ARCTIC
VOL. 73, NO. 4 (DECEMBER 2020) P. 509–528
https://doi.org/10.14430/arctic71674

Climate-Change Induced Permafrost Degradation in Yakutia, East Siberia

Jolanta Czerniawska[1] and Jiri Chlachula[1,2,3]

(*Received 27 May 2019; accepted in revised form 14 July 2020*)

ABSTRACT. Current climate change in the northern regions is a well-recognized phenomenon. In central Yakutia (the Sakha Republic), the long-term trend displays a consistent mean annual air temperature (MAAT) increase from −9.6˚C (1980) to −6.7˚C (2019), corresponding to an average 0.07˚C annual rise, with pronounced temperature anomalies in the last decade. The analyzed meteorological records of the past 40 years indicate a progressing climate change pattern of increased MAAT and mean annual precipitation (MAP) that occurs in 5–7 yr cycles. The complex interactions of regional climatic variations with local geological and environmental conditions influence the frozen ground's thermal balance, which, in turn, impacts thermokarst development. Co-acting factors of temperature rise and higher precipitation rates activate thermokarst lake dynamics and lake expansion following snow- and rainfall-rich preceding years. April experiences the greatest warming trend with a present (2020) 5˚C rise from 1980 with shortening of the winter season. Climate warming together with natural forest fires and anthropogenic activities (pastoral practices and logging) contribute to the taiga landscape opening due to reduced albedo and the greater exposure to solar radiation. The regional hydrologic network undergoes restructuring caused by drained meltwater released from the degraded cryolithozone with peaks of the fluvial discharge in late spring and early summer generating bank erosion. The negative effects of the progressing ground thaw, which are particularly observed in lowland locations, pose risks to local settlements and generate major environmental and engineering problems in the formerly permafrost-stable central and northern areas of Siberia.

Key words: Yakutia; meteorology records; warming; permafrost; thermokarst lakes; alases; hydrology; geo-environmental risks; regional development

RÉSUMÉ. Le changement climatique actuel dans les régions du nord est un phénomène bien connu. Dans le centre de la Yakoutie (République de Sakha), la tendance à long terme affiche une augmentation annuelle moyenne constante de la température de l'air (MAAT) de −9,6 ˚C (1980) à −6,7 ˚C (2019), correspondant à une augmentation annuelle moyenne de 0,07 ˚C, avec des anomalies de température prononcées au cours de la dernière décennie. Les relevés météorologiques analysés au cours des 40 dernières années indiquent un schéma de changement climatique progressif d'augmentation du MAAT et de la précipitation moyenne annuelle (MAP) qui se produisent sur des cycles de cinq à sept ans. Les interactions complexes des variations climatiques régionales avec les conditions géologiques et environnementales locales influencent l'équilibre thermique du sol gelé qui, à son tour, influe sur le développement des thermokarsts. Des facteurs co-agissants d'augmentation de la température et de taux de précipitation plus élevés activent la dynamique des lacs thermokarstiques et l'expansion des lacs après les années précédentes riches en neige et en précipitations. Le mois d'avril connaît la plus grande tendance au réchauffement, avec la hausse actuelle (2020) de 5 ˚C par rapport à 1980 et le raccourcissement de la saison d'hiver. Le réchauffement climatique, les incendies de forêt naturels et les activités anthropiques (pratiques pastorales et exploitation forestière) contribuent à l'ouverture du paysage de la taïga en raison d'un albédo réduit et d'une plus grande exposition au rayonnement solaire. Le réseau hydrologique régional subit une restructuration causée par les eaux de fonte drainées libérées de la cryolithozone dégradée avec des pics de débit fluvial à la fin du printemps et au début de l'été, produisant ainsi une érosion des berges. Les effets négatifs du dégel progressif observé en particulier dans les plaines présentent des risques pour les établissements locaux et génèrent des problèmes environnementaux et d'ingénierie majeurs dans les régions du centre et du nord de la Sibérie, autrefois stables au pergélisol.

Mots clés : Yakoutie; relevés météorologiques; réchauffement; pergélisol; lacs thermokarstiques; alas; hydrologie; risques géoenvironnementaux; développement régional

Révisé pour la revue *Arctic* par Nicole Giguère.

[1] Institute of Geoecology and Geoinformation, Adam Mickiewicz University, B. Krygowskiego 10, 61-680, Poznan, Poland
[2] Environmental Research Centre, Nerudova, 2181, 686 03 Stare Mesto, Czech Republic
[3] Corresponding author: paleo@amu.edu.pl

INTRODUCTION

Continuous and discontinuous permafrost occupies about 24% of the terrestrial surface of the Northern Hemisphere (Zhang et al., 2008), about 70% of which is distributed between 45 ˚N and 67 ˚N and with about two-thirds of this territory located in Siberia, Russia (Duchkov, 2006; Fedorov et al., 2018). Changes in the distribution of frozen ground and the conditions of the subsurface cryolithic zone have a direct bearing on natural ecosystems, forest cover, and hydrology, as well as human occupation habitats (e.g., Abaimov et al., 2002; Henry and Molau, 2003; Kirdianov et al., 2003; Harada et al., 2006; Costard et al., 2007; Tchebakova et al., 2009; Bonnaventure et al., 2012; Brown and Lemay, 2012). Climatic warming, which is most pronounced in high latitude and alpine regions, causes development of a thermal permafrost-free base, a thickening of the seasonally active layer, and an overall size reduction of the permafrost-underlain surface cover (Pavlov and Moskalenko, 2002; ACIA, 2004; Wickland et al., 2006; Callaghan et al., 2010; Romanovsky et al., 2010; Konishchev, 2011; Turner and Marshall, 2011; Ohta et al., 2019; van Huissteden, 2020).

Present permafrost degradation generates major landscape and relief distortions (Jorgenson et al., 2006; Lyle and Hutchinson, 2006; Kirpotin et al., 2009; Connon et al., 2014). This process, acting on regional scales, has direct implications for local settlements and economic development, oil and gas exploitation, mining and the mineral resource processing industry, building construction, and infrastructure (Lloyd, 1963; Johnston, 1965; Couture et al., 2003; U.S. Arctic Research Commission Permafrost Task Force, 2003; Instanes et al., 2005; Tart, 2006; Fortier et al., 2011; Grandmont et al., 2012; Glotov et al., 2018). Studies of climate-triggered frozen ground destabilization and the associated geo-hazard assessment, monitoring, and prediction are gaining importance (Alasset et al., 2010; Kunitsky et al., 2013; Hong et al., 2014; Jorgenson and Grosse, 2016).

In Yakutia, which is the principal continuous-permafrost area of Siberia, the mean annual air temperature (MAAT) increase of 2˚C – 3˚C over the past years (mainly the dramatically higher temperatures in late spring and early summer) induces progressive ground ice melting and relief subsidence due to underground mass compaction and ice volume loss (Rowley et al., 2015). These processes of the subsurface ice melt trigger the formation of shallow boggy depressions—alases (from the Yakutian Алаас) occupied by numerous thermokarst lakes (Pollard, 2018). Around 16 000 active thermokarst depressions are found in the Central Yakutia Lowland alone, corresponding to ~17% of its total geographic size. From the 1970s, a progressing spatial extension and an increase in lake density have been observed (Bosikov, 1991). This trend has accelerated during the last decades in connection with global warming. The current climate change in the sub-Arctic regions poses severe problems for occupied habitats, with significant impacts to settlement sustainability and adaptation to new environmental conditions (Nihoul and Kostianoy, 2009; Iijima and Federov, 2019).

This paper discusses the past 40 yr climate change record and the geo-environmental risks generated by the progressing permafrost degradation affecting rural areas in east-central Yakutia due to the rising territorial MAAT. Using our geomorphological and hydrological field investigations in 2009 and 2013 – 18, along with analysis of meteorological records from 1980 to 2019, we focus on a regional multi-proxy assessment of the current cryolithic retreat status within the study area and the evaluation of settlement risks because of the increased ground instability and the top surface water saturation. Using regional and site-specific data, we provide a present-day insight into the natural impacts and the ongoing environmental transformations of the territory of East Siberia affected by the current climate change.

STUDY AREA

Field investigations of permafrost degradation feedback were conducted in the lowland east-central part of Yakutia (Sakha Republic) between the Lena, Aldan, and Amga Rivers ~50 – 200 km east of Yakutsk (Fig. 1). The territory is characterized by ice-rich permafrost and climate conditions with extreme seasonal temperature deviations (up to 80˚C), deep-ground winter freezing, and intensive summer thaw (Solov'ev, 1973). The documented rising summer temperature of the Yakutsk region over the past decades, up to +40˚C, causes major surface thaw and formation of a morphologically dynamic thermokarst terrain (Fedorov and Konstantinov, 2003; Fedorov et al., 2014). The restructured landscape is portrayed by sinking top-surface depressions (alases) formed by the subsidence of the thawed permafrost ground, with large-scale formation of thermokarst lakes. The expanding alas country occupies over 50% of central Yakutia (Ivanov, 1984) and close to 75% of the sub-Arctic and Arctic coastal plains in the northern regions of East Siberia (Bosikov, 1978).

The broader area of the Lena-Amga Plain (200 – 250 m asl altitude) lies in the zone of continuous permafrost controlled by the strongly continental climate regime. The 2019 annual air temperature (Yakutsk/Amga) was −6.7˚C/−8.3˚C, average January temperature was 35.7˚C /−37.6˚C, and July temperature was +19.3/+17.7˚C; in Yakutsk in 2019, the maximum t˚C deviations ranged from −43.4˚C to +33.8˚C. The average long-term annual precipitation is 354 mm/year with ~30% – 40% as snowfall in winter and 60% – 70% as rainfall between May and September. The territorial hydrologic cycle is characterized by periodic late spring flooding (May – June), a mid-summer and early fall high flow, and a zero flow for the fall-spring season (October to May) when rivers freeze completely. The Lena basin with the Aldan River (the principal eastern tributary) represents the main fluvial catchment

FIG. 1. Location of the study region, south-central Yakutia, East Siberia.

area. Total water discharge is greater than 100 km^3/year (Shiklomanov and Rodda, 2003). The seasonally active cryolithic layer varies in thickness from tens of centimetres on north-facing slopes to over a metre on south-facing relief exposures. This layer is underlain by solid permafrost from 200 – 300 m in depth, mostly preserved from the Last Ice Age and geologically bound to the organic-rich silty Yedoma Formation (Grosse et al., 2013).

The adjoining Lena River valley is aligned by four Pleistocene terraces formed by silty or sandy alluvia blanketed by loess-like sediments: Bestyakh (55 – 75 m), Tyungyulyu (65 – 100 m), Abalakh (115 – 135 m), and Magan (155 – 175 m) (Gupta, 2008). The main study area is positioned on the second-highest (3rd) Tyungyulyu terrace above the flat Lena River plain; the terrace is filled by fluvial accumulations, and its surface is covered by aeolian (sandy, loessic), lacustrine, and palustrine deposits (Ivanov, 1984; Spektor et al., 2011) (Fig. 2). Northern taiga forest dominated by larch (*Larix sibirica*) is the principal arboreal cover.

METHODS AND APPROACHES

The fieldwork for our study was conducted during the summers of 2009 and 2013 – 14, with subsequent site monitoring from 2015 to 2018. The multidisciplinary geo-environmental research included mapping of permafrost

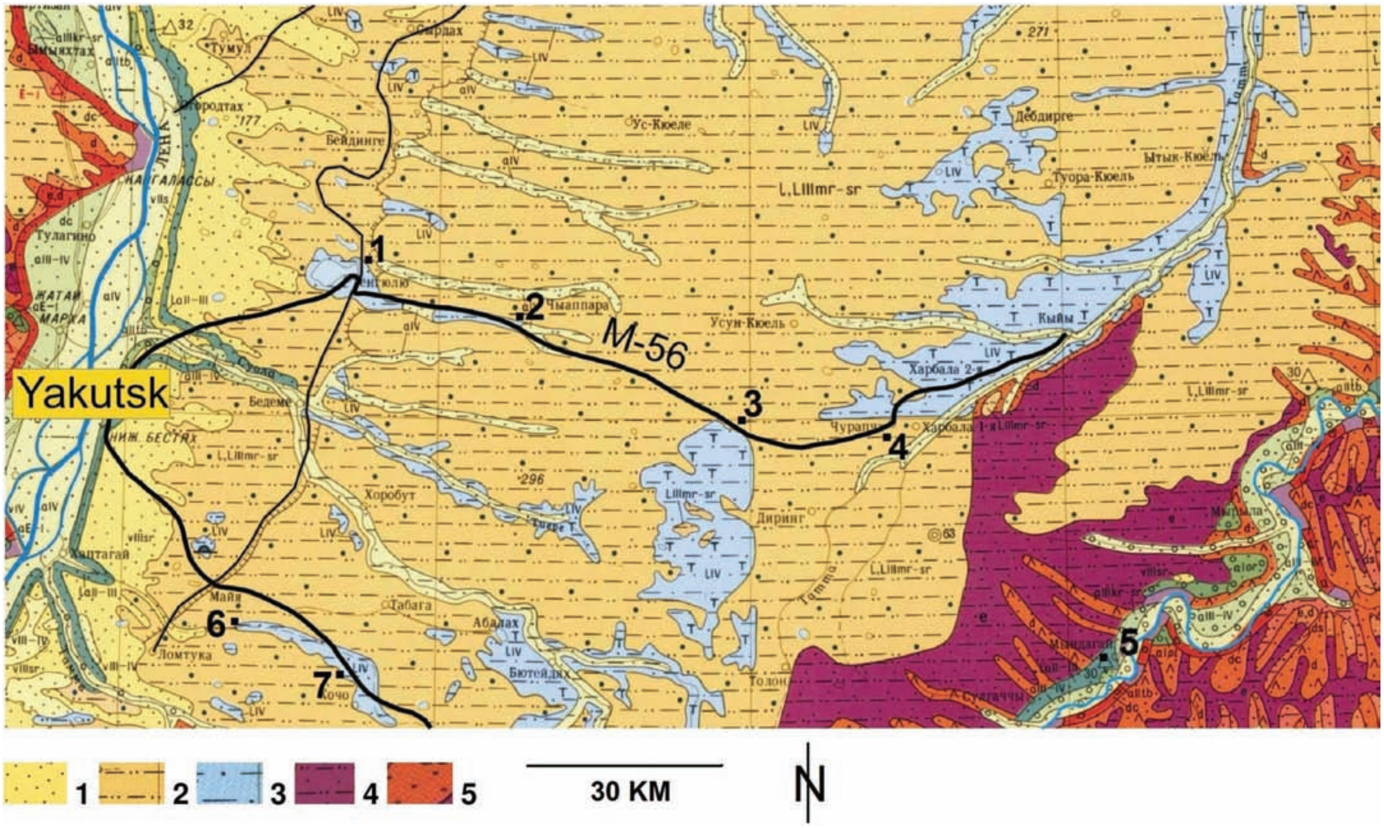

FIG. 2. Surficial geology of the study area and location of the investigated settlement sites (villages) along the main M56 regional road: 1 Tyungyulyu, 2 Noragana, 3 road site, 4 Churapcha, 5 Myndagay, 6 Mayya, 7 Moro. Legend of the relief-cover geological deposits: (1) aeolian, (2) lacustrine and aeolian, (3) lacustrine and palustrine, (4) colluvial, (5) alluvial (Geological map of Russia 1:1 000 000, Kolpakov, 1998; modified by the authors).

thaw intensity, the resulting permafrost degradation relief forms, and the environmental effects of regional cryolithic melting, supplemented by interviews with local residents on the former landscape status. The field mapping made use of the only road (M56) available; this road is aligned with the W – E geographic line transecting the Megino-Kalgalas, Churapcha, and Amga administrative districts (Fig. 2).

The relief documentation and geomorphic monitoring of the active thermokarst processes were carried out at the sites with the most visible evidence of present permafrost degradation and the resulting top-surface instability. We developed a digital elevation model (DEM) for the key loci from digitalized maps at the scale of 1:200 000 by using the Quantum GIS (QGIS 2.8) software (Netzel et al., 2016). The DEM (90 m resolution) was transformed into a digitalized 3D slope map and an aspect map. The slope map describes the slope for each raster cell in degrees based on the elevation at each point. The aspect map displays the aspect of each raster cell grouped into compass directions (N, NE, E, SE, S, SW, W, NW).

To evaluate the surficial geomorphic and thermokarst lake hydrology in the investigated area, we used multispectral satellite images with under 10% cloud cover (Landsat-8 OLI, Landsat-5 TM; 30 m resolution) of the U.S. Geological Survey database (https://earthexplorer.usgs.gov). The normalized difference water index (NDWI), as defined by McFeeters (1996), was applied for the automatic extraction of open-water bodies using the NDWI green and near-infrared (NIR) bands of the remote sensing images. The NDWI was expressed by the equation NDWI = (GREEN − NIR)/(GREEN + NIR), where GREEN is bands 3 (Landsat 8) and 2 (Landsat 5) that encompass the reflected green light. NIR reflects the near-infrared radiation (band 5, Landsat 8, and band 4, Landsat 5). The morphometric features of the thermokarst lakes were defined from the Landsat images (surface area), the Lake Tyungyulyu hydrology data (Cadastral Report, 2019) (max. depth), and mathematical formulas (lake radius, volume). The fluctuating water volume of the lakes for the particular years was estimated by calculating the known depths with the same equation taking into account almost conical shapes of the thermokarst ponds (Cole and Weihe, 2016).

Raw meteorological data of the Yakutsk Meteorology Station from the Russian Meteorology Stations database (Bulygina et al., 2019) (monthly mean air temperature [MMAT] and mean annual air temperature [MAAT] together with the published data (Bulygina and Razuvaev, 2012) were used as the regional climate-change background for the 1980 – 2019 period.

The analyzed current and archival meteorology records with the generated climate trends were used as a proxy assessment of the climate trend and for modeling the future climate development for central Yakutia completed by former statistical meteorology and the regional permafrost stability studies (Malkova et al., 2011). The field-observed climate-change impact on the local natural and occupation environments was evaluated. The analyzed sediment and water chemistry samples from the mapped site sections and the investigated alas lake settings added to the overall picture of the current geo-environmental transformations, with the most acute geo-hazard effects seen in rural Native residential sites.

RESULTS: REGIONAL CLIMATE CHANGE FEEDBACK

Meteorology Records

The processed meteorology raw data from the Yakutsk State Meteorology station displays a uniform trend of steadily rising temperature, both seasonally and annually in the study area over the 1980–2019 period. This trend is in agreement with the meteorology data and observations from other parts of Yakutia (J. Chlachula et al., unpubl. data).

The long-term monthly temperature average shows marked seasonal temperature deviations (Fig. 3A), with an average January temperature of −38.0˚C and an average July temperature of +19.7˚C; together, these averages account for about a 58˚C maximum deviation temperature range (amplitude). Average ground-frost temperatures (i.e., < 0˚C) characterize early October through to early May. The long-term MAAT trend for the last 40 years displays a steady temperature rise from −9.6˚C in 1980 to −6.7˚C in 2019, corresponding to an average annual temperature increase of 0.073˚C annually, that is, close to 3˚C over the four decades. The results suggest a higher mean annual temperature rise in continental northeast Siberia when compared to former studies (Duchkov, 2006), presuming an air temperature increase of 0.02˚C –0.05˚C per year, which corresponds to a ~1.2˚C–2˚C projected increase by 2050 based on a 2019 air temperature datum. Keeping with only a linear trajectory and the present t˚C rate, in 30 years (2050) the MAAT would reach approximately –5.5˚C, which is about half of the original (1970s) value. The historical MAAT record shows more pronounced variations (up to 3.9˚C) between particular years in the 1980s, whereas the trend during the last decade demonstrates more stable values with much smaller MAAT differences of ~0.8˚C maximum. A more progressive increasing mean annual air temperature is evident during the preceding 30 years (Fig. 4A) with a shortening of the winter season.

The atmospheric evidence points to greater MAAT anomalies since the end of the 20th century (Fig. 4B). The anomaly values with respect to the average MAAT of −8.4˚C for the investigated period (1980–2019) show that the last 15 years (2006–19) were the warmest, whereas the first two decades (1980s–90s) were the coldest. An apparent 5–7-year cyclicity and a more balanced climate-change pattern characterize the transitional years

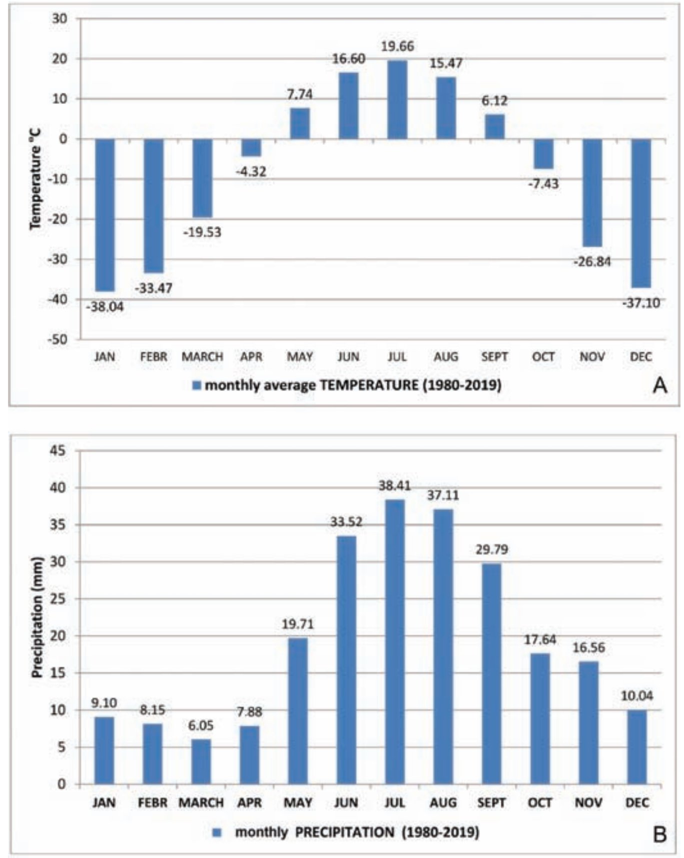

FIG. 3. Monthly average temperature and precipitation records for central Yakutia for the 1980–2019 period. A: Monthly average temperature; B: Monthly average precipitation (analysis of raw meteorological data from the Yakutsk Meteorological Station).

(1988–2006). The calculated average annual climate warming values (reconstructed air temperature trends) in central East Siberia are very close (just slightly below) to those observed in the southern part of the territory (the discontinuous permafrost zone), reaching air temperature differences of up to 0.08˚C annually (Malkova et al., 2011).

The regional field studies further demonstrate a dependence of the lake surface size variations on total atmospheric precipitation volumes and annual air temperatures (Fig. 3B). This tendency is also reflected in the observable changes of the top-surface stability and the local hydrology regime (Chlachula and Czerniawska, 2016). The increased regional precipitation values for the last 20 years may contribute to the raised ground temperatures (Iijima et al., 2010). The long-term precipitation rate is, however, more or less constant, with just a slight MAP rise from ~230 mm to 240 mm over the 1980–2019 period (Fig. 5A). Nevertheless, the previously markedly arid years with 148–170 mm annual precipitation, culminating in the 6-year cycles in 1980, 1986, 1992–95, and 2001, are less pronounced. The direct relationship for the alas thermokarst lake-size fluctuations in central Yakutia was previously suggested as a factor of varying precipitation particularly for every two consecutive years of negative or positive atmospheric water volumes (Tarasenko, 2013).

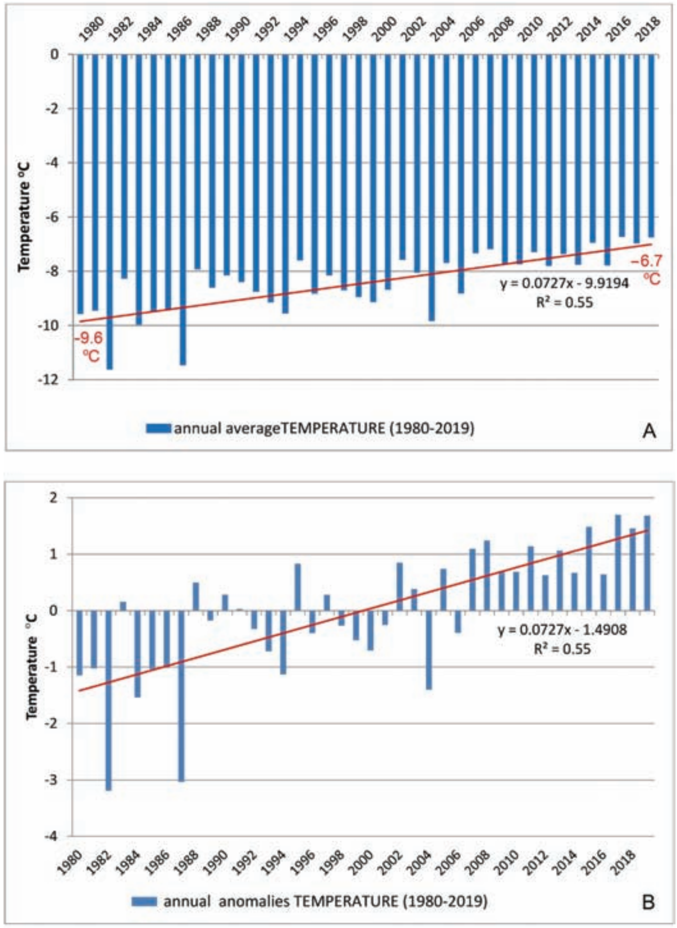

FIG. 4. A: Annual average temperature record for central Yakutia for the 1980–2019 period showing the progressively rising regional temperature trend accelerating during the last years; B: Trend-line and regression equation of the MAAT anomalies for 1980–2019 (analysis of raw meteorological data from the Yakutsk Meteorological Station).

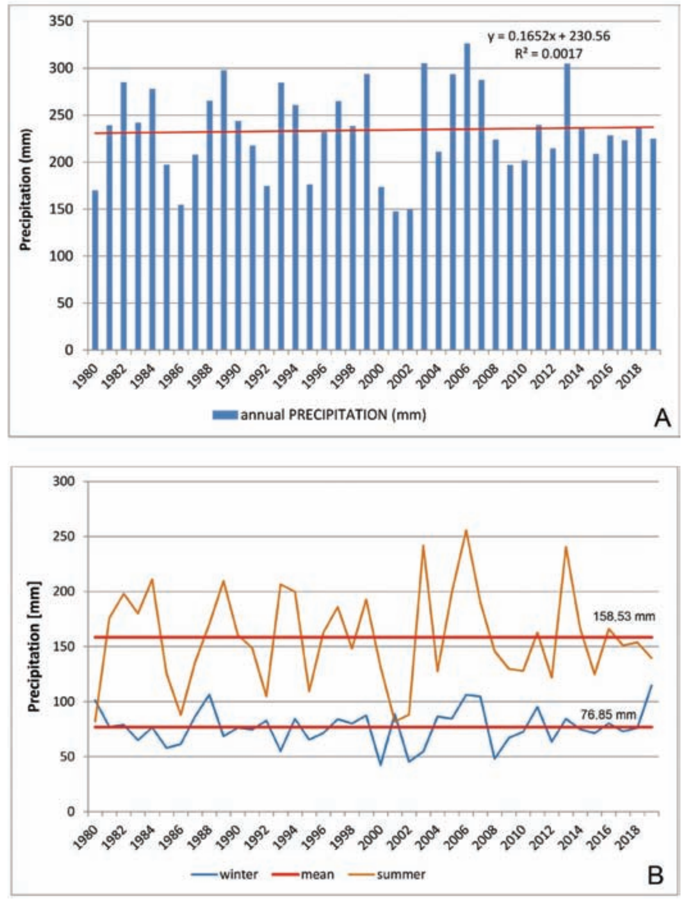

FIG. 5. A: Annual precipitation record for 1980–2019 from the study area showing just a minor long-term precipitation value increase over the four past decades; B: Summer (April–September) and winter (October–March) precipitation records for the 1980–2019 period (analysis of raw meteorological data from the Yakutsk Meteorological Station).

This view corresponds with our findings from the years of the monitoring in the area, with a clear link between lake expansion and total annual precipitation volume (see below). Shifts towards the lake surface reduction further reflect seasonal evaporation of the shallow ponds in correspondence with the rising MAAT trend.

Dry summers are assumed to account for the declines of the exposed open-water bodies, along with the overall increasing MAAT trends. Over the course of monitoring the study sites, the major expansion of the thermokarst lakes in the central Yakutia in 2008 (Fig. 6) is interpreted to be due to the precipitation-rich years of 2006 and 2007, when heavy summer rainfalls (up to 250 mm) and a thick snow cover (corresponding to ~100–110 mm of winter precipitation volume) had occurred (Fig. 5B). These "wet years" followed the anomalous dry year of 2005, which experienced a pronounced restricted summer precipitation budget (130 mm). In spite of the slightly rising trend of the annual precipitation regime, the role of the regional rainfall and snowfall with the largely balanced mean annual rates over the past few years is considered to have a minor influence relative to the climate warming over northeast Siberia. Climate warming is believed to be the principal controlling mechanism forcing regional permafrost degradation and associated enhanced thermokarst process dynamics.

Thermokarst Landscape

The mapped topographic settings exhibit vigorous cryolithic ablation and ground collapse. Among other places, the effects of the ongoing permafrost thaw are best observed near the Tyungyulyu township area (50 km east of Yakutsk) (Figs. 1, 7), which is situated on the southern side of a large alas system hosting several thermokarst lakes. Analyses of the regional satellite images over the last two decades show major landscape transformations related to the large-scale cryolithic melting. The LANDSAT (5 and 8 series) data interpretations are confirmed by the on-site geomorphic mapping and analysis with the generated DEM (Fig. 2, site 1).

The ground collapse features occur most intensively at the low relief sites below ~180–190 m elevation (Fig. 8A). The regional digitalized relief models display the most active geomorphic processes and the present thermokarst lake expansion predominantly in the low places with

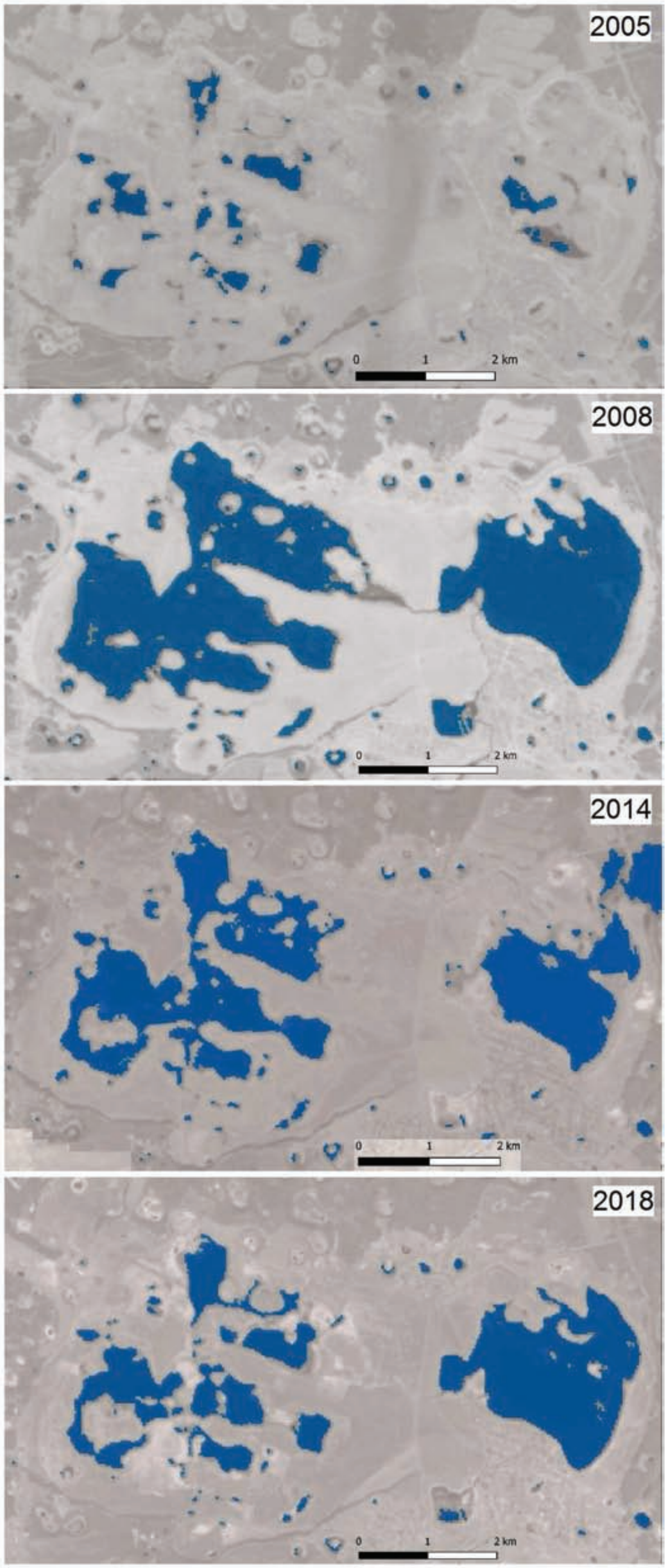

FIG. 6. Thermokarst lakes dynamics in response to yearly climate variations (seasonal temperature, MAAT, and precipitation changes) in the Tyungyulyu study area for 2005, 2008, 2014, and 2018 expressed by the satellite image analysis (NDWI). The open thermokarst lakes' water-body reduction within the monitored alas system following 2008 is primarily due to fluctuating seasonal precipitation (annual rainfall and snowfall decrease) and summer evapotranspiration in congruence with the regional meteorological records.

topographic exposures oriented SW – S susceptible to mass wasting (Fig. 8B), and the locations of the most dynamic cryolithic thaw in the NW – SE longitudinal depressions (Fig. 8C). Pervasive permafrost degradation and the intense spring and summer active layer, impacted greatly by the strong fragmentation and orientation of the regional relief, directly affect the rural occupation habitat. The local brick or log-built houses constructed since the 1960s on top of the south- and southwest-exposed slopes are at major risk of collapse due to progressive early summer ground melting and surface saturation (Fig. 9C). Above the present lake, there are several alas terraces that exhibit lateral retreat due to permafrost degradation and the associated geo-environmental changes (Fig. 10B).

This local topography demonstrates an increased solar energy supply inducing the progressive thaw of frozen ground and the development of an active thermokarst landscape with seasonally saturated boggy alas depressions and palsa fields (Fig. 10A). These processes are exacerbated by abundant surface and subsurface water flowing into expanding partly interconnected shallow lakes drained through spillways (Figs. 7A, B). Seasonal variations in precipitation and evapotranspiration together with partial drainages between the lakes explain the fluctuating (temporarily decreasing) lake size in addition to the MAAT changes. Lake drainage (both natural and anthropogenic) and ground sinking trigger further ablation of the exposed permafrost flanks. The effects of the unconsolidated collapse along the lake margins and the elevated alas terraces are also seen nearby at the other settlements, particularly in the lowland locations and along the river channels (Figs. 10C – E). The geotechnical properties of the disintegrating surface cover are closely related to the regional bedrock structure and lithology formed by fine-grain sandy and silty sediments (Figs. 2, 9). The maximum active layer thaw in July – early August varies from 0.6 to 1.3 m deep, but occasionally reaches up to 2 m on the open forest-free thermokarst terrace exposures (Fig. 10C).

The major documented ground disturbances also occur at other monitored sites along the M56 regional road (Fig. 2), with the most intensive permafrost degradation processes taking place on south-facing slopes with pervasive erosion. The ground subsidence threatens residential buildings and the local infrastructure, including power lines (Fig. 11D). The mapping of similar geo-hazards associated with ground-ice decay throughout the Lena and Amga lowlands of central Yakutia provides evidence of the territorial climate amelioration-triggered geomorphological impact and large-scale erosion (Fig. 10D). Saturation of the upper-most surfaces generates the formation of marshes with forest retreat and vegetation shifts along the margins (Fig. 11A). Seasonal thermokarst lake expansion and water evaporation promote the precipitation of colloidal minerals and fine clay particles along the shorelines mobilized from the defreezing loose bedrock deposits (Fig. 11B, C). Epigenetic precipitation of the dissolved salts in alases occurs during the spring active layer thaw with subsequent

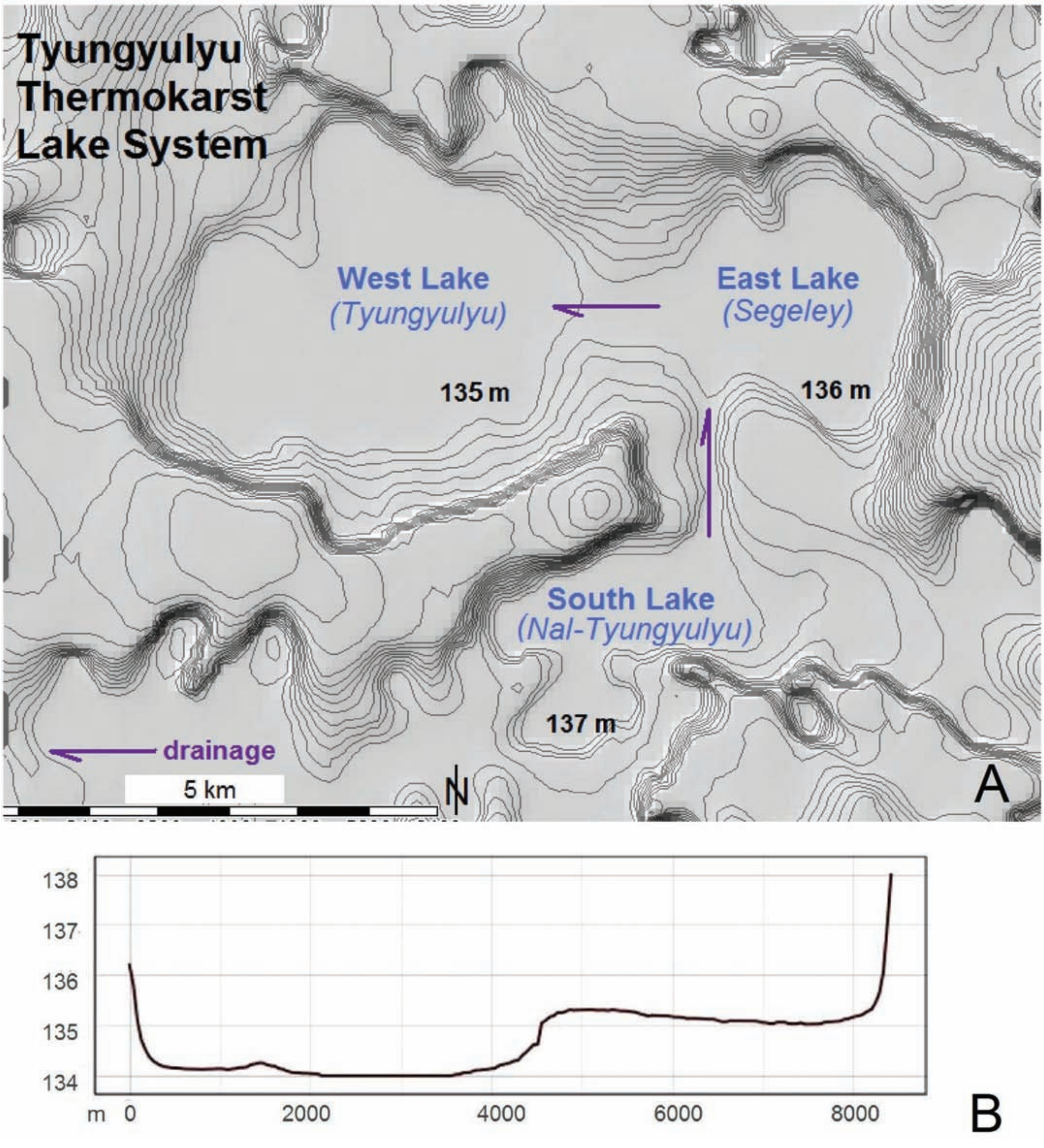

FIG. 7. A: Relief map of a segment of the investigated Tyungyulyu alas system hosting the thermokarst lakes Nal-Tyungyulyu, Segeley, and Tyungyulyu, with the present gradually receding shoreline elevation at ~137 m, 136 m, and 135 m, respectively; B: Lateral profile of the water-filled alas depression. The local thermokarst processes reflect progressing permafrost thaw and thermokarst expansion following ground ice depletion with the earliest drying up (South) lake interconnected by a narrow spillway in the form of a small perennial stream to the adjoining (East) lake, which drains into the largest and deepest (West) lake as observed for the monitored year 2008 (Fig. 6). The seasonal disruption (closure) of the drainage outlets between the single lakes explains their differential dynamics in consecutive years, characterized by an autonomous hydrology behavior of the thermokarst water basins. The relief prediction model suggests that the East Lake (Segeley) will eventually dry up following the South Lake (Nal-Tyugyulyu), whereas the most active West Lake (Tyugyulyu) will progressively expand at the current warming trend in connection with increased summer heat absorption of the larger open-water body generating further permafrost retreat along the lake banks.

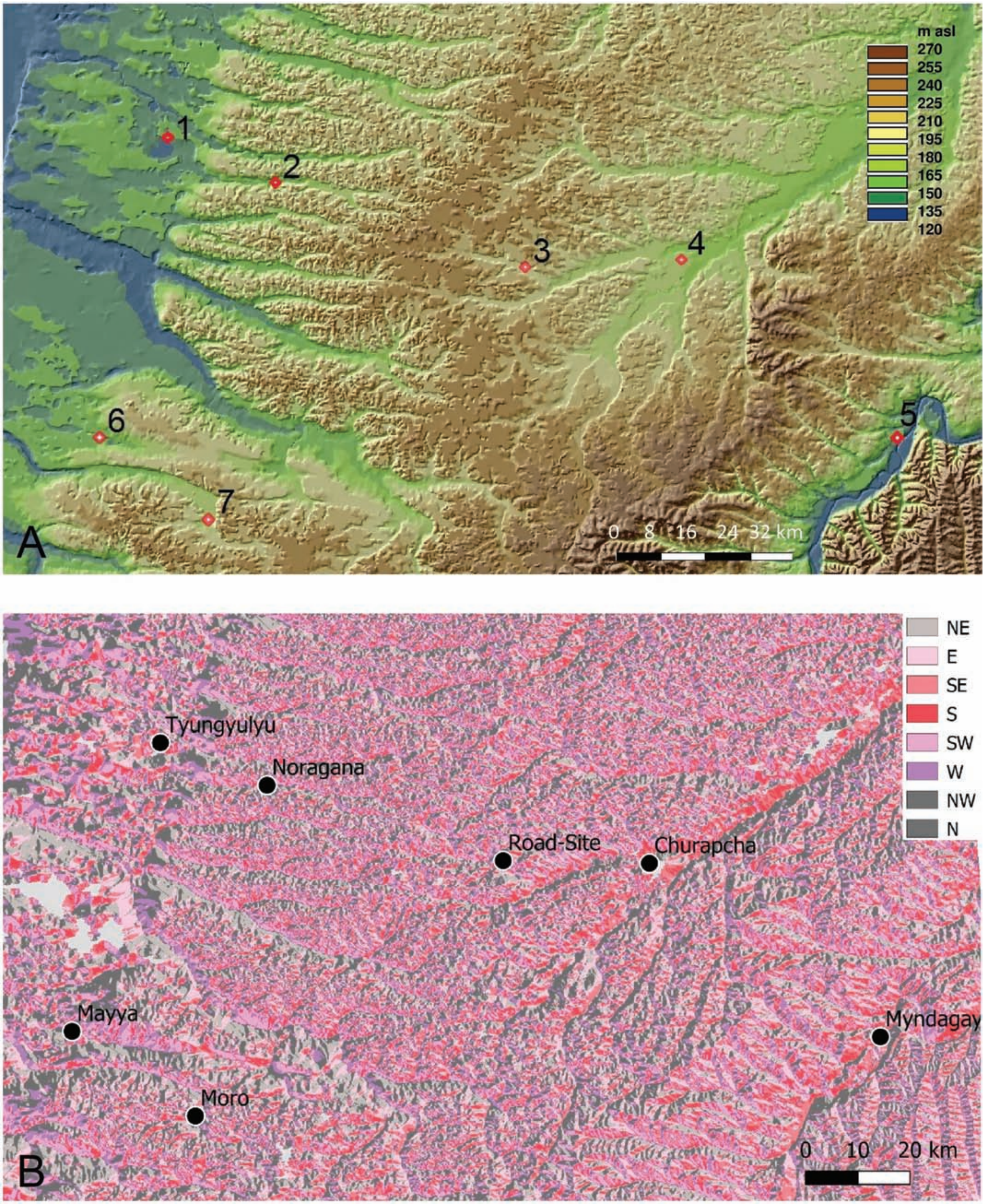

FIG. 8. A: The Digital Elevation Model (DEM) for the study area with the investigated sites pointing to most dynamic thermokarst processes occurring below the 180–190 m elevation; B: the digital model of slope orientation of the regional thermokarst landscape with the most active permafrost thaw on the south- and southwest-oriented slopes with the highest capacity of late spring and summer solar radiation; C: (*see next page*) the digital model of the regional relief configuration (sloping nature in degrees) with the investigated sites located in the E–W-oriented drainage valleys, which transect the surficial cryolithic bedrock formed of the unconsolidated fine clastic deposits.

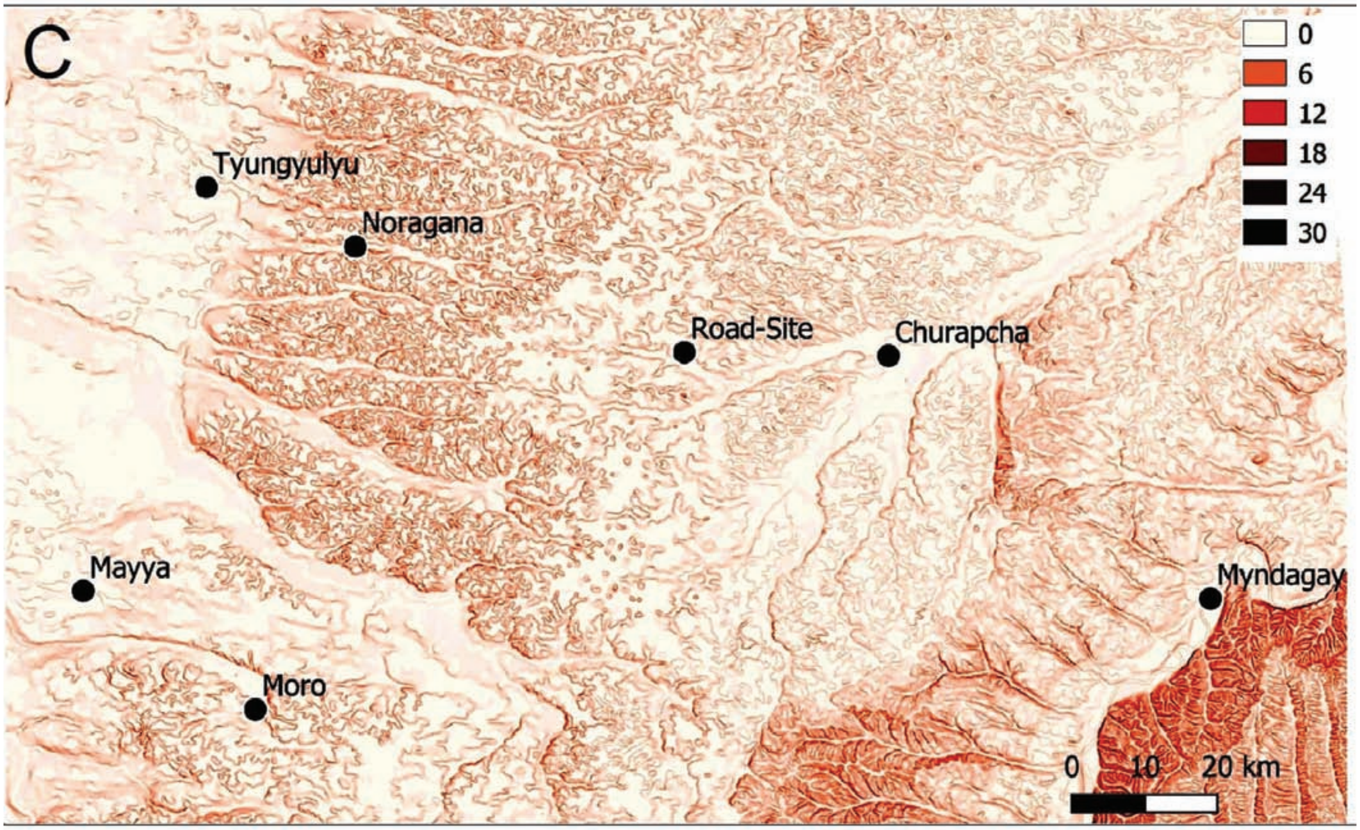

FIG. 8.C: The digital model of the regional relief configuration (sloping nature in degrees) with the investigated sites located in the E–W-oriented drainage valleys, which transect the surficial cryolithic bedrock formed of the unconsolidated fine clastic deposits.

high-summer evaporation (Larry Lopez et al., 2007). The current permafrost degradation enhances the risks of topsoil salinization in the lowlands of eastern Siberia.

In sum, several synergic factors—temperature, precipitation, topography, ground lithology, insolation rate of the surrounding (drained) geo-relief, as well as human landscape modification such as construction activities and logging exposing the cryolithic base—account for the differences in permafrost degradation between particular sites. All the involved and mutually co-acting environmental variables demonstrate the complexity of the present thermokarst processes.

Permafrost Hydrology

The effects of steadily progressing climate warming in central Yakutia are particularly evident by the increased density of the thermokarst lacustrine ponds of ground ice melt and changes in the local surficial hydrology system. Seasonally mobilized lake dynamics with expanding open-water bodies correlate with warmer years that also exhibited increased rates of total annual precipitation. In the Tyungyulyu area, this is correlation is seen in the major retreat of open-water bodies in 2005 and their reduction to a few small ponds (Fig. 6) after the dry and very cold preceding year of 2004, which was the coldest year since 1988 with a MAAT close to −10˚C. Conversely, the marked annual temperature rise to −7.2˚C due to the unusually warm summer in 2008 (Fig. 4A) generated progressive thermokarst processes. The warmer water surface in contact with the frozen ground along the shorelines generated further lake enlargement and permafrost regression. Similar retreating or expanding permafrost thaw dynamics are obvious for the consecutive years from 2014 to 2018 (Fig. 6). The calculated mean rate of change in thermokarst lake radius for the investigated period (1980–2019) varies significantly with up to an 80% reduction in shoreline extent and up to 95% water volume loss in the dry years compared to the high-water-level stands (Table 1). The short-term lake size changes responding to climate variations are most evident during the monitored years 2005 and 2008, with expansion of the total open-water surface from 1.37 km^2 to 12.07 km^2, respectively. The temporal coalescence of smaller thermokarst ponds through recurrent spillways suggests an ice-rich, impermeable permafrost base allowing for a larger water body, which enhances the local thermal site disturbance. Finally, the observed gradual drying up of some thermokarst lakes indicates a depletion of the basal permafrost, which allowed for drainage of the lake water to the nearby active lake (Fig. 7).

The lake bottoms are solidly frozen in summer and overlain by shallow muddy (silty clay) organic-rich sediments with local textural variations depending on the structural surficial geology. The solid permafrost layer

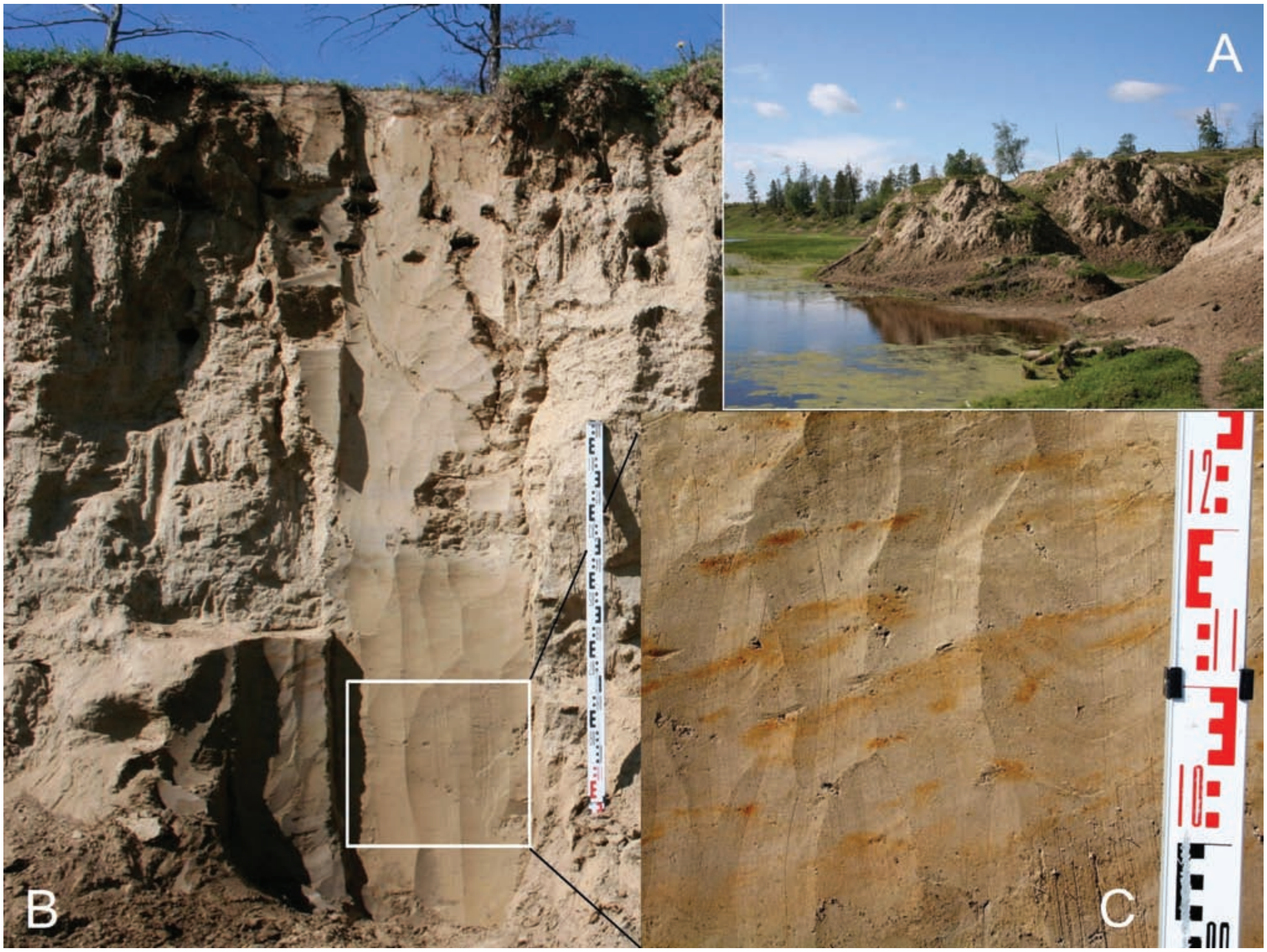

FIG. 9. The geological profile at the active margin of the Chuya alas (A). The bottom part of the section (B) shows groundwater percolation of the fine sedimentary matrix due to seasonal permafrost thaw evidenced by brownish layering from iron hydroxide precipitation (C). The on-site ground sinking due to the melted underground ice reaches up to several tens of centimeters per year (August 2013).

predetermines the impermeability of the lake bottoms. Permafrost degradation allows the lakes to drain into the groundwater systems as documented in some parts of the Canadian Arctic (E. Little, pers. comm. 2020). Subsurface drainage due to a cryolithic bedrock failure in historical times is presumed from the disappearance of a large lake in the Tyungyulyu vicinity that existed in the late 19th century but was transformed into several small separate and partly dried-up ponds (local residents' pers. comm. 2014). The lake basin distribution pattern in response to climate variations is not spatially uniform, with the most recent shallow boggy thermokarst depressions being the most dynamic. Permafrost degradation conveys the melted water into the regional hydrology network during the active (frost-free) season so the real amount of the temporarily stored and released water may be difficult to estimate.

The drops in thermokarst lake level are interpreted to be due to both climate cooling and anthropogenic activities, including partial lake drainage for pasture irrigation and other land disturbances. Human influence over the changes in water volume is, however, considered to be rather minor as the same thermokarst lake dynamics have been observed in uninhabited, pristine natural areas of the region. The decrease in thermokarst lake volumes may also indicate alas pond drainage and thermo-erosion, as documented in the northern Alaska lowland where the main spill-out events were correlated with years of high annual temperature and precipitation variations triggering ablation water release (Swanson, 2019).

The present study shows that the single thermokarst basins do not react uniformly to annual climate variations, with some basins expanding while others are retracting in size compared to the lake status of the preceding or succeeding years. This lack of uniformity is well documented in the Tyungyulyu alas system (currently encompassing ~58 lakes) for the year 2014 when other hydrogeology drivers like shoreline slumping along the steep banks (Fig. 9A) caused the lake surface area to increase (Fig. 6: 2014, left side). The simultaneous retreat of the open-water body in the neighbouring and perennially disconnected thermokarst lake (Fig. 6: 2014, right side; Fig. 7A: East Lake) are interpreted to be the result of permafrost degradation leading to external leakage of the lake water or infiltration into the active layer underneath followed by drainage as the cryolithic boundary

FIG. 10. Permafrost-generated geo-environmental hazards (south-central Yakutia). A: Summer-melting of an expanding palsa field (Churapcha); B: Progressing permafrost thaw evidenced by sinking step-like terrace platforms (Tyungyulyu, East Lake); C: Thermokarst terrace collapse of south-facing slopes generated by summer insolation (Moro) posing major risks for the population and household animals (cows, horses); D: Permafrost degradation-generated mass wasting and slumping due to seasonally defreezing fine-grain bedrock alluvia (Myndagay); E: The top ground collapse triggered by a local cryolithozone compactness failure; F: Active thermokarst lake formation along the main road (M56) causing the unpaved road rampant instability due to summer water infiltration and winter freezing. Photographs by the authors.

FIG. 11. Permafrost-generated geo-environmental hazards (south-central Yakutia). A: Forming thermokarst lake with retreating taiga along the active shore margins (Mayya); B: Seasonally desiccated shallow alas depression with mineral evaporate (salt) precipitation (Tyungyulyu, West Lake); C: Expanding alas in the middle of the local community (Churapcha); D: Destruction of the local electricity line due to ground destabilization and unconsolidated bedrock movement (Nuoragana); E: Pastures for cattle and horse breeding on open grasslands promoted by regional warming and permafrost thaw; F: Ice cubes cut from a frozen alas lake stored in an underground house cellar with year-round freezing temperature provide drinking (mineral-deficient) water (Tyungyulyu). Photographs by the authors.

TABLE 1. Variations of the water surface extent, maximum depth, radius, and total water volume of the East (Segeley) Lake and the total extent for all the lakes in the Tyungyulyu thermokarst system for the selected monitored years. The lake water volume is calculated from the recorded depth for the particular years using the same equation formula (V) = 1.047 r^2h in respect to the conical shape of the East Lake basin relief, where r is the radius of the top (surface) of the cone (lake) and h is the height (maximum depth) of the cone (lake).

Year	East Lake ha	East Lake km^2	All Lakes km^2	East Lake max. depth in m	East Lake radius in m	East Lake volume $m^3 \times 10^3$
2005	22.77	0.23	1.37	1.8	269.3	136.7
2008	440.19	4.40	12.07	2.3	1184.0	3375.9
2014	248.67	2.49	8.19	2.1	889.9	1741.2
2018	381.24	3.81	7.11	2.2	1101.9	2796.6

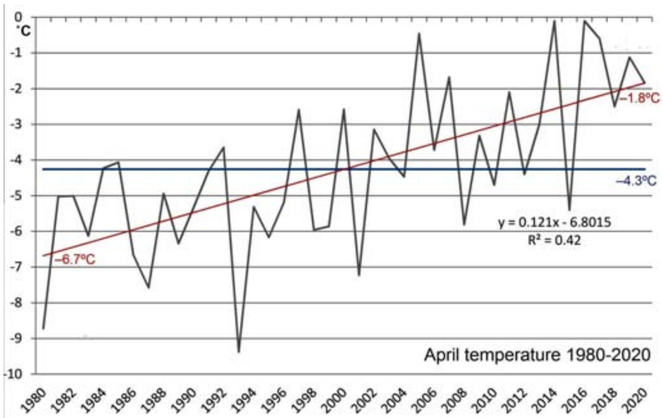

FIG. 12. The temperature trend in April for central Yakutia (the Yakutsk meteorological station record 1980–2020) showing ~5˚C temperature rise over the 40 yr period.

retracts. At East Lake, the water table drop due to permafrost degradation and bottom drainage causing lake volume to shrink are both at play. The differential hydrological dynamics of two nearby lakes in the Tyungyulyu alas systems show the complexity of the thermokarst lakes' behaviour. The yearly lake water volume thus fluctuates greatly with an estimated water loss of up to 90% in years of minimum lake level stands (Table 1).

DISCUSSION

Permafrost Degradation Factors

The present cryolithic degradation in both the continuous and discontinuous permafrost zones of the sub-Arctic and the intra-continental regions of North Asia is well defined. The MAAT increase over northeastern Siberia with milder winters and hot summers is the principal driver behind longer-term frozen ground thaw. Several other geo-environmental factors observed in the investigated area of central Yakutia play major roles as well: 1) site geomorphology, 2) surficial geology, 3) slope orientation, 4) vegetation cover affecting albedo, and 5) top soil thermal energy budgets. Together with meltwater drainage, these factors further influence the differential degradation of permafrost and changes to the water supply into both the existing and newly forming thermokarst lakes. These lacustrine basins experience enhanced water level fluctuations due not only to climate warming, but also to human actions (pastoral practices and forest logging), which both contribute to the expansion of open lands with a higher thermal capacity from intensified spring and summer insolation. The present results corroborate the former studies on the central Yakutia alas lakes' fluctuations over the past century, with winter precipitation (snow cover thickness) and summer temperature rates thought as the principal controlling drivers (Solov'ev, 1961; Tarasenko, 2013), together with rainfalls.

The current trend of regional warming (Fig. 4) in northeastern Siberia is controlled primarily by the Siberian High, which has a major impact on tundra-forest and steppe ecosystems, with an earlier start of the spring season and river-ice disintegration. The countryside residents take advantage of the effects of climate warming by exploiting the new grasslands around lakes and in drying-up alases for cattle grazing and hay production and storage for winter feeding of animals (Fig. 11E). The changing practices of local land use control the surface albedos. These albedos are significantly higher in northern taiga forest settings relative to open-meadow settings, which makes for higher ground temperature potential in cultivated land and meadow environments (Brouchkov et. al., 2004; Likens, 2010). Increased summer precipitation is believed to contribute to ice-melt dynamics. May 2020 was absolutely the warmest spring month meteorologically registered in western and central Siberia, with temperatures ~10˚C above the 40 yr mean values, which led to early breakup of river ice (MacNamara and Hood, 2020). Similar values have been registered in eastern Siberia where April is the month with the greatest warming trend with a current temperature increase of 5˚C compared to 1980 (Fig. 12); this increase is well apparent at the earlier start of spring.

Except for the MAAT increases, frequent and spatially extensive taiga forest fires (both natural and anthropogenic) are considered as another principal driver that locally accelerates permafrost degradation in northeastern Siberia. Former studies in the most populated central Yakutia region suggest that the risk of human-induced forest fires during the summer months is significantly high (Vasiliev and Solovyev, 2013). The highest frequency of recorded natural fires in Siberia is correlated with those years when El Niño had occurred (Balzter et al., 2007). Overall, the synergic effect of global warming in the circumpolar regions is the increase of fire occurrence (Stocks et al., 1998).

TABLE 2. Hydrochemical parameters of the Tyungyulyu thermokarst lake (East Lake) used for drinking water (analysis IGG, AMU, Poznan).

	TDS g/l	EC μS/m	pH	HCO_3 mg/l	F mg/l	Cl mg/l	SO_4 mg/l	PO_4 mg/l	Mg mg/l	NaI mg/l	K mg/l
Tyungyulyu East Lake	0.46	880	9	454.6	0.32	50.1	9.8	0.37	80.9	69.8	20.2

Wildfires open the Siberian taiga and northern boreal forest landscapes and remove the protective vegetation cover, providing increased insolation and heat absorption generated by solar radiation. As an analogue example for continental northeastern Russia, increased surface heating in periglacial regions of northern Canada has significant environmental implications for present-day thermokarst development; this heating has contributed to ~25% of thermokarst bog expansion over the past 30 years (Gibson et al., 2018).

Socioeconomic Impacts of Permafrost Thaw

Current permafrost degradation is causing major environmental and engineering problems. The cryolithic melting in the northern regions of Siberia and associated environmental shifts in thermokarst development and expansion have local effects on infrastructure, construction, pipelines, natural resource exploration, and the maintenance of industrial facilities, among others. The significance of these issues is most acute in the context of progressing global warming and the regional socioeconomic development of both continuous and discontinuous permafrost regions such as Yakutia. Climate change-related environmental transformations in high-latitude continental regions are not just of major economic concern, but create major ecologic hazards and pose fundamental problems for safety management. For example, the most recent accident near Norilsk because of a diesel oil storage-dam failure due to regressing permafrost caused massive contamination of an Arctic river system (Skarbo, 2020). Large-scale mid-term economic consequences are anticipated in central and northern Siberia where the terrain is dominantly (80%) in the continuous permafrost zone. The current thermokarst processes demonstrate the periglacial landscape's vulnerability and exacerbated environmental risks. Surface instability often appears close to the Yakut settlements (Fig. 10C, D). The effects of ground collapse due to permafrost thaw pose major risks to local inhabitants and have been well documented at the study sites and nearby loci for the past few consecutive years (Chlachula and Czerniawska, 2017) (Fig. 10E).

The transport system in the Sakha Republic (Yakutia) is mainly based on natural resource (e.g., oil, gas, and coal) extraction industries and forestry. These are largely dependent on land and riverine transportation corridors (mainly alongside the Lena River and its major tributaries, the Viluy and Aldan Rivers), which have become a high risk to local economics due to the decrease in transportation reliability. With continued climatic amelioration and permafrost thaw, such transportation corridors are becoming problematic from an engineering perspective and with respect to seasonal availability (e.g., seasonal frozen roads). Road communication and riverine transport, particularly for rural regions, are crucial. The republic's road network encompasses 24 050 km, of which 3616 km is classified as first-class road, which is regularly maintained but largely unpaved with just a gravel cover. About 11 218 km are regional unpaved roads of technically less-demanding construction built over unstable permafrost ground (Fig. 10E). Progressive road distortion because of cryolithic thaw with construction embankment saturation imposes high demands for regular infrastructure maintenance. The local people are becoming increasingly aware of the ongoing climate-driven environmental shifts harming rural industry and domestic facilities (Boyakova, 2013). Systematic monitoring and environmental mitigation in the most threatened places of the study area constitute the priority in order to minimize permafrost-related risks (Pavlov, 2008) and mitigate economic losses among Yakutia communities.

The thermokarst lakes are the main source of utility and drinking water for local residents and community use. Because of a low mineral content, the shallow permafrost ponds do no provide a quality drinking water. Over the winter months, cut ice cubes are stored in underground cellars for water consumption (5 – 10 m^3 per family) when needed (Fig. 11F). Because of the regional hydrogeology background, this low mineral water content (Table 2) causes acute health problems (Desyatkin, 2004; Pavlova et al., 2016). Other consequences of ongoing permafrost degradation are the spatial expansion of open northern grasslands and parkland forests at the expense of taiga forest, and the formation of new farmlands used for seasonal pastures (Fig. 11E).

Perspectives of Circumpolar Climate and Permafrost

The long-term air and ground temperature records for the East Siberian climate-geographic transect show significant warming trends during the 1956 – 90 period (Romanovsky et al., 2007), with the most pronounced temperature deviations occurring in the last few decades (J. Chlachula et al., unpubl. data). The actual warming rate in central Yakutia is very similar to the long-term circumpolar climate predictions by the global circulation models for the 21st century (ACIA, 2005; Anisimov et al., 2007). The thermal conditions beneath the expanding thermokarst lakes in central Yakutia predict ground thaw within the range of 10–17 m in depth over the next 50–80 years, and a shift of the southern discontinuous and continuous permafrost limits by 300–400 km northward (Duchkov, 2006). Although there is a high degree of uncertainty surrounding these values, they are believed to be accurate enough to suggest a complete melting of a significant portion of the subsurface permafrost. The observed shortening of the snow-free season in the study area further decreases albedo and promotes atmospheric and ground-surface warming over the territory.

Global climate research and climate change scenarios for the 21st century suggest high levels of environmental risk in regions with present moderate- or high-hazard potential for thawing permafrost in major northern settlements such as Barrow and Nome in Alaska, Inuvik in Canada, and Vorkuta and Yakutsk in Siberia (e.g., Nelson et al., 2001; U.S. Arctic Research Commission Permafrost Task Force, 2003; Instanes et al., 2005; Chapin et al., 2005; Streletskiy and Shiklomanov, 2013; Boyakova, 2013; Jonassen et al., 2014). Warming rates are the highest (up to 0.08˚C/yr) in southern Siberia and the lowest (< 0.03˚C/yr) in northern Europe and west and central Siberia (Malkova et al., 2011). Nevertheless, numerical models show that deep permafrost is much more resistant to global warming than was previously assumed. In Yakutsk, even at the high rate of climate warming (0.08˚C/year), the average annual temperature of the ground surface will become positive only after 50 years (Pavlov et al., 2010), although melting of the active layer may increase. Cryolithic thaw may cause significant (> 25%) reduction in the stability of rural (Fig. 10F) and urban infrastructure in Russian permafrost regions by the mid 21st century (Shiklomanov, et al., 2017). Permafrost degradation is likely to be accelerated by the presumed dramatically increased fire frequency in forested areas of the Northern Hemisphere by the end of the century (Flannigan et al., 2013).

The territorial occurrences of newly formed thermokarst lakes and slumping or collapsing ground in East Siberia will further expand with the predicted future rise in temperature and precipitation. At the same time, the northern underground ice-rich lowlands will in the long-term experience gradual landscape aridification and a reduction of open-water bodies due to evaporation and drying up once the ground ice is depleted, with negative effects on the aquatic ecosystems.

CONCLUSION

The climate change and geo-environmental studies show prominent changes in the natural and occupation settings of Yakutia during the last 40 years. These changes have been generated by increasingly higher late spring–early summer air temperatures causing accelerated permafrost thaw with the expansion of the active layer. The meteorological data analysis points to the current climate trend cyclicity of 5–7 yr periods. The regional MAAT increase during 2006–19 is most evident when compared to the period between 1980 and 2005. Steady warming since 2006 has triggered a dynamic suite of geomorphic processes that is evidenced by DEM models and satellite images, including ground collapses, slope slumping or mass wasting, thermokarst bog and lake expansion, and ground salinization. Increasing wild and human-induced forest fires as well as logging are synergic drivers of permafrost degradation and top ground destabilization. Seasonal ice-melt processes generate major risks to transport infrastructure and regional development. Monitoring of the cryogenic hazards and assessment of the socioeconomic impact are crucial for the sustainability of the local communities and regional economic planning in the most vulnerable areas of the Sakha Republic, primarily for the geographically broadly distributed rural settlements encompassing ~50% of the population. In addition to relief distortion, permafrost degradation leads to major shifts in the hydrological system and changes in vegetation cover. The expansion of open landscapes within the tundra-forest zone due to permafrost retreat provides new pastures, which contributes positively to rural economies.

ACKNOWLEDGEMENTS

Fieldwork of this study was supported by the North-Eastern Federal University (Yakutsk) research program “Environmental Change and Human Adaptations in Central Yakutia” and by the Institute of Geoecology and Geoinformation, Adam Mickiewicz University, Poznan. The authors especially thank Dr. Kunney A. Pestereva and Dr. Dmitry A. Pesterev (NEFU, Yakutsk) for field assistance in 2013–14 investigations, Dr. Edward Little (Geological Survey Canada, Alberta Branch, Calgary) for stylistic improvement of the original manuscript and productive discussions on subarctic thermokarst processes, and two anonymous reviewers for valuable comments and suggestions contributing to the final version of this paper.

REFERENCES

Abaimov, A.P., Zyryanova, O.A., and Prokushkin, S.G. 2002. Long-term investigations of larch forests in cryolithic zone of Siberia: Brief history, recent results and possible changes under global warming. Eurasian Journal of Forest Research 5(2):95–106.

ACIA (Arctic Climate Impact Assessment). 2004. Impacts of a warming Arctic: Arctic climate impact assessment. ACIA Overview report. Cambridge: Cambridge University Press. 140 p.

———. 2005. Arctic climate impact assessment: Scientific report. Cambridge: Cambridge University Press. 1020 p.

Alasset, P.-J., Chamberland, J., English, J., and Volkov, N. 2010. Monitoring and assessing geohazards in permafrost terrain using space-born synthetic aperture radar (SAR). In: Kwok, C., Moorman, B., Armstrong, R., and Henderson, J., eds. Proceedings of GeoCalgary 2010, Calgary, Alberta. 1329–1337.
http://pubs.aina.ucalgary.ca/cpc/CPC6-1329.pdf

Anisimov, O.A., Lobanov, V.A., and Reneva, S.A. 2007. Analysis of changes in air temperature in Russia and empirical forecast for the first quarter of the 21st century. Russian Meteorology and Hydrology 32:620–626.
https://doi.org/10.3103/S1068373907100020

Balzter, H., Gerard, F., Weedon, G., Grey, W., Los, S., Combal, B., Bartholome, E., Bartales, S. 2007. Climate, vegetation phenology and forest fires in Siberia. 2007 IEEE International Geoscience and Remote Sensing Symposium (IGARSS). Barcelona, Spain. 3843–3846.
https://doi.org/10.1109/IGARSS.2007.4423682

Bonnaventure, P.P., Lewkowicz, A.G., Kremer, M., and Sawada, M.C. 2012. A permafrost probability model for the southern Yukon and northern British Columbia, Canada. Permafrost and Periglacial Processes 23(1):52–68.
https://doi.org/10.1002/ppp.1733

Bosikov, N.P. 1978. Alas distribution in central Yakutia: Geocryological conditions in the highlands and plains of Asia (in Russian). Yakutsk, Russia: Melnikov Institute of Permafrost. 113–118.

Boyakova, S. 2013. Assessment of the impact of climate change on transport infrastructure Yakutia. Proceedings of the 2nd International Conference, Global warming and the human-nature dimension in Siberia: Social adaptation to the changes of the terrestrial ecosystem, with an emphasis on water environments, 8–11 October 2013, Yakutsk, Russia. 45–48.
https://www.chikyu.ac.jp/siberia/2nd_International_Conference.pdf

Brouchkov, A., Fukuda, M., Fedorov, A., Konstantinov, P., and Iwahana, G. 2004. Thermokarst as a short-term permafrost disturbance, central Yakutia. Permafrost and Periglacial Processes 15(1):81–87.
https://doi.org/10.1002/ppp.473

Brown, R., and Lemay, M. 2012. Climate variability and change in the Canadian Eastern Subarctic IRIS region (Nunavik and Nunatsiavut). In: Allard, M., and Lemay M., eds. Nunavik and Nunatsiavut: From science to policy. An Integrated Regional Impact Study (IRIS) of climate change and modernization. Quebec City, Quebec: ArcticNet Inc. 57–93.
https://doi.org/10.13140/RG.2.1.3745.0323

Bulygina, O., and Razuvaev, V. 2012. Daily temperature and precipitation data for 518 Russian meteorological stations. Oak Ridge, Tennessee: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.
https://doi.org/10.3334/CDIAC/cli.100

Bulygina, O.N., Razuvaev, V.N., Trofimenko, L.T., Shvets, N.V. 2019. Description of the data set of average monthly air temperature at Russian stations.
http://meteo.ru/data/156-temperature

Cadastral Report. 2019. The Cadastral report on the specially protected natural areas of Russia – Lake Tyungyulyu (in Russian). Yakutsk, Russia: Government of the Sakha Republic (Yakutia).

Callaghan, T.V., Bergholm, F., Christensen, T.R., Jonasson, C., Kokfell, U., and Johansson, M. 2010. A new climate era in the sub-Arctic: Accelerating climate changes and multiple impacts. Geophysical Research Letters 37(14), L14705.
https://doi.org/10.1029/2009GL042064

Chapin, F.S., III, Sturm, M., Serreze, M.C., McFadden, J.P., Key, J.R., Lloyd, A.H., McGuire, A.D., et al. 2005. Role of land-surface changes in Arctic summer warming. Science 310(5748):657–660.
https://doi.org/10.1126/science.1117368

Chlachula, J., and Czerniawska, J. 2016. Ground stability and hydrology feedback to pesent MAT rise in central Yakutia. In: Maximov, T., Hiyama, T., Sugimoto, A., Ota, T., Dolman, J.A., Schaepman-Strub, G., Heijmans, M., Kononov, A., and Petrov, R., eds. Climate and permafrost ecosystems: Proceedings of the IXth International Symposium C/H_2O/energy balance and climate over the boreal and Arctic regions with special Eemphasis on Eastern Eurasia, 1–4 November 2016,Yakutsk, Russia. Nagoya University Press. 90–93.

———. 2017. Present landscape development and geo-risks in the thermokarst areas of Central Yakutia. In: Bhawan, V., ed. Abstract volume, 9th Conference on Geomorphology: "Geomorphology and Society." 6–11 November 2017, New Delhi, India. Section S19: Glacial and Periglacial Geomorphology. Abstract no. 791.178–179.

Cole, G.A., and Weihe, P.E. 2016. Textbook of limnology, 5th ed. Long Grove, Illinois: Waveland Press. 440 p.

Connon, R.F., Quinton, W.L., Craing, J.R., and Hayashi, M. 2014. Changing hydrologic connectivity due to permafrost thaw in the lower Liard River valley, NWT, Canada. Hydrological Processes 28(14):4163–4178.
https://doi.org/10.1002/hyp.10206

Costard, F., Gautier, E., Brunstein, D., Hammadi, J., Fedorov, A., Yang, D., and Dupeyrat, L. 2007. Impact of the global warming on the fluvial thermal erosion over the Lena River in Central Siberia. Geophysical Research Letters 34(14), L14501.
https://doi.org/10.1029/2007GL030212

Couture, R., Smith, S., Robinson, S.D., Burgess, M.M., and Solomon, S. 2003. On the hazards to infrastructure in the Canadian north associated with thawing of permafrost. In: Proceedings of GeoHazards 2003: 3rd Canadian Conference on Geotechnique and Natural Hazards, 9–10 June 2003, Edmonton, Alberta. 97–104.

Desyatkin, R.V. 2004. Water resources of taiga-alas landscapes in central Yakutia and problems of water supply for the population. In: Matsumnoto, J. ed. Proceedings, 6th International Study Conference on GEWEX in Asia and GAME, 3–5 December 2004, Kyoto, Japan.
http://www.hyarc.nagoya-u.ac.jp/game/6thconf/html/abs_html/pdfs/T7RVD30Jul04101621.pdf

Duchkov, A.D. 2006. Characteristics of permafrost in Siberia. In: Lombardi, S., Altunina, L.K., and Beaubien, S.E., eds. Advances in the geological storage of carbon dioxide. NATO Science Series: IV. Earth and Environmental Sciences, Vol. 65. Dordrecht, Netherlands: Springer. 81–92.

Fedorov, A., and Konstantinov, F. 2003. Observations of surface dynamics with thermokarst initiation, Yukechi site, central Yakutia. In: Phillips, M., Springman, S.M., and Arenson, L.U., eds. Permafrost. Proceedings of the Eighth International Conference on Permafrost, 21–25 July 2003, Zurich, Switzerland. Lisse, Netherlands: A.A. Balkema Publishers. 239–243.

Fedorov, A.N., Gavriliev, P.P., Konstantinov, P.Y., Hiyama, T., Iijima, Y., and Iwahana, G. 2014. Estimating the water balance of a thermokarst lake in the middle of the Lena River basin, eastern Siberia. Ecohydrology 7(2):188–196. https://doi.org/10.1002/eco.1378

Fedorov, A.N., Vasilyev, N.F., Torgovkin, Y.I., Shestakova, A.A., Varlamov, S.P., Zheleznyak, M.N., Shepelev, V.V., et al. 2018. Permafrost-landscape map of the Republic of Sakha (Yakutia) on a scale 1:1 500 000. Geosciences 8(12): 465. https://doi.org/10.3390/geosciences8120465

Flannigan, M., Cantin, A.S., de Groot, W.J., Wotton, M., Newbery, A., and Gowman, L.M. 2013. Global wildland fire season severity in the 21st century. Forest Ecology and Management 294:54–61. https://doi.org/10.1016/j.foreco.2012.10.022

Fortier, R., LeBlanc, A.-M., and Yu, W. 2011. Impacts of permafrost degradation on a road embankment at Umiujaq in Nunavik (Quebec), Canada. Canadian Geotechnical Journal 48:720–740. https://doi.org/10.1139/t10-101

Gibson, C.M., Chasmer, L.E., Thompson, D.K., Quinton, W.L., Flannigan, M.D., and Olefeldt, D. 2018. Wildfire as a major driver of recent permafrost thaw in boreal peatlands. Nature Communications 9: 3041. https://doi.org/10.1038/s41467-018-05457-1

Glotov, V.E., Chlachula, J., Glotova, L.P., and Little, E. 2018. Causes and environmental impact of the gold-tailings dam failure at Karamken, the Russian Far East. Engineering Geology 245:236–247. https://doi.org/10.1016/j.enggeo.2018.08.012

Grandmont, K., Cardille, J.A., Fortier, D., Gibéryen, T. 2012. Assessing land suitability for residential development in permafrost regions: A multi-criteria approach to land-use planning in northern Quebec, Canada. Journal of Environmental Assessment Policy and Management 14(1): 1250003. https://doi.org/10.1142/S1464333212500032

Grosse, G., Robinson, J.E., Bryant, R., Taylor, M.D., Harper, W., DeMasi, A., Kyker-Snowman, E., Veremeeva, A., Schirrmeister, L., and Harden, J. 2013. Distribution of late Pleistocene ice-rich syngenetic permafrost of the Yedoma Suite in east and central Siberia, Russia. U.S. Geological Survey Open-File Report 2013-1078. 24 p. https://doi.org/10.3133/ofr20131078

Gupta, A., ed. 2008. Large rivers: Geomorphology and management. Chichester, West Sussex, England: John Wiley & Sons. 712 p.

Harada, K., Wada, K., Sueyoshi, T., and Fukuda, M. 2006. Resistivity structures in alas areas in central Yakutia, Siberia, and the interpretation of permafrost history. Permafrost and Periglacial Processes 17(2):105–118. https://doi.org/10.1002/ppp.551

Henry, G.H.R, and Molau, U. 2003. Tundra plants and climate change: The International Tundra Experiment (ITEX). Global Change Biology 3(S1):1–9. https://doi.org/10.1111/j.1365-2486.1997.gcb132.x

Hong, E., Perkins, R., and Trainor, S. 2014. Thaw settlement hazard of permafrost related to climate warming in Alaska. Arctic 67(1):93–103. https://doi.org/10.14430/arctic4368

Iijima, Y., and Fedorov, A.N. 2019. Permafrost-forest dynamics. In: Ohta, T., Hiyama, T., Iijima, Y., Kotani, A., and Maximov, T.C., eds. Water-carbon dynamics in eastern Siberia. Singapore: Springer Nature. 175–206.

Iijima, Y., Fedorov, A.N., Park, H., Suzuki, K., Yabuki, H., Maximov, T.C., and Ohata, T. 2010. Abrupt increases in soil temperatures following increased precipitation in a permafrost region, central Lena River basin, Russia. Permafrost and Periglacial Processes 21(1):30–41. https://doi.org/10.1002/ppp.662

Instanes, A., Anisimov, O., Brigham, L., Goering, D., Khrustalev, L.N., Ladanyi, B., and Larsen, J.O. 2005. Infrastructure: Buildings, support systems, and industrial facilities. In: Arctic climate impact assessment: Scientific report. Cambridge: Cambridge University Press. 907–944.

Ivanov, M.S. 1984. The cryostructure of Quaternary deposits in the Lena-Aldan Basin (in Russian). Novosibirsk: Nauka. 125 p.

Johnston, G.H. 1965. Engineering problems and site investigations in the discontinuous permafrost zone. In: Brown, R.J.E., ed. Proceedings of the Canadian Regional Permafrost Conference, 1–2 December 1964. Technical Memorandum No. 86. Ottawa, Ontario: Associate Committee on Soil and Snow Mechanics, National Research Council Canada. 22–31. https://doi.org/10.4224/40001170

Jonassen, R., Jafarov, E., Schaefer, K., Horsfall F., and Timofeyeva, M. 2014. Achieving the NOAA Arctic Action Plan: The missing permafrost element. NOAA's National Weather Service, 39th Annual Climate Diagnostics and Prediction Workshop, 20–23 October 2014, St. Louis, Missouri. Science and Technology Infusion Climate Bulletin. 70–73. https://www.nws.noaa.gov/ost/climate/STIP/39CDPW/39cdpw-RJonassen.pdf

Jorgenson, M.T., and Grosse, G. 2016. Remote sensing of landscape change in permafrost regions. Permafrost and Periglacial Processes 27(4):324–338. https://doi.org/10.1002/ppp.1914

Jorgenson, M.T., Shur, Y.I., and Pullman, E.R. 2006. Abrupt increase in permafrost degradation in Arctic Alaska. Geophysical Research Letters 33, L02503. https://doi.org/10.1029/2005GL024960

Kirdyanov, A., Hughes, M., Vaganov, E., Schweingruber, F., and Silkin, P. 2003. The importance of early summer temperature and date of snow melt for tree growth in the Siberian Subarctic. Trees 17:61–69.
https://doi.org/10.1007/s00468-002-0209-z

Kirpotin, S.N., Polishchuk, Y., and Bryksina, N., 2009. Abrupt changes of thermokarst lakes in western Siberia: Impacts of climatic warming on permafrost melting. International Journal of Environmental Studies 66(4):423–431.
https://doi.org/10.1080/00207230902758287

Kolpakov, D.W. 1998. State geological map of Russia 1:1 000 000. Quaternary deposits map. Sankt Petersburg.

Konishchev, V.N. 2011. Reaktsiya vechnoi merzloty na poteplenie klimata [Permafrost response to climate warming]. Kriosfera Zemli 15(4):13–16.

Kunitsky, V.V., Syromyatnikov, I.I., Schirrmeister, L., Skachkov, Yu.B., Grosse, F., Wetterich, S, and Grigoriev, M.N. 2013. L'distnye porody I termodenudatsii v rayone posyolka Batagay (Yaskoye Ploskogorye, Vostochnaya Sibir' [Ice-rich permafrost and thermal denudation in the Batagay area (Yana Upland, East Siberia)]. Kriosfera Zemli 17(1):56–68.

Larry Lopez, C.M., Brouchkov, A., Nakayama, H., Takakai, F., Fedorov, A.N., and Fukuda, M. 2007. Epigenetic salt accumulation and water movement in the active layer of central Yakutia in eastern Siberia. Hydrological Processes 21(1):103–109.
https://doi.org/10.1002/hyp.6224

Likens, G.E. 2010. River ecosystem ecology: A global perspective. San Diego, California: Academic Press. 424 p.

Lloyd, T. 1963. The influence of permafrost on northern development. In: Brown, R.J.E., ed. Proceedings of the First Canadian Conference on Permafrost, 17–18 April 1962, Ottawa, Ontario. Technical Memorandum No. 76. Ottawa, Ontario: Associate Committee on Soil and Snow Mechanics, National Research Council Canada. 1–17.
https://doi.org/10.4224/40001156

Lyle, R., and Hutchinson, D.J. 2006. Influence of degrading permafrost on landsliding processes: Little Salmon Lake, Yukon Territory, Canada. Geohazard International Conference Proceedings, 18–21 June 2006, Lillehammer, Norway. ECI Digital Archives.
http://dc.engconfintl.org/geohazards/4

MacNamara, K., and Hood, M. 2020. Warmest May on record, Siberia 10C hotter. *Phys.Org*, June 5.
https://phys-org.cdn.ampproject.org/c/s/phys.org/news/2020-06-warmest-siberia-10c-hotter.amp

Malkova, G.V., Pavlov, A.V., and Skachkov, Yu.B. 2011. Assessment of permafrost stability under contemporary climatic changes. Kriosfera Zemli (Earth Cryosphere) 15:29–32.

McFeeters, S.K. 1996. The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. International Journal of Remote Sensing 17(7):1425–1432.
https://doi.org/10.1080/01431169608948714

Nelson, F.E., Anisimov, O.A., and Shiklomanov, N.I. 2001. Subsidence risk from thawing permafrost. Nature 410:889–890.
https://doi.org/10.1038/35073746

Netzel, P., Jasiewicz, J., and Stepinski, T. 2016. TerraEx – a GeoWeb app for world-wide content-based search and distribution of elevation and landforms data. International Conference on GIScience Short Paper Proceedings 1(1):212–215.
https://doi.org/10.21433/B3110dk1t0vc

Nihoul, J.C.J., and Kostianoy, A.G., eds. 2009. Influence of climate change on the changing Arctic and sub-Arctic conditions. NATO Science for Peace and Security Programme, Series C: Environmental Security. Dordrecht, Netherlands: Springer Science + Business Media B.V. 232 p.
https://doi.org/10.1007/978-1-4020-9460-6

Ohta, T., Hiyama, T., Iijima, Y., Kotani, A., and Maximov, T.C., eds. 2019. Water-carbon dynamics in eastern Siberia. Singapore: Springer Nature. 309 p.
https://doi.org/10.1007/978-981-13-6317-7

Pavlov, AV. 2008. Permafrost monitoring (in Russian). Novosibirsk: Geo. 229 p.

Pavlov, A.V., and Moskalenko, N.G. 2002. The thermal regime of soils in the north of western Siberia. Permafrost and Periglacial Processes 13(1):43–51.
https://doi.org/10.1002/ppp.409

Pavlov, A.V., Perlstein, G.Z., and Tipenko, G.S. 2010. Actual aspects of modeling and prediction of the permafrost thermal state under climate change conditions (in Russian). Kriosfera Zemli 15(1):3–12.

Pavlova, N.A., Kolesnikov, A.B., Efremov, V.S., Shepelev, V.V. 2016. Groundwater chemistry in intrapermafrost taliks in central Yakutia. Water Resources 43:353–363.
https://doi.org/10.1134/S0097807816020135

Pollard, W. 2018. Periglacial processes in glacial environments. In: Menzies, J., and van der Meer, J.M., eds. Past glacial environments, 2nd ed. Amsterdam, Netherlands: Elsevier. 537–564.
https://doi.org/10.1016/B978-0-08-100524-8.00016-6

Romanovsky, V.E, Sazonova, T.S, Balobaev, V.T, Shender, N.I., and Sergueev, D.O. 2007. Past and recent changes in air and permafrost temperatures in eastern Siberia. Global and Planetary Change 56(3-4):399–413.
https://doi.org/10.1016/j.gloplacha.2006.07.022

Romanovsky, V.E., Drozdov, D.S., Oberman, N.G., Malkova, G.V., Kholodov, A.L., Marchenko, S.S., Moskalenko, N.G., et al. 2010. Thermal state of permafrost in Russia. Permafrost and Periglacial Processes 21(2):136–155.
https://doi.org/10.1002/ppp.683

Rowley, T., Giardino, J.R., Granados-Aguilar, R., and Vitek, J.D. 2015. Periglacial processes and landforms in the critical zona. Developments in Earth Surface Processes19:397–447.
https://doi.org/10.1016/B978-0-444-63369-9.00013-6

Shiklomanov, I.A., and Rodda, J.C., eds. 2003. World water resources at the beginning of the twenty-first century. International Hydrology Series. Cambridge: Cambridge University Press. 435 p.

Shiklomanov, N.I., Streletskiy, D.A., Swales, T.B., and Kokorev, V.A. 2017. Climate change and stability of urban infrastructure in Russian permafrost regions: Prognostic assessment based on GCM cimate projections. Geographical Review 107(1):125–142.
https://doi.org/10.1111/gere.12214

Skarbo, S. 2020. State of emergency in Norilsk after 20,000 tons of diesel leaks into Arctic river system. *The Siberian Times*, June 2.

Solov'ev, P.A. 1961. Tsiklicheskiye variatsii vodnosti alasov Tsentral'noy Yakutii v kontekste variatsiy klimaticheskikh elementov [Cyclic variations in water abundance in Alassy Lakes in central Yakutia in the context of climate element variations]. Voprosy Geografii Yakutii (Issues of Yakut Geography) 1:48–54.

———. 1973. Thermokarst phenomena and landforms due to frost heaving in central Yakutia (in Russian). Biuletyn Peryglacialny 23:135–155.

Spektor, V.B., Spektor, V.V., and Bakulina, N.T. 2011. Buried snow in the Lena-Amga plain. Kriosfera Zemli 15(4):16–21.
http://www.izdatgeo.ru/pdf/krio/2011-4/16_eng.pdf

Stocks, B.J., Fosberg, M.A., Lynham, T.J., Mearns, L., Wotton, B.M., Yang, Q., Jin, J.-Z., et al. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. Climatic Change 38:1–13.
https://doi.org/10.1023/A:1005306001055

Streletskiy, D., and Shiklomanov, N. 2013. Arctic urban sustainability and permafrost. Arctic Urban Sustainability Conference, 30–31 May 2013, Washington, D.C.

Swanson, D.K. 2019. Thermokarst and precipitation drive changes in the area of lakes and ponds in the national parks of northwestern Alaska, 1984–2018. Arctic, Antarctic, and Alpine Research 51(1):265–279.
https://doi.org/10.1080/15230430.2019.1629222

Tarasenko, T.V. 2013. Interannual variations in the areas of thermokarst lakes in central Yakutia. Water Resources 40(2):111–119.
https://doi.org/10.1134/S0097807813010107

Tart, R.G., Jr. 2006. Pipeline geohazards unique to northern climates. In: Proceedings of the ASME International Pipeline Conference, 25–29 September 2006, Calgary, Alberta. Paper No. IPC2006-10085. Vol. 1:909–916.
https://doi.org/10.1115/IPC2006-10085

Tchebakova, N.M., Parfenova, E., and Soja, A.J. 2009. The effects of climate, permafrost and fire on vegetation change in Siberia in a changing climate. Environmental Research Letters 4(4): 045013.
https://doi.org/10.1088/1748-9326/4/4/045013

Turner, J., and Marshall, G.J. 2011. Climate change in the polar regions. Cambridge: Cambridge University Press. 434 p.

U.S. Arctic Research Commission Permafrost Task Force. 2003. Climate change, permafrost, and impacts on civil infrastructure. Special Report 01-03. Arlington, Virginia: U.S. Arctic Research Commission.
https://www.hsdl.org/?view&did=757493

van Huissteden, J. 2020. Thawing permafrost: Permafrost carbon in a warming Arctic. Cham: Springer Nature Switzerland. 508 p.
https://doi.org/10.1007/978-3-030-31379-1

Vasiliev, M.S., and Solovyev, V.S. 2013. The influence of human activities on forest fires (in Russian). Proceedings of the 2nd International Conference, Global warming and the human-nature dimension in Siberia: Social adaptation to the changes of the terrestrial ecosystem, with an emphasis on water environments, 8–11 October 2013, Yakutsk, Russia. 63–65.
https://www.chikyu.ac.jp/siberia/2nd_International_Conference.pdf

Wickland, K.P., Striegl, R.G., Neff, J.C., and Sachs, T. 2006. Effects of permafrost melting on CO_2 and CH_4 exchange of a poorly drained black spruce lowland. Journal of Geophysical Research: Biogeosciences 111(G2), G02011.
https://doi.org/10.1029/2005JG000099

Zhang, T., Barry, R.G., Knowles, K., Heginbottom, J.A., and Brown, J. 2008. Statistics and characteristics of permafrost and ground-ice distribution in the Northern Hemisphere. Polar Geography 31(1-2):47–68.
https://doi.org/10.1080/10889370802175895