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Nanisivik Revisited: Ice Pressure Measurements from Winter 1985-86

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ABSTRACT

A project was carried out over the winter of 1985/86 to measure ice forces on the Nanisivik wharf and associated environmental factors. The ice regime was land-fast first year sea ice which attained a maximum thickness of 1.6 m in May. Five panel-type transducers 1-m wide and divided into 0.5-m vertical sections were frozen into the ice cover 40-m out from the vertical wharf face. Measured ice pressures in the panels indicated that the majority of the ice pressure was in the top 0.5 m of the ice cover and all panels responded in a similar/synchronous manner to temperature and tidal inputs. Major loading events were systematic associated with a large or rapid temperature increase. Superimposed on these events were ice pressure oscillations having a frequency twice the tidal frequency. Maximum measured ice pressure on one panel section was 450 kPa. Averaged ice pressure measurements reached a maximum of 155 kN/m. A conceptual model relating ice pressure to tide is proposed to guide interpretation.

KEY WORDS: Ice pressure; Arctic wharf; Tidal effects; Thermal pressure.

INTRODUCTION

Gathering field experience and developing models of ice interactions with wharf structures in the Arctic assists in advancing design of such structures. The wharf at Nanisivik, a sheet-pile structure, was the first deep-water dock in the Canadian Arctic (Girgrah and Shah, 1978). Measurement programs have also been carried out at other docks in the Arctic (Marchenko et al, 2011). At Nanisivik a number of field projects have been undertaking over the years to document ice actions on the wharf. Frederking and Sayed, 1988 reported on ice pressure measurements made in the ice cover over the winter 1985-86 and attributed high ice pressure events to thermal factors. In connection with recent refurbishment of the wharf, new measurements were undertaken with ice pressure instrumentation affixed directly to the face of the wharf (Poirier et al, 2019). These measurements showed a significant relation of ice pressure to tide, engendering this revisit of the 1986 ice pressure measurements in relation to tide. A tidal jacking model had been proposed by Frederking and Nakawo (1984) but there was no measurement data to support it. Stander et al (1988) did obtain measurements of horizontal ice movements on a natural shore and presented results and a tidal jacking model. While no tide measurements were made in 1986, the Canadian Hydrographic Service was able to provide tidal predictions for the area. This paper will revisit the 1986 ice pressure measurements, relate them to both tides and climate information and propose a conceptual model for tidal jacking.

MEASUREMENT SITE

The Nanisivik Wharf is located on the south shore of Strathcona Sound (73'04'N-84'33'W) about 20 km east from its outlet to Admiralty Inlet. Admiralty Inlet is at the north end of Baffin Island in the eastern Canadian Arctic. The width of the Sound at the wharf site is about 5 km; maximum tidal range is 2.5 m. The wharf comprises three sheet pile cells 21 m in diameter, 38 m on centres, about 50 m offshore, see Figure 1. The ice regime was land-fast first year sea ice which attained a thickness of 1.1 m in early March and 1.6 m in May. Between the land-fast level ice was an “Active Zone” of ice which will be discussed later in the paper.

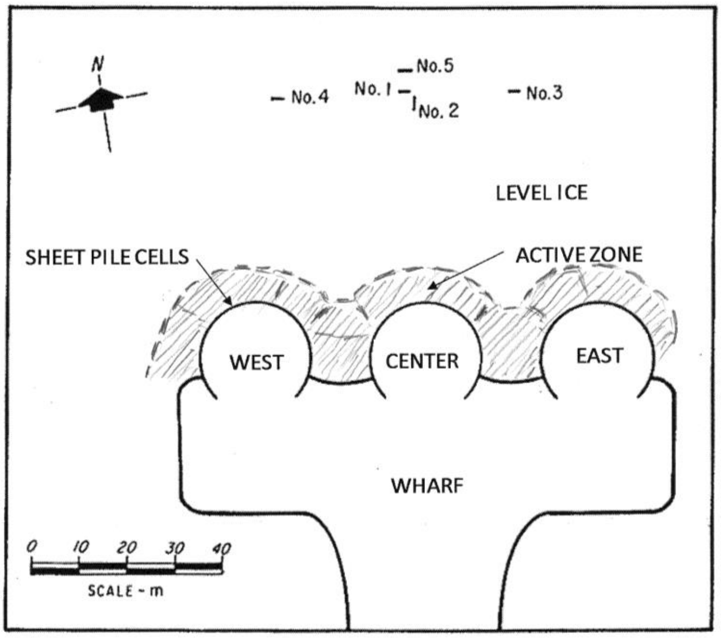

Figure 1. Schematic showing locations of ice pressure-measuring panels installed adjacent to Nanisivik wharf, winter 1985-86

MEASUREMENT PROGRAM

The measurement program covered the following elements: in situ pressures in the ice cover adjacent to the wharf, horizontal movements of the ice cover, ice temperatures, and meteorological conditions. Ice conditions were observed during a series of site visits and unattended data loggers were used to record ice pressures and metrological data. Instruments were installed in November 1985, their operation verified in March, and they were recovered in May 1986.

In early November, five panel-type transducers were installed in the level ice cover adjacent to the wharf to measure in situ ice pressures. Four panels (Nos. 1, 3, 4 and 5) were aligned parallel to the dock and one (No. 2) was placed normal to it (Figure 1). Panels No. 1 to 4 were 1 m x 1 m, sectioned horizontally so that the average pressure in the top 0.5 m and lower 0.5 m could be measured independently. Panel No 5, 1 m x 2 m, was horizontally sectioned in four sections each 0.5 m high. This allowed vertical distribution of pressure in the ice cover to be measured. Output was recorded at 15-minute intervals. As problems were encountered initially with the logger, no reliable recordings were obtained until January 1986.

In November an automatic meteorological station was set up on the ice surface half-way across the Sound to measure wind speed and direction, air temperature, and ice temperatures. Data were recorded at half-hour intervals. The thermocouple probe for measuring ice temperatures had individual sensors at depths of 0.0, 0.25, 0.5, 0.75, 1.0, 1.5 and 2.0 m.

RESULTS AND DISCUSSION

Results from measurements of the top 0.5 m section of ice pressure Panels No. 3, 4 and 5 for the period 1986 Jan 21 to May 20 are shown in Figure 2, the suffix 't' designation the top section . There were interruptions in the record in March and April due to logger problems. Ice pressure results for the panels were remarkably similar. The zero pressure level established for these readings was taken in November just after the panels had been placed in the ice cover. In early March slots were cut around the panels to relieve the pressure on them, thereby checking the zeros. A final set of zero readings was obtained in May when the panels were removed.

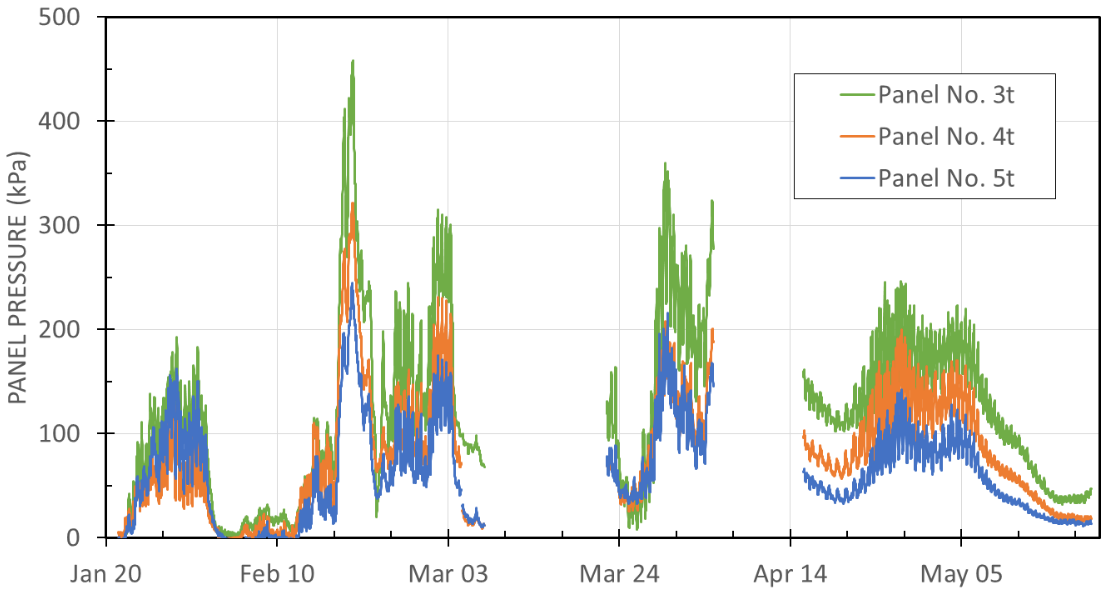

Figure 2. Ice pressure measurement in the top 0.5 m of Panels No. 3, 4 and 5 for 1986.

The results from Panel No. 5, which had 4 sections are presented in Figure 3. This plot indicates that the majority of the ice pressure is in the top 0.5 m of the ice cover (No. 5t). Ice pressures on section 5a (0.5 to 1.0 m depth) are much lower than the top section. Pressures deeper in the ice as designated as 5b (1.0 to 1.5 m depth) and 5c (1.5 to 2.0 m depth) experienced no measurable ice pressure. Similar distributions were obtained for the other panels.

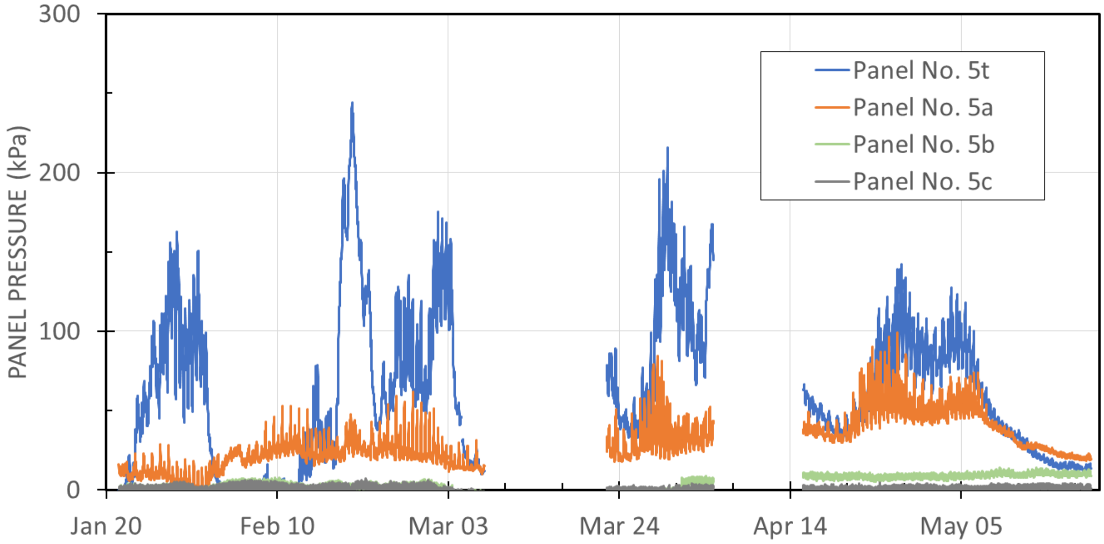

Figure 3. Vertical distribution of ice pressures on Panel No. 5

Air temperature and ice temperatures at various depths in the ice cover measured at the centre of the Sound for the period 1986 Jan 20 to May 21 and are plotted in Figure 4.

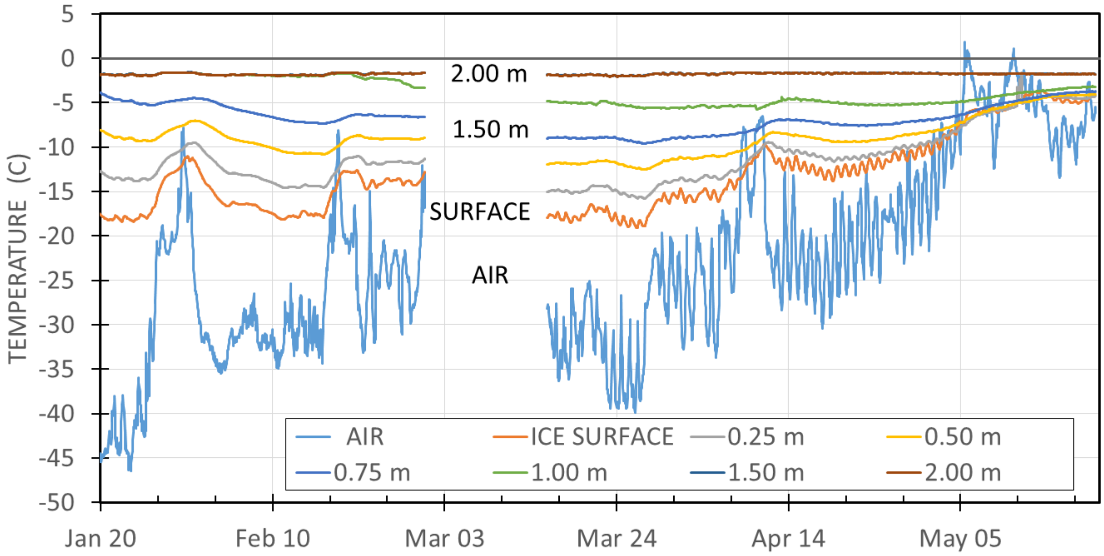

Figure 4. Air temperature and ice temperatures at depth through the ice cover

Comparing Figures 2 and 4 there appears to be similarity between ice pressures and temperatures. To make this comparison easier to see, pressure from the top section of Panel No. 3 and temperature at the ice surface are plotted in Figure 5. Generally the high pressure events correspond to large or rapid ice temperature increases and low ice pressures to periods of decreasing or steady temperatures. From March onwards there was a progressive warming of the ice cover as well as diurnal temperature cycles of increasing amplitude. Four events have been identified in Figure 5 and will be examined in greater detail to try to show the relative importance of temperature and tide on ice pressures.

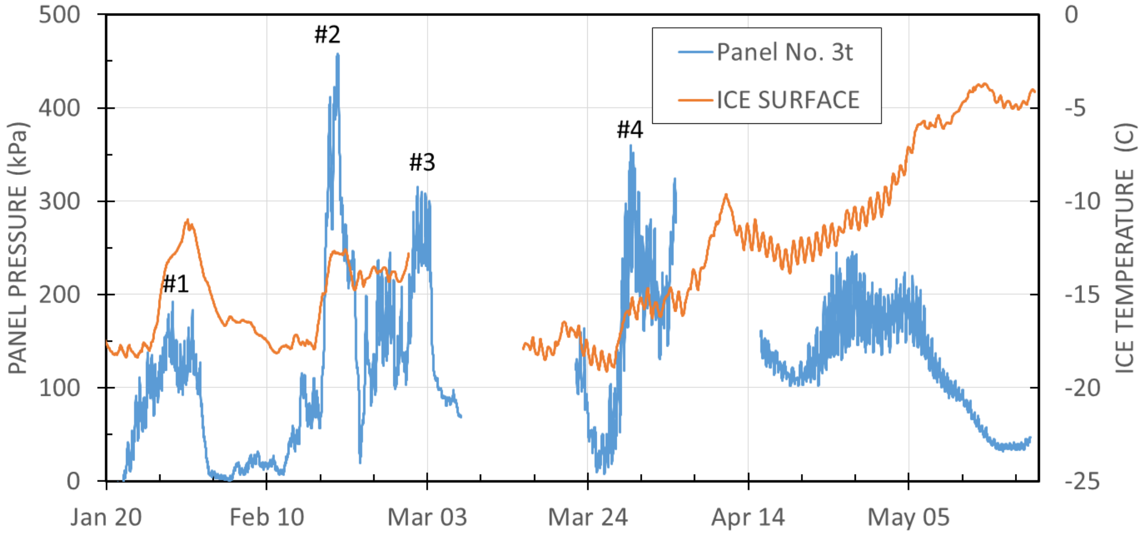

Figure 5. Comparison of Panel No. 3 top section ice pressure and ice surface temperature

Event #1

In late January the sun was below the horizon so there was no discernable diurnal ice temperature cycling, making this a good event to examine the ice pressure variations in relation to tidal actions. Figure 6 plots ice pressures from Panels No. 3, 4 and 5 and ice surface and 0.25 m depth temperatures. From Jan 22 through Jan 25 temperatures were stable, although ice pressure increased. Ice surface temperature then increased rapidly (2 C/day) from Jan 26 to 28, accompanied by an ice pressure increase, the rate of ice temperature increase at a slower rate of 0.75 C/day for Jan 28 to 30, accompanied by a decrease in ice pressure. The rapid ice temperature decrease starting Jan 31 engendered a rapid ice pressure decrease. Weather conditions for this period were also examined. Associated with the temperature rise, there was also a period of high winds (30 to 50km/hr) Jan 27-31 inclusive, swinging from south to east to north and back to east. Wind speed reached 90 km/hr from the north on Jan 30 and could have generated an onshore ice pressure, but none was noted. Also from Jan 28 to 30 barometric pressure fell by 5 kPa or the equivalent of a 0.5-m rise of sea level which was superimposed on the tidal cycles. This event was associated with a storm, high winds, falling barometer and rising temperature. Figure 6 also shows a distinct periodicity in the ice pressures, with pressure peaks at 6.17 hr intervals, about half the tidal period. Panel No. 5 ice pressures at low and high tide for two cycles are marked with x's in the figure, which will be examined further.

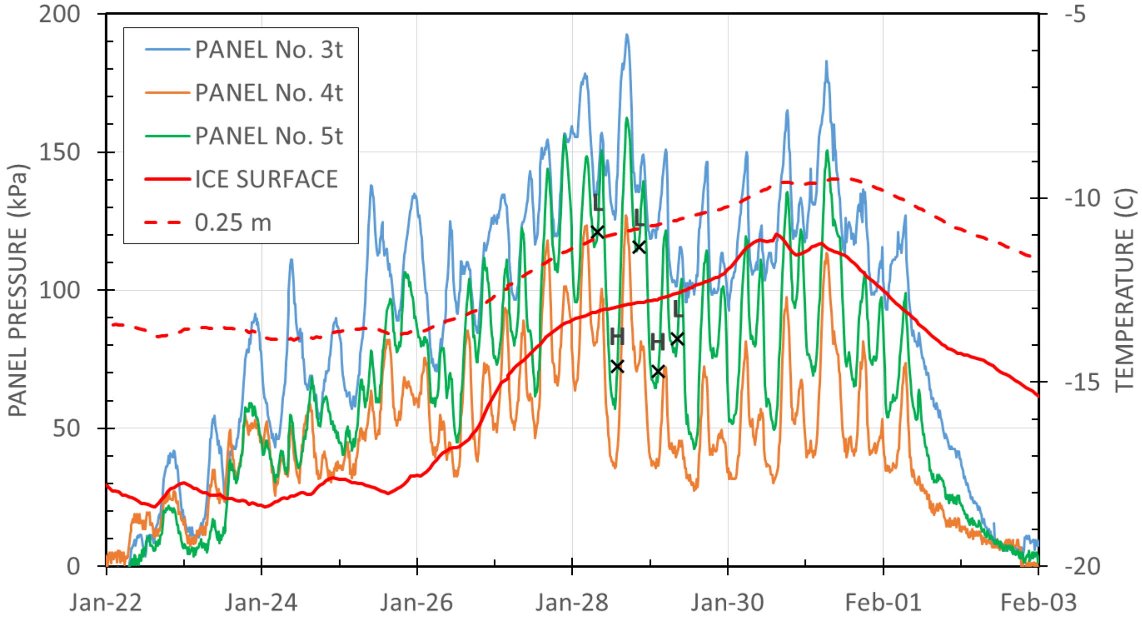

Figure 6. Ice pressure and ice surface and 0.25-m depth temperatures (in red) during event #1 in late January

Both tide and ice pressure were measured at 15-minute intervals and were synchronized. A cross plot of tide versus ice pressure was made to visualize the relation between them, see Figure 7. The spacing between the dots (15 minutes) is an indication of the rate of tide or ice pressure change. Starting with low tide at Jan 28 07:45 ice pressure first increases rapidly to a maximum, then more slowly decreased to a minimum just before high tide and then increases rapidly through high tide at Jan 28 14:00 to a maximum of 160 kPa at mid tide, before decreasing at a lower rate until low tide at Jan 29 20:30. For this cycle the tide range was about 2 m and the ice pressure range across high tide was 100 kPa. The end point of the first cycle is the start of the second cycle, which has a similar pattern, but with a smaller ice pressure range of 60 kPa across high tide. The pattern can be described as a maximum then a minimum in going from low to high tide and then a maximum and minimum in going from high to low tide. There is a continuous ice pressure increase across high tide as well as across low tide, however the ice pressure range across low tide is smaller than the one across high tide.

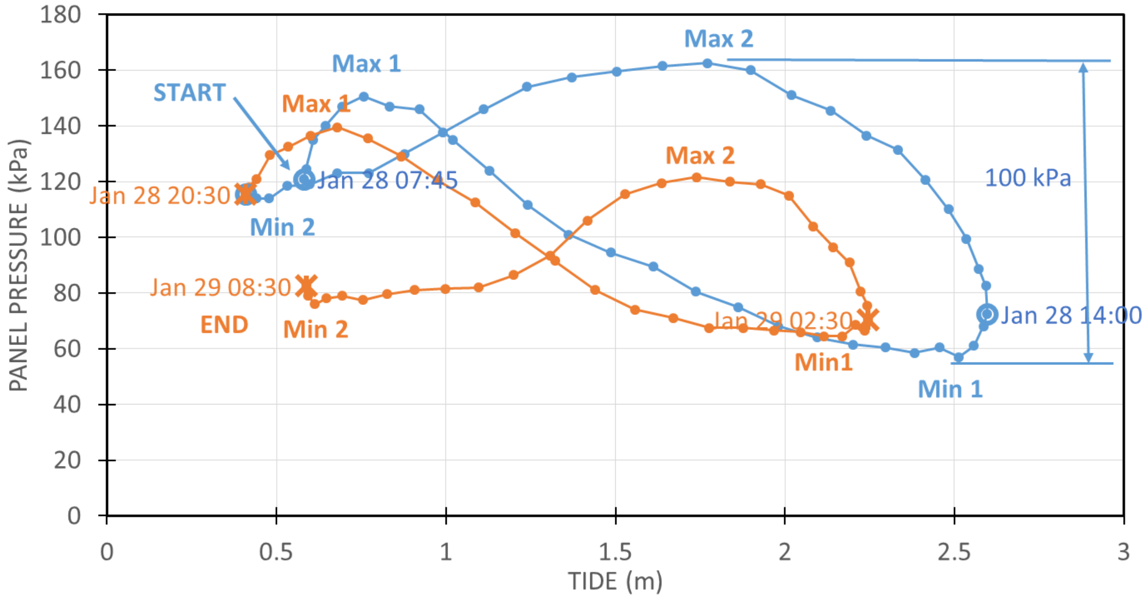

Figure 7. Ice pressure versus tide stage for Panel No. 5, event #1 Jan 28 07:45 to Jan 29 08:30

Event #2

Event #2 occurred February 17-22, and was associated with a rapid ice surface temperature rise, 4C over 2 days, see Figure 8. This was the event with the largest ice pressures which, when taken together were equivalent to a maximum line load of 155 kN/m. The temperature rise was accompanied by winds about 40 km/hr from the south-east which increased to 70 km/hr for a period in mid-day Feb 18. The tide range was less than 1 m during the 5-day period of the event. Ice pressures of Panel No. 5 at low and high tide for two cycles are marked with X's in the figure. Cross plots of tide versus panel pressure were examined, but no systematic behavior similar to that observed in Figure 7 for Event #1, could be observed. The last 3 X's show a progressive ice pressure increase.

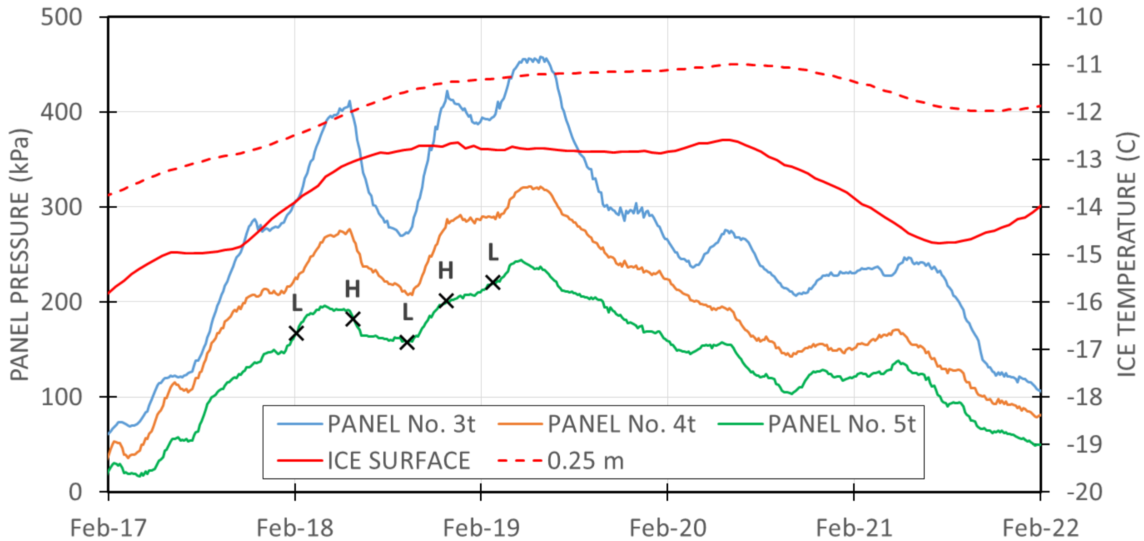

Figure 8. Ice pressure and ice surface and 0.25-m depth temperatures during event #2 in late February

Event #3

Event #3 occurred in early March (see Figure 9). Ice pressures of Panel No. 5 at low and high tide for three cycles are marked with x's in the figure. It can be seen that ice pressure peaks follow both low tide and high tide. Thus frequency of ice pressure peaks was twice the tidal frequency. Due to recorder failure no temperature record beyond Feb 28 was obtained for this event. Fortunately, climate data from Nanisivik airport, about 10 km to the south, was obtained and indicated air temperatures remained warm on March 1 before dropping to about -30 C on March 3, explaining the rapid drop in ice pressures. Winds were 30 to 40 km/hr from the south-east dropping sharply on Mar 4. The barometer fell by 5 kPa from Feb 27 to Mar 4, producing a 0.5 m rise in sea level, but no apparent effect on ice pressures.

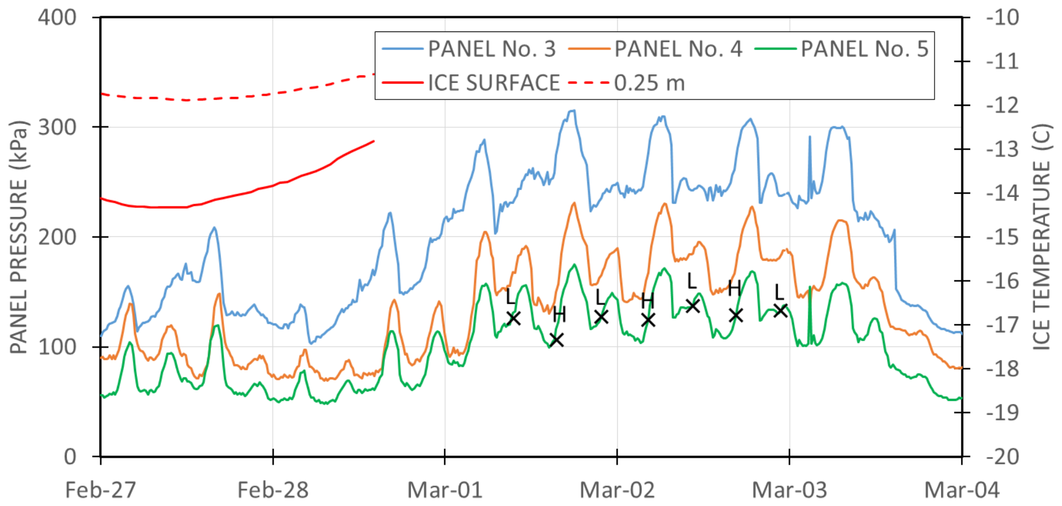

Figure 9. Ice pressure and ice surface and 0.25-m depth temperatures during event #3 in early March

Event #4

Event #4 occurred in late March. Figure 10 plots ice panel pressures for the period Mar. 28 to Apr. 3. Diurnal cycling of ice surface temperature is evident with an amplitude of about 1 C superimposed on an increase of about 2 C over 3 days. The ice pressure frequency is again twice the tidal frequency for Panels No. 4 and 5. For this event the ice pressure signal from Panel No. 3 is different from that of Panels No. 4 and 5 and has a frequency similar to the tide. The ice pressure amplitude is much larger, almost double the other two panels. The times of high tide and low tide for Panel No. 4 are marked with an x and labeled H or L, respectively. Cross plots of tide versus Panel No. 4 pressure are presented in Figure 11. From the start, Mar 28 08:00, the ice pressure decreased slowly to a minimum and then increased through high tide before reaching a maximum just shortly after high tide at Mar 28 14:00. Following this maximum pressure there was a slight pressure decrease before increasing progressively to low tide. A similar, but more exaggerated pattern followed for the next cycle. Both cycles had a maximum ice pressure close to both high tide and low tide.

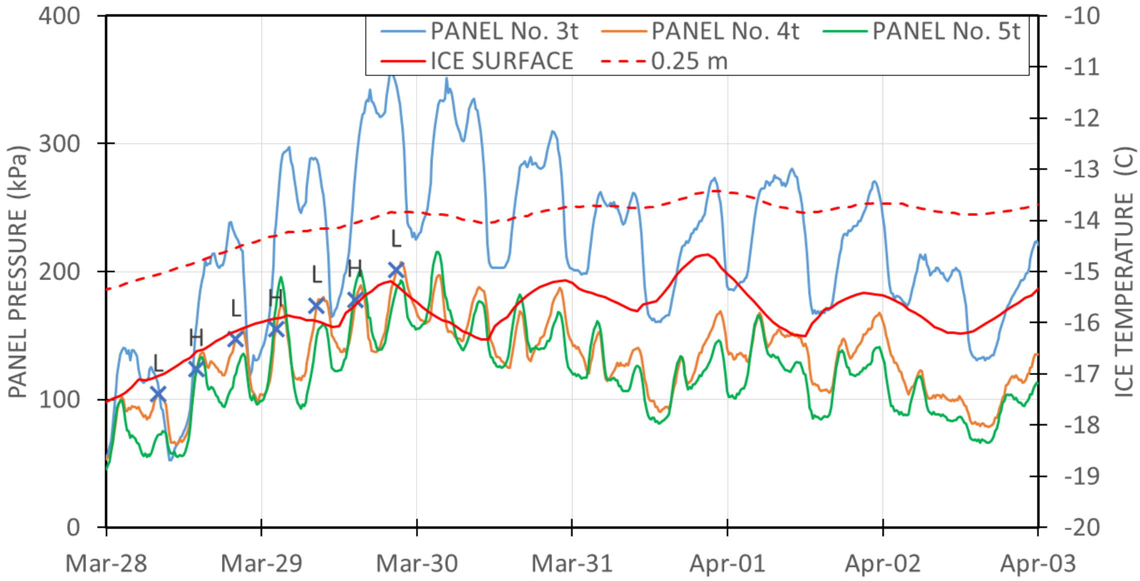

Figure 10. Ice pressure and ice surface and 0.25-m depth temperatures during event #4 in late March

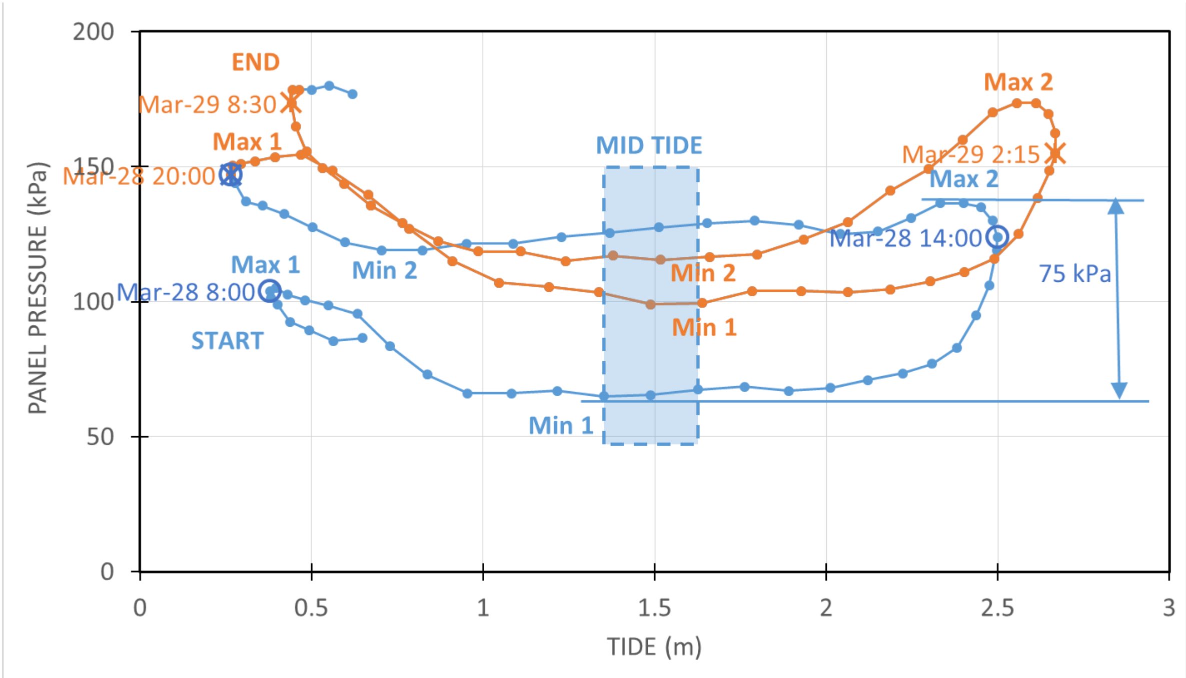

Figure 11. Ice pressure versus tide stage for Panel No. 4 event #4, Mar 28 08:00 to Mar 29 08:30

MODEL PROPOSED

In earlier work, Frederking and Nakawo (1984) proposed a model of tidal jacking based on the progressive accretion of ice on vertical and horizontal surfaces of an 'active zone' of ice between the wharf and the adjacent floating ice cover. When the tide range was large, flooding occurred on the top surface which froze increasing the thickness of the active zone. This successive size increase of the active zone, friction at the wharf face and constraint from the adjacent ice cover resulted in the active zone of ice tilting in addition to moving upwards and downwards under tidal action, thereby generating cyclic horizontal pressures in the ice cover. Recent measurements of local ice pressures on the wharf face at Nanisivik (Poirier et al, 2019) indicated tidal related ice pressure events of 200 kPa to 600 kPa with durations of 1 to 4 hours. This stimulated revisiting the 1986 ice pressure measurements to look for the tidal component. Ice pressure – tide cross-plots were made to study the relation between them. A few cycles from two events (#1 and #4) were presented. These can be generally described as 'figure-of-eight' (Figure 7) or 'flattened ellipse' (Figure 11) patterns. Chronological progression was clockwise in the illustrated events, but counter-clockwise cycles were also observed.

Figure 12 presents a schematic for describing tidal jacking; at low tide (**L**) (dashed outlines of Active Zone **AZ** and Ice Sheet **IS**) and high tide (**H**) (solid outline of Active Zone **AZ** and Ice Sheet **IS**). The tide range is **T**, however friction at the interface between the wharf and **AZ** results in a lower range of vertical movement of the **AZ** adjacent to the wharf, **αT**, and resulting rotations of **AZ**. Frederking (1980) observed the tilt to be 1° downwards towards the wharf at high tide and 14° upwards towards the wharf at low tide. At high tide water flooded the surface of **AZ** next to the wharf face and froze on the horizontal and vertical surfaces adjacent to **a**. An interference **δ** between **c** and **d** generates the ice pressure in **IS**, which is transmitted to and measured by the panels. Note, this is a simplified 2-D view, **AZ** is circular-shaped in plan as shown schematically in Figure 1 (Frederking and Nakawo, 1984).

The tide-ice pressure process of Figure 11 will be described with the aid of Figure 12. Tide rises from the low point (**L**) resulting in **AZ** rotating about **b** and making **a** and **c** move horizontally towards the wharf and away from **d**, reducing the ice pressure in **IS** to a minimum by mid tide. As tide continues to rise the **AZ** rotates counter-clockwise and the recently accreted ice on the vertical surface at **a** moves **AZ** way from the wharf, increasing the force at **d** and ice pressure in **IS**. The ice pressure continues to increase even as the tide falls. The reason for this overshoot is unclear. As tide continues to fall, the ice pressure remains relatively constant. Approaching low tide (**L**) **AZ** rotates further about **b** and moves **c** towards **d** increasing ice pressure in **IS**. Passing through low tide (**L**) there is a slightly delayed reversal of ice pressure and the cycle repeats. This results in an ice pressure peak with each tidal reversal and thus a frequency twice tidal frequency.

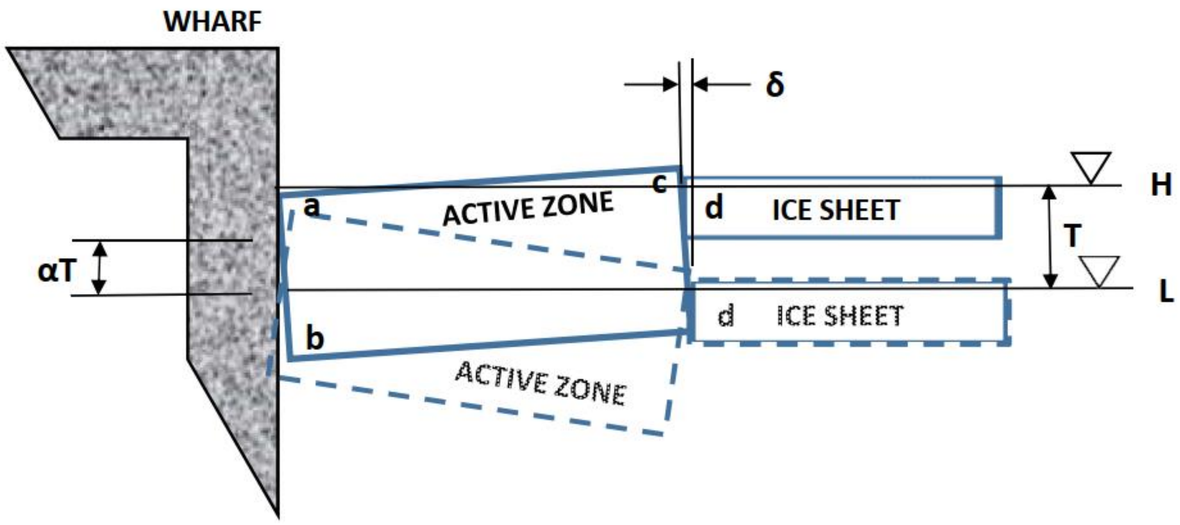

Figure 12. Schematic of Ice pressure versus tide stage, solid outline at high tide, dashed outline at low tide

CONCLUSIONS

While major ice pressure events were generally associated with large or rapid rises of ice temperature, tidal cycling was responsible for shorter period loading peaks during these events. The following aspects of tidal related ice loading were identified:

- Loading frequency was twice that of the tide, there was a loading peak associated with both legs of a tidal cycle, low to high and high to low.
- Progressing through high tide or low tide, continuing increases or decreases of ice pressures were observed, a puzzling observation; possibly due to the three dimensional shape of the active zones encircling the cells.
- Ice pressures amplitudes of 100 kPa contributed significantly to total ice pressure.
- A simplified 2-D tidal jacking model proposed provides a starting point for interpreting and potentially predicting ice pressures, but more work is required to extend to 3-D.

Measurements showed the majority of ice pressure was in the top 0.5 m of a first year ice cover. Ice pressure at three locations across a 50-m front were relatively similar and varied in a synchronous fashion.

ACKNOWLEDGEMENTS

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