number and location of these sensors.

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