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Brief communication: How deep is the snow at the Mount Everest?

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Abstract. Exploring the snow thickness at the Mount Everest has long been a topic of interest for studying geodesy, cryosphere and climate change, but has not yet been measured successfully. Here, we report the ground-penetrating radar survey of snow thickness along the northern slope of the Mount Everest in May 2022. Our radar measurements display a gradual increasing transition of snow thickness along the north slope, and the mean snow thickness estimates at the Mount Everest is approximately 9.5 m. This updated snow thickness at the Mount Everest is much deeper than previously reported values (0.9~3.5m).

1 Introduction

Mount Everest, or Chomolungma, is the Earth summit, which is considered to be the most iconic peak (Kang et al., 2022; Matthews et al., 2020). There are very strong scientific and public motivations for determining the snow thickness at the Mount Everest. Although China and Nepal jointly declared that the snow height of the Mount Everest is 8848.86 metres above sea level (m asl) in 2020, the true rock height was not precisely determined due to the unknown snow thickness below. And the snow thickness at extreme high elevations may vary dynamically with different seasons and climate changes (Potocki et al., 2022). Knowledge about snow depth during different periods will be helpful for explaining the discrepancy of reported snow heights at the Mount Everest, which has been introduced by repeated surveys (Angus-Leppan, 1982; Chen et al., 2010; Xie et al., 2021). In additions, similar to other snow/glacier-covered summits (Thompson et al., 2009), the snow and glaciers are the sentinels for climate change and therefore offer a potential natural platform for understanding ongoing climate change at such extreme high elevation (Matthews et al., 2020; Potocki et al., 2022) and their possible widespread influence on the Asian Water Tower (Immerzeel et al., 2020). Thus, the state of snow at the Mount Everest are critical for studies related to the geodesy, the cryosphere, and climate change.

However, previous attempts to measure the snow thickness at the Mount Everest were not successful due to harsh environment and instrument/method limitation. In 1975, a Chinese expedition team reported an estimated snow thickness of 0.92 m by inserting a wooden stake into the snow (Chen et al., 2010). In 1992, a China-Italian joint expedition team estimated a thickness of 2.52 m by inserting a steel stake into the snow (Chen et al., 2010). Radio echo sounding is a suitable technique for imaging snow-ice environments and their internal structures (Rignot et al., 2013). In 2005, a Chinese mountaineering and surveying team claimed a snow thickness of ~3.5 m by utilizing ground penetrating radar; however, the boundary between the snow and rock on the radar image was too ambiguous (Sun et al., 2006). In 2019 and 2020, various Nepalese and Chinese expedition teams measured the snow thickness using different radar instruments; however, no results were reported (GSSI, 2021; Tone, 2020). Supported by the Second Tibetan Plateau Scientific Expedition and Research, we organized "The Earth Summit Missions 2022" expedition during the period from April to May 2022. One of our key goals is to measure the snow thickness at the Mount Everest.

2 Data and method

Ground penetrating radar (GPR) is a powerful tool in the field of cryosphere that has been widely used to survey snow depth (Holbrook et al., 2016; Yamamoto et al., 2004). To maximize portability at the Mount Everest, we conducted our GPR survey with a single transmitter–receiver antenna at a frequency of 1000 MHz using a Sensor & Software Pulse EKKO Pro system on May 4th 2022. In contrast with the previous radar survey at the summit (Sun et al., 2006), our measurement started from the exposed metamorphosed limestone at an elevation approximately 15 m lower than the Mount Everest to ensure a gradual transition in the radar reflection profile and thus produce more easily post-discerning boundaries between the snow and rock (Fig. 1a). For all GPR measuring points, a portable global navigation satellite system (UniStrong G138BD) continuously recorded the antenna locations. We obtained a total of 57 radar wavelet traces at irregularly space intervals (~0.5-1 m along the north slope and 0.2-0.4 m at the summit) during the time of 12:30-13:00 (Fig. 1b).

The transmission velocity is the most critical parameter for estimating snowpack thickness. Because of the limited measurement time window in so-called 'death zone', we did not measure common midpoint data to evaluate the transmission velocity of radar waves inside the snowpack at the Mount Everest t. In general, the transmission velocity in snow ranges from 0.20 m/ns to 0.27 m/ns, which depend on snow properties (Fortin and Fortier, 2001; Singh et al., 2017). A transmission velocity of 0.23 m/ns was obtained in a snowpack according to radar measurements with a steel stake (40 cm in length and 2 cm in diameter) that was buried in snowpack at elevations of 6500 m and 7028 m in 2005 (Sun et al., 2006). Therefore, we adopted a mean transmission velocity of 0.23 m/ns in this study.

To produce radar images that were more suitable for straightforward interpretations, the raw GPR data were processed using the Sensors & Software EKKO_project processing package by apply a frequency bandpassing filter and time-variable gain corrections. The processing steps increase the signal-to-noise ratio to improve the imaging results while maintaining the original data signature, thus producing data that can be easily interpreted. The boundary between the snow and rock and the subsurface stratigraphies were visually traced.

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3 Results and discussion

The radar wavelet traces showed strong signal contrast between the snow and the rock surface (the red dashed curve in Fig. 1c). It displays a well-defined gradual trend of radar reflection along the direction from the exposed limestone to the Mount Everest (from wavelet No.1 to No.31), which indicating the thickening inclination of snow thickness along the north slope of the Mount Chomolungma. Such thickening pattern agrees with the observed thick snowpack exposed by the nearby cliff and the topographic condition for snow accumulation (Fig. 1a). The radar wavelet traces of the other 26 measuring points (No.32-57), which mainly concentrated at the Mount Everest (Fig. 1b), display the similar radar reflection. Such homogeneity not only indicates the reliability of repeated radar measurements within this limited area, but also insights the relative flat topography along the ridge of the Mount Everest.

The magnitude of the estimated snow depth at the Mount Everest greatly depends on the choice of the mean transmission velocity.Taking the mean snow transmission velocity of 0.23 m/ns obtained at 6500 m asl and 7028 m asl on the Mount Chomolungma (Sun et al., 2006), we obtained the snow thickness distribution from the starting measurement point to the summit. The maximum two-way travel time of the reflecting horizon of the rock surface was approximately 88 ns at the Mount Everest. The snow thickness estimates gradually increased from ~2.0 m near the starting exposed limestone to a maximum of ~10.1 m along the north slope. The snow thickness of a total of 26 measuring points concentrated near the Mount Everest was averaged to be approximately 9.5 m. Such thick accumulated snowpack at the Mount Everest may be partially explained by the westerly-introduced snowfall accumulation on the eastern leeward side. Moreover, compared with the less snow accumulation in the unfavourable steep slope, our radar image covered the relatively flat platform at the Mount Everest (Fig. 1c), which may provide the favourable topography for snow accumulation.

Although the adopted transmission velocity in snow was determined at elevations of 6500 m and 7028 m in Mount Chomolungma, there may be still some uncertainties introduced by the distinct snow condition at the Mount Everest (*e.g.* snow density, snow properties). The colder air temperature and stronger wind at higher elevations may favor the significant morphological changes by strong sublimation and thus the snowpack was compacted for producing high snow density. Therefore, if a higher snow density of ~0.5 g/cm^3 were assumed at the Mount Everest, the mean transmission velocity would reduce to be ~0.21 m/ns (Fortin and Fortier, 2001). The mean snow thickness at the Mount Everest will slightly reduce from ~9.5 m to ~8.7 m. The snow depth estimate will be changed by 0.4m in 0.01 m/ns step of transmission velocity.

In addition to reveal the magnitude of snow thickness at the Mount Everest, the radar wavelet traces showed two possible subsurface reflections within the snowpack (the yellow dashed lines in Fig. 1c). The upper weak subsurface reflection displays a shallow trend from a burial depth of ~2-3 m along the north slope to ~0.8-1.0 m. Another weak reflection layer was existed at a relatively uniform depth of appropriately 4.5 m (Fig.1c). Such features maybe attributed to the transition boundary between fresh snow, compacted older snow and granular firn. However, this remains speculative due to the weak signal contrasts between layers.

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4 Conclusions

Overall, our measurements in May 2022 provide the first clear radar image of snowpack at the top of Mount Everest in the world. This updated snow thickness at the Mount Everest is considerably deeper than previously reported values during the past five decades (0.9~3.5m). Such effort gives the new insights for not only deciphering the true rock height and bottom geomorphology of the Mount Everest, but also for projecting future dynamic changes in the cryosphere at such extremely high elevations due to anthropogenic warming. It is worth noting that recent debates on the surface melting occurred at extremely high elevations (above 8000m asl) in the Everest (Brun et al., 2022; Potocki et al., 2022). Indeed, future snow core drilling and repeated ground penetrating radar measurements at the Mount Everest is also necessary to not only increase our understanding of snow dynamic changes, but also favor for detecting the possible influence of anthropogenic source warming at the Earth summit.

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Data availability

The GPR data (.sgy) are available from the corresponding author on reasonable request.

Author Contributions

T.Y. designed research; T.Y., H.Z. and W.Y. analyzed data; and T.Y., H.Z., W.Y., B.X., J.Li., W.W., G.Wu and Z.W. jointly discuss the result and wrote the paper.

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Competing interests

The authors declare no competing financial interests.

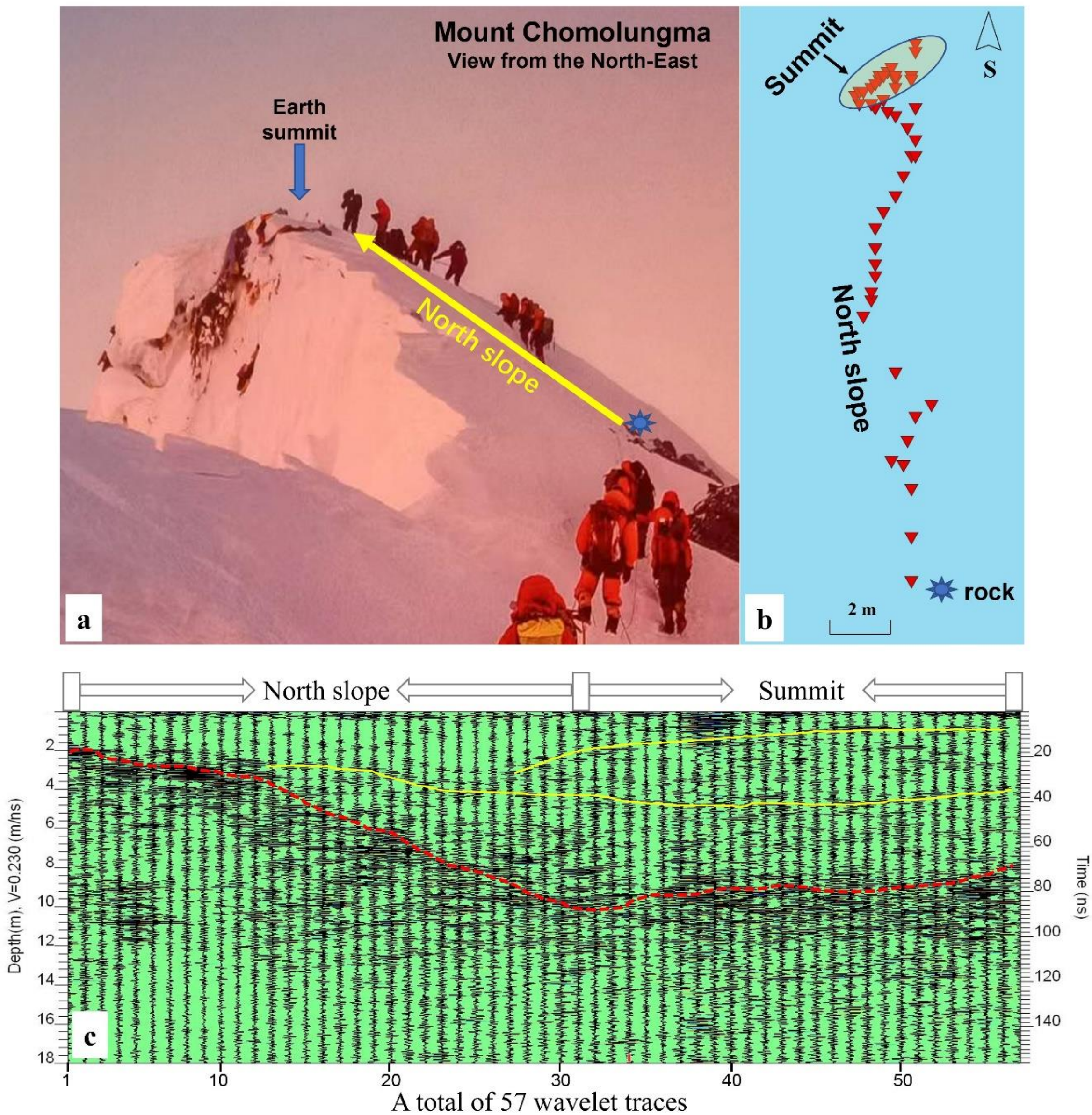

Figure 1. Radar measurements along the north slope to the Mount Everest acquired on May 4th, 2022. (a) Photo of Mount Everest showing the summit topography and radar measurement direction, as viewed from the northeast. (b) Distribution of 57 radar measurement points (red triangles), which started at the downwards exposed metamorphosed limestone. (c) Radar wavelet traces showing the boundary between the snow and rock (red dashed line) and the possible internal stratigraphies (yellow dashed lines) along the radar measurement profile at the estimated depth according to a constant transmission velocity (left axis) and the two-way wave travel time (right axis).