

Permafrost

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Highlights

- In 2012, new record high temperatures at 20 m depth were measured at most permafrost observatories on the North Slope of Alaska and in the Brooks Range, where measurements began in the late 1970s. Only two coastal sites show exactly the same temperatures as in 2011.
- A common feature at Alaskan, Canadian and Russian sites is greater warming in relatively cold permafrost than in warm permafrost in the same geographical area.
- During the last fifteen years, active-layer thickness has increased in the Russian European North, the region north of East Siberia, Chukotka, Svalbard and Greenland.
- Active-layer thickness on the Alaskan North Slope and in the western Canadian Arctic was relatively stable during 1995-2011.

The most direct indicators of permafrost stability and changes in permafrost state are the permafrost temperature and the active layer thickness (ALT). The ALT is the top layer of soil and/or rock that thaws during the summer and freezing again during the fall, i.e., it is not permafrost. Permafrost temperature measured at a depth where seasonal variations in ground temperature cease to occur is the best indicator of long-term change. This depth varies from a few meters in warm, ice-rich permafrost to 20 m and more in cold permafrost and in bedrock (Smith et al., 2010; Romanovsky et al., 2010a). However, if continuous year-round temperature measurements are available, the mean annual ground temperature (MAGT) at any depth within the upper 15 m can be used for detection of changing conditions. International Polar Year (IPY 2007-2009) resulted in significant enhancement of the permafrost observing system in the Arctic, where there are now ~600 boreholes (**Fig. 5.20**; Brown et al., 2010; Romanovsky et al., 2010a). A borehole inventory, including mean annual ground temperatures for most of these boreholes, is available online (<http://nsidc.org/data/g02190.html>).

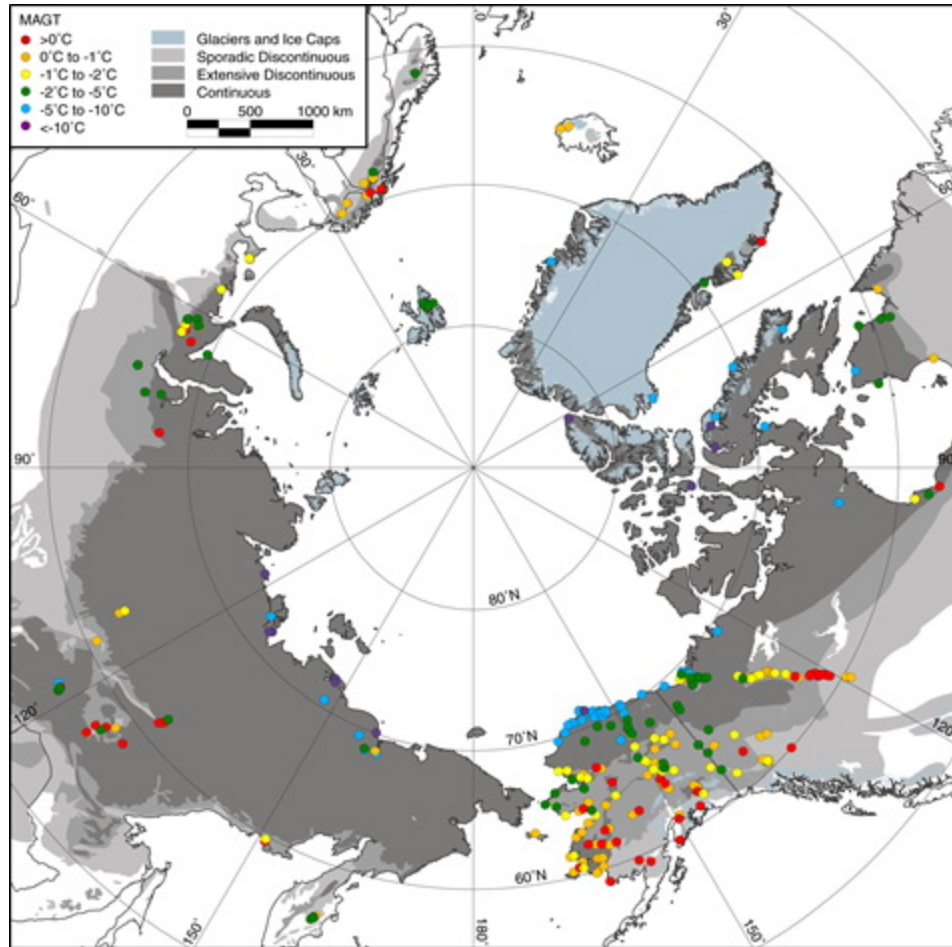


Fig. 5.21. Circum-Arctic view of mean annual ground temperature (MAGT) in permafrost during the International Polar Year (IPY 2007-2009; from Romanovsky et al., 2010).

Permafrost temperatures in the Arctic and sub-Arctic lowlands generally decrease from south to north. Higher ground temperatures are found in the southern discontinuous zone, where MAGT is above 0°C at many locations (**Fig. 5.21**). The temperature of warm permafrost in the discontinuous zone generally falls within a narrow range, with MAGT at most sites being $>-2^{\circ}\text{C}$ (Christiansen et al., 2010; Romanovsky et al., 2010a; Smith et al., 2010) (**Fig. 5.21**). Temperatures as low as -3°C , or even -4°C , however, may be observed in some specific ecological or topographic conditions (Jorgenson et al., 2010). A greater MAGT range occurs within the continuous permafrost zone, from $>-1^{\circ}\text{C}$ at some locations to as low as -15°C at others (Christiansen et al., 2010; Romanovsky et al., 2010a; Romanovsky et al., 2010b; Smith et al., 2010). MAGT $>0^{\circ}\text{C}$ is observed at some locations near the southern boundary of the continuous zone (**Fig. 5.21**), which may indicate that this boundary is shifting northward (Romanovsky et al., 2010b). Permafrost temperatures $<-10^{\circ}\text{C}$ are presently found only in the Canadian Arctic Archipelago (Smith et al., 2010) and near the Arctic coast in Siberia.

Our understanding of the thermal state of mountain permafrost in northwestern Canada (Yukon) has improved in recent years (e.g. Lewkowicz et al., 2012). In the sporadic permafrost zone of southern Yukon, warm, thin permafrost formed under earlier, colder conditions persists in organic soils in valley floors (Lewkowicz et al., 2011). Recent research also indicates that air temperature inversions are an important factor influencing mountain permafrost distribution

(Lewkowicz and Bonnaventure, 2011; Lewkowicz et al. 2012). Thus, permafrost may be less extensive at higher elevations than suggested by predictions based on air temperatures measured at standard weather stations located in valley floors (Smith et al., 2010).

Systematic observations of permafrost temperature in Alaska, Canada and Russia since the middle of the 20th Century provide several decades of continuous data from several sites. The records allow assessment of changes in permafrost temperatures on a decadal time scale. A general increase in permafrost temperatures is observed during the last several decades in Alaska (Osterkamp, 2008; Smith et al., 2010; Romanovsky et al., 2010a), northwest Canada (Smith et al., 2010) and Siberia (Oberman, 2008; Romanovsky et al., 2010b). At most Alaskan permafrost observatories there was substantial warming during the 1980s and especially in the 1990s (**Fig. 5.22**). The magnitude and nature of the warming varies between locations, but is typically from 0.5°C to 2°C at the depth of zero seasonal temperature variations over this 20 year period (Osterkamp, 2008). At the beginning of the 2000s, permafrost temperature was relatively stable on the North Slope of Alaska (Smith et al., 2010) (**Fig. 5.22**), and there was even a slight decrease (from 0.1°C to 0.3°C) in Interior Alaska during the last four years (**Fig. 5.22**), but the permafrost warming has resumed since 2007. This warming trend is initially evident at the Arctic coastal sites and then propagates into the northern foothills of the Brooks Range (**Fig. 5.22b**), where a noticeable warming in the upper 20 m of permafrost has become evident since 2008 (Romanovsky et al., 2011).

In 2012, new record high temperatures at 20 m depth were measured at most permafrost observatories on the North Slope of Alaska, i.e., north of the Brooks Range, where measurements began in the late 1970s (**Fig. 5.22b**). The exceptions were West Dock and Deadhorse, where temperatures in 2012 were the same as the record-high temperatures observed in 2011. Record high temperatures were also observed in 2012 in the Brooks Range (Chandalar Shelf) and in its southern foothills (Coldfoot). These distinct patterns of permafrost warming on the North Slope and a slight cooling in the Alaska Interior in 2010-2011 are in good agreement with air temperature patterns observed in the Arctic and the sub-Arctic (see the essay on [Air Temperature, Atmospheric Circulation and Clouds](#)) and might also be a result of snow distribution variations (see the [Snow](#) essay for more information on changing snow cover).

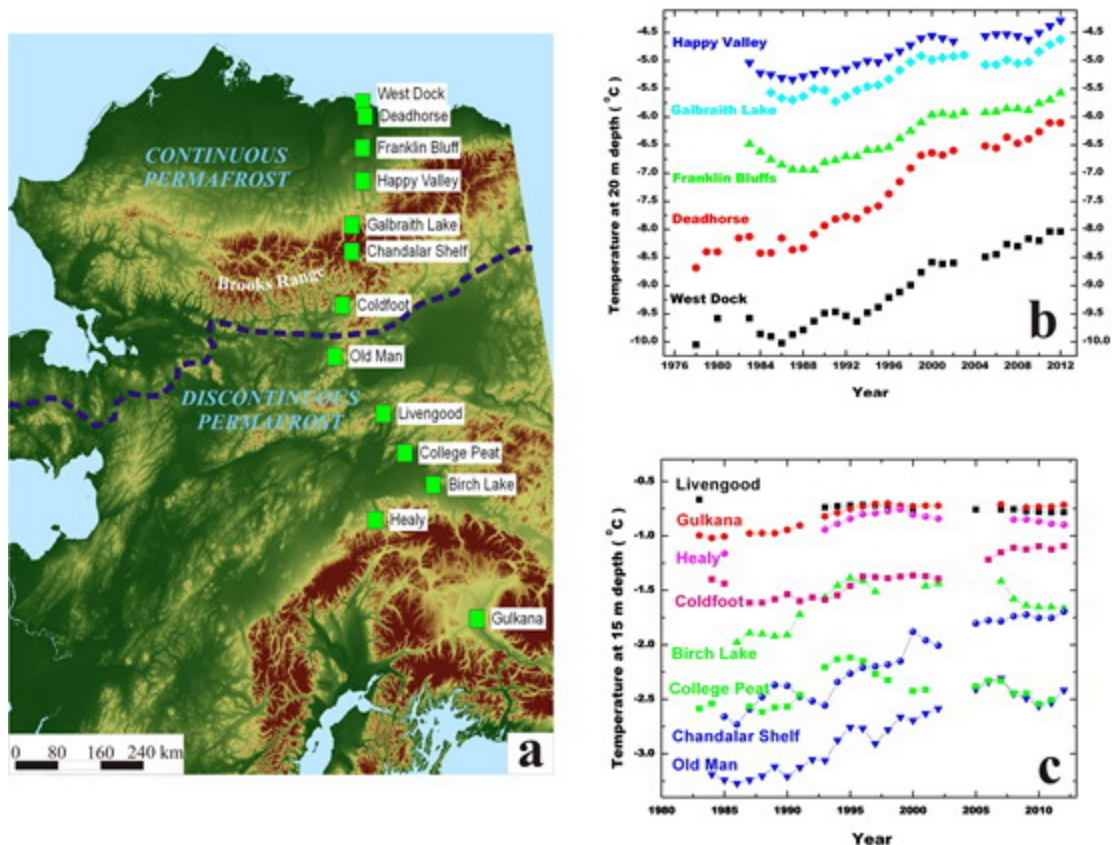


Fig. 5.22. Time series of annual permafrost temperatures (b and c) measured from north to south across Alaska (a) in the continuous and discontinuous permafrost zones.

A similar temperature increase in colder permafrost during the last 40 years in northwest Canada was determined by comparison of measurements made between 2003 and 2007 with those made in the late 1960s and early 1970s (Burn and Kokelj, 2009). In the discontinuous zone of western Canada, the increase in permafrost temperature continues to be small, e.g., not exceeding 0.2°C per decade in the central and southern Mackenzie Valley (**Fig. 5.23**, Norman Wells and Wrigley) (Smith et al., 2010; Derksen et al. 2012). In the eastern and high Canadian Arctic, greater warming has been observed, and since 2000 there has continued to be a steady increase in permafrost temperature (**Fig. 5.23**, Alert). Significant increases in winter air temperature appear to be largely responsible for the recent increases in permafrost temperature in northern Canada, particularly at polar desert sites where snow cover is minimal (Smith et al., 2012). These changes in permafrost conditions are consistent with the recent observed reduction in spatial extent and mass of the cryosphere across the Canadian Arctic (Derksen et al., 2012).

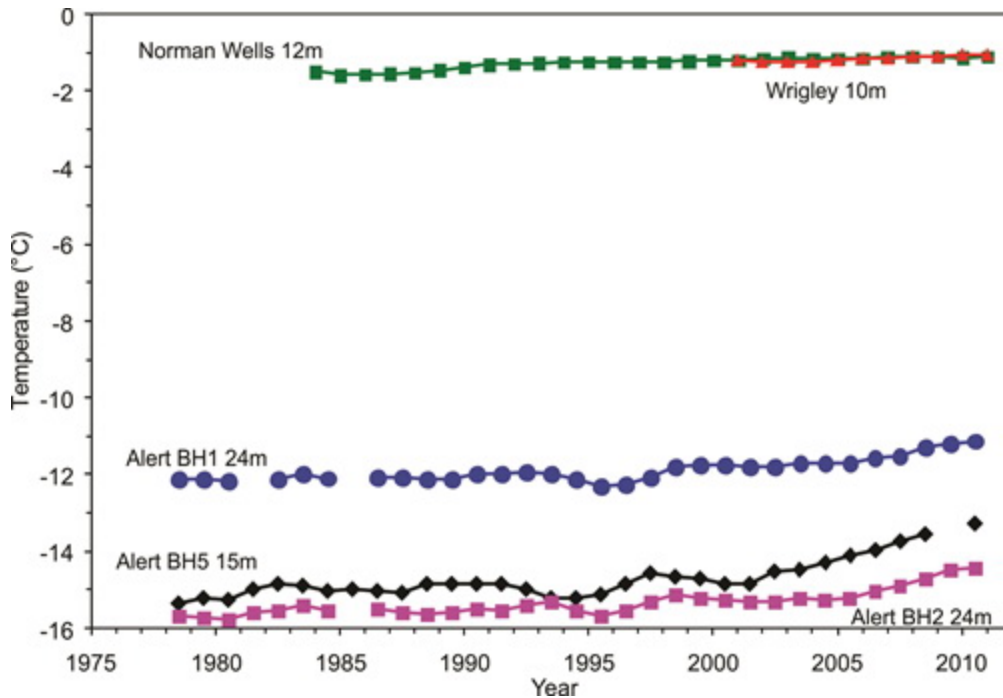


Fig. 5.23. Time series of mean annual permafrost temperature at 12 m depth at Norman Wells and Wrigley in the discontinuous permafrost zone of the central Mackenzie Valley, Northwest Territories, Canada and at 15 m and 24 m depth at CFS Alert, Nunavut, Canada (updated from Smith et al., 2010, 2012). The method described in Smith et al. (2012) was used to address gaps in the data record and produce a standardized record of mean annual ground temperature. Note the large temperature difference between the low (a) and high (b) latitude sites.

Permafrost temperature has increased by 1°C to 2°C in northern Russia during the last 30 to 35 years (Oberman, 2008; Romanovsky et al., 2010b; Drozdov et al., 2012). An especially noticeable temperature increase was observed during the late 2000s in the Russian Arctic, where the mean annual temperature at 15 m depth increased by >0.35°C in the Tiksi area and by 0.3°C at 10 m depth in the north of European Russia during 2006-2009. However, relatively low air temperatures during summer 2009 and the following winter of 2009-2010 interrupted the warming trend at many locations in the Russian Arctic, especially in the western sector. Nevertheless, many sites in East Siberia show continuous increase in permafrost temperatures at 15 to 25 m depth (**Fig. 5.24**; Kholodov et al., 2012).

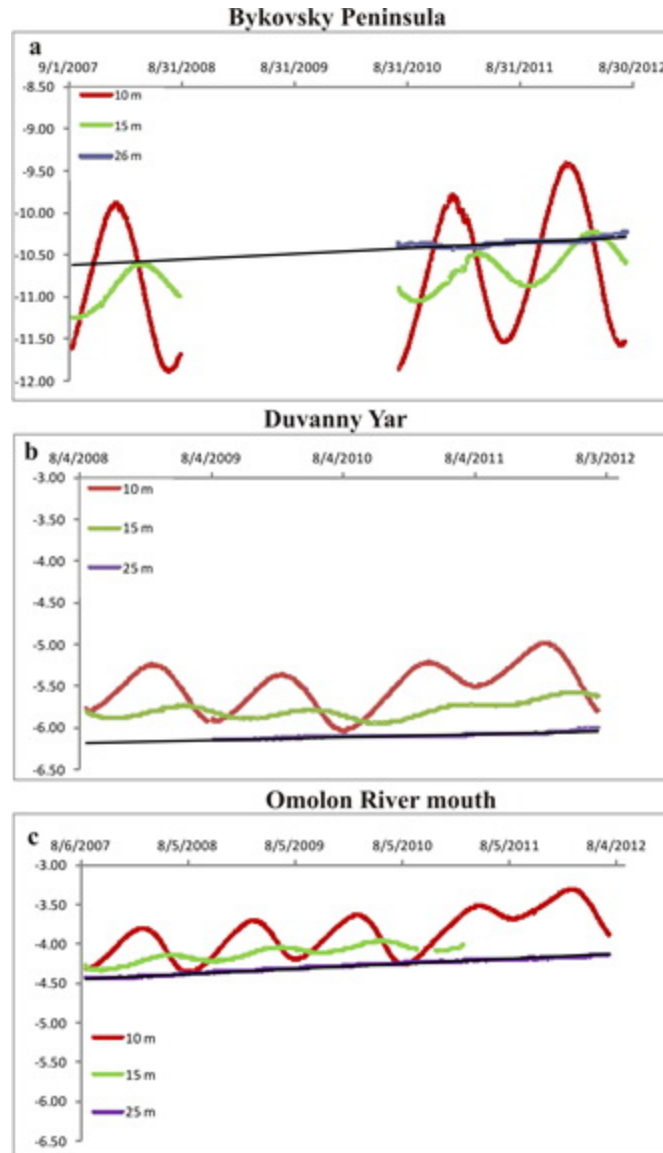


Fig. 5.24. Time series of permafrost temperatures at observation sites located in tundra (a) and boreal forest (b and c) eco-zones in East Siberia. Note that the temperature range on the y-axis of (b) and c) is the same and narrower than (a). Figure updated from Kholodov et al. (2012).

A common feature at Alaskan, Canadian and Russian sites is greater warming in relatively cold permafrost than in warm permafrost in the same geographical area (Romanovsky et al., 2010a). With a long-term warming at the ground surface, more constituent ice in fine-grained frozen sediment turns into water in the upper 5 to 15 m of permafrost, with little effect on permafrost temperature (Romanovsky and Osterkamp, 2000). In contrast, temperatures in colder permafrost are much more responsive to changes in temperature at the ground surface. This difference in the rate of permafrost warming is responsible for the fact that permafrost temperatures at such distant sites in Alaska as Chandalar Shelf in the Brooks Range and Birch Lake in Interior Alaska, which are 445 km apart, now have exactly the same permafrost temperatures. Another such example is the Old Man and College Peat sites, which are 225 km apart (Fig. 5.22).

In the Nordic area, including Greenland, most permafrost temperature monitoring sites were established during IPY 2007-2009 (Christiansen et al., 2010). There are only a few sites with moderately long records dating back to the late 1990s. The latter also show a recent decadal warming, of 0.04 to 0.07°C/yr, 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).

Long-term observations of changes in active-layer thickness (ALT) are less conclusive. Thaw depth observations exhibit substantial inter-annual fluctuations, primarily in response to variations in summer air temperature (e.g., Smith et al. 2009; Popova and Shmakin, 2009). Decadal trends in ALT vary by region. (Shiklomanov et al., 2012).

A progressive increase in ALT has been observed in some Nordic countries, e.g., in the Abisko area of Sweden since the 1970s, with a faster rate after 1995 that resulted in disappearance of permafrost in several mire landscapes (e.g., Åkerman and Johansson, 2008; Callaghan et al., 2010). This increase in thaw propagation ceased during 2007-2010, coincident with drier summer conditions (Christiansen et al., 2010). Increases in ALT since the late 1990s have been observed on Svalbard and Greenland, but these are not spatially and temporarily uniform (Christiansen et al., 2010).

Increase in ALT during the last fifteen years has been observed in the north of European Russia (Drozdov et al., 2012; Kaverin et al., 2012), in the north of East Siberia (Fyodorov-Davydov et al., 2008) and in Chukotka (Zamolodchikov, 2008), but ALT was relatively stable in the northern regions of West Siberia (**Fig. 5.25**).

Active-layer trends are different for North American sites, where a progressive increase of ALT is evident only at sites in Interior Alaska; there, the maximum ALT for the 18-year observation period occurred in 2007 (**Fig. 5.25**). Active-layer thickness on the North Slope of Alaska is relatively stable, without pronounced trends during 1995-2008 (Streletskiy et al., 2008; Shiklomanov et al., 2010). Similar results are reported from the western Canadian Arctic. Smith et al. (2009) found no definite trend in the Mackenzie Valley during the last 15 years, with some decrease in ALT following a maximum in 1998. Although an 8 cm increase in thaw depth was observed between 1983 and 2008 in the northern Mackenzie region, shallower thaw has been observed since 1998 (Burn and Kokelj, 2009). In the eastern Canadian Arctic, ALT has increased since the mid-1990s, with the largest increase occurring in bedrock of the discontinuous permafrost zone (Smith et al., 2010).

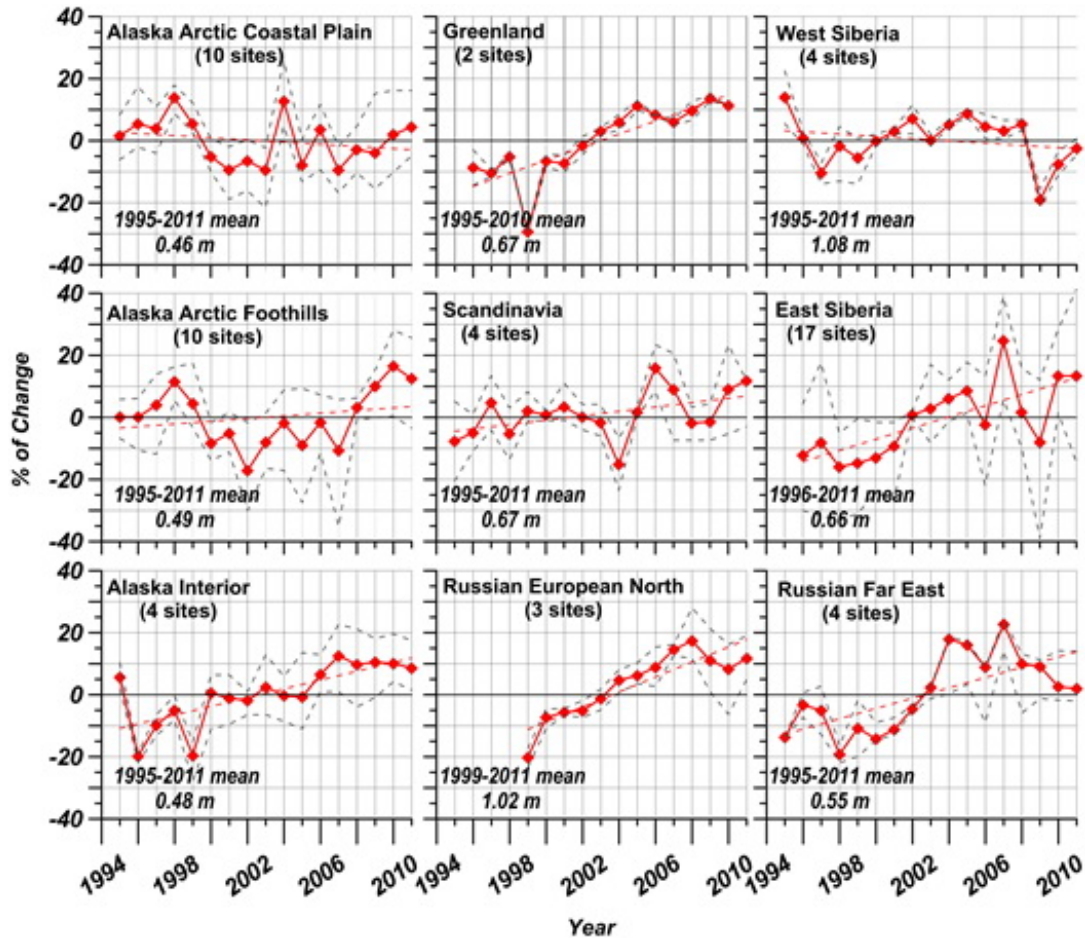


Fig. 5.25. Active-layer change in nine different Arctic regions according to the Circumpolar Active Layer Monitoring (CALM) program. The data are presented as annual percentage deviations from the mean value for the period of observations (indicated in each graph). Solid red lines show mean values. Dashed grey lines represent maximum and minimum values. Thaw depth observations from the end of the thawing season were used. Availability of at least ten years of continuous thaw depth observations through to the 2011 thawing season was the only criterion for site selection. For Greenland sites, 2011 data are not available. The number of CALM sites within each region varies and is indicated in each graph. Figure updated from Shiklomanov et al. (2012).

The last 30 years of ground warming have resulted in the thawing of permafrost in areas of discontinuous permafrost in Russia (Oberman, 2008; Romanovsky et al., 2010b). This is evidenced by changes in the depth and number of taliks (a sub-surface layer of year-round unfrozen ground within permafrost), especially in sandy and sandy loam sediments compared to clay. A massive development of new closed taliks in the southern continuous permafrost zone, resulting from increased snow cover and warming permafrost, was responsible for the observed northward movement by several tens of kilometers of the boundary between continuous and discontinuous permafrost (Oberman and Shesler, 2009; Romanovsky et al., 2010b). The frequently-reported long-term permafrost thawing in the Central Yakutian area around the city of Yakutsk is directly related to natural (forest fire) or anthropogenic (agricultural activities, construction sites) disturbances (Fedorov and Konstantinov, 2008) and are not significantly correlated with climate (Romanovsky et al., 2010b).

References

- Åkerman, H. J. and M. Johansson. 2008. Thawing permafrost and thicker active layers in sub-arctic Sweden. *Permafr. Periglac. Process.*, 19, 279-292. doi:10.1002/ppp.626.
- Brown J., A. Kholodov V. Romanovsky K. Yoshikawa S. Smith H. Christiansen, G. Viera and J. Noetzli. 2010. The Thermal State of Permafrost: the IPY-IPA snapshot (2007-2009). In *Proceedings of the 63rd Canadian Geotechnical Conference & 6th Canadian Permafrost Conference*, Calgary, Canada, September 2010, 12-16, 6 pp.
- Burn C. R. and S. V. Kokelj. 2009. The environment and permafrost of the Mackenzie Delta area. *Permafr. Periglac. Process.*, 20(2), 83-105, doi: 10.1002/ppp.655.
- Callaghan, T. V., F. Bergholm, T. R. Christensen, C. Jonasson, U. Kokfelt and M. Johansson. 2010. A new climate era in the sub-Arctic: Accelerating climate changes and multiple impacts. *Geophys. Res. Lett.*, 37, L14705, doi:10.1029/2009GL042064.
- Christiansen, H. H., B. Etzelmüller, K. Isaksen, H. Juliussen, H. Farbrøt, O. Humlum, M. Johansson, T. Ingeman-Nielsen, L. Kristensen, J. Hjort, P. Holmlund, A. B. K. Sannel, C. Sigsgaard, H. J. Åkerman, N. Foged, L. H. Blikra, M. A. Pernosky and R. Ødegård. 2010. The Thermal State of Permafrost in the Nordic area during the International Polar Year. *Permafr. Periglac. Process.*, 21, 156-181, doi: 10.1002/ppp.687.
- Derksen, C., S. L. Smith, M. Sharp, L. Brown, S. Howell, L. Copland, D. R. Mueller, Y. Gauthier, C. Fletcher, A. Tivy, M. Bernier, J. Bourgeois, R. Brown, C. R. Burn, C. Duguay, P. Kushner, A. Langlois, A. G. Lewkowicz, A. Royer and A. Walker. 2012. Variability and change in the Canadian cryosphere. *Climatic Change*, 115, 59-88. doi:10.1007/s10584-012-0470-0.
- Drozdo, D. S., G. V. Malkova, N. G. Ukraintseva and Yu. V. Korostelev. 2012, Permafrost Monitoring of Southern Tundra Landscapes in the Russian European North and West Siberia. *Proceedings of the 10th International Conference on Permafrost, Salekhard, Russia, June 25 - 29, 2012*, Vol. 2, 65-70.
- Fedorov A. N, and P. Y. Konstantinov. 2008. Recent changes in ground temperature and the effect on permafrost landscapes in Central Yakutia. *Proceedings of the 9th International Conference on Permafrost*, D. L. Kane and K. M. Hinkel (eds), June 29-July 3, Fairbanks, Alaska, Institute of Northern Engineering, University of Alaska Fairbanks, vol. 1, 433-438.
- Fyodorov-Davydov, D. G., A. L. Kholodov, V. E. Ostroumov, G. N. Kraev, V. A. Sorokovikov, S. P. Davydov and A. A. Merekalova. 2008. Seasonal Thaw of Soils in the North Yakutian Ecosystems. *Proceedings of the 9th International Conference on Permafrost*, D. L. Kane and K. M. Hinkel (eds), June 29-July 3, Fairbanks, Alaska, Institute of Northern Engineering, University of Alaska Fairbanks, vol. 1, 481-486.
- Isaksen, K., R. S. Oedegård, B. Etzelmüller, C. Hilbich, C. Hauck, H. Farbrøt, T. Eiken, H.O. Hygen and T. F. Hipp. 2011. Degrading mountain permafrost in southern Norway: spatial and temporal variability of mean ground temperatures, 1999-2009. *Permafr. Periglac. Process.*, 22(4), 361-377, doi: 10.1002/ppp.728.

Jorgenson, M. T., V. E. Romanovsky, J. Harden, Y. L. Shur, J. O'Donnell, T. Schuur and M. Kanevskiy. 2010. Resilience and vulnerability of permafrost to climate change. *Can. J. Forest Res.*, 40, 1219-1236, doi:10.1139/X10-060.

Kaverin, D., G. Mazhitova, A. Pastukhov and F. Rivkin. 2012. The Transition Layer in Permafrost-Affected Soils, Northeast European Russia. *Proceedings of the 10th International Conference on Permafrost*, K. M. Hinkel (ed.), Salekhard, Yamal-Nenets Autonomous District, Russia. The Northern Publisher Salekhard, vol. 2, 145-148.

Kholodov, A., D. Gilichinsky, V. Ostroumov, V. Sorokovikov, A. Abramov, S. Davydov and V. Romanovsky. 2012. Regional and local variability of modern natural changes in permafrost temperature in the Yakutia coastal lowlands, northeastern Siberia. *Proceedings of the 10th International Conference on Permafrost*, K. M. Hinkel (ed.), Salekhard, Yamal-Nenets Autonomous District, Russia. The Northern Publisher Salekhard, vol. 1, pp. 203-208.

Lewkowicz, A. G., P. P. Bonnaventure, S. L. Smith and Z. Kuntz. 2012. Spatial and thermal characteristics of mountain permafrost, northwest Canada. *Geogr. Annaler, Series A Physical Geography*, 94, 195-215, doi: 10.1111/j.1468-0459.2012.00462.x.

Lewkowicz, A. G., B. Etzelmüller and S. L. Smith. 2011. Characteristics of discontinuous permafrost from ground temperature measurements and electrical resistivity tomography, southern Yukon, Canada. *Permafr. Periglac. Process.*, 22(4), 320-342, doi: 10.1002/ppp.703.

Lewkowicz, A. G. and P. P. Bonnaventure. 2011. Equivalent elevation: A new method to incorporate variable surface lapse rates into mountain permafrost modelling. *Permafr. Periglac. Process.*, 22(4), 153-162, doi: 10.1002/ppp.720.

Oberman, N. G. 2008. Contemporary permafrost degradation of northern European Russia. *Proceedings of the 9th International Conference on Permafrost*, D. L. Kane and K. M. Hinkel (eds.), June 29-July 3, Fairbanks, Alaska, Institute of Northern Engineering, University of Alaska Fairbanks, vol. 2, 1305-1310.

Oberman, N. G. and I. G. Shesler, 2009. Observed and projected changes in permafrost conditions within the European north-east of the Russian Federation. *Problemy Severa I Arctiki Rossiiskoy Federacii* (Problems and Challenges of the North and the Arctic of the Russian Federation), vol. 9, 96-106 (in Russian).

Osterkamp, T. E. 2008. Thermal state of permafrost in Alaska during the fourth quarter of the Twentieth Century (Plenary Paper). *Proceedings of the 9th International Conference on Permafrost*, D. L. Kane and K. M. Hinkel (eds.), June 29-July 3, Fairbanks, Alaska, Institute of Northern Engineering, University of Alaska Fairbanks, vol. 2, 1333-1338.

Popova, V. V. and A. B. Shmakin. 2009. The influence of seasonal climatic parameters on the permafrost thermal regime, West Siberia, Russia. *Permafr. Periglac. Process.*, 20, 41-56, doi:10.1002/ppp.640.

Romanovsky, V. E. and T. E. Osterkamp. 2000. Effects of unfrozen water on heat and mass transport processes in the active layer and permafrost. *Permafr. Periglac. Process.*, 11, 219-239.

Romanovsky, V. E., S. L. Smith and H. H. Christiansen. 2010a. Permafrost thermal state in the polar Northern Hemisphere during the International Polar Year 2007-2009: A synthesis. *Permafr. Periglac. Process.*, 21,106-116, doi: 10.1002/ppp.689.

Romanovsky, V. E., D. S. Drozdov, N. G. Oberman, G. V. Malkova, A. L. Kholodov, S. S. Marchenko, N. G. Moskalenko, D. O. Sergeev, N. G. Ukraintseva, A. A. Abramov, D. A. Gilichinsky and A. A. Vasiliev. 2010b. Thermal state of permafrost in Russia. *Permafr. Periglac. Process.*, 21,136-155, doi: 10.1002/ppp.683.

Romanovsky, V., N. Oberman, D. Drozdov, G. Malkova, A. Kholodov and S. Marchenko. 2011. Permafrost [in "State of the Climate in 2010"]. *Bull. Amer. Meteor. Soc.*, 92(6), S152-S153.

Shiklomanov, N. I., D. A. Streletskiy, F. E. Nelson, R. D. Hollister, V. E. Romanovsky, C. E. Tweedie, J. G. Bockheim and J. Brown. 2010. Decadal variations of active-layer thickness in moisture-controlled landscapes, Barrow, Alaska. *J. Geophys. Res.*, 115, G00I04, doi:10.1029/2009JG001248.

Shiklomanov N. I., D. A. Streletskiy and F. E. Nelson. 2012. Northern Hemisphere component of the global Circumpolar Active Layer Monitoring (CALM) Program. *Proceedings of the 10th International Conference on Permafrost*, K. M. Hinkel (ed.), Salekhard, Yamal-Nenets Autonomous District, Russia. The Northern Publisher Salekhard, vol. 1, 377-382.

Smith, S. L., S. A. Wolfe, D. W. Riseborough and F. M. Nixon. 2009. Active-layer characteristics and summer climatic indices, Mackenzie Valley, Northwest Territories, Canada. *Permafr. Periglac. Process.*, 20, 201-220, doi:10.1002/ppp.651.

Smith, S. L., V. E. Romanovsky, A. G. Lewkowicz, C. R. Burn, M. Allard, G. D. Clow, K. Yoshikawa and J. Throop. 2010. Thermal state of permafrost in North America - A contribution to the International Polar Year. *Permafr. Periglac. Process.*, 21,117-135.

Smith, S.L., J. Throop and A. G. Lewkowicz. 2012. Recent changes in climate and permafrost temperatures at forested and polar desert sites in northern Canada. *Can. J. Earth Sci.*, 49, 914-924, doi:10.1139/e2012-019.

Streletskiy D. A., N. I. Shiklomanov, F. E. Nelson and A. E. Klene. 2008. 13 years of observations at Alaskan CALM sites: Long-term active layer and ground surface temperature trends. *Proceedings of the 9th International Conference on Permafrost*, D. L. Kane and K. M. Hinkel (eds.), June 29-July 3, Fairbanks, Alaska, Institute of Northern Engineering, University of Alaska Fairbanks, vol. 2, 1727-1732.

Zamolodchikov, D. 2008. Recent climate and active layer changes in northeast Russia: Regional output of Circumpolar Active Layer Monitoring (CALM). *Proceedings of the 9th International Conference on Permafrost*, D. L. Kane and K. M. Hinkel (eds.), June 29-July 3, Fairbanks, Alaska, Institute of Northern Engineering, University of Alaska Fairbanks, vol. 2, 2021-2027.