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Topographic effects on the thermal structure of Himalayan glacial lakes: Observations and numerical simulation of wind

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Abstract

The thermal structure of two Himalayan glacial lakes, Tsho Rolpa and Imja in the eastern Nepal, was examined by observations in the pre-monsoon seasons of 1996 and 1997. Tsho Rolpa had an isothermal mixed layer at water depths of 0–20 m, whereas Imja did not possess such an isothermal layer. This difference in the thermal structure is explained by the condition that diurnal valley winds, producing wind-driven currents, blow strongly near the water surface of Tsho Rolpa, but very weakly near that of Imja. The wind observations above or near the end moraine indicated that a daily wind system of strong, diurnal valley winds and weak, nocturnal mountain winds is common to the lakes. It was suggested that with respect to the valley winds, the weak winds near the surface of Imja result from topographic screening effects of the upwind dead-ice zone and end moraine 20–25 m higher than the water surface. In order to ascertain the topographic effects, three-dimensional numerical simulation of airflow was carried out by making topographic models of actual size in the calculation domain, corresponding to Tsho Rolpa and Imja and their surrounding topography. The simulation revealed that, when winds blow at constant velocities of 1–5 m s^{-1} at 2 m above the points corresponding to the weather stations, the wind velocity at 2 m above the water surface for Imja is 33–42% smaller than for Tsho Rolpa. With increasing heights of the end moraine and dead-ice zone, the wind velocity near the lake surface efficiently decreased by decreasing the lake length from 3.1 or 2.2 km to 1.2 km.

Keywords: Glacial lakes; Nepal Himalayas; Thermal structure; Wind-driven currents; Calving

1. Introduction

Many Himalayan glacial lakes have been expanding by the glacial retreat, probably due to global warming after the Little Ice Age in the 16th–18th centuries. For example, the surface area of Tsho Rolpa Glacial Lake in the Nepal Himalayas linearly increased from 0.23 km^2 in 1958 to 1.39 km^2 in 1994 (Sakai et al., 2000; Yamada, 2001). In Nepal, such glacial lakes have produced the GLOF (Glacial Lake Outburst Flood) somewhere by the collapse of the end moraine with one GLOF per three years on average (Yamada, 1996). The calving at the glacier terminus (ice cliff) during the recent lake expansion may result from the instability of the ice cliff, which of the basal part keeps direct contact with lake water heated by solar radiation (Yamada, 1996). However, in order to continue calving over the summer, both a heat transport in the surface layer toward the ice cliff and the output of lake water cooled by the glacier melt are needed. By using a turbidity-temperature profiler and mooring systems of current meters and turbidimeters, Chikita et al. (1999) revealed that a lake-current system in Tsho Rolpa is composed of wind-driven, vertical water circulation and sediment-laden underflows from the input of turbid meltwater at the base of the glacier terminus. It was pointed out that the vertical water circulation simultaneously induces vertical thermal circulation to promote the lake expansion by calving at the glacier terminus.

In this study, differences in thermal and density structures between two Himalayan glacial lakes, Tsho Rolpa and Imja, are explained by differences in the intensity of

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wind-driven currents and the turbidity of input meltwater. By simulating airflow three-dimensionally around the lakes, it is pointed out that the difference in the intensity of wind-driven currents is caused by a difference in the magnitude of wind velocity near the lake surface affected by the topography around the lakes.

2. Observations

2.1. Study areas and methods

The dynamics of two glacial lakes, Tsho Rolpa (4580 m asl) and Imja (5010 m asl) in the eastern Nepal has been examined in the pre-monsoon season of 1996 and 1997 (Fig. 1) (Chikita et al., 1999, 2000). Tsho Rolpa is dammed up by the end moraine and side moraine, whereas Imja is dammed up by the dead-ice zone at downlake and the side moraine. As the histories of lake expansion by the glacial retreat, Tsho Rolpa has been expanding from near the end moraine since 1950s (Mool, 1995), but Imja started to expand from some 100-m scale ponds around site A (Fig. 1) in 1960s. In order to know the thermal and density structures of the lakes, vertical measurements of water temperature and turbidity were conducted at 0.2 or 1 m intervals at the observation sites by using a TTD (Temperature-Turbidity-Depth) profiler (model ATU200-P-64K, Alec Electronics Inc., Japan: accuracies of $\pm 0.04\ g\,l^{-1}$ for turbidity and ±0.05 °C for temperature). The water turbidity in ppm was converted into suspended sediment concentration (SSC) in $g\,l^{-1}$, using the significant correlation of $R^2 = 0.88–0.89$ between turbidity and SSC. The weather conditions (solar radiation, wind velocity, air pressure, air temperature and relative humidity) were observed at site M at ca. 2 m above the end moraine (Fig. 1). The weather station in Tsho Rolpa is located on the island of dead-ice near the end moraine. In Tsho Rolpa, in order to clarify the dynamic behaviors of lake water and thereby the condition of heat transport, a mooring sand-bag-buoy system of a current meter with a temperature probe (model ACM-8M, Alec Electronics Inc., Japan: accuracies of $\pm 0.5\ cm\,s^{-1}$ for horizontal current speed, ±3° for horizontal current direction and ±0.01 °C for temperature), a turbidimeter and temperature data loggers were fixed at each of site G, site A and site H. Topographic surveys around Tsho Rolpa and Imja were performed sporadically with a theodolite, which furnished three-dimensional shapes of the end moraine and dead-ice zone at downlake and their height above the lake surface, and heights of ice cliff and side moraine above the lake surface.

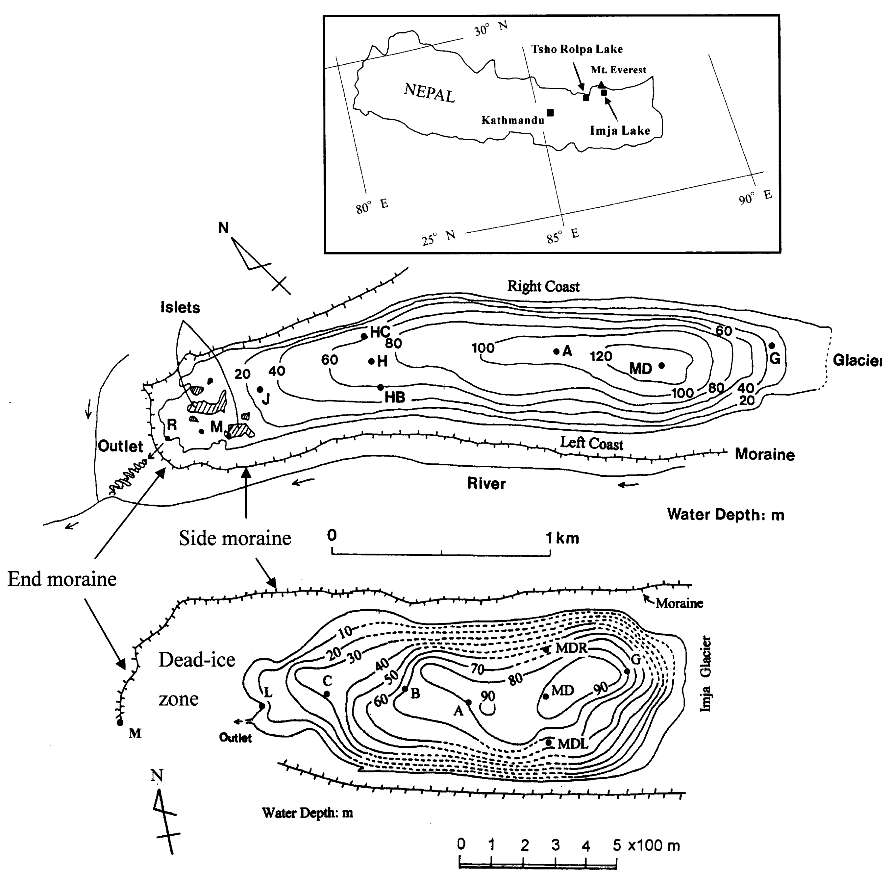

Fig. 1. Location of Tsho Rolpa (upper) and Imja (lower) glacial lakes in Nepal, and observation sites in the lakes on bathymetric maps. Weather stations are located at site M.