c. Cryosphere

1) Permafrost thermal state—J. Noetzli, B. K. Biskaborn, H. H. Christiansen, K. Isaksen, P. Schoeneich, S. Smith, G. Vieira, L. Zhao, and D. A. Streletskiy

The first globally consistent assessment of permafrost temperature changes revealed a mean increase in all permafrost regions worldwide by 0.29° ± 0.12°C over the decade 2007–16 based on field data recorded close to the depth of the zero annual amplitude (ZAA) in 154 boreholes (Biskaborn et al. 2019). The ZAA is the depth where seasonal variations become negligible (less than 0.1°C), which is typically between ca. 10 m to 20 m depending on the thermo-physical properties at the site. The most substantial increase was observed where permafrost temperatures are lowest. At ice-rich locations with permafrost temperatures little below 0°C, the increase is typically smaller because of the energy needed for ice-water phase change (latent heat; e.g., Romanovsky et al. 2010; PERMOS 2019; Biskaborn et al. 2019): permafrost temperatures in the continuous permafrost zone in the high Arctic increased by 0.39° ± 0.15°C during this period (Biskaborn et al. 2019), which is nearly twice as much as in the discontinuous permafrost zone (0.20° ± 0.10°C). The overall trend and pattern described in the decadal assessment continued in 2018. Across the entire Arctic, permafrost continued to warm in 2018, with permafrost temperatures among the highest ever recorded (see Section 5f for more details).

Mountain permafrost data are primarily available from boreholes in the European Alps, the Nordic countries, and central Asia, which show a permafrost temperature increase of 0.19° ± 0.05°C during 2007–16. Absolute values are, however, highly heterogeneous, particularly related to topography, snow regime, and ground ice. The pronounced warming trend observed in the European Alps during the reference period (PERMOS 2019; Pogliotti et al. 2015, Fig. 1) was interrupted in debris slopes and rock glaciers due to a late and thin snow cover in winter 2015/16 and 2016/17 (Noetzli et al. 2018; PERMOS 2019), especially at colder sites in the eastern Swiss Alps (e.g., Corvatsch, Schafberg). Due to the large thermal inertia of the subsurface thermal regime, permafrost temperatures remained stable or even decreased in 2018 at depths between about 10 m and 20 m (Fig. 2.10). In contrast, as a result of the warmest year on record in many central European countries (see Section 7f3), ground temperatures in the uppermost meters were above average or at record level at the majority of the observed sites (PERMOS 2019; Noetzli et. al. 2018). Time series from steep bedrock locations above 3000 m a.s.l. are sparse and only cover the past decade

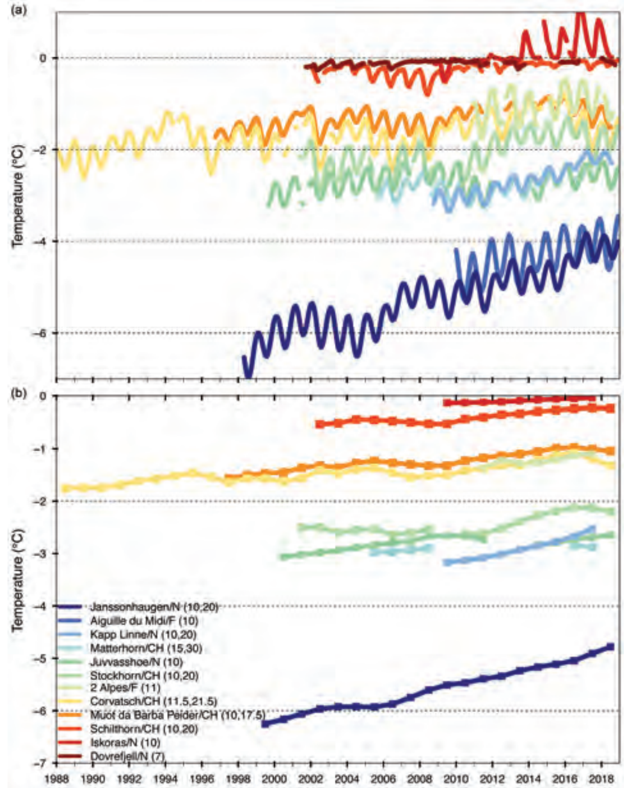

Fig. 2.10. Permafrost temperature (°C) measured in boreholes in the European Alps and the Nordic countries at a depth of approximately (a) 10 m (monthly means) and (b) 20 m (annual means). [Sources: Swiss Permafrost Monitoring Network (PERMOS); Norwegian Meteorological Institute and the Norwegian Permafrost Database (NORPERM); and French Permafrost Monitoring Network (PermaFRANCE).]

(Magnin et al. 2015; PERMOS 2019). Here, permafrost temperature increased without interruption and at high rates due to low ice content and the negligible influence of winter snow cover (e.g., Aiguille du Midi). In Nordic countries, mountain permafrost temperatures continued to increase in both cold and warm permafrost (updated from Isaksen et al. 2007; Christiansen et al. 2010). In southern Norway, permafrost temperatures were the highest on record (e.g., Juvvasshøe since 1999 and Dovrefjell since 2001), and in northern Norway (Iškoras since 2008), permafrost has been thawing. Here, ground temperatures have been well above 0°C at 10-m depth since 2013/14 and have now risen to 0°C at a depth of 20 m (Fig. 2.10). During the period 2005–17, permafrost temperature rose significantly on the Qinghai-Tibetan Plateau in central Asia (Fig. 2.11). All observation sites there showed remarkable warming tendencies, but the increments and rates are highly variable. The rate of annual temperature increase at 10-m depth varies

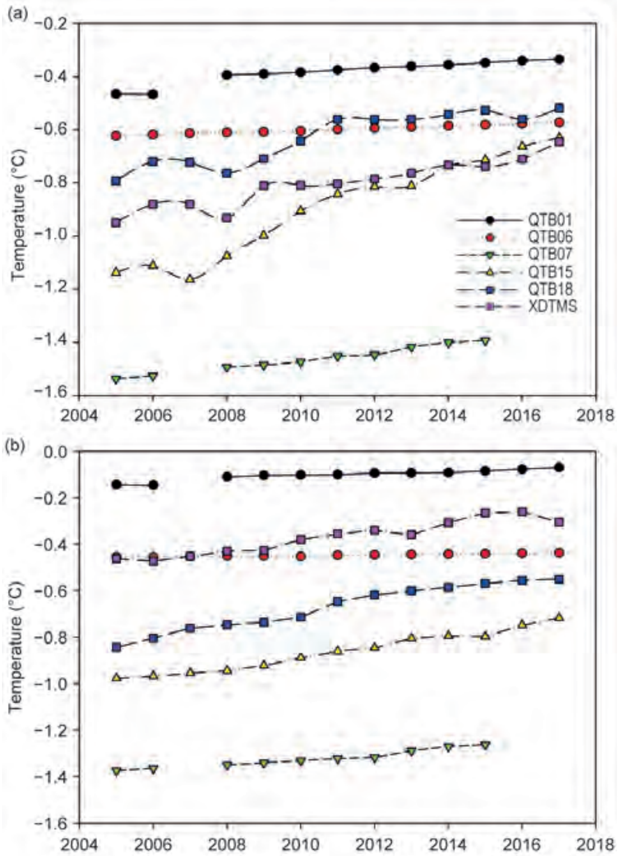

Fig. 2.11. Temperature (°C) measured in permafrost boreholes along the Qinghai-Xizang Highway on the Tibetan Plateau at 10- and 20-m depth. (Source: Cryosphere Research Station on Qinghai-Xizang Plateau, CAS.)

from 0.04°–0.47°C per decade (max: QTB15; min: QTB06). At 20-m depth, the decadal rates of increase are in the range of 0.02°–0.26°C.

Permafrost temperature in Antarctica increased by 0.37° ± 0.1°C during the decade 2007–16 (Biskaborn et al. 2019). However, deep boreholes and complete time series data in Antarctica are scarce, the warming trends are not evident everywhere, and lack statistical significance. For example, Cierva Cove on the western Antarctic Peninsula showed stable permafrost temperatures at 10- and 15-m depth during 2012–18, with the summers of 2016–18 showing lower temperatures than during 2012–15.

The maximum thaw depth in summer, the active layer thickness (ALT), generally follows summer temperature anomalies. The warm summer of 2018 in the North American sub-Arctic, Eurasian Arctic, and mountain regions of Eurasia resulted in continued ALT increase in the majority of the observation sites since the mid-1990s (Fig. 2.12). Of 85 sites reporting data to Circumpolar Active Layer Monitoring (CALM) in 2018, 64 had an above-average ALT. In the Nordic countries and European Alps, new record values were observed at several sites (e.g., PERMOS 2019). Active layer thickness also continued to increase in 2018 at sites located in permafrost regions along the Qinghai-Tibet highway, reaching 28 cm above the 1981–2018 mean. The Eurasian Arctic, with the exception of a few sites located in southeastern Siberia and Chukotka, had above-average ALT in 2018. Sites located in northern Canada have been characterized by an overall increase of ALT since 2003. Sites in northern Alaska had generally lower ALT in 2018 relative to 2017, while interior Alaska had record high ALT in 2018. Greenland was the only region with significantly lower ALT, close to its minimum values since 1996, reflecting cold summer conditions in 2018 (see Section 5g for more details on Arctic sites). The ALT in Antarctica showed no clear trend for 2006–15 and significant spatial variability (Hrbáček et al. 2018). Some sites in the South Shetlands have shown a decreasing ALT because of increased snow cover (Ramos et al. 2017).

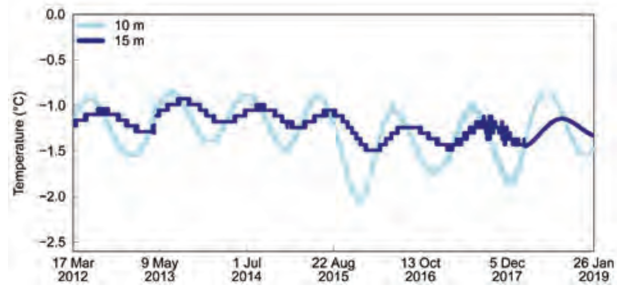

Fig. 2.12. Temperature (°C) measured in a permafrost borehole on the Antarctic Peninsula in Cierva Cove at 10–m and 15–m depth.

Long-term observation of permafrost change relies on ground temperatures measured in boreholes, which are collected in the framework of the Global Terrestrial Network for Permafrost as part of the Global Climate Observing System of the World Meteorological Organization. Borehole temperatures are recorded manually or continuously using multisensor cables down to at least the depth of the zero annual amplitude. An assessment of the measurement accuracy of borehole temperatures in permafrost worldwide varied from 0.01°C to 0.25°C (Biskaborn et al. 2019) and a mean overall accuracy of about 0.1°C can be assumed (Biskaborn et al. 2019; Romanovsky et al. 2010).