Antarctic Science page 1 of 3 *(2023)* © The Author(s), 2023. Published by Cambridge University Press on behalf of Antarctic Science Ltd. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited. doi:10.1017/S0954102023000366

Short Note: 2022 Hunga Tonga-Hunga Ha'apai tsunami measured beneath the Ross Ice Shelf

CRAIG STEWART[1], HUW HORGAN[2,3,4] and CRAIG STEVENS [1,5]

[1]*NIWA National Institute for Water and Atmospheric Research, Wellington, New Zealand*
[2]*Antarctic Research Centre, Victoria University of Wellington, Wellington, New Zealand*
[3]*VAW - ETH, Zurich, Switzerland*
[4]*WSL, Birmensdorf, Switzerland*
[5]*Department of Physics, University of Auckland, Auckland, New Zealand*
Craig.Stevens@niwa.co.nz

Introduction

On 15 January 2022, 04h:15 UTC, the volcano Hunga Tonga-Hunga Ha'apai in the south-west Pacific Ocean (20°32'32.37"S, 175°23'38.67"W) erupted in what proved to be the most powerful such event since Krakatau in 1883. Among the many impacts of the eruption, a substantial tsunami propagated throughout the south-west Pacific Ocean. The signatures of the eruption were recorded at a wide range of recording stations globally, including the atmospheric pressure wave, the tsunami itself and, in addition, higher-order responses, such as a tsunami associated with the pressure wave (Carvajal *et al.* 2022).

Here we describe what is probably the most southerly oceanic measurement of the tsunami arrival, as the event was detected in a sub-ice mooring at the grounding line of the Ross Ice Shelf at 82.47°S. It was recorded on the margin of the Ross Ice Shelf along the Siple Coast at the Kamb Ice Stream 2 (KIS2) field camp by instruments deployed to record ice-ocean interactions in order to improve understanding of ocean effects on ice-sheet stability (Whiteford *et al.* 2022).

Analyses of tsunamis and ice shelves tend to focus on the observable stability of the terminal face (e.g. Brunt *et al.* 2011) as well as implications for research infrastructure (Burbidge *et al.* 2020). However, there is evidence that the tsunami propagates into the ice shelf cavity, as demonstrated by the analysis of the 2011 Honshu (Tōhoku) event's impact on the Sulzberger Ice Shelf (Papathanasiou *et al.* 2015). Extending this, the effects of a 2015 Chilean earthquake-driven tsunami were observed with a broadband seismic array deployed in a north-south line through the middle of the Ross Ice Shelf (Bromirski *et al.* 2017), revealing the wave propagation. The Tongan wavefront event described here followed a more direct oceanic route to the cavity than the 2015 Chilean event. The Tongan tsunami is closer in path to a modelled response due to a 2011 event in the Kermadec region (Bromirski *et al.* 2017).

Results

The data were recorded at the KIS2 camp (latitude -82.470442°; longitude -152.291643°; see Fig. 1). The sampling was measuring ocean processes in a 6 km-long sub-ice channel that extends landward from the edge of the ice-shelf cavity. The channel is ~240 m high and 150 m wide beneath 410 m of ice and snow. In early 2022, a hot-water borehole was drilled through the ice shelf to access the ocean at the head of the channel. Hydrographic instruments were suspended in the ocean cavity late on 11 January 2022 local time, and 4 days later and 7000 km to the north the Hunga Tonga-Hunga Ha'apai eruption occurred.

The instruments providing the data were three RBR Concerto conductivity-temperature-depth (CTD) instruments. These instruments included a pressure sensor rated to 1000 (dbar) with an initial accuracy of ± 0.05% full scale and a resolution of < 0.001% full scale, equating to 1 cm. Sensors were sampled at 60 s intervals with a response time of < 0.01s. The three instruments were at pressures of 425, 495 and 648 dbar, respectively, and all three gave consistent readings, so only information from the 495 dbar unit is described here (i.e. ~85 m beneath the ice underside and 155 m above the sea floor).

Considering the central instrument as representative, the timeseries of the pressure, after high-pass filtering to remove the 0.75 m-amplitude tide (primarily diurnal and including the spring-neap cycle), clearly shows the arrival of the tsunami (Fig. 2a). The record (Fig. 2b) shows an initial perturbation ~6.4 h after the eruption. This was followed 7 h later (i.e. 13.4 h after the eruption) by a sudden and sustained burst of variability due to the tsunami's arrival. The variability in the high-passed signal persisted for ~4 days and did not return to background variability seen prior to the arrival until approximately day 20.

Discussion

The initial perturbation 6.4 h after the eruption is the air pressure wave, and the 7000 km separation implies a

https://doi.org/10.1017/S0954102023000366 Published online by Cambridge University Press

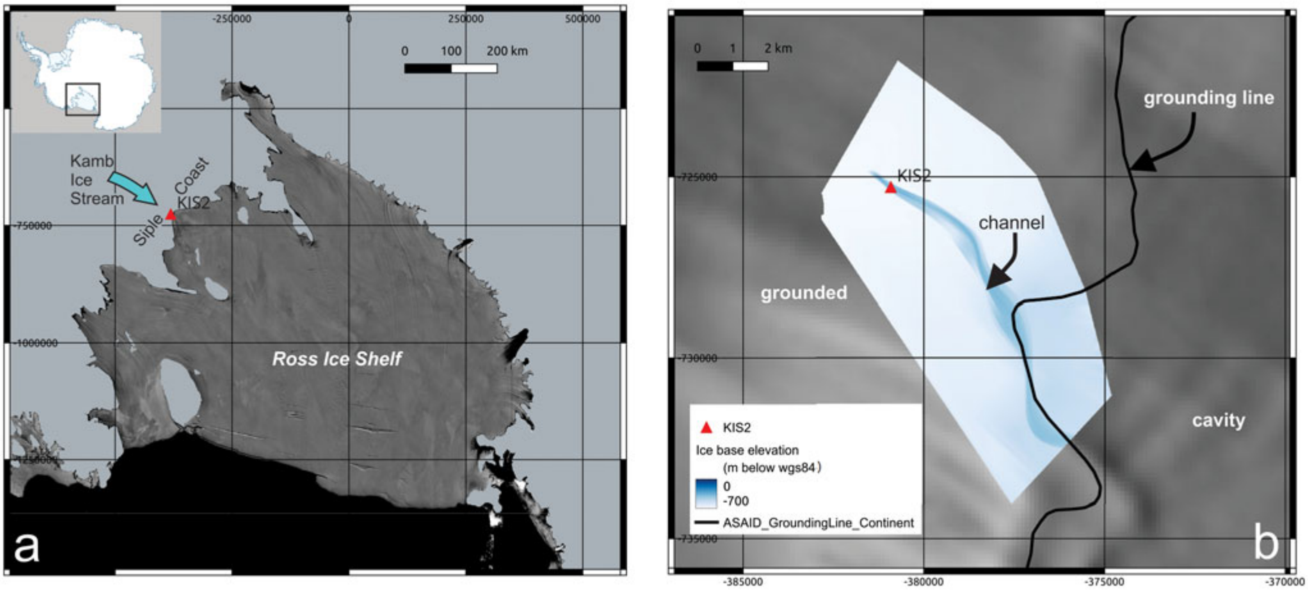

Figure 1. a. Ross Ice Shelf and the location of the Kamb Ice Stream 2 (KIS2) channel (inset shows location within Antarctica) with **b.** an outline of the known extent of the channel (see Whiteford *et al.* 2022) and the KIS2 sample station near the channel head. The solid black line is the estimated edge of the ice-shelf cavity. ASAID = Antarctic Surface Accumulation and Ice Discharge project; wgs84 = World Geodetic System 1984 coordinate reference frame.

propagation speed of 300 m s^{-1}. This compares favourably to the pulse speed of 307 m s^{-1} described by Carvajal *et al.* (2022). The tsunami arrival 13.4 h after initiation is ~4 h longer than the direct travel time implied by a deep-water propagation speed. This reflects the slower wave travel on the continental shelf and the propagation response to varying topography.

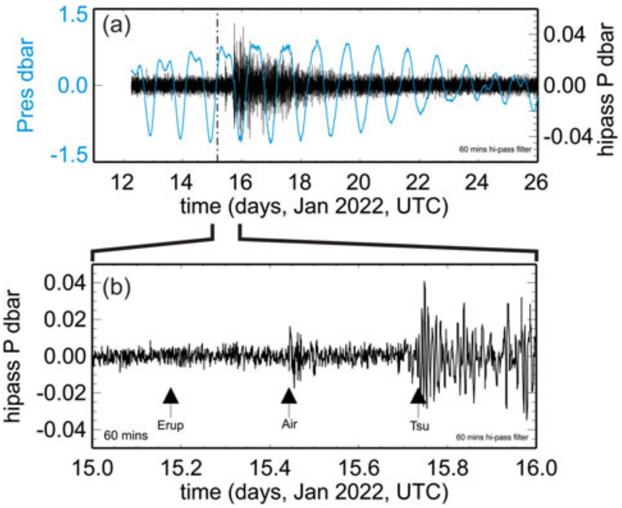

Figure 2. The ice-cavity channel pressure timeseries showing **a.** the raw (blue) and high-pass-filtered (black) pressure perturbation timeseries (note that for clarity time here starts at 1 so that noon on 1 January = 1.5). **b.** An expanded version of the high-pass-filtered pressure record for 15 January 2022, showing the arrival of the initial atmospheric front and the start of the tsunami-driven response (1 dbar ≈ 1 m).

Closer examination of the timeseries over the days following the wave's arrival shows short bursts of oscillating events of periods of ~3–6 h (Fig. 2a). Assuming that the channel is a rigid lid cavity, we expect pressure variations at the channel mouth to propagate into the mooring site as acoustic waves with a velocity of ~1445 m s^{-1} and a transit time of <5 s. In addition, the channel is ~150 m wide and the sampling location is ~500 m from the end of the channel, so the effects of these boundaries will be felt very quickly at the sample location. Current meters were included in the sampling but in a lower-frequency regime (30-min interval). The near-bed unit shows a perturbation of ~2 cm s^{-1} at approximately the time of the tsunami's arrival, but there is no clearly distinguishable associated response in the surface-mounted precision GPS data.

The 2015 Chilean event produced elevated high-frequency perturbations of the Ross Ice Shelf surface for < 2 days (Bromirski *et al.* 2017). The implication then is that the 3–6 h variations and the 4 day decay period seen at KIS2 are associated with the wider cavity embayment and not the 5 km-long sub-ice channel. Such post-event 'ringing' could be associated with either the local coast or the regional continental shelf shape. Being ~750 km from the continental shelf break, this would tend to rule this out. However, local to the channel are a number of features of the Siple Coast

https://doi.org/10.1017/S0954102023000366 Published online by Cambridge University Press

that would enable a complex wave response, including the concave-curved coastline and the presence of some islands and headlands (Fig. 1).

Notably, in terms of our normal sampling protocols for ice-cavity instruments, in the case of the 2022 deployment we were working on ice fixed to the bedrock and so not moving with the tides. In addition, we were trialling a sampling protocol that provided a faster sampling rate (60 s). If we had been sampling as per earlier experiments, our observations of the tsunami would have been far less clear. This serendipitous dataset has implications for understanding high-latitude shallow-water wave processes beneath ice shelves.

Acknowledgements

The work was funded by the Antarctic Science Platform (ANTA1801) and Antarctica New Zealand. We thank the Victoria University of Wellington Hot Water Drilling Team led by Darcy Mandeno, the NIWA capex programme and the IceFin team led by Britney Schmidt. Andy Mullan, Regine Morgenstern and the camp team assisted with the field deployment. We thank the traverse team, the KIS2 camp team and Paul 'Woody' Woodgate. Yusef Karim and Nicolas Zuluaga at RBR Systems provided timely technical support. We thank two anonymous reviewers for their comments.

Competing interests

The authors declare no known competing interests.

Data availability

Data are available at SeaNoe (https://doi.org/10.17882/96263).

Author contributions

Craig Stewart developed the instrumentation, led the deployment and first identified the signal. Huw Horgan led the overall experiment and mapped the channel. Craig Stevens conducted the analysis and led the write-up. All authors contributed to the manuscript.

References

Bromirski, P.D., Chen, Z., Stephen, R.A., Gerstoft, P., Arcas, D., Diez, A., *et al.* 2017. Tsunami and infragravity waves impacting Antarctic ice shelves. *Journal of Geophysical Research - Oceans*, **122**, 10.1002/2017JC012913.

Brunt, K.M., Okal, E.A. & MacAyeal, D.R. 2011. Antarctic ice-shelf calving triggered by the Honshu (Japan) earthquake and tsunami, March 2011. *Journal of Glaciology*, **57**, 10.3189/002214311798043681.

Burbidge, D., Power, W., Gusman, A., Wang, X., Lukovic, B., Black, J., *et al.* 2020. The Scott Base redevelopment: Ross Sea geological hazards. Presented at *NZSEE 2020 Annual Conference*. Retrieved from https://repo.nzsee.org.nz/handle/nzsee/1739.

Carvajal, M., Sepúlveda, I., Gubler, A. & Garreaud, R. 2022. Worldwide signature of the 2022 Tonga volcanic tsunami. *Geophysical Research Letters*, **49**, 10.1029/2022GL098153.

Papathanasiou, T.K., Karperaki, A.E., Theotokoglou, E.E. & Belibassakis, K.A. 2015. Hydroelastic analysis of ice shelves under long wave excitation. *Natural Hazards and Earth System Sciences*, **15**, 10.5194/nhess-15-1851-2015.

Whiteford, A., Horgan, H.J., Leong, W.J. & Forbes, M. 2022. Melting and refreezing in an ice shelf basal channel at the grounding line of the Kamb Ice Stream, West Antarctica. *Journal of Geophysical Research - Earth Surface*, **127**, 10.1029/2021JF006532.

https://doi.org/10.1017/S0954102023000366 Published online by Cambridge University Press