2014 was the warmest since measurements began in 1949 at Kangerlussuaq (relative to the 1981–2010 average, the June–August temperature anomaly was +1.6°C, with a June anomaly of +2.3°C), and the second warmest (together with summer 2010) since 1784 at Nuuk (the June–August anomaly was +2.3°C, with a July anomaly of +2.9°C).

### g. Terrestrial permafrost


Permafrost is defined as soil, rock, and any other subsurface earth material that exists at or below 0°C for two or more consecutive years. On top of the permafrost is the active layer, which thaws during the summer and freezes again the following winter. The mean annual temperature of permafrost and the thickness of the active layer are good indicators of changing climate. Changes in permafrost temperatures and active layer thickness in Alaska, Canada, Russia, and the Nordic region are reported here.

Permafrost temperature (at depths of 10–200 m) is a sensitive indicator of the decade-to-century climate variability and long-term changes in the surface energy balance. This is because the range of the interannual temperature variations (“noise”) decreases rapidly with depth, while decadal and longer time-scale variations (“signal”) penetrate to greater depths in the permafrost with less attenuation. Consequently, the “signal-to-noise” ratio increases rapidly with depth and the ground acts as a natural low-pass filter of the climatic signal, making temperature-depth profiles in permafrost useful for studying past temperature changes at the ground surface. Increasing permafrost temperatures and active layer thickness caused by climate warming affect the stability of northern ecosystems and infrastructure, and are predicted to cause the release of carbon into the atmosphere in the form of the greenhouse gases carbon dioxide and methane.

In 2014, new record high temperatures at 20-m depth were measured at all permafrost observatories on the North Slope of Alaska (hereafter North Slope), except for the Happy Valley site (Fig. 5.16a,b). Changes in permafrost temperatures at 20-m depth typically lag about one year behind the changes in surface temperatures. The summer of 2013 was particularly warm on the North Slope and thus contributed to the 20-m temperature increase. The permafrost temperature increase in 2014 was substantial; 20-m temperatures in 2014 were 0.07°C higher than in 2013 at West Dock and Deadhorse, and 0.06°C higher at Franklin Bluffs (Fig. 5.16b) on the North Slope. A 0.09°C increase was observed at Galbraith Lake (Fig. 5.16b) in the northern foothills of the Brooks Range. Permafrost temperature in 2014 at Happy Valley was 0.03°C higher than in 2013, but still 0.03°C lower than the record maximum set in 2012. Temperature at 20-m depth has increased between 0.18° and 0.56°C decade$^{-1}$ since 2000 on the North Slope (Fig. 5.16b).

Permafrost temperatures in Interior Alaska generally continued to decrease slightly in 2014 (Fig. 5.16c), a cooling that dates back to 2007. Consequently, temperatures in 2014 at some sites in Interior Alaska were lower than those located much farther north, for example, temperatures at College Peat are now lower than at Old Man (Fig. 5.16c). However, at two sites, Birch Lake and Healy, this cooling trend was interrupted in 2014 by a warming of 0.1°C and 0.05°C, respectively (Fig. 5.16c).

In 2013/14, temperatures in the upper 25 m of ground at Alert, northernmost Ellesmere Island, Canada, were among the highest recorded since 1978, but have remained stable at 24-m depth for the past two years while a slight cooling is observed at 15-m depth (Fig. 5.17). At Alert BH5, temperature at 15-m depth has increased by ~1.3°C decade$^{-1}$ since 2000, which is about 0.8°C decade$^{-1}$ higher than the rate for the entire record. Even at a depth of 24 m, temperature at the Alert BH1 and BH2 sites has increased since 2000 at a rate approaching 1°C decade$^{-1}$. The slower rate of temperature increase at 24-m depth and the slight cooling at 15-m depth over the last two years is likely a response to a decrease in air temperatures between 2010 and 2013.

A similar pattern is observed in the shorter records from eastern Arctic sites, where permafrost tempera-
Features at 15-m depth have increased between 2008 and 2013 (Fig. 5.17). Temperatures in the warm permafrost of the central Mackenzie River valley in northwestern Canada continue to increase, but at a much slower rate than in the high Arctic, and which has slowed further in the last decade (Fig. 5.17). At depths of 10–12 m, the permafrost temperature at Norman Wells and Wrigley has risen by 0.01°–0.2°C decade⁻¹ since 2000. Permafrost temperatures measured since 2007 at 8.75-m depth in the northern Mackenzie Valley near Inuvik have increased by about 0.4°C decade⁻¹.

Permafrost temperature has increased by 1°–2°C in northern Russia during the last 30 to 35 years (Romanovsky et al. 2010), similar to the increase observed in northern Alaska and the Canadian high Arctic. In the European north of Russia and in the western Siberian Arctic, for example, temperatures at 10-m depth have increased by ~0.4°C to 0.6°C decade⁻¹ since the late 1980s at colder permafrost sites (Fig. 5.18, Bolvansky #59, Urengoy #15-5, and Urengoy #15-10). Less warming has been observed at warm permafrost sites in both regions (Fig. 5.18, sites Bolvansky #56 and Urengoy #15-6).

Limited long-term permafrost temperature records for the Nordic area indicate increases since the late 1990s of 0.4°–0.7°C decade⁻¹ in the highlands of southern Norway, northern Sweden, and Svalbard, with the largest warming in Svalbard and in northern Scandinavia (Isaksen et al. 2011; Christiansen et al. 2010). New sites established in Greenland are providing new information on the thermal state of permafrost. In western Greenland, permafrost temperatures are relatively warm, from ~1°C to ~3°C (Christiansen et al. 2010). In eastern Greenland, at Zackenberg Research Station, permafrost temperature at 18-m depth was ~6.8°C within a flat open area and ~5.8°C at a snowdrift site, based on the two-year record collected in summer 2014. At the new Villum Research Station at Station Nord in north Greenland, the temperature measured in August 2014 at 20-m depth was ~8.2°C.

Decadal trends in the active layer thickness (ALT) vary by region (Shiklomanov et al. 2012). In 2014, sites on the Alaska North Slope reported lower ALT values.
than in 2013 (Fig. 5.19). Out of 28 observational sites in northern Alaska, only one, located on the Seward Peninsula, reported a slight increase in the ALT in 2014. The average ALT in 2014 for the 20 North Slope sites with a long (≥10 years) observational record was 0.48 m, similar to the 1995–2013 average of 0.47 m. In the interior of Alaska, however, ALT increased substantially in 2014; three of the four sites reported the highest 2014 ALT values in the 1995–2014 observational record.

Records from 25 sites with thaw tubes in the Mackenzie Valley, northwestern Canada, indicate that ALT in 2013 (the most recent year data are available) was greater than the 2002–12 average for most sites (Duchesne et al. 2014). In this region ALT has generally increased since 2008, although in 2013 it was slightly less than in 2012, which was on average about 10% greater than the long-term mean (Fig 5.19).

In Russia, standardized active layer observations in 2014 were conducted at 36 sites. A decrease in ALT in 2014 was observed in west Siberia (Fig. 5.19). Out of the eight West Siberian sites that reported data in 2014, only three, located in the southernmost part of the region, have a substantial (0.6–0.22 m) increase in ALT. The other five sites reported 0.08–0.15 m ALT decreases. Locations in the Russian European North have been characterized by almost monotonic thickening of the active layer over the last 15 years and reached a record maximum in 2012. However, in 2014, all four sites within the region reported a decrease in ALT ranging from 0.02 to 0.22 m compared to 2013 (Fig. 5.19). In north central Siberia, ALT increased by 0.07–0.09 m, while ALT in the center of the region (Yakutsk) was largely unchanged. Sites in south central Siberia reported a 0.10–0.13 m decrease in ALT in 2014, while in eastern Siberia ALT in 2014 increased by an average of 8% compared to 2013, and only 4 out of 17 sites reported a slight decrease in ALT. In 2014, ALT in Chukotka (Russian Far East) was about 2% higher than in 2013, marking a slight increase during 2011–14 that reversed a sharp decline in 2008–10 (Fig. 5.19).

![Fig. 5.18. Time series of mean annual permafrost temperatures (°C) at 10-m depth at six research sites in the European north of Russia (Bolvansky #56, 59, and 65) and in the western Siberian Arctic (Urengoy #15-5, 15-6, and 15-10).](image)

![Fig. 5.19. Long-term active-layer change in six different Arctic regions as observed by the Circumpolar Active Layer Monitoring project. The data are presented as annual percentage deviations from the mean value for the period of observations. Thaw depth observations from the end of the thawing season were used. Only sites with at least 10 years of continuous thaw depth observations are shown. Solid red lines show mean values; dashed black lines represent maximum and minimum values.](image)