Reply to the comments from Referee 2

Acoustic Emission investigation for avalanche formation and release: A case study of dry-slab avalanche event in Great Himalaya by Kapil et al. (tc-2020-38)

Below are the replies (in 'blue' text) from authors against the comments made by the reviewer (in 'black' texts) on above manuscript.

Comment (Ref 2):
I found the paper to be too long for the subject matter. I appreciate the efforts of using AE technique towards avalanche mitigation processes. It's a good tool to have; no doubt. The authors, however, should have refrained from making comments with buzzwords, again and again, on micro mechanisms because they seem to be not aware of the "fundamental fact" that snow is an extremely "High-temperature material" undergoing stress-temperature-time induced morphological changes. The micro- and macro failure mechanisms and their kinetics are very complicated. Nonetheless, significant progresses has been made in the past on physics of failure in polycrystalline solids (not necessarily porous media) at high-homologous temperatures, close to 0.99 Tm, but snow is porous and the authors do not seem to be aware of those developments. For example, there were AE studies in pure ice for examining the microstructure property relations - way back in the early 1980's. Specifically, they looked at polycrystalline ice as a "high-temperature" material (existing in our cryosphere at extremely high homologous temperatures, higher than about 0.9 Tm, where Tm is the melting point in Kelvin). Old ideas on AE, based on micro-mechanisms in other engineering or geological materials at low homologous temperatures should be discarded. However, the use of AE technology can still be used as a tool - such as monitoring the snow states. The authors tried to use AE for real practical application - and should have stayed in that arena - instead of going beyond the realm of the data and speculating about dislocations, etc. They seem to impress the audience with mechanisms that they actually do not fully understand. The manuscript, in this regard, should be modified significantly to bring out the real strength of the work.

Reply:

Authors sincerely thank to reviewer for his insightful comments on our manuscript submitted to 'The Cryosphere'. We do agree that the manuscript is lengthy; it is because authors wanted to report most of the relevant information collected during a natural avalanche release event, registered successfully for the first time, through acoustic emission (AE) monitoring of the avalanche starting zone. Authors agree to reviewer that certain aspects like the failure of polycrystalline ice at higher homologous temperature were not covered and such information would indeed improve the quality of the work done. Authors have cited the published literature in contexts of recent understanding deformation and failure behaviour of polycrystalline ice particularly at higher homologous temperatures, dislocation dynamics relative to migration of ice grain boundaries, the mechanism of slab failure, and are discussed within the revised manuscript. In response to reviewer's comments the manuscript has been modified and improved significantly. The buzz-words are removed and corrected.

The deformation characteristics of the snow grains define the mechanical behaviour of a snowpack which is an aggregate of polycrystalline ice grains (Sommerfeld, 1970). The changes in snow morphology and structure are quite sensitive to temperature and load (McClung, 1996); therefore, the deformation and failure behaviour of polycrystalline ice can provide some key insights about the failure mechanism of a snowpack as polycrystalline ice is a constituent of snow itself. In present study, the snow (surface) temperature was observed varying from -2.1^{0}C to -2.5^{0}C (0.92 T_m to 0.99 T_m) during the study period; therefore, the deformation behaviour of the snowpack would be affected by prevailing temperature conditions, and correspondingly to the released AE. In fact, the process of AE generation and its propagation is a complex process within a snowpack; however, it is essential to correlate the released AE to the deformation and failure processes occurring from microscopic to macroscopic scales during formation and release of an avalanche. Sinha (1978) related the deformation behaviour of polycrystalline ice as a function of temperature, time, and stress through phenomenological relation for creep. The crystallographic structure, direction of application of load and strain history of ice affects the deformation behaviour of polycrystalline ice. At high homologous temperature (>0.9 T_m), Sinha (1984) has shown that the grain boundary sliding and delayed elasticity can initiate the micro-cracking of polycrystalline ice and once a critical state stress is achieved, the cracking in ice may occur depending upon temperature but independent of the grain size. The dislocation dynamics of deforming snow represents the strain bursts in which the grain boundary deformation mediates the dislocation stress fields to nearby grains. The deformation and failure of a snowpack resulted from the dislocation could be manifested by stress waves (AE) propagating within the weak layer.

The grain boundary (GB) interaction during creep may act as a source of lattice dislocations and an obstacle to the dislocation movement whereas the dislocations can be generated both from free surface GB intersections and from the interiors of GBs (Liu et al., 1995). The strain in ice may tend to concentrate near the grain boundaries (GB) and sub-grain boundaries (SGB) in relation to the stress field heterogeneities, and a strong connection between nucleation and local internal stress field (Grennerat et al., 2012) is inferred from dislocation arrangements. The high temperature ($T = -5°C$, $\sigma = 0.5$ MPa) creep response of polycrystalline columnar ice is shown by Chauve et al., (2017) where strain heterogeneity may result in strain induced grain boundary migration (SIBM). The nucleation mechanism in ice occurs due to grain boundary bulging as a result of SIBM. The tilt SGBs or kink bands composed of basal edge dislocations are commonly observed in deformed poly-crystalline ice. The ductile-to-brittle transition is an effect of constant striving among crack-tip creep and crack propagation. The cohesive zone models are also applied to simulate the dynamics of fracture during crack development in ice (Gribanov et al., 2018). Journaux et al. (2019) have characterised the stress strain heterogeneities and deformation mechanisms in polycrystalline ice at high temperature. They proposed the nucleation by bulging, sub-grain boundary formation followed by grain growth to explain the evolution of crystallographic preferred orientation (CPO) during dynamic recrystallization. The AE response of creep cracking in polycrystalline ice at high homologous temperature > 0.96T_m was studied by Sinha (1996) where decelerating primary creep followed by accelerating tertiary creep effects were seen in relation to AE. The AE behaviour of creeping ice is investigated by Richeton et al. (2005) and they have shown that plasticity in polycrystalline ice is characterized by intermittency in the dislocation avalanches but the grain boundaries may hinder the avalanche propagation.

Snow exhibits characteristic AE responses under different processes such as dislocation movements, plastic deformation, breakage of bonds and grain ruptures (St. Lawrence, 1980). The dislocation dynamics, a critical phenomenon for AE generation, is useful to understand the plastic deformation complexity of crystalline materials (Weiss et al., 2000) which was further related to AEs for visco-elastic materials (Miguel et al. 2001). For the release of a dry-snow slab avalanche, the failure of a weak layer below a cohesive slab is necessary and sufficient condition and the crack would propagate across a slope once the crack length exceeds a critical size which is almost independent of slope angle for crack propagation (Gaume et al., 2017) and the avalanche release is attributed to the formation of shear bands as an outcome of localization of micro-fractures during the deformation of snow (McClung, 1981). The pattern of AE observed during shearing is suggestive of slip surface formation in snow which acts as stress concentrators even in absence of natural imperfections (McClung, 1987). In a snowpack, the unstable conditions may prevail until a weak layer exist below a cohesive slab, and release of avalanche is associated to the initiation and propagation of the cracks within the weak layer (Schweizer et al., 2003; Gaume et al., 2018). To explain the dry slab failure at high homologous temperature (> 0.90 T_m), micromechanical models were applied by Schweizer et al. (2003), where two competing processes such as damage and sintering collectively affecting the snow deformation and slab rupture. Recently, Gaume et al. (2018) have presented the volumetric collapse of a cohesive slab leading to the localization of compacting shear bands following the anticrack propagation. A pre-existing shear stress across thin weak layer could be a significant factor deciding the fracture of a slab (Bazant et al., 2003). For release of an avalanche, the critical crack length is essential before any shear fracture occurs, McClung (2011) estimated the ratio of critical crack length and slab depth to vary from 0.1 to 2.0. For quantitative assessment of snow instability, the crack propagation propensity (Schweizer et al., 2016; Reuter and Schweizer, 2018) is considered as a measure of complex slab-weak layer interaction. The total amount of mechanical energy supplied during loading of a snowpack may result into the increase of its internal energy, fracture surface energy, dissipation (viscous and thermal) energy and kinetic energy. A new fracture surface can be created at the cost of the free surface energy which can be contributed by stored internal energy of the system, and a part of the fracture surface energy could be experienced in terms of the AE.

Additional References:

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