c. Cryosphere

1) Permafrost thermal state—J. Noetzli, H. H. Christiansen, F. Hrbacek, K. Isaksen, S. L. Smith, L. Zhao, and D. A. Streletskiy

Ongoing increases in global permafrost temperatures have occurred over the past several decades, with regional variability in magnitude. There have been short breaks in the warming trend due to shorter-term meteorological fluctuations, such as summer heat waves or snow-poor winters (e.g., Biskaborn et al. 2019; Romanovsky et al. 2007; Harris et al. 2009; Wu and Zhang 2008; PERMOS 2019; Etzelmueller et al. 2020). The largest increases were observed for sites with low permafrost temperatures, i.e., several degrees below 0°C, and low ground ice contents. Warmer and ice-rich permafrost warms up at a lower rate due to latent heat uptake during ice melt. This global picture continued in 2020. Record values were observed at many sites in polar and mountain regions. However, data could not be collected from all permafrost observation sites in 2020 (particularly in North America) due to pandemic-related travel restrictions.

Permafrost temperatures reported in 2020 for the Arctic regions were the highest on record at a majority of the observation sites. Warming rates for colder permafrost were as high as 0.8°C decade^{-1}, compared to less than 0.3°C decade^{-1} for permafrost at temperatures close to 0°C. Details on Arctic permafrost are given in section 5h. Increasing permafrost temperatures were reported from the Antarctic Peninsula and Victoria Land for the past decade up to 2018 (cf. Noetzli et al. 2019); however, deep boreholes and complete time series were scarce and the trend lacks statistical significance.

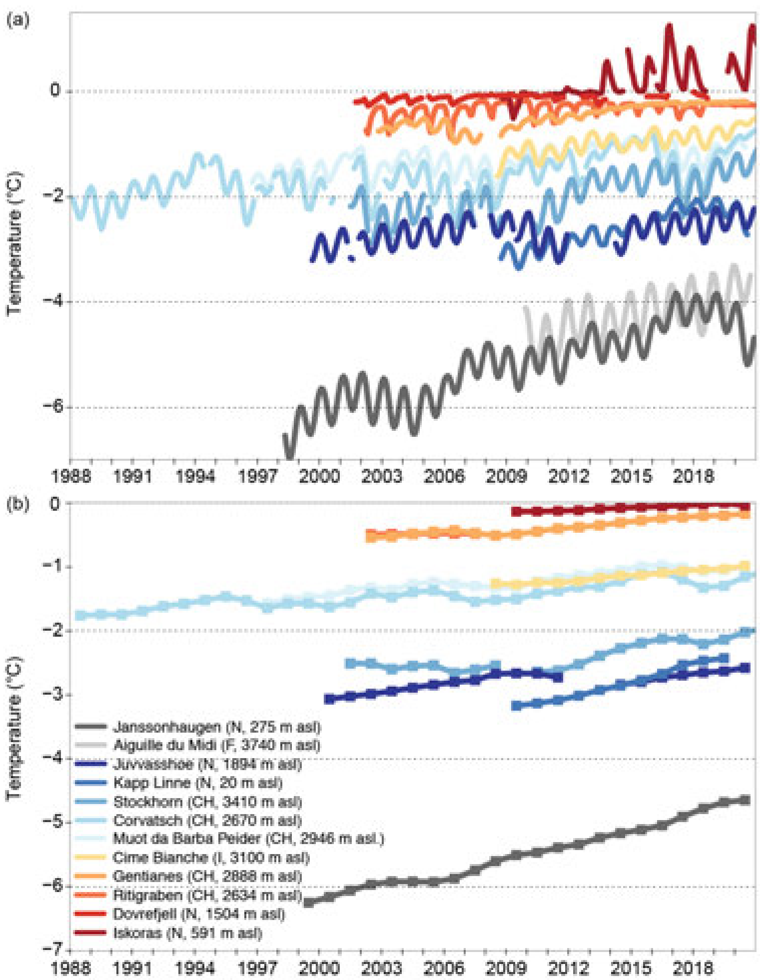

Fig. 2.10. Permafrost temperature measured in boreholes in the European Alps and the Nordic countries at a depth of approximately 10 m (monthly means, upper panel) and 20 m (annual means, lower panel). (Sources: Switzerland: Swiss Permafrost Monitoring Network PERMOS; Norway: Norwegian Meteorological Institute and the Norwegian Permafrost Database NORPERM; France: updated from Magnin et al. 2015; Italy: updated from Pogliotti et al. 2015.)

Mountain permafrost accounts for approximately 30% of the global area underlain by permafrost (Hock et al. 2019). Data are primarily available from the European Alps, the Nordic countries, and central Asia (Qinghai-Tibetan Plateau; QTP), but they are sparse for other mountain regions. A mean permafrost temperature increase of 0.19°C decade^{-1} was observed for 2007–16 (Biskaborn et al. 2019). Warming rates are heterogeneous due to the high spatial variability in thermal conditions resulting from complex topography, snow regime, and ground ice content. Highest rates are observed for bedrock with a low ice content and permafrost temperatures several degrees below 0°C and without a thicker winter snow cover. Permafrost temperatures recorded in 2020 in the European Alps were higher than in 2019 and close to or above the previous maximum observed in 2015 at the majority of sites (Fig. 2.10; Noetzli et al. 2020; updated from Pogliotti et al. 2015; PERMOS 2019) due to an early onset of the snow cover in autumn 2019 and the warmest year recorded in Europe (Copernicus Climate Change Service 2021). Permafrost temperatures are thus higher or similar as before the temporary cooling in 2016 and 2017, which persisted in 2018 and only started to reverse in 2019. Temperatures at Murtèl-Corvatsch in the Engadin (Switzerland) increased by ~0.6°C at 20-m depth and by more than 1°C at 10-m depth over the past 3 decades. On Stockhorn above Zermatt (Switzerland), temperatures at 23-m depth increased by ~0.4°C over the past 2 decades. Surface velocities of rock glaciers generally follow the evolution of the permafrost temperatures. In the European Alps, rock glacier surface velocities for the year 2020 are at or above the previous maximum observed in 2015 (see Sidebar 2.1).

In the Nordic countries, permafrost temperatures measured in 2020 were the highest or second highest on record, continuing the reported warming trend (Fig. 2.10; Noetzli et al. 2020; Etzelmüller et al. 2020). In the cold mountain permafrost at Juvvasshøe in southern Norway, permafrost temperatures at 20-m depth increased by 0.5°C from 1999 to 2020. Permafrost temperatures decreased in Svalbard at 10-m depth compared to the previous extremely warm years due to the relatively cold winters in 2019 and 2020 (Christiansen et al. 2021). However, they are still above the long-term average; for example, at Kapp Linne they were 0.7°C higher in 2020 than at the start of the record in 2009.

Permafrost temperatures measured in the hinterland of the QTP in Central Asia continued to increase at all sites, with remarkable warming trends but variable rates: at 10-m depth they range between 0.45°C decade^{-1} (QTB15, Fig. 2.11) and 0.04°C decade^{-1} (QTB06), and at 20-m depth between 0.24 and 0.02 °C decade^{-1} (Zhao et al. 2020, 2021).

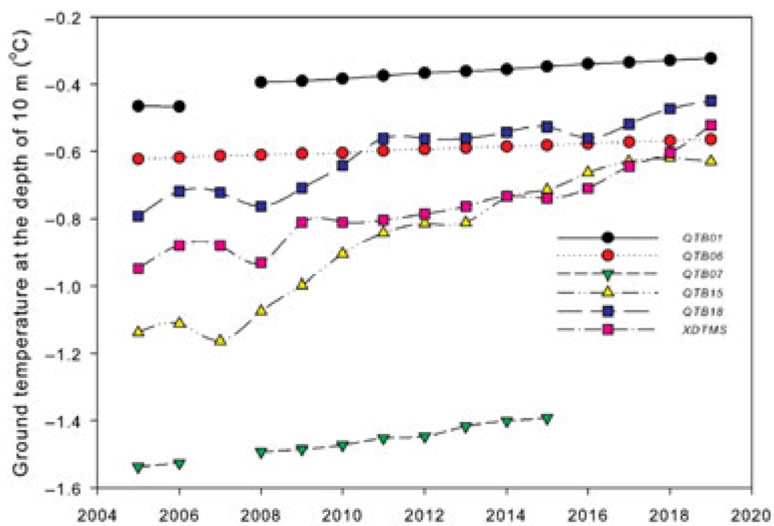

Fig. 2.11. Temperature measured in permafrost boreholes along the Qinghai-Xizang Highway on the Tibetan Plateau at 10-m depth from 2005 to 2019. (Source: Cryosphere Research Station on Qinghai-Xizang Plateau, CAS.)

The active layer thickness (ALT) is the ground layer that freezes and thaws annually and lies above the permafrost. Changes in ALT are a key indicator for changing permafrost conditions. ALT was not or only partly reported for some sites in Canada and Alaska due to COVID-19 travel restrictions. The ALT in northern Alaska was 6 cm thinner in 2020 than the decadal average (2008–17) and 8 cm thinner than in 2019. In the Alaska Interior, ALT was thicker than average, but 5 cm thinner than in 2019. ALT at the majority of sites in the Nordic region was similar to the previous year, at or close to record values. In Russia, ALT was thicker than average and thicker than in 2019 in all regions, except for Chukotka, where ALT was thinner than in 2019. The Siberian heat wave (see section 7g2, Sidebar 5.1) caused particularly thick ALT, with more than 10 cm larger values than in 2019 in West Siberia and neighboring sites in northwestern Russia. ALT in the regions of central and eastern Siberia was only 3 cm above previous regional averages. More details on ALT in Arctic regions are given in section 5h.

In the Scandinavian and European Alps, ALT values for 2020 were at or close to the previous maximum at most of the sites. In the Swiss Alps, record values were observed in 2020 for most sites, with values up to 10 m in extreme cases. Along the Qinghai-Tibet Highway (Kunlun mountain pass to Liangdaohe), an ALT increase was observed with a mean of 19.5 cm decade^{-1} from 1981 to 2019 (Fig. 2.12). In Antarctica, the February 2020 heat wave in the northwest Weddell Sea sector (section 2b3) accelerated active layer thickening. Thaw depth on James Ross Island reached 80 cm. This is comparable to observations in 2016/17 (Hrbáček et al. 2021), one of the warmest years so far measured in this sector (J. Turner et al. 2020).

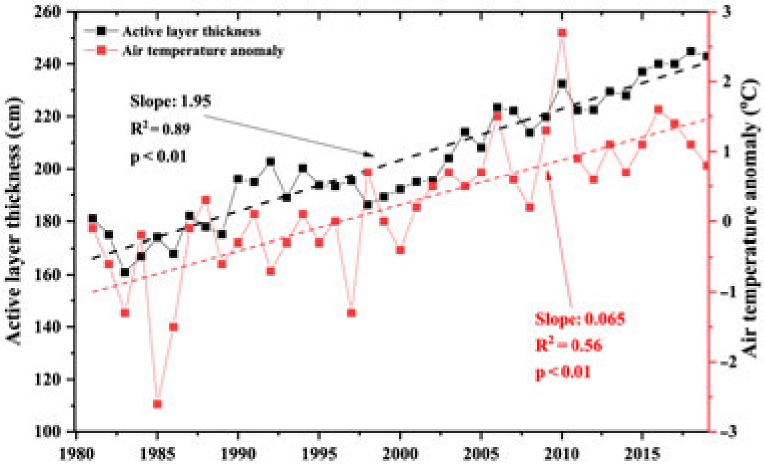

Fig. 2.12. The active layer thickness (cm) and air temperature anomaly (°C) in the permafrost zone along the Qinghai-Tibet Highway during the period 1981–2019. The air temperature anomaly is estimated relative to the climate baseline 1981–2010.

Long-term observation of permafrost relies on field observations of ALT and permafrost temperatures measured in boreholes. International data are collected by the Global Terrestrial Network for Permafrost (GTN-P) as part of the Global Climate Observing System (GCOS). Permafrost temperatures are logged manually or continuously using multi-sensor cables in boreholes reaching at least the depth of the zero annual amplitude. An assessment of the measurement accuracy of permafrost temperatures worldwide varied from 0.01° to 0.25°C, with an assumed overall accuracy of about 0.1°C (Biskaborn et al. 2019; Romanovsky et al. 2010). ALT is determined by mechanical probing where possible and has an accuracy of ~1 cm. Probing is not possible in bedrock or debris material, particularly in mountain regions. Here, ALT is interpolated from temperature sensors in boreholes. The current global coverage of permafrost monitoring sites is sparse; it is particularly limited in regions such as Siberia, central Canada, Antarctica, and the Himalayan and Andes Mountains.

Sidebar 2.2: Rock glacier kinematics—C. PELLET, X. BODIN, R. DELALOYE, V. KAUFMANN, J. NOETZLI, E. THIBERT, AND A. KELLERER-PIRKLBAUER

Rock glaciers are geomorphological indicators of permafrost occurrence in mountain areas and develop in most mountain ranges worldwide. Their kinematics derived from surface displacement measurements typically range from several centimeters up to several meters per year (Kääb and Vollmer 2000). Long-term studies from the European Alps have shown that the velocity of rock glaciers in a specific region responds sensitively and synchronously to interannual and decennial changes in ground temperature (e.g. Bodin et al. 2009; Delaloye et al. 2008, 2010; Kääb et al. 2007; Kellerer-Pirklbauer and Kaufmann 2012, 2018; Staub et al. 2016; Thibert et al. 2018; PERMOS 2019). Measurements of the surface velocity of rock glaciers based on aerial images and geodetic surveys first started in the 1960s in the European Alps (Haeberli 1985). Today, the majority of monitored rock glaciers are in the European Alps, and surface velocity measurements based on repeated terrestrial geodetic surveys have become part of operational permafrost monitoring in several European countries (Austria, France, Switzerland; see PERMOS 2019). In addition to their importance as climate indicators, rock glaciers are highly relevant for natural hazards risk management in mountain regions as well as for land use planning. Active rock glaciers are sediment conveyers and their increasing velocity can lead to a higher frequency of rock fall or debris flows from their frontal parts (e.g., Kummert et al. 2018).

The surface velocity of the majority of the observed rock glaciers in the European Alps behaved similarly during the past decades, despite variable size, morphology, and velocity range (Fig. SB2.4). The surface velocity increased by a factor of 2 to 10 from 1980s to 2015, and a maximum was reached in 2015. The acceleration was temporarily interrupted (i.e., velocity decrease was observed) for most of the landforms between 2004 and 2006, as well as between 2016 and 2018, coinciding with a decrease in ground temperatures (Noetzli et al. 2018; PERMOS 2019). The acceleration resumed in 2018. In 2020, the surface velocity of rock glaciers was close to or even higher than the maximum observed in 2015, which corresponds to the high ground temperatures observed (see section 2c1). Compared to the values of 2019, the surface velocity increase spans from +17% (Dösen [Austria] and Gemmi/Furggentälti [Switzerland]) to +45% (Grosses Gufer [Switzerland] and Hinteres Langtalkar [Austria]), which is in the same range as the acceleration observed between 2014 and 2015.

Long-term in situ measurements of rock glacier kinematics are scarcely available from other regions of the world. However,