A multi–parameter study of iceberg calving and the retreat of *Haupapa*/Tasman Glacier, South Island, New Zealand

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Abstract

Iceberg calving is an efficient ablation process which introduces mechanical instability to glacier systems and can cause a non–linear climatic response. This thesis quantifies the calving retreat of the freshwater–terminating Tasman Glacier and the coeval expansion of Tasman Lake, at a range of temporal and spatial scales. Tasman Glacier is the longest glacier (*c.* 23 km) in New Zealand, and lies east of the Main Divide of the Southern Alps, extending from a névé at 2400 m to an ice–contact lake at *c.* 727 m. Although 20th century warming caused down–wastage, it remained at its Little Ice Age terminus until the late 20th century. Since then, calving retreat has occurred, allowing a large proglacial lake to form. Remote sensing datasets, namely satellite imagery, time–lapse photography, and passive seismic recording were used to observe and characterise retreat and calving style and magnitude at inter–annual, sub–annual, and intra–event time–scales.

Between 2000 and 2013 Tasman Glacier has retreated *c.* 6 km, corresponding to an average decrease in ice surface loss at the terminus of 0.37 km^2 a^{-1}, through a combination of melting of the lower glacier and iceberg calving. However, an order of magnitude increase in retreat occurred since 2006 with peak retreat rates in excess of 1.5 km^2 a^{-1}. This retreat has seen a continuation of accelerated ice loss since the formation of Tasman Lake in the late 1980s. A four–stage model for the transition between melt and calving regimes refined in this study has indicated that the processes and factors that contribute to the development of a proglacial lake at the termini of debris–covered glaciers worldwide are similar, although they act over different time–scales depending on glacier dynamics and climate regimes.

At a sub–annual time–scale calving events between October 2011 and November 2012 were identified at a rate of 0.94 events d^{-1}, with significant seasonal differences, in that the number of calving events increased during the ablation season. Calving events driven by thermo–erosional notching at the waterline were the most frequent of all calving events, followed by events initiated by over–steepening of the subaerial ice cliff, then sub–aqueous and buoyancy–driven calving events. Buoyancy–driven calving events were of the largest magnitude, and had the greatest effect on glacier retreat. Such events are initiated by a combination of glacier thinning, increased water–depth at the terminus, terminus geometry, subaqueous melt and calving, perturbations in lake level and near–field earthquakes.

The increase in calving frequency during spring and summer 2011/12 was directly related to the increase in thermo–erosional notch events. Correlation of calving frequency, lake level and lake temperature time–series data reveals that the frequency changes are related to the stability in lake level and elevated lake temperatures. This indicates that although calving retreat rate has increased, low–magnitude calving events are the most frequent, but low frequency, high magnitude buoyancy–driven events have had the greatest influence on net glacier retreat.

Calving events at Tasman Glacier emit seismic signals similar to those found at other calving margins globally. All calving events generated seismic signals that had emergent onsets with weak frequencies above 5 Hz, followed by a high amplitude phase with frequency content between 1 and 5 Hz and a protracted coda. The study highlighted relationships between calved iceberg size and seismic parameters (e.g., signal duration, peak amplitude and integrated amplitude) that can be used to remotely assess the frequency, style and magnitude of calving events. It was shown that seismic waveforms, signal duration, and energy indicate order–of–magnitude differences in calving event size and style. However, due to the continuum of spatial and temporal scales over which calving operates, seismic signals are generally too variable to completely substitute direct observational data. Signal analysis algorithms analogous to those used in volcano seismology have been developed for the automatic detection of iceberg calving and were thoroughly tested against independent observational datasets. The algorithms and thresholds can be readily deployed in future seismic studies of dynamic ice margins at freshwater–terminating glaciers.

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