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Static ice loads on a dam in a small Norwegian reservoir

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Ice loads on a concrete dam have been calculated from stress measurements in Taraldsvikfossen Reservoir, a small reservoir in Narvik, Norway, during three winter seasons. Ice thickness was in the range of 0.5 to 1.0 m, and both thermal ice loads were observed and water level fluctuations up to 30 cm were observed when the ice cover froze to the spillway. The maximum global line load measured was 60 to 90 kN/m, in line with current design guidelines in Norway. Consistent with earlier reports, line loads were not evenly distributed along the dam face. A thermal line load model was able to reproduce the approximate shape and magnitude of many line load peaks even when the measured vertical stress profile could not be reproduced by the model. The results add to an extremely small body of data in Norway and motivate investigations in other parts of the country with expected higher or lower ice loads.

pressure gauge had been installed at the dam at 1.3 m water depth in winter 2013/14. It froze in that winter but provided valuable data the following winter.

A limitation of the stress measurement method is that flatjacks cannot reliably measure tension because the ice may detach from the probes, or the oil inside the probes may start to boil in the presence of a vacuum. The latter problems may arise from approx. 100 kPa in tension. Hence, it is assumed in this study that measured line loads are systematically biased high in the presence of tensile stresses (cf. Section 3).
The configuration of stress cells differed between seasons. However, in each case there were both measurement stations that measured vertical profiles and measurement stations with only one cell. Only stations with multiple cells are used in this study, and those were located near the center of the dam. Cells that were frozen into the ice in 2012/13 and 2013/14 showed characteristic stresses during freeze-in (e.g., Fransson 1988), and data analysis stared after those freeze-in peaks had relaxed during warmer weather.

During winter 2012/13, stations were installed 1 m in front of the dam and in the middle of the reservoir, approx. 10 m from dam (cf. Petrich et al., 2015). At the time of measurement, ice thickness was approx. 0.85 m near the dam (Stations 3 and 5) and 1.0 m at Station W. During winter 2013/14, the first half of each station was installed at the dam early in the season and the second half in the ice 2 m in front of the dam in February. These were intended for inter-comparison but are interpreted as single stations here due to unexpected, excessive superimposed ice formation at the dam (Figure 2). During winter 2014/15, cells were installed at the dam with one cell placed above the water line to account for anticipated superimposed ice formation. As a result, only a comparatively small amount of superimposed ice formed above the upper-most cell (Figure 3).

Line loads were calculated as a lower and nominally upper bound. For lower bound calculations, each stress measurement was multiplied by the vertical separation of the stress cells, i.e. 0.15 m in all seasons (exception: 0.25 m at Station W in 2012/13), and the results were summed. However, due to the peculiar cell configuration in winter 2013/14, the lower-most cell 2 m in front of the dam was averaged with the upper-most cell at the dam (cf. Figure 2).

Simple stress extrapolations were performed to estimate nominally upper bound line loads, i.e., to account for ice above and below the stress cells. In season 2012/13 the depth weights of the upper and lower most cells at each station were changed to 0.25, and 0.35 m, respectively (0.275 and 0.45, respectively at Station W), in season 2013/14 they were 0.25 and 0.25 m, respectively, and in season 2014/15 they were 0.3 and 0.15 m, respectively. There was insufficient linearity in the stress profiles to justify a linear extrapolation.

Usually, loads to not act homogeneously along the dam which implies that the average load experienced by a section of the dam will be less than the peak load (e.g., Côté et al., 2016). Hence, a global line load was calculated as the average of the line loads of all stations at a given time (local line loads) to quantify the magnitude of the influence of dam design.

2.2 Thermal Modeling

Modeling of thermal ice loads assumes knowledge of ice thickness and temperature in addition to (implicit) assumptions about properties of ice and dam. While ice growth and temperatures are reasonably straight-forward to model (e.g., Bergdahl 1978; Petrich and Arntsen, 2018), measurements are used in this study since they are available. Temperature fixed the bulk of the ice at 0 °C, explaining the absence notable loads in spite of air and ice temperature variations at the dam.

3.1 Winter 2012/13

Figure 4 shows line load data of two stations mounted 2 m in front of the dam (Stations 3 and 5, Figure 4b and c, respectively), and one station mounted 10 m in front of the dam (Station W, Figure 4d). Ice thickness 1 m in front of the dam was 0.75 m on 9 February (0.3 m freeboard at the sites of deployment due to ice formation from surface flooding at the end of December).

Freeze-in artifacts lasted from probe deployment until a week-long warm spell at the end of February. The ice cover remained detached from the spill way following the warm spell and there were no further indications of water level fluctuations in the timelapse imagery or otherwise until break-up. After the warm spell, phase 1 started with a load event that, counter-intuitively, corresponded to a 10 °C drop in air temperature, followed by small load variations (Figure 4). The thermal model reacted on the initial decrease in air and ice temperature by predicting a negative load, i.e. ice pulling the dam, modulated by temperature fluctuations that correlate positively with the load variations at Stations 3 and 5, and negatively with loads calculated for Station W 10 m away from the dam. Phase 2 is characterized by five consecutive load events that are reasonably well reproduced by the thermal load model. Following an abrupt decrease in temperature, the thermal model and observations show fluctuations between tension and compression loads in phase 3. Like in phase 1, measured line load variations correlated positively with modeled loads at Stations 3 and 5, and negatively at Station W. The week-long load period of phase 4 and subsequent smaller variations in line load are reproduced reasonably well by the thermal load model. The ice decayed during phase 5 when no more load events were recorded or modeled.

There is a phase lag in the temperature data and stress signal from the top-most to the bottom-most stress cell as one would expect in the presence of vertical heat conduction through the ice (Figure 7).

With the exception of the initial peak in phase 1, the peak local line loads were between 60 and 90 kN/m, depending on how stresses are extrapolated. The nature of the initial peak in phase 1 is not clear. However, since they are entirely due to high stresses at the top-most cells they could potentially be a form of freeze-in artifacts. Peak global line loads (Figure 4e) were lower than local loads, i.e. 40 to 80 kN/m, depending on extrapolation.

3.2 Winter 2013/14

Figure 5 shows line load data of three stations that combine stress cells at the dam with stress cells in the ice. The period shown starts following the freeze-in period of the ice-borne sensors and ends prior to melt-out artifacts of the dam-borne sensors (i.e., dam-borne sensors were torn out of anchorage). No vertical movement was visible in the timelapse camera sequences since 4 February 2014. There was 50 cm superimposed ice at the dam since January, and ice thickness was 0.75 m during deployment on 11 February.

Three major load events (phases 1, 3, 7) appear to have been thermal loads based on their agreement with the thermal model. However, there is a small discrepancy in either time or magnitude between measurements and thermal model in phase 1. At this point we cannot assess whether this is a phenomenon that merits further investigation. Phases 2, 4, and 6 are marked by only small measured and modeled loads. In fact, the ice was flooded during phase thermal load. Since the flooding did not extend over the entire ice surface, no corresponding temperature signal was detected by the temperature sensors at any of the stations during phase 1, and at station D during phase 3 and hence those are not modeled as a thermal load (Figure 6b,c,d).

It is difficult to unambiguously distinguish loads due to waterlevel changes from thermal loads in phases 1, 3, 5, and 6 since water level changes were accompanied by partial flooding of the ice surface. The vertical stress profile that developed in the flooded areas could have averaged out in the regions that were not flooded closer to the dam where it got further modified by cracks and an upward-moving ice cover, removing the characteristic staggered stress development through depth that was observed in 2012/13. Similarly, the stress profiles during phases 4 and 7 do not show thermal characteristics (Figure 9) even though the aggregated local line loads do (Figure 6). Hence, the local line load may be a more robust measure of ice processes than the depth-resolved stress profile.

Peak line loads this season were related to inrush of water into the reservoir that caused upward-movement and partial flooding of the ice surface. Separating the contributions of the two mechanisms is not trivial.

The registered local peak line load was 170 to 240 kN/m at Station C, phase 6, just before readings at two stress cells exceeded 50 kPa in tension. The global line loads were 60 to 90 kN/m at this point.

4. Conclusion

Local line loads have been calculated for three years of ice stress measurements at Taraldsvikfossen Reservoir near Narvik. While the reservoir had nominally no waterlevel varions in winter it did show significant excursions while the ice cover was frozen to the spillway.

It was found that local line loads may follow development predicted by the thermal load model even when individual stress measurements within the corresponding profiles do not (2013/14 and 2014/15). It was hypothesized that this is related to inhomogeneous ice temperature profiles across the reservoir (in particular, local flooding) and cracks in the ice.

The maximum global line load registered was 60 to 90 kN/m with a local maximum of 170 to 240 kN/m. The ranges result from uncertainty because the measured vertical stress profiles did not extend through the entire depth of the ice and the stress profiles generally did not suggest linearity. The assessment excludes periods where at least one stress cell recorded tensile stresses >50 kPa due to systematic limitations of the method to measure tension. Season 2013/14 had been excluded from this assessment due to additional uncertainties that stem from the stress cell configuration. However, global line loads were probably in the same range. Since the maximum line load experienced by a section of the dam decreases with increasing width of the construction sections (e.g., Côté et al., 2016), the dam-dependent relevant peak line load should lie between local and global loads.

Rarely discussed aspects of the measurements include the observation of negative line loads, i.e. ice pulling the dam, and the implicit assumption that the dam is a rigid body that does not move in response to thermal or mechanical forces. The latter could potentially introduce dam-dependence of line load measurements.

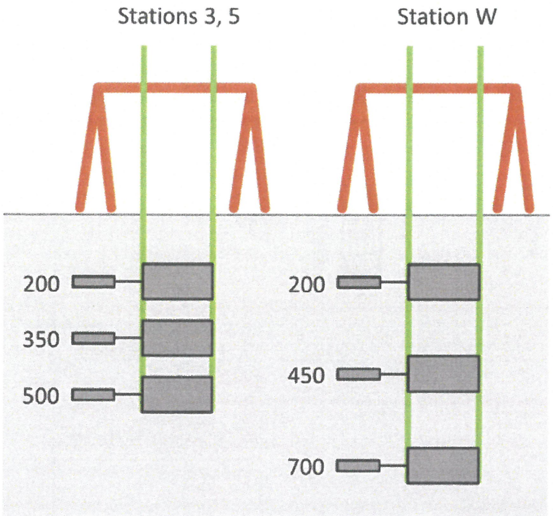

Figure 1. Sketch of the vertical positions of stress cells in winter 2012/13. Numbers indicate distance to the ice surface in mm at the time of depoyment. Stations 3 and 5, and Station W were placed 1 m and 10 m in front of the dam, respectively.

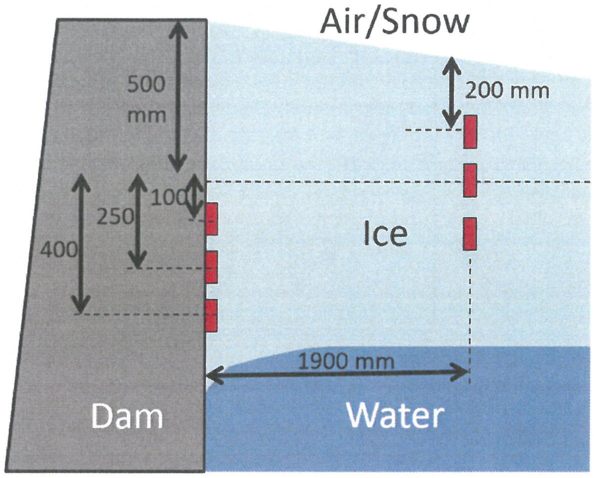

Figure 2. Sketch of the vertical positions of stress cells in winter 2013/14. The dashed horizontal line indicates the water level (i.e., approx. ice level) at the time of deployment of the dam-borne sensors. Sketch is not to scale.

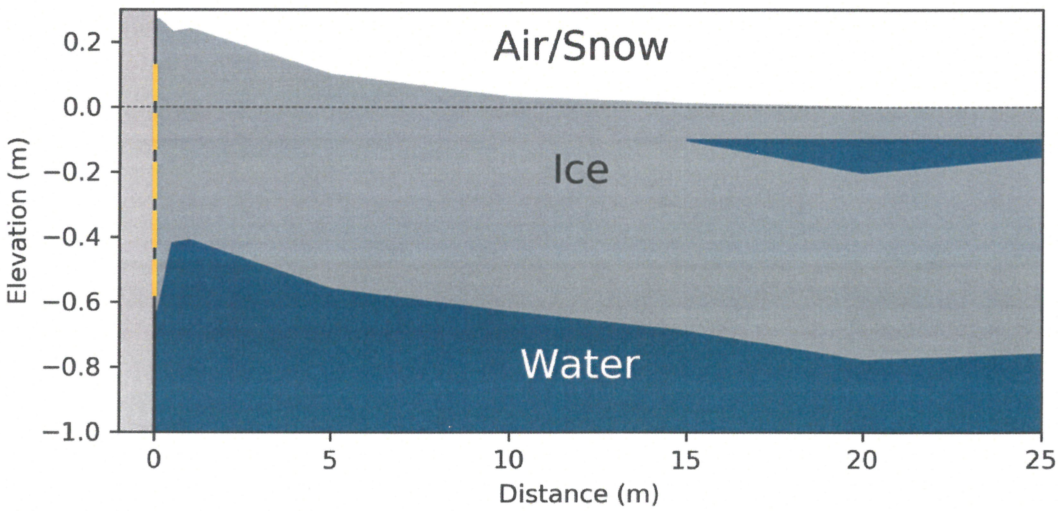

Figure 3. Measured vertical ice profile along a transect normal the dam (distance 0 m) on 6 March 2015 (phase 8), i.e. several weeks after significant load signals had been recorded. Positions of the stress cells at the dam during winter 2014/15 are marked (yellow lines at distance 0 m). 0 m elevation is the waterline at the time of measurement. Note the gap layer in the ice from 15 m onwards.

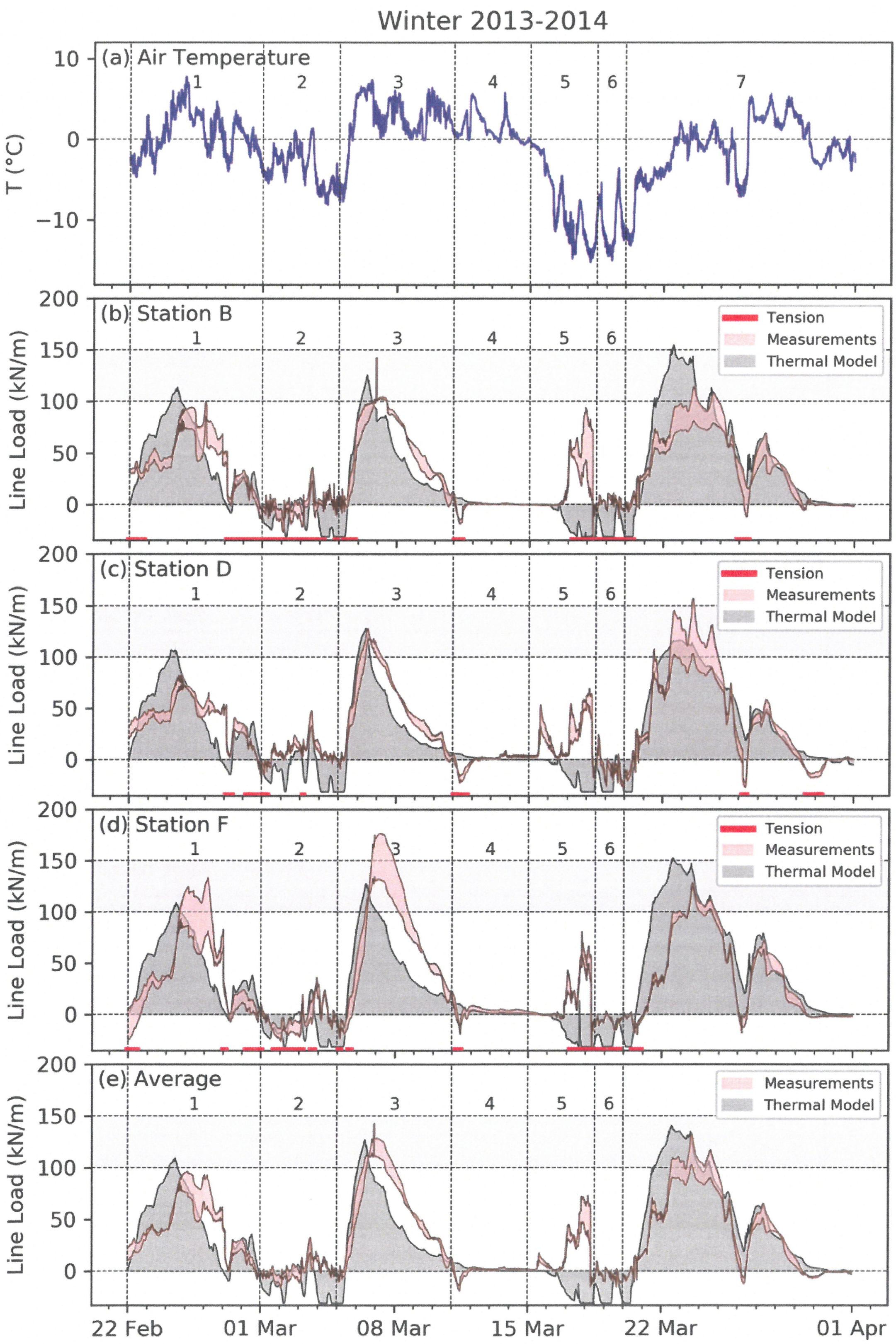

Figure 5. (a) Air temperature, (b,c,d) ice loads in winter 2013/14 measured and modeled at three stations, and (e) averaged loads. Red lines in (b), (c), and (d) indicate that tensile stresses >50 kPa were measured.

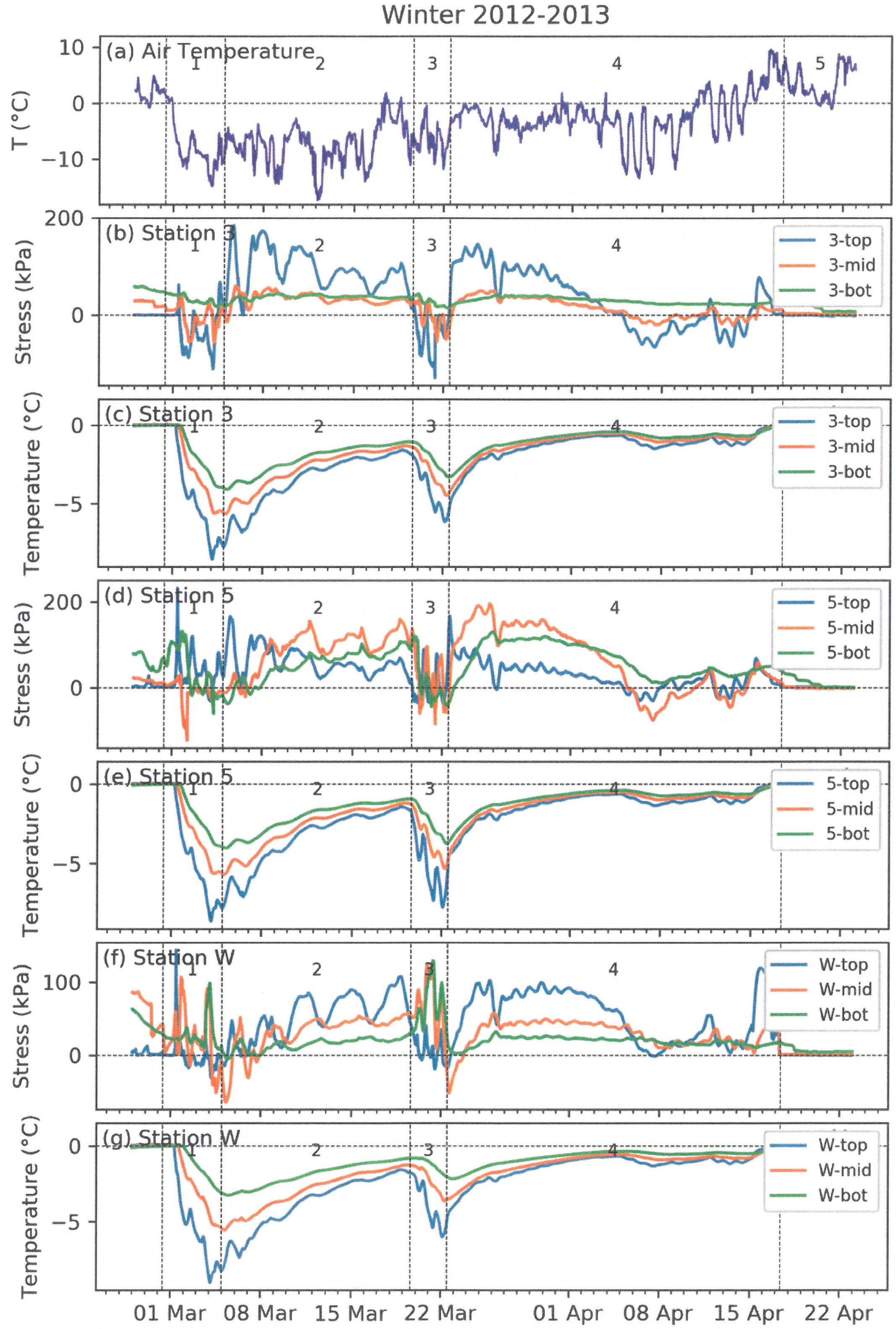

Figure 7. (a) Air temperature, (b,d,f) stresses positive in compression, and (c,e,g) ice temperatures measured in 2012/13. Cells are labeled top to bottom "top", "mid", "bot", respectively.

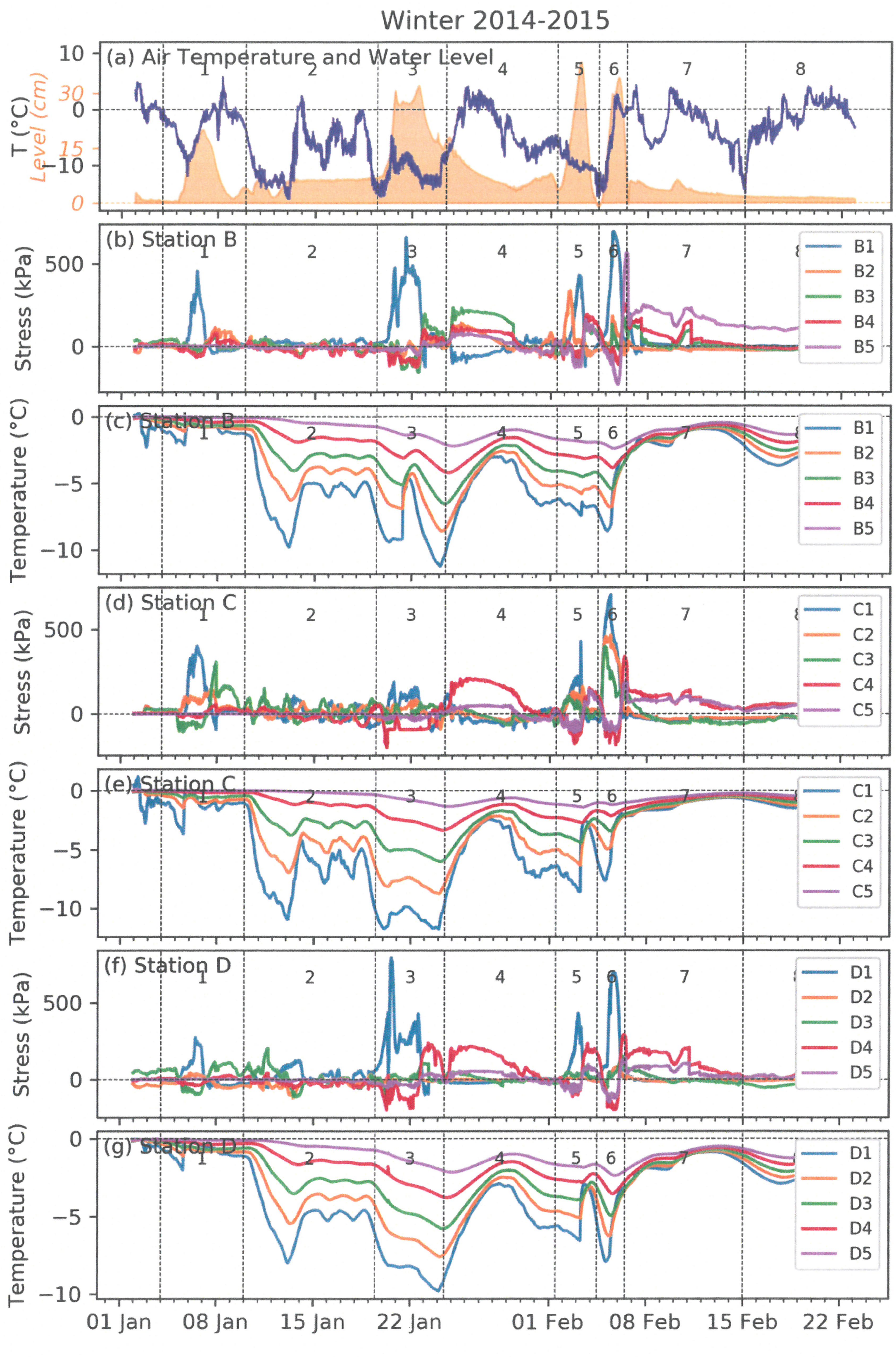

Figure 9. (a) Air temperature and water level, (b,d,f) stresses positive in compression, and (c,e,g) ice temperatures measured in 2014/15. Cells are labeled top to bottom from 1 to 5 where cell 1 had been installed above the nominal water line.