

Transient but common features of stratospheric temperature variability are polar SSWs that occur episodically during winter, mainly in the NH. At least one SSW occurred in 34 of the past 62 winters in the NH, while only one was observed in the SH (in 2002) prior to 2019. Time series of 50-hPa temperature over the Antarctic during the last several years are shown in Fig. 2.9, in the context of the historical average and range of observations. The September 2019 SSW resulted in a 50-hPa temperature increase over the polar cap of  $\sim 30^{\circ}\text{C}$  over two weeks, with temperatures well outside the range of previous variability. While these SSW events have strong effects on polar temperatures, they have minimal influence on global mean stratospheric temperatures. However, Australian hot and dry extremes are statistically associated with weakening and warming of the Antarctic stratospheric polar vortex (Lim et al. 2019). The September 2019 SSW is one of many possible factors contributing to this year's eastern Australian bushfires (see section 7h4 for more details; Phillips and Bogrady 2020).

### c. Cryosphere

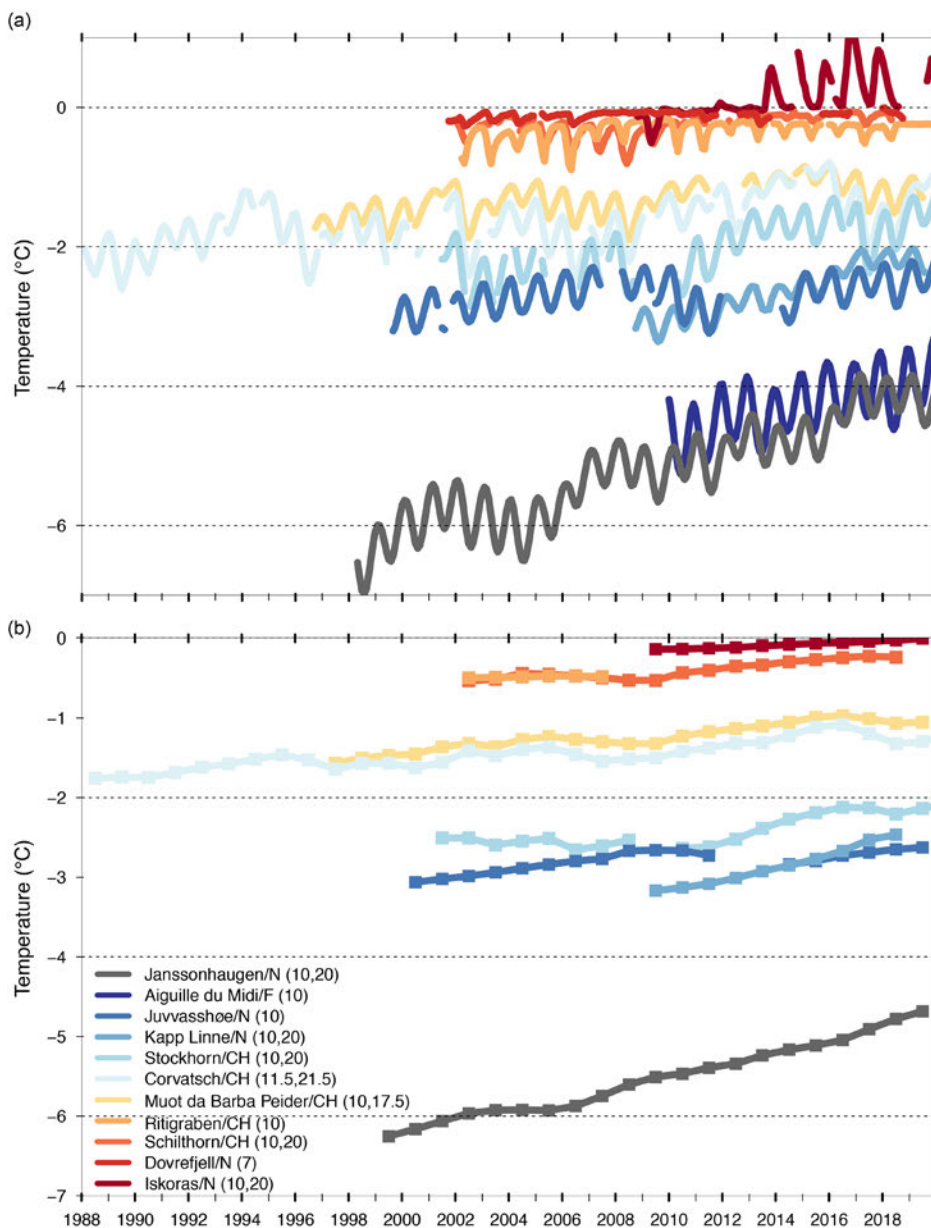
#### 1) *Permafrost thermal state*—J. Noetzli, H. H. Christiansen, K. Isaksen, S. Smith, L. Zhao, and D. A. Streletskiy

The global picture of permafrost state and changes continued in 2019: permafrost is warming in both mountain and polar regions, and the highest increase is observed where permafrost temperatures and ice contents are lowest. At warmer and ice-rich locations the temperature change is smaller due to the energy uptake during ice melt processes. The thickness of the active layer (ALT)—the uppermost ground layer above the permafrost subject to positive temperatures during summer—is globally increasing.

In the Arctic regions, permafrost temperatures measured at 20-m depth at many of the monitoring sites during 2019 were the highest observed during the observation period, continuing the trend reported by Meredith et al. (2019). Observations now cover up to four decades at several sites. At some locations, temperatures were  $2^{\circ}$ – $3^{\circ}\text{C}$  higher than 30 years ago. More details on the Arctic region are given in Chapter 5. For Antarctica, increasing permafrost temperatures were reported for the past decade (cf. Noetzli et al. 2019). However, for 2019 no data update is available yet.

Mountain permafrost accounts for nearly 30% of the global permafrost area (Hock et al. 2019), but datasets for many mountain regions are obtained at only a limited number of sites. Data are primarily available from boreholes and networks in the European Alps, the Nordic countries, and central Asia (Qinghai-Tibetan Plateau, QTP). A general warming trend during recent decades until 2016 is also reported for mountain ranges in Canada, Mongolia, and Tien Shan in central Asia (Hock et al. 2019). Due to the high spatial variability in characteristics and permafrost temperatures, warming rates are highly heterogeneous, depending on topography, snow regime, and ground ice content.

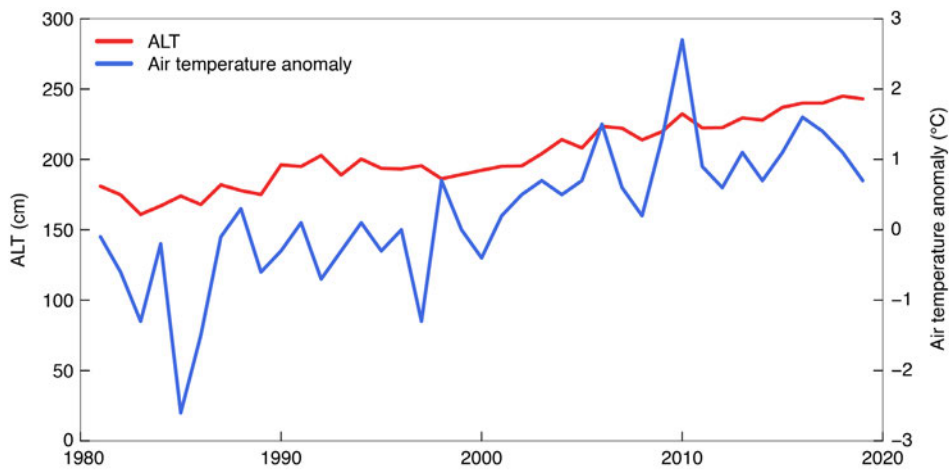
Permafrost temperatures observed in the European Alps in 2019 were influenced by an early and long-lasting snow cover—trapping the heat from summer 2018—followed by another extremely warm summer in 2019. Permafrost temperatures continued the increasing trend since 2010 after a temporary interruption of the warming trend due to snow-poor winters reported in 2017 (Fig. 2.10; Noetzli et al. 2018; PERMOS 2019). At most sites, the temperatures at 10-m depth in 2019 were slightly below the record temperatures measured in 2015 (updated from PERMOS 2019). Likewise, permafrost temperatures at 20-m depth increased since 2018, but not above the previous high from 2015. Repeated electrical resistivity tomography at several borehole sites indicate a decrease in ice content, particularly for sites close to  $0^{\circ}\text{C}$  (Mollaret et al. 2019; PERMOS 2019). Permafrost temperatures measured at steep bedrock sites at high elevation are typically not influenced by annual snow conditions and have continuously increased, with 2019 values higher than those previously recorded down to 10-m depth (updated from PERMOS 2019; Magnin et al. 2015). Further, rock glacier creep velocities generally follow permafrost temperatures and have increased considerably in the past decade (PERMOS 2019).



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

In Nordic countries, permafrost temperatures increased to their highest levels in both cold and warm permafrost (updated from Isaksen et al. 2007; Christiansen et al. 2010). In southern Norway, permafrost at 20-m depth warmed between 2015 and 2019 (for Juvvasshøe + 0.04°C yr<sup>-1</sup>), following a period of cooling between 2010 and 2014 (Fig. 2.10). In northern Norway (Iskoras since 2008), latent heat exchanges appeared to dominate the annual temperature amplitude at 10-m depth in the beginning of the series. Since 2013/14, an increase in annual temperature amplitude has been observed with present temperatures well above 0°C (Fig. 2.10). At 20-m depth, ground temperatures have risen to 0°C. Borehole temperatures measured in the hinterland of the QTP showed remarkable warming tendencies with variable rates that are highest in lower-temperature permafrost (Cheng et al. 2019; Sun et al. 2019).

The ALT continued to increase in 2019 for the majority of the observational sites. Out of 92 sites that reported data in 2018/19 in the Northern Hemisphere (NH), only a few had below-average ALT relative to the 2003–12 period. About 66% of the sites had larger 2019 ALT than in 2018. At North American sites, ALT continues to increase since the beginning of the observations in the mid-1990s, with the highest increase in the Alaskan Interior and smaller increases in the Mackenzie Valley of northwestern Canada and the Alaska North Slope. In 2019, ALT was close to maximum values at the group of sites located in the Pacific Arctic sector (Alaska, Chukotka). At many interior Alaska sites, the active layer did not freeze completely down to the underlying permafrost due to a combination of long-term warming and the relatively mild and snowy past two winters (2017/18 and 2018/19). During all previous years of observations, complete active layer freeze-up was observed. North Atlantic Arctic sites had the largest or close-to-largest ALT in 2019; sites in Svalbard and Greenland show at least 0.05 m larger ALT than average. The Russian Arctic, with the exception of northeast Siberia, experienced a



**Fig. 2.11.** Annual ALT (cm) and air temperature anomaly (°C) across the Qinghai Tibet Highway.

larger-than-average ALT, with deviations from the mean of 0.05 m in northern European Russia to 0.02 m in West Siberia (see section 5h for more details). In Scandinavia and the European Alps, values up to about 0.05 m above or near-record maximum values were observed at many of the sites. ALT also continued to increase at sites located in permafrost regions of the hinterland of the QTP

by about  $0.2 \text{ m decade}^{-1}$  since the 1980s (Fig. 2.11; Cheng et al. 2019; Zhao et al. 2019). In 2019, ALT was, on average, slightly smaller in the QTP than in 2018 (0.02 m).

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 (GTN-P) as part of the Global Climate Observing System of the World Meteorological Organization. Borehole temperatures are logged manually or continuously using multi-sensor cables down to at least the depth of the zero annual amplitude (ZAA), the depth where seasonal variations become negligible. An assessment of the measurement accuracy of borehole temperatures in permafrost worldwide varied from  $0.01^\circ$  to  $0.25^\circ\text{C}$  and a mean overall accuracy of about  $0.1^\circ\text{C}$  can be assumed (Biskaborn et al. 2019; Romanovsky et al. 2010). The current global coverage of permafrost temperature monitoring in boreholes is sparse and very limited in regions such as Siberia, central Canada, Antarctica, and the Himalayan and Andes Mountains. The distribution of observation sites is typically biased to accessible locations (highways or cable cars).

## 2) Northern Hemisphere snow cover extent—D.A. Robinson

Annual snow cover extent (SCE) over NH lands averaged 24.8 million  $\text{km}^2$  in 2019. This is 0.8 million  $\text{km}^2$  smaller than the 2018 mean extent and 0.3 million  $\text{km}^2$  smaller than the 50-year average (mapping extends back to late 1966; however, several early years in the record are incomplete) and ranks 2019 as having the 17th-least extensive cover on record (Table 2.4). SCE over Eurasia and North America, including the Greenland ice sheet (GrIS), is considered in this analysis. Monthly SCE in 2019 ranged from 47.2 million  $\text{km}^2$  in January to 2.5 million  $\text{km}^2$  in August.

January 2019 NH SCE was near average, ranking as the 27th-most extensive over the past 53 years. Both Eurasia and North America ranked similarly. The NH as a whole had near-average SCE in February; however, North America and Eurasia ranked fourth and 42nd largest, respectively. The continental disparity continued into March with the combined rank falling into the lowest third. This decline became greater through the spring and early summer, with both continents ranking in the lower tercile throughout this interval. June had the largest negative monthly NH anomaly of the year (3.6 million  $\text{km}^2$  or 38% below normal). NH SCE has been below average for 14 of the past 15 years in May and all of the past 15 years in June (Fig. 2.12).

Autumn SCE emerged at an average pace in September but increased rapidly in October, having the largest positive monthly anomaly of 2019 at 3.8 million  $\text{km}^2$ . October and November SCE each ranked fifth largest of the satellite era for their respective months. NH SCE has now been above average in 10 of the past 11 years in October and all of the past 11 years in November. December SCE was also above average over North America, but Eurasian cover increased slowly during