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Cyclic step on ice: experiments and theoretical study aiming to spiral troughs on Mars' North Polar ice cap

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The spiral troughs observed on the Mars' North Polar Layered Deposits (NPLD) contain a detailed stratigraphic record of surface processes in Mars' recent polar history. SHARAD radar data showed that the troughs have migrated towards the north during the accumulation of the uppermost ˜600 m of NPLD, and Smith et al. (2013) concluded that the spiral troughs should be a kind of cyclic steps formed by katabatic wind blowing on the ice cap. Cyclic steps are spatially periodic bedforms where each wavelength is delineated by an upstream and downstream hydraulic jump. They migrate upstream keeping the same wavelength. Cyclic steps have been reported from various environments on the Earth, such as fluvial and deep-sea settings, and in various bed materials, such as bedrock, non-cohesive sediments, and cohesive sediments. While the formation of cyclic steps on bedrock or beds composed of sediment is a mechanical process, the formation of cyclic steps on ice is not only a mechanical but thermodynamic process. There have not been many studies on the thermodynamics of the formation of cyclic steps on ice to authors' knowledge. In this study, we conducted a series of experiments on the formation of cyclic steps on ice due to flowing water over it. In addition, we performed a linear stability analysis of the water-ice interface and show that the formation of cyclic steps can be explained by the results of the analysis in part.

The experiments were conducted in the cold chamber owned by the Institute of Low Temperature Science, Hokkaido University. We have conducted 8 cases of experiments by the use of the experimental apparatus that consists of a flume, a cooling system of the flume, and a circulating system of water. We kept the ice temperature to be below zero degrees in Celsius, the flowing water temperature to be from 0.2 to 2 degrees in Celsius, and the room temperature to be about 5 degrees in Celsius. As a result, it is found that trains of steps are formed when the Froude number is larger than a value around unity. Those steps are associated with hydraulic jumps, and steps mostly migrate in the upstream direction. Based on these diagnoses and the morphologic feature, these steps can be evaluated as cyclic steps on ice bed.

We performed a linear stability analysis on instability of interface between flowing water and ice, and made physical explanation of the formation of cyclic steps. According to the results of the analysis, the interface becomes unstable when the Reynolds number is relatively large under the condition that the heat flux from ice is sufficiently weak, that is to say, the temperature at the ice bottom is not so low, and the ice thickness is sufficiently large. In addition, the unstable region in the wave number - Reynolds number plane hardly depends on the heat transfer coefficient of air normalized by the heat diffusivity of water and the flow depth.

We compared the results of experiments and the analysis, and found that the experimental data fall on the unstable region both in the wave number - Reynolds number plane and the wave number - Froude number plane where interfacial instability takes place. This indicates that at least the experimental results are consistent with the analytical results. The critical Froude number derived from the analysis is approximately unity in the range of small slope angles, and slightly increases with the slope angle. In the experiments, cyclic steps are not formed in the case of the Froude number smaller than unity while cyclic steps are formed in all the case of the Froude number larger than unity. In terms of the critical Froude number, the experimental results are well explained by the analysis.

Keywords: cyclic step, ice, spiral troughs