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Contribution of summer net precipitation to winter river discharge in permafrost zone of the Lena River basin

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ABSTRACT

Winter discharge of the Lena River (Russia) has increased over the previous several decades. However, the impact of permafrost thawing and of changing hydrological processes induced by climate change on the river's winter discharge is not well-quantified. Here, using a coupled land surface model and a distributed discharge model, we conducted trend analyses to examine the sensitivity of winter discharge to permafrost thawing and water budget change in the Lena River basin during 1979–2016. An increasing trend of winter baseflow was found in upper parts of both the Lena River basin and the Aldan River basin, where summer net precipitation showed a statistically significant increase. The increased summer net precipitation resulted in higher soil moisture in the deepened active layer in late summer and early autumn, which was linked to autumn and winter baseflow. These implications were examined from the perspective of interrelations among the trends of active layer thickness, soil moisture, and baseflow in the cold season by identifying regions in which all the variables exhibited positive trends. The identified source regions were primarily in the lower Lena River basin and upper basins of the Lena and Aldan rivers, although winter baseflow was more dominant in the latter regions owing to the freezing effect of the active layer. Thinning of river ice induced by warming temperatures also contributed to the increase of winter river discharge. These results suggest that the increased winter discharge was strongly associated with climate-change-related enhancement of permafrost thawing and increase in net precipitation that affected soil hydrological processes, which will be strengthened further in the context of global warming.

1. Introduction

Climate change has progressed notably in the Arctic circumpolar region (McBean et al., 2005; Turner et al., 2007) resulting in drastic changes in hydrological processes, particularly increased discharge from Arctic rivers (Walsh et al., 2005; Hinzman et al., 2005; Serreze et al., 2000; Walvoord and Kurylyk, 2016). Historical observations and model simulations clearly reveal the increases of discharge from Arctic rivers over the previous several decades (Peterson et al., 2002; McClelland et al., 2006; Overeem and Syvitski, 2016). Specifically, the increase in river discharge has been substantial in northern Eurasia since the 1980s (Holmes et al., 2015). Peterson et al. (2002) presented evidence that

annual river discharge to the Arctic Ocean from the six largest river basins in northern Eurasia increased by 7 % during 1936–1999. Moreover, these increases are projected to amplify further under the influence of future climate change (Zhang et al., 2018; Brinje et al., 2017).

Arctic rivers are characterized by a dynamic hydrological flow regime with peak discharge during spring caused by high snowmelt runoff (Yang et al., 2007). The snow-related hydrological regime has also experienced marked changes over recent decades. The effects of climate change are causing a notable shift toward an earlier peak in spring discharge due to earlier snowmelt (Shiklomanov et al., 2007; Tananaev et al., 2016; Suzuki et al., 2020). The earlier onset of snowmelt and resultant soil thawing likely cause advanced activity of soil moisture

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linked to evapotranspiration (ET) and runoff processes, in addition to earlier development of the active layer. The advanced usage of soil moisture by ET can lead to drier soil, whereas increased precipitation induced by climate change can offset this dryness and lead to soil wetting (Walvoord and Striegl, 2007; Jacques and Sauchyn, 2009). Intensification of soil drying and wetting can affect water budget components linked to soil moisture. Climate change can also enhance deepening of the active layer during the warm season, which increases mixing, mobilization, and flux of soil moisture within the active layer (Park et al., 2021). Soil wetting likely strengthens the connectivity of soil moisture to the generation of subsurface runoff, while soil drying has a limiting effect on the relationship.

The ice-rich permafrost is vulnerable to the effects of a warming climate. In situ and satellite remote sensing observations have been used to identify the expansion of thermokarst lakes and wet areas induced by permafrost thawing and degradation under the impact of climate change (Liljedahl et al., 2016; Ulrich et al., 2017), and the resultant effects on local and regional hydrology have been analyzed (Liljedahl et al., 2016). Earlier works documented that permafrost thawing played a minor role in the observed long-term increase in river runoff in northern Eurasia, in comparison with the larger contribution associated with increased precipitation (Fukutomi et al., 2003; McClelland et al., 2004). Recent studies have proposed the importance of thickening of the active layer because it can cause localized increase in groundwater storage within the active layer (Walvoord and Kurylyk, 2016), thereby enhancing regional surface-groundwater interactions as a result of permafrost thawing (Evans et al., 2020). These changes can lead to more groundwater discharging into rivers (Wang et al., 2021). Previous works that analyzed long-term hydrological and meteorological data detected statistically significant increases in winter discharge of Arctic rivers, on the basis of which they implied that permafrost thawing was linked to the increase in discharge (Han and Menzel, 2022; Smith et al., 2007; Walvoord and Striegl, 2007; Wang et al., 2021).

The quantitative degree of winter river discharge is considerably low in comparison with the discharge induced by spring snowmelt. Under future climate change, permafrost thawing is projected to increase (IPCC, 2021) such that engagement of permafrost-thawing-induced groundwater to winter river discharge will be further intensified. Wang et al. (2021) considered that for every 1 °C rise in temperature, the groundwater discharge of Siberian rivers would likely increase by 6.1 %–10.5 %, depending on permafrost condition.

Of all the Arctic rivers that flow into the Arctic Ocean, the Lena River in Russia has the second largest annual discharge. The Lena River is underlain almost entirely by continuous and discontinuous permafrost. Because climate change can lead to thawing and degradation of permafrost, it can have considerable impact on permafrost-implicated hydrological processes in the Lena River basin. Observations have already detected permafrost thawing initiated by rapid warming, and the resultant increasing of the active layer thickness (ALT) and its wetting (Iijima et al., 2010; Hiyama et al., 2021), together with their potential contributions to the increasing discharge of the Lena River, particularly in the low-flow season (Brutsaert and Hiyama, 2012) or in the cold season (Han and Menzel, 2022; Tananaev et al., 2016; Wang et al., 2021). Liu et al. (2022) recently analyzed the climate-change-related response of streamflow in four rivers (the Lena, Kolyma, Yukon, and Mackenzie rivers) during early, mid-, and late winter, considering relatively few dam effects, and concluded that winter streamflow generation under warming climate conditions was strongly associated with enhanced surface and subsurface hydrological cycles. Similarly, previous findings have clearly highlighted the possibility of permafrost-thawing–winter river discharge connectivity in the context of global warming (Smith et al., 2007). However, a spatially and temporally comprehensive picture of recent changes in the discharge of the Lena River remains lacking.

The discharge regime during the winter season is strongly related to river ice that is critical in terms of the magnitude and timing of northern

hydrologic extremes (i.e., low flows and floods). Historical data analyses (Shiklomanov and Lammers, 2014; Yang et al., 2002) and model studies (Park et al., 2016b) clearly show widespread decrease in both the thickness and the duration of ice in Arctic rivers due to the effects of global warming across northern regions. Increase in air temperature and resultant thinning of river ice could also be partly responsible for larger winter streamflow. Thinned river ice increases exchange between the surface and the bottom river water, leading to a higher runoff rate that restricts the vertical movement of floating ice cover occurring in mainly larger rivers; hence, leading to larger discharge (Prowse and Gridley, 1993). In small rivers, river ice thickness is comparable to winter river depth. Thus, in comparison with the contribution of large rivers, the contribution of small rivers is relatively low in a cold winter but it increases during a warmer winter (Markov, 2003). These results, which illustrate that the observed increase in winter discharge of Arctic rivers is particularly sensitive to climate change via thinning of river ice, highlight the need for more comprehensive examination of the underlying relationships.

In this study, we asked the following questions:

- How does climate change contribute to the increased winter discharge in the Lena River basin?
- How does permafrost thawing influence this discharge?
- How useful can a physics-based hydrological model be to investigate climate-change-induced permafrost dynamics and the associated hydrological processes?

Using observational data and model results for the period 1979–2016 in the Lena River basin, this study investigated the seasonal and long-term trends of the Lena River discharge including soil moisture and ALT to detect patterns of hydroclimatological change, and identified those regions contributing to the increase in winter river discharge in the Lena River basin. The results were examined using statistical correlation analysis and model sensitivity simulations with surface air temperature and precipitation as model forcing data.

2. Data and methods

2.1. Study site

This study considered the Lena River basin (Russia). Fig. 1 illustrates a geographical perspective of the basin, classified into four categories of permafrost zones. The Lena River basin includes the subbasins of several tributaries. The length of the main river channel is 4,400 km and the entire basin area is 2,430,000 km², the third largest among all of the Arctic circumpolar river basins (Hiyama et al., 2019). Annual discharge of the Lena River is 530 km³/yr (Peterson et al., 2002), which is the second largest of all northern Eurasian rivers and accounts for approximately 7 % of freshwater input into the Arctic Ocean (Serreze et al., 2006; Dickson et al., 2007). The main hydrological stations that measure the daily water levels and discharges in the Lena River basin are located at Kusr, Tabaga, Verkhoyanski Perevoz, and Khatyrik-Khomo (Fig. 1). The Kusr and Tabaga stations are at the lowest and middle points of the Lena River, respectively, and the Verkhoyanski Perevoz and Khatyrik-Khomo stations are at the lowest points of the Aldan and Vilui rivers, respectively (Fig. 1). A reservoir (maximum volume: 35.9 km³) is located in the upper and middle parts of the Vilui River (Yang et al., 2005). The maximum water storage of this reservoir accounts for approximately 77 % of the annual discharge (46.7 km³/yr) of the Vilui River and the winter river discharge of the Vilui River increased following the construction of the dam (Ye et al., 2003). Reservoir regulation also affects the discharge gauged at the Kusr station, particularly during winter when total discharge is low.

Permafrost thickness in the basin is estimated to be deeper than 100 m, and it is deeper than 500 m in the northern part of the basin. Mean annual ground temperature at the depth of zero annual amplitude

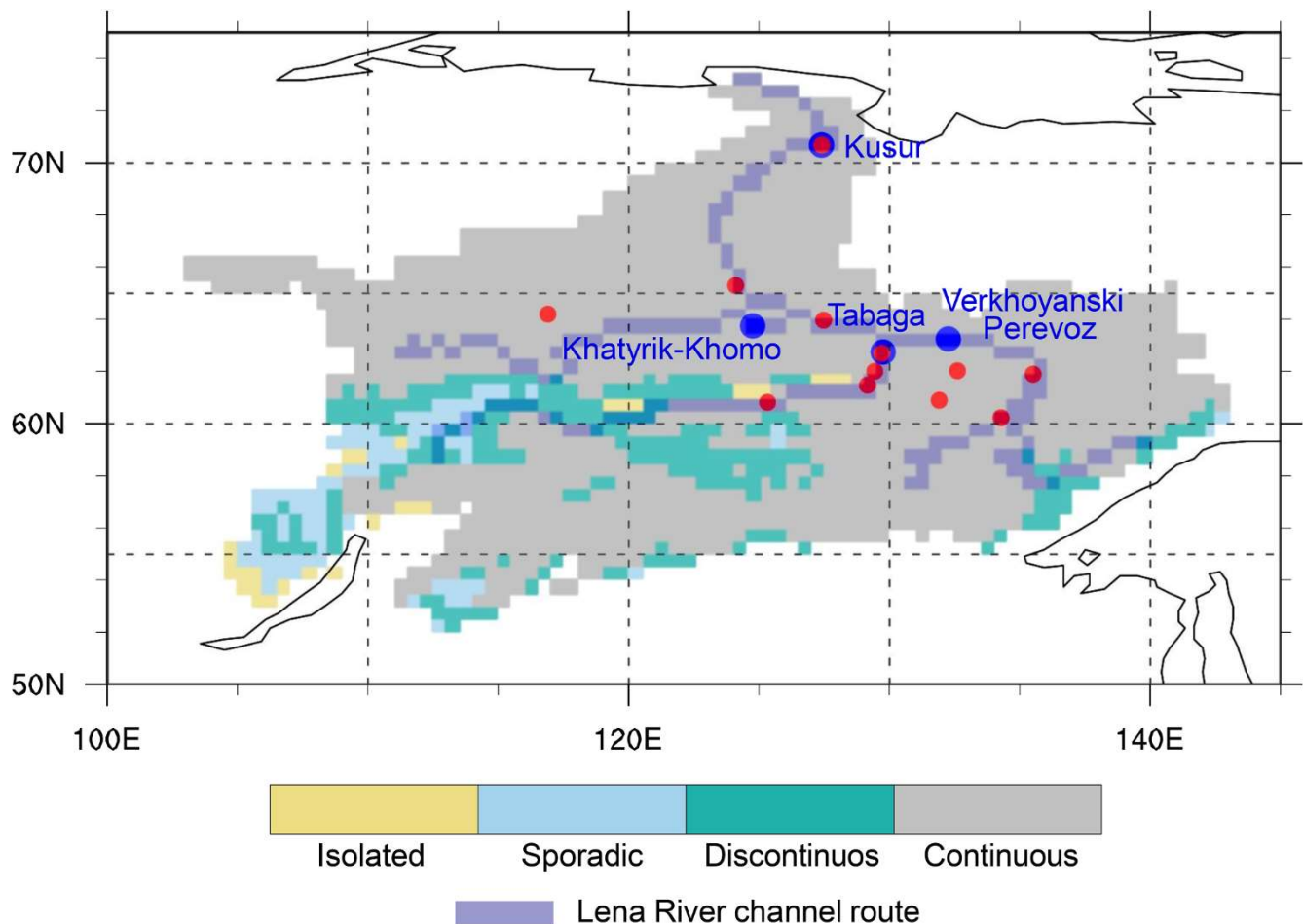


Fig. 1. Map showing permafrost distributions in the Lena River basin, where dark blue dots are the hydrological stations of Kusr, Khatyrik-Khomo, Verkhoyanski, and Perevoz. Red dots represent ALT observation sites, used for the validation of the simulations.

ranges from 0 to -12°C (Shestakova et al., 2021). The ALT are less than 0.3 m in the northern part and 3.5 m in the southern part of the basin (Shestakova et al., 2021). The classification of the permafrost zones (Fig. 1) shows that the upper part of the Lena River basin is underlain by continuous (90 %–100 %), discontinuous (50 %–90 %), sporadic (10 %–50 %), and isolated (0 %–10 %) permafrost. Similarly, the permafrost in the upper Aldan River basin is continuous and discontinuous. The other basin areas, including the Vilui River basin and the middle and lower parts of the basins of the Lena and Aldan rivers, are underlain by continuous permafrost.

2.2. Model

2.2.1. CHANGE

This study used the process-based land surface model CHANGE, which is a coupled hydrological and biogeochemical model (Park et al., 2011, 2018), for evaluation of the trends in terrestrial water budgets in the Lena River basin. CHANGE calculates the heat, water vapor, and carbon dioxide fluxes in the atmosphere–vegetation–snow–soil system, including snow and soil hydrology, soil freezing/thawing phase change, and stomatal physiology and photosynthesis (Fig. 2). The model-simulated snow meltwater is divided into infiltration and surface runoff at the soil surface layer, even during precipitation events. The infiltrated water flows up or down in the soil system depending on the water potential gradient between soil layers, and the excess water at either the permafrost table or the bottom soil boundary layer is converted to subsurface flow. ET is simulated as the sum of soil evaporation, transpiration, and rainfall interception by the canopy. Canopy

interception is assumed to occur at the potential rate without exceeding the canopy water storage capacity. Transpiration is expressed as the accumulated water extraction from soil layers weighted by the root fraction in each layer. Soil evaporation is limited by energy and atmospheric forcing and by a maximum exfiltration rate derived from soil properties for a given soil moisture. The model explicitly represents the dynamics of water and heat flows in permafrost soil by considering the freezing/thawing phase transitions in a soil column (depth: 50.4 m) to explicitly capture the thermal inertia of deep ground.

2.2.2. TRIP2

The grid-based river network model TRIP2 (Ngo-Duc et al., 2007) was coupled to CHANGE to simulate river discharge (Park et al., 2016b, 2017, Fig. 2). TRIP2 is a storage-based, distributed river routing model that adopts spatially effective subgrid parameters and broadly represents a more realistic travel time without calibration. The global river network TRIP with 0.5° spatial resolution (Oki and Sud, 1998) was used for TRIP2 that calculates riverine water storage, river discharge, water depth, and channel width in each grid cell at every time step. Water storage is the only prognostic variable, and the other variables are diagnosed from the water storage term. The CHANGE-calculated inflowed surface and subsurface runoff are stored in individual storage reservoirs and the water is routed along a prescribed channel network to the basin outlet. The model also includes river ice formation, growth, and melt, which affect heat storage and river hydraulics (Park et al., 2016b). The distribution of water temperature along a river is described by the one-dimensional advection–diffusion equation, based on heat inflow from upstream, heat exchange at the air–water interface, and

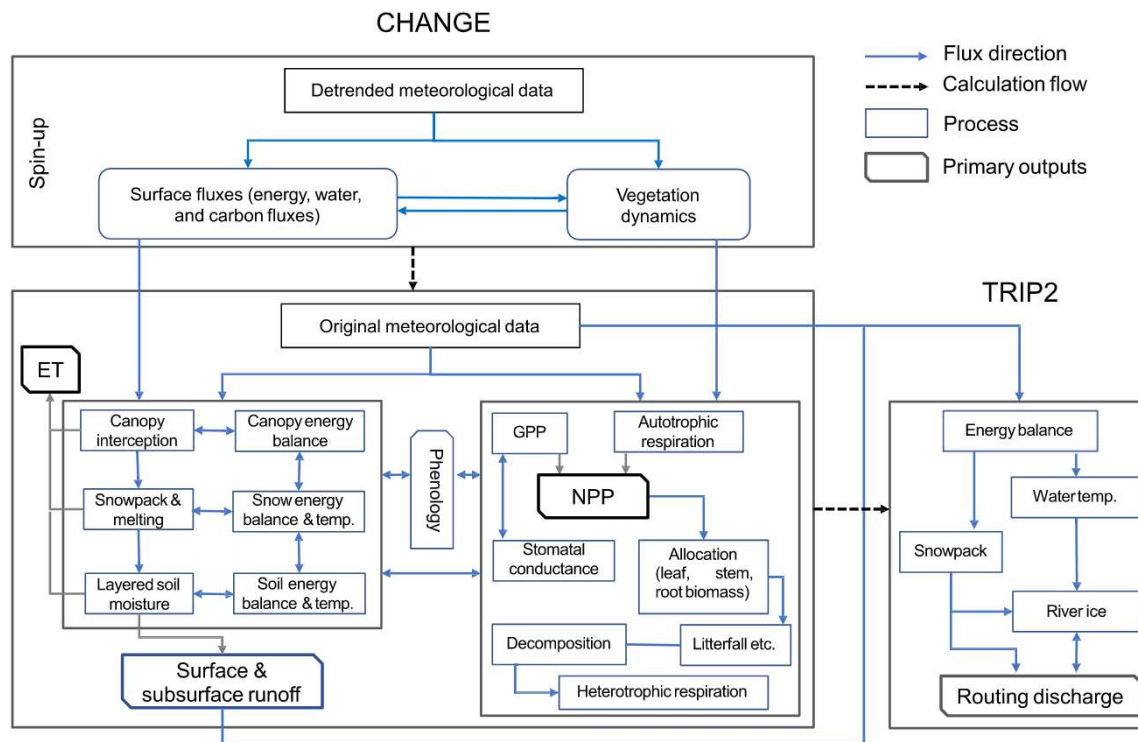


Fig. 2. Schematic representation of the modelling steps in CHANGE and TRIP2, including couplings and feedbacks between models or physical processes.

inflow of heat and water from tributaries (Park et al., 2017). The estimated water temperature is linked to determine the breakup and freeze-up of river ice. Reservoir regulation in the vilui River basin, which affects the discharge gauged at downstream stations was not considered in CHANGE simulations. This can yield increased uncertainties in the routed discharge and river ice thickness estimates.

2.3. Data

In Arctic regions, strong winds and sparse weather station measurements increase biases in observed precipitation. Using a specific forcing dataset dependent on such observational data can increase the uncertainty of simulated river discharge. We therefore used three different gridded climatic datasets as inputs for the CHANGE simulations (i.e., WATCH Forcing-Data ERA-Interim (WATCH, 1979–2016), <https://doi.org/10.24381/cds.20d54e34>; CRJNCEP - Atmospheric Forcing Data for the Community Land Model (CLIMATE, 1979–2016), <https://rda.ucar.edu/datasets/ds314.3/>; and Global Meteorological Forcing Dataset for land surface modeling of Princeton University (Princeton, 1979–2012), http://hydrology.princeton.edu/data_jgf.php). Datasets with 0.5° latitude/longitude spatial resolution were constructed by combining a suite of global observation-based datasets with different reanalysis datasets (i.e., ERA-Interim and NCEP/NCAR) to reduce biases related to low station density and data gaps. Using the three forcing datasets is useful to understand the uncertainties originating from the forcing data. CHANGE has already produced scientific results on river discharge and water temperature of Arctic rivers using the WATCH dataset (Park et al., 2016b, 2017). Therefore, the WATCH-forced simulation results are considered the main target for data analysis. The WATCH dataset, which was constructed from several data sources with corrections and interpolations, was described comprehensively by Weeden et al. (2011, 2014).

The forcing dataset for the 38-year period 1979–2016 consisted of the daily mean, maximum, and minimum air temperature, precipitation, water vapor pressure, specific humidity, wind speed, and solar radiation used for the CHANGE simulations of discharge, ET, and river ice

coverage and water temperature in the Lena River basin. Land cover was fixed to its present-day distribution, while vegetation phenology was prognostically determined from the simulated carbon and nitrogen fluxes, climates, and soil thermal and moisture conditions in individual time steps. CHANGE used vertical soil texture fractions for sand, silt, and clay derived from the IGBP Soil Data System to estimate the thermal and hydraulic properties of the soil, in combination with the simulated soil organic matter at every time step. Model simulations were run with a one-hour time step and a $0.5^\circ \times 0.5^\circ$ spatial resolution. A spin-up run was conducted for 1200 years using detrended forcing data from the initial 20 years to establish a dynamic equilibrium of the total ecosystem carbon and nitrogen contents (Fig. 2).

The Global Runoff Data Centre (GRDC) has archived monthly global river discharge data acquired from more than 9900 stations during 1980–2015 (https://www.bafg.de/GRDC/EN/04_speldebss/41_ARDB/arcticHycos.html?un=201698). The GRDC dataset includes the river discharge observed at four stations (i.e., Kusur, Khatyrik-Khomo, Tabaga and Verkhoyanski Perevoz; Fig. 1), although there are data gaps in both 2004 and 2005. The observed monthly data from the four stations were used to validate the model-simulated discharge.

We also used monthly discharge data obtained at 26 gauges in the Aldan River basin (Table 1), operated by the Russian Hydrological Service (Roshydromet). The dataset was lengthened to cover the period 1979–2016. The time series were evaluated for stationarity in relation to the presence of monotonic trends using Mann–Kendall and Spearman rank correlation tests. Details of the trend analysis were given by Lebedeva and Gustafsson (2021).

2.4. Sensitivity simulations

Different sets of numerical experiments forced by the WATCH dataset were designed to diagnose how changes in air temperature and precipitation affect river discharge and the permafrost thermal and hydrological regimes. The experiments were based on four scenarios, which included a control run forced by WATCH. Air temperature is a

Table 1

Gauge code, station name, and the geographical information of the 26 gauges in the Aldan River basin, operated by the Russian hydrological service (Roshydromet). A summary of trend analysis results for monthly discharges in the cold season (October–March) during the 38-year study period from 1979 to 2016 is also given (“Trend” column).

Gauge Code	Basin Area (km ²)	Altitude (m)	Latitude (°)	Longitude (°)	Discharge (km ³ /yr)	Trend*	Station Name
3218	18,500	390.8	58.06667	123.7167	324	positive	riv.Aldan - Suon Tiit
3219	19,500	272.6	58.96667	126.2667	807		riv.Aldan - Toramot
3220	102,000	210.6	58.33333	128.5	1788	positive	riv.Aldan - Ugino
3222	269,000	152.6	59.63333	133.0333	4267	positive	riv.Aldan - Ust Mil
3225	514,000	125.3	61.86667	135.5	6136		riv.Aldan - Okhotskii Perevoz
3229	696,000	74.1	63.31667	132.0167	8245	positive	riv.Aldan - Verkhovanskii Perevoz
3234	1,900	843.0	58.05	125.4833	44	positive	riv.Ulakh-Nymnyr - Bolshoi Nimnyr
3237	1,050	347.8	58.4	125.8	23		riv.Iakokit - Iakokit
3245	23	283.0	58.96667	126.2667	0.13		riv.Radio-Uruiete - 1.8 km ot ustia
3246	613	830.5	55.96667	124.8833	17		riv.Timpton - Nagornyi
3247	13,300	547.2	56.95	125.45	337		riv.Timpton - Ust-Baralas
3248	43,700	261.1	58.65	127.05	871	positive	riv.Timpton - Ust-Timpton
3250	961	800.8	56.21667	124.8333	28		riv.Iengra - Zolotinka
3252	3,840	639.5	56.83333	124.8667	94		riv.Chulman - Chulman
3254	316	704.1	56.66667	124.65	8.23		riv.Verkhniaia Neriunga - Neriungri
3564	196	713.9	56.66667	124.6833	5.79		riv.Malyi Berkakit - Snezhnyi
3257	152	553.5	56.96667	125.3833	4.17		riv.barylas - Gremuchii
3258	473	913.4	57.36667	124.9	8.98		riv.bolshaia Khatami - Bolshoi Khatyma
3259	101	917.8	57.4	124.9	1.54		riv.Sivagli - Martitovy
3261	2,710	350.2	58.58333	126.75	58	positive	riv.Bolshoi Yllymakh - Yllymakh
3263	30	274.0	58.65	127.0333	0.95		riv.Malyi Yllymakh - Sobolyni
3264	108,000	230.4	57.76667	130.9	1754	positive	riv.Uchur - Chiulbiu
3277	24,200	N/A	60.61667	135.1333	350		riv.Allakh-Un - Allakh
3291	23,900	270.2	59.66667	127.05	409		riv.Amga - Buiaga
3292	56,800	134.4	60.9	131.9833	441	positive	riv.Amga - Amga
3293	65,400	112.5	62.21667	134.1333	479	positive	riv.Amga - Teriut

Remarks:

* Gauges showing positive trend for more than 3 months in the cold season (October–March) are indicated as “positive,” and those showing positive trend for all 6 months are shown as “**positive**” (See Supplementary Table 1).

critical variable for vegetation activity, permafrost temperature, and snow cover variation. Therefore, two scenarios included an increase in air temperature of either 2 °C or 4 °C during the simulation period, excluding the 1200-year spin-up period. The fourth scenario included an increase in air temperature of 2 °C in combination with a 30 % increase in precipitation.

3. Results

3.1. Validation of model performance

3.1.1. Active layer thickness (ALT)

Notably, the thawed soil depth of the active layer during the warm season has an impact on the increase in winter river discharge from the Lena River basin (Smith et al., 2007). Consequently, it was necessary to compare the simulated ALT with observations; however, basin-scale observational data of ALT are not available. The CHANGE-simulated ALT has previously been compared with that monitored at 147 sites,

and their comparison showed reasonable performance by CHANGE on the pan-Arctic scale (Park et al., 2013). CHANGE also simulated the interannual variability of permafrost temperature observed at 10 m depth (Park et al., 2015). An empirical model was suggested to estimate ALT on the global scale using reanalysis surface air temperature data and thawing/freezing data based on satellite remote sensing retrievals, for which CHANGE-simulated ALT was in good agreement with method-derived results and observations in eastern Siberia, including the Lena River basin, from 1979 to 2009 (Park et al., 2016a). In this study, the CHANGE-simulated ALT was additionally compared with the ALT observed at soil temperature monitoring sites, located in the Lena River basin and installed by the Melnikov Permafrost Institute. ALT was linearly estimated from observed soil temperature profiles for individual sites (Table 2). The CHANGE-simulated ALT values were in agreement with observations ($r = 0.68$, $p < 0.001$) acquired at 12 sites with different climatic and topographic conditions (Fig. 1), while the compared ALT between averaged observations and simulations in individual stations showed differences, within −23 % (−55 cm) to +23 %

Table 2

Comparison of observed and CHANGE-simulated mean ALT values at soil temperature monitoring sites in the Lena River basin.

Latitude (°)	Longitude (°)	Observed ALT (m)	Simulated ALT (m)	RMSE (m)	Error (%)	r	Period
62.01	129.43	2.27	1.78	0.55	−21.7	0.37*	1979–2004
61.48	129.15	2.25	1.75	0.47	−22.3	0.37**	1979–1990
61.90	135.50	1.87	1.70	0.19	−9.1	0.29	1979–1990
60.90	131.90	1.57	1.72	0.24	+10.0	0.20	1979–1990
65.30	124.10	1.61	1.71	0.22	+6.1	0.17	1979–1987
60.82	125.32	1.33	1.64	0.24	+23.0	0.08	1979–1997
62.70	129.70	1.63	1.80	0.20	+10.1	0.46	1979–1990
63.97	127.47	1.94	1.67	0.47	−13.8	0.43**	1979–1999
64.20	116.90	1.36	1.26	0.11	−7.4	0.34	1980–1990
62.03	132.60	1.93	1.76	0.32	−8.9	0.57***	1979–2006
60.23	134.27	2.29	1.94	0.37	−15.2	0.71***	1979–2005
70.68	127.40	1.21	1.07	0.24	−11.3	0.24	1979–2000

RMSE: root mean square error (m), Error: percentage of simulated values departed from observations, r : correlation coefficient.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

(+31 cm) with root mean square error ranging 11 cm to 55 cm (Table 2). These differences were attributed to spatial resolution differences and to the influence of homogeneous soil texture on the vertical soil profile, affecting soil thermal and hydraulic properties in the model (Park et al., 2013).

3.1.2. River discharge

Comparison of CHANGE-simulated river discharge with observational records obtained at the mouths of major Arctic rivers with differing climate, topography, and landscape showed reasonable agreement in terms of seasonal and interannual variation (Park et al., 2016b). Thereafter, a process that simulates the water temperature of Arctic rivers based on the energy budget equation was improved in CHANGE (Park et al., 2017). The improved model-simulated river water temperature likely affects the breakup/freezing of river ice, closely implicated in the discharge processes in spring and autumn. Therefore, the simulated seasonal river discharges using the three forcing datasets were compared with the observed data at the outlet (Kusur) and internal (Khatyrik-Khomo, Verkhoyanski Perevoz, and Tabaga) hydrological stations on the Lena River (Fig. 3). A reservoir constructed at the upstream of the Khatyrik-Khomo station regulated river flow. However, the model did not consider the regulation, affecting the discharge of the Lena River mouth. Thus, the discussion for the model performance is limited to the inner two stations of Verkhoyanski Perevoz and Tabaga. The comparison reveals that the model generally simulated the seasonal variability of discharge observed at the two stations, performing well in terms of the start-up and timing of the spring peak discharge closely implicated in snowmelt processes (Fig. 3). However, the model was found to produce underestimation for summer discharge of the Tabaga

station (Fig. 3d) while overestimations of discharge in autumn and early winter for both stations (Fig. 3c and d), as identified by the lowest monthly Nash–Sutcliffe coefficients, particularly in November and December (Fig. 3). The deviations of the simulated discharges are attributable to the impact of runoff derived by the seasonally biased precipitation from the upstream mountain regions. The influence of mountain runoff on river discharge is discussed in section 3.2.1. Moreover, the overestimated ET (Park et al., 2008) is likely implicated to the underestimated summer discharge of the Tabaga station. The CHANGE-simulated annual mean ET was 200 mm over the Lena River basin, larger than the 160–182 mm value estimated from reanalysis data (Fukutomi et al., 2003; Serreze et al., 2003). In the Aldan River basin, the simulated annual mean ET of 228 mm was comparable to the 233 mm derived with the water budget method (Berezovskaya et al., 2005), but lower than the 300 mm (or more) estimated with a numerical model (Han and Menzel, 2022). Underestimated ET could partially explain overestimated discharge simulations at the Verkhoyanski Perevoz station.

The simulated seasonal discharges revealed differences between the forcing datasets: simulations with CRUNCEP data yielded the lowest discharge estimate, whereas simulations using WATCH data yielded the highest values (Fig. 3). Differences between the datasets were attributed to quantitative differences in precipitation, showing the difference of annually 30 mm. Consistent differences were also identified in the interannual discharge variations (Fig. 4). Comparison between observations and the ensemble mean of the three simulations consistently showed some differences, illustrating particularly limited model performance at the two upstream stations, with Nash–Sutcliffe coefficients lower than 0.2. The observed and simulated annual discharges showed increasing trends during the study period. The analysis also revealed

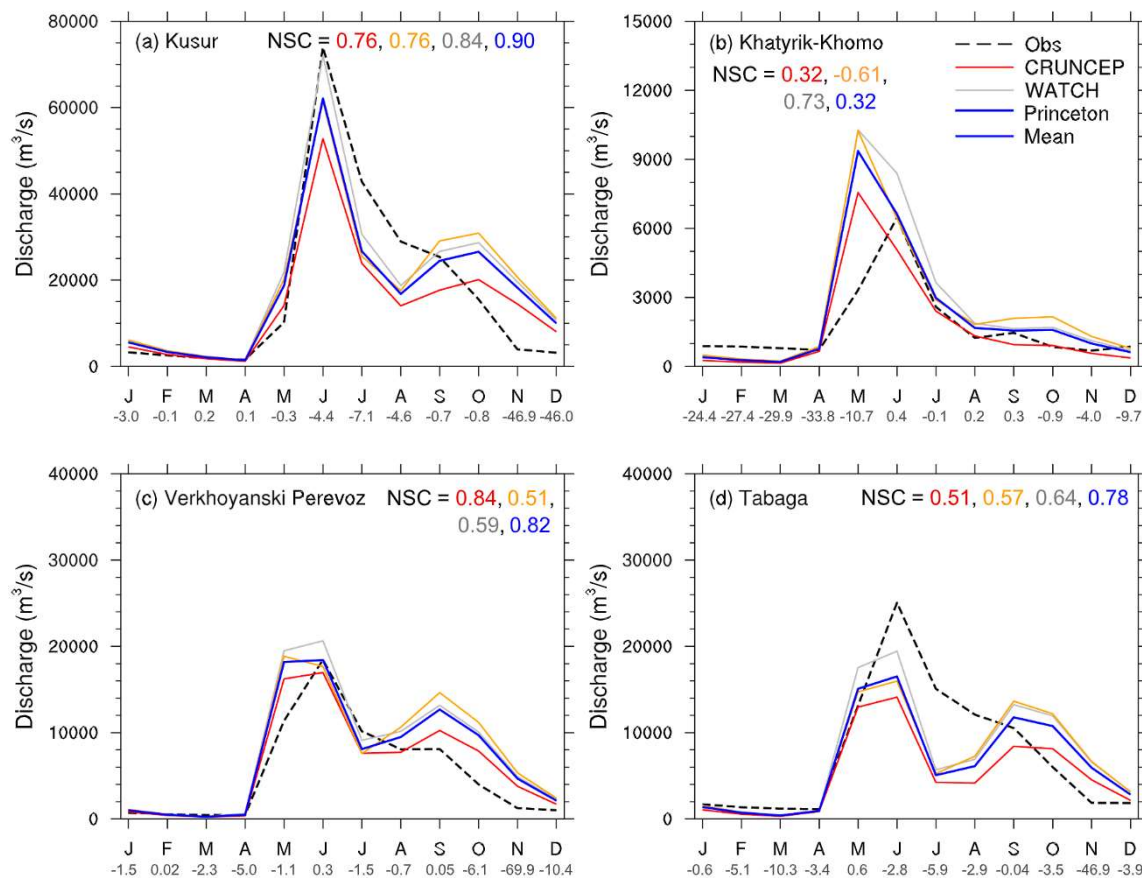


Fig. 3. Seasonal variation in climatological mean river discharge (for 33 years from 1980 to 2012) at (a) Kusur, (b) Khatyrik-Khomo, (c) Verkhoyanski Perevoz, and (d) Tabaga stations. The simulated river discharges forced by the three forcing datasets (red, gray and orange solid lines) and the ensemble mean (blue solid line) were compared with the observed records from the GRDC (dashed line). NSC in each panel means the Nash–Sutcliffe coefficient. The numbers below each panel represent the monthly NSC calculated with the ensemble mean of the three datasets and observed discharges.

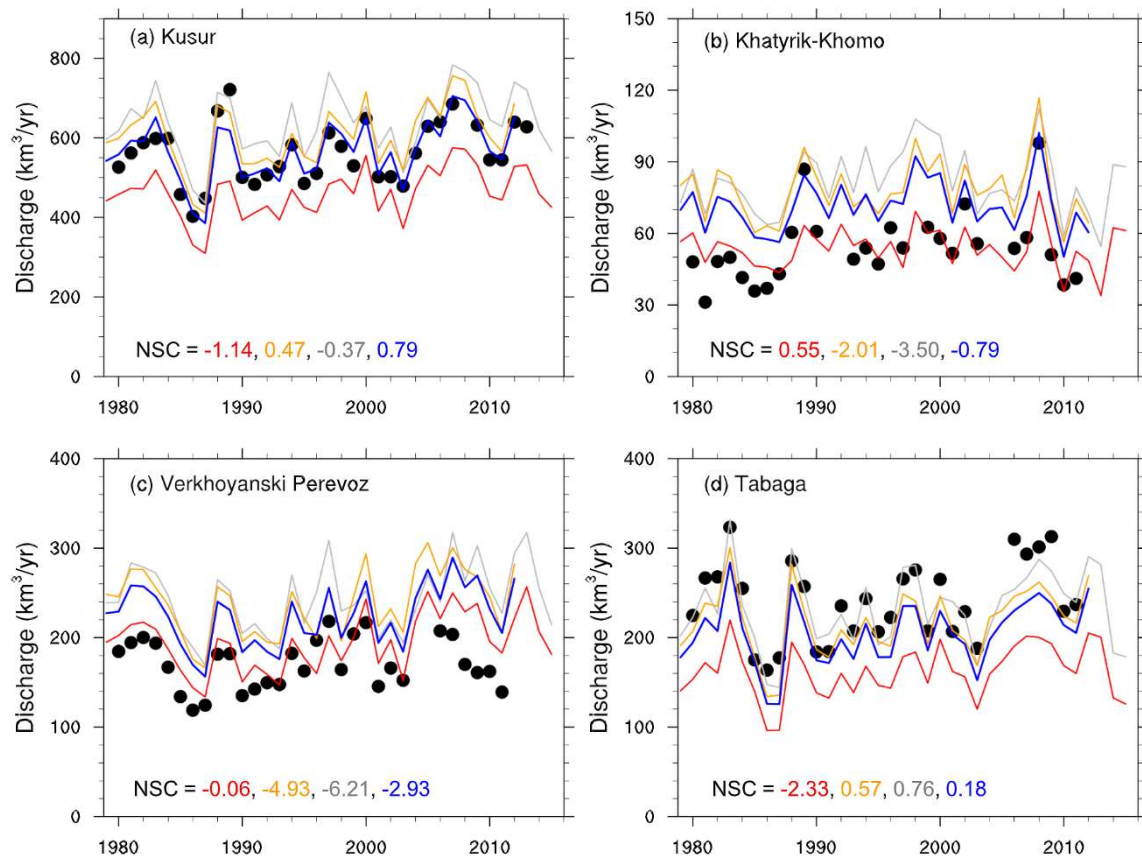


Fig. 4. Interannual variation of the observed and simulated annual river discharge from 1979 to 2016 at (a) Kusur, (b) Khatyrik-Khomo, (c) Verkhoyanski Perevoz, and (d) Tabaga stations. The comparison includes the observation sourced from the GRDC (black dots), the simulations forced by the three forcing datasets (red, gray and orange solid lines) and the ensemble mean (blue solid line). Color-coding is consistent with Fig. 3. NSC in each panel means the Nash-Sutcliffe coefficient.

statistically significant increasing trends in autumn and winter and decreasing trends in summer (Supplementary Fig. 1). Thus, results on the trend analysis are shown in the following sections.

3.2. Trend of water budget components

3.2.1. Net precipitation and soil moisture content

Runoff that occurs within the soil system is largely dependent on the water budget of precipitation and ET, vegetation and soil type, and topography. The trends in monthly mean precipitation from 1979 to 2016 were consistently positive, except in December, and particularly high in the summer (JJA) and early autumn (SO) seasons (Supplementary Fig. 2). ET indicated marked increasing trends during the growing season, especially in early summer (Supplementary Fig. 2) when vegetation activity is vigorous and the active layer develops. Climatological values of the calculated monthly net precipitation (i.e., precipitation minus ET) peaked at 50 mm month^{-1} in summer in southern regions of the Lena River basin (Supplementary Fig. 3b), corresponding to the upstream areas of the Verkhoyanski Perevoz and Tabaga stations (Fig. 1), characterized by mountain climates. Conversely, summer net precipitation indicated negative values in middle and lower parts of the Lena River basin, representing larger ET than precipitation (Supplementary Fig. 3b), which was likely linked to the underestimation of river discharge in summer from the Tabaga station (Fig. 3d). Generally, in the autumn in which rainfall becomes the water source on the land surface, net precipitation is broadly positive over the entire basin (Supplementary Fig. 3), resulting in larger autumnal discharge (Fig. 3).

Fig. 5 shows the interannual trend distribution of seasonally different net precipitation from 1979 to 2016 in the Lena River basin. Summer (JJA) net precipitation showed regionally heterogeneous trends that

were significantly increased in the upper parts of the basins of the Lena and Aldan rivers as well as in the lower part of the Lena River basin, but decreased in parts of the upper area of the Lena and Aldan River basins (Fig. 5b). These results were generally consistent with the interannual trend variation rates (Supplementary Fig. 4a). The trend of distribution of net precipitation in both spring (MAM) and autumn (SON) also presents a similar pattern to that in summer, although there are differences in magnitude (Fig. 5a, c). In winter (DJF), decreasing trends in net precipitation are evident throughout much of the Lena River basin, excluding some regions (Fig. 5d); the lowest negative trends ($< -0.2 \text{ mm month}^{-1} \text{ yr}^{-1}$) were probably caused by a decrease in fractional snowfall amount relative to winter precipitation.

Net precipitation in winter is not directly coupled to the variation of soil moisture because it exists as snow on the soil surface during this season. As it melts in spring, the meltwater becomes connected to soil moisture. The soil moisture in the active layers during the warm season likely contributes to the generation of subsurface runoff. Therefore, we analyzed the linear trends of the simulated monthly soil moisture in the active layers during the study period; the analysis assumed that the maximum ALT was no deeper than 3.6 m in the Lena River basin and that the moisture in the soil layers deeper than 3.6 m remained steady over the entire basin (Shestakova et al., 2021). Fig. 6 shows the distribution of the analyzed linear trend of monthly soil moisture within the active layer in May–October. The regions in which soil moisture is increased are generally consistent with areas of increased net precipitation (Fig. 5). The increasing trend of soil moisture is also associated with the ALT. The model simulation identified the increasing trend of ALT throughout the entire Lena River basin (Supplementary Fig. 5). The ALT increase physically represents storage of large amounts of soil moisture, and thus the increased net precipitation during the warm

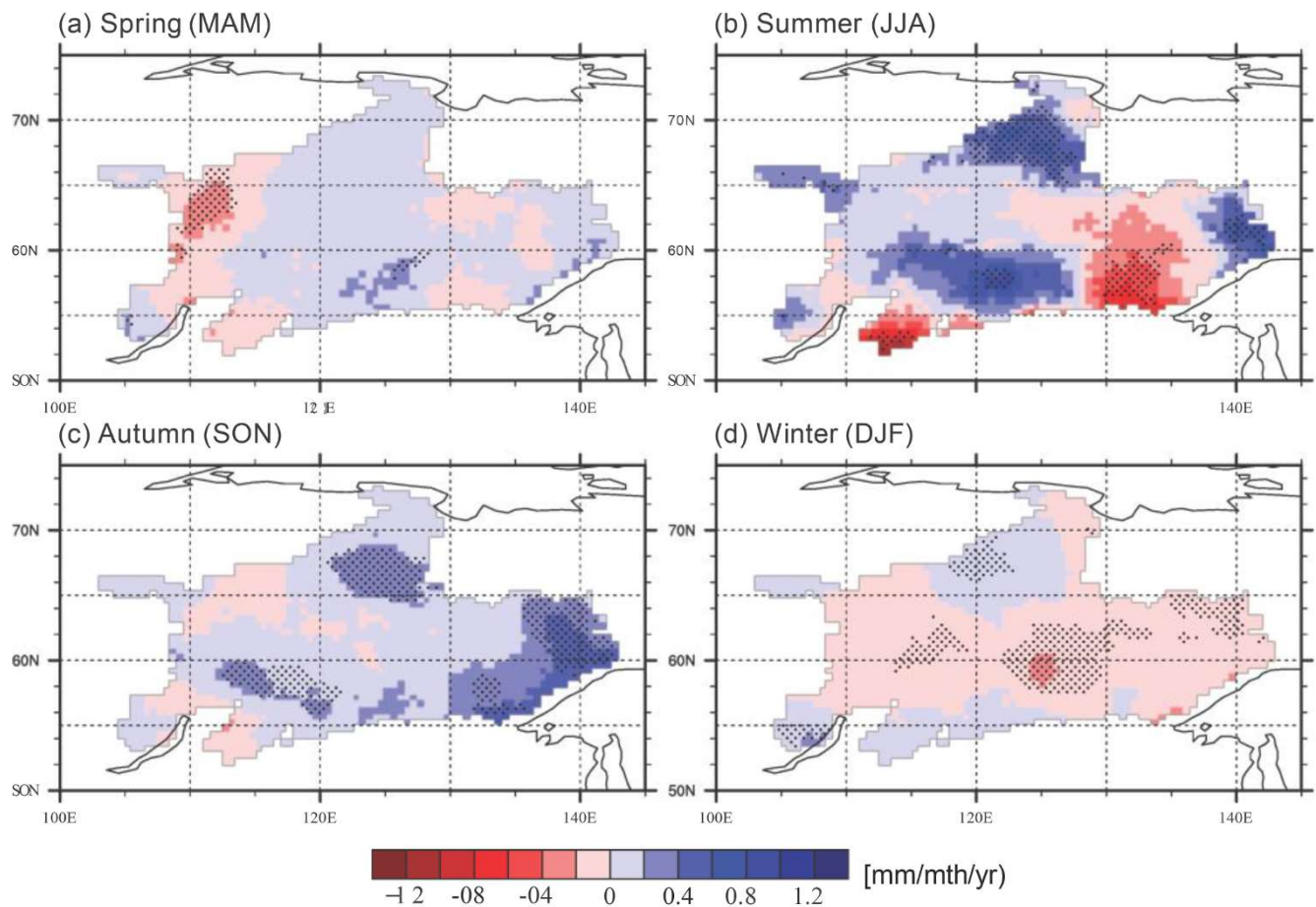


Fig. 5. Distributions of linear trend in seasonal net precipitation (precipitation minus evapotranspiration) from 1979 to 2016 in the Lena River basin. Precipitation was obtained from WATCH and evapotranspiration was calculated by CHANGE. The dotted areas represent statistically significant results at the 95% confidence level in the trend analysis from the Mann-Kendall test.

season (Fig. 5) is likely easily recharged to the deepened active layers as soil moisture. The ALT increase also enhances permafrost thawing, and the ground ice meltwater is added to the soil moisture. The soil moisture in the active layer might be the source of groundwater and its discharge (baseflow), which is a hypothesis confirmed in section 3.2.2.

3.2.2. Baseflow in the cold season

The CHANGE-simulated fractional discharge amount in the Lena River basin was higher in the surface runoff than in the baseflow (Supplementary Fig. 6). The source areas generating the runoff water were evidently different; the surface runoff fraction was higher in the lower plain areas, while baseflow was the primary source in the southern and eastern mountain regions. The source areas of the higher baseflow are consistent with the regions characterized by higher net precipitation in the warm seasons, particularly summer (Supplementary Fig. 3b), which suggests a relationship between baseflow and soil moisture closely linked to summer net precipitation. CHANGE simulations indicated that baseflow at the Kusur station occurred primarily in autumn and early winter, whereas the largest surface runoff, associated with snow meltwater, occurred in late spring and summer (Supplementary Fig. 7). Slight amounts of baseflow continued until late spring.

Statistical analysis was conducted to examine the seasonal and spatial trend of baseflow during 1979–2016. Fig. 7 shows distributions of the linear trend in baseflow for the 33 years in the cold season (October–March). The baseflow exhibits a significant trend of increase in the upper and lower parts of the Lena River basin as well as in the upper basin of the Aldan River, where the increase was significant in October and November. The identified regions and months are generally

consistent with those in which net precipitation increased (Fig. 5). Net precipitation during the warm season largely becomes the supply of soil moisture in the active layers, reducing soil drying; thus, the wetted soil moisture is likely connected to the subsurface flow system. The increase of baseflow (groundwater discharge) in the upper and lower parts of the Lena River basin is probably associated with the increase in soil moisture in these regions, contributing to the trend of increase in river discharge in the cold season. The active layers of the Lena River basin become frozen during the winter season owing to the colder air temperatures. Baseflow from frozen soil rarely occurs in winter. Therefore, soil moisture in late summer or autumn could be the main contributor to winter baseflow and thereby river discharge. This hypothesis is examined based on lag correlation analysis between soil moisture and winter baseflow.

Fig. 8 shows distributions of the lag correlation in interannual variation between monthly soil moisture in the active layer and winter baseflow. The analysis indicates higher lag correlations between soil moisture in late summer (August and September) and winter baseflow, particularly in the upper parts of the basins of the Lena and Aldan rivers. The surface soil layers (0–1 m) are generally frozen in October (as a monthly mean situation), while the deeper soil layers remain as a thawed layer until early winter, in which unfrozen water could also contribute to winter baseflow. The regions in which there was winter baseflow indicated a trend of increase in summer net precipitation (Fig. 5), associated with small values of ALT freezing in later months (Supplementary Fig. 8). The resultant higher soil moisture in late summer (August–September, Fig. 6) is likely linked to the increase in baseflow in the cold season (Fig. 7).

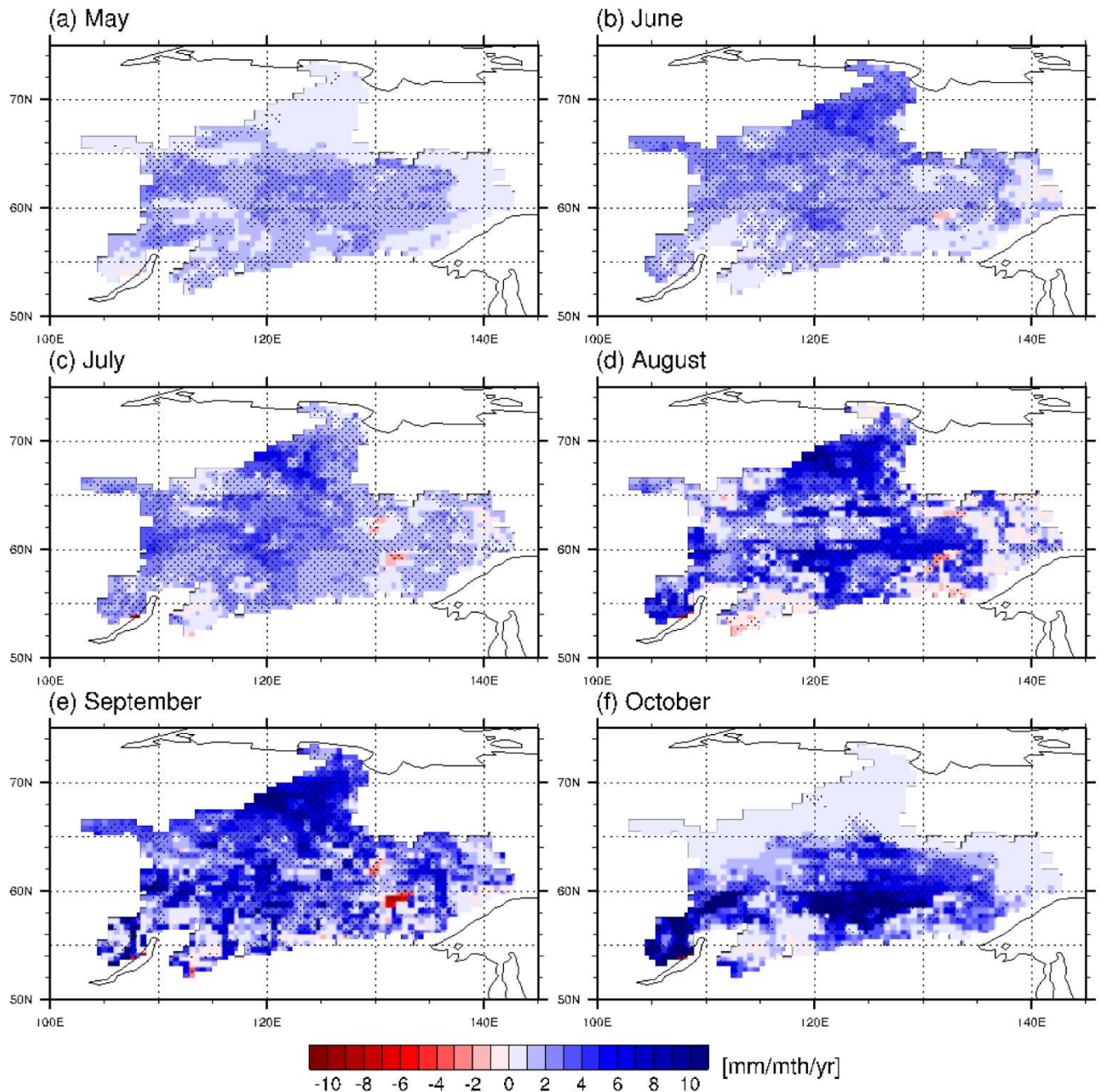


Fig. 6. Distributions of linear trend in monthly soil moisture within the active layer from 1979 to 2016. It is assumed that the maximum active layer thickness (ALT) is not deeper than 3.6 m and the soil moisture deeper than 3.6 m is steady for the whole basin. The dotted areas represent statistically significant results at the 95 % confidence level in the trend analysis from the Mann-Kendall test.

3.3. Source region of winter river discharge

The above analytical results indicate that increased summer net precipitation resulted in increase of soil moisture in the active layer in late summer, which was connected to the increase in baseflow in the cold season, especially in the upper parts of the basins of the Lena and Aldan rivers. These implications were investigated by performing correlation analyses among ALT, soil moisture, and baseflow in the cold season (Fig. 9). Fig. 9a shows a scatter plot between the linear trends of soil moisture in the active layer and ALT during 1979–2016 in the Lena River basin, additionally visualizing the trend of the autumnal baseflow on their relationship. The trend of soil moisture is clearly shown to be almost entirely correlated positively with that of ALT; as the ALT

increased, the soil moisture correlating to the increased net precipitation increased. Meanwhile, the trend of autumnal baseflow was not homogeneous with the positive relationship between the two variables; negative baseflow trends were found at the range of their positive trend. However, the plots showing positive trend in the baseflow were concentrated in the ranges of the positive trends at 0–2 cm yr⁻¹ for ALT and 0–10 mm yr⁻¹ for the soil moisture. Here, a geographical plotting method was used to detect regions presenting positive trends in ALT (0–10 cm yr⁻¹), soil moisture (0–10 mm yr⁻¹), and autumnal baseflow (0.1–8 mm mth⁻¹ yr⁻¹, Fig. 9b). The regions in which the trends of the three variables were positive were distributed randomly throughout the entire Lena River basin, especially in the lower (northern) and upper (southern) parts of the Lena River basin and the Aldan River basin. These

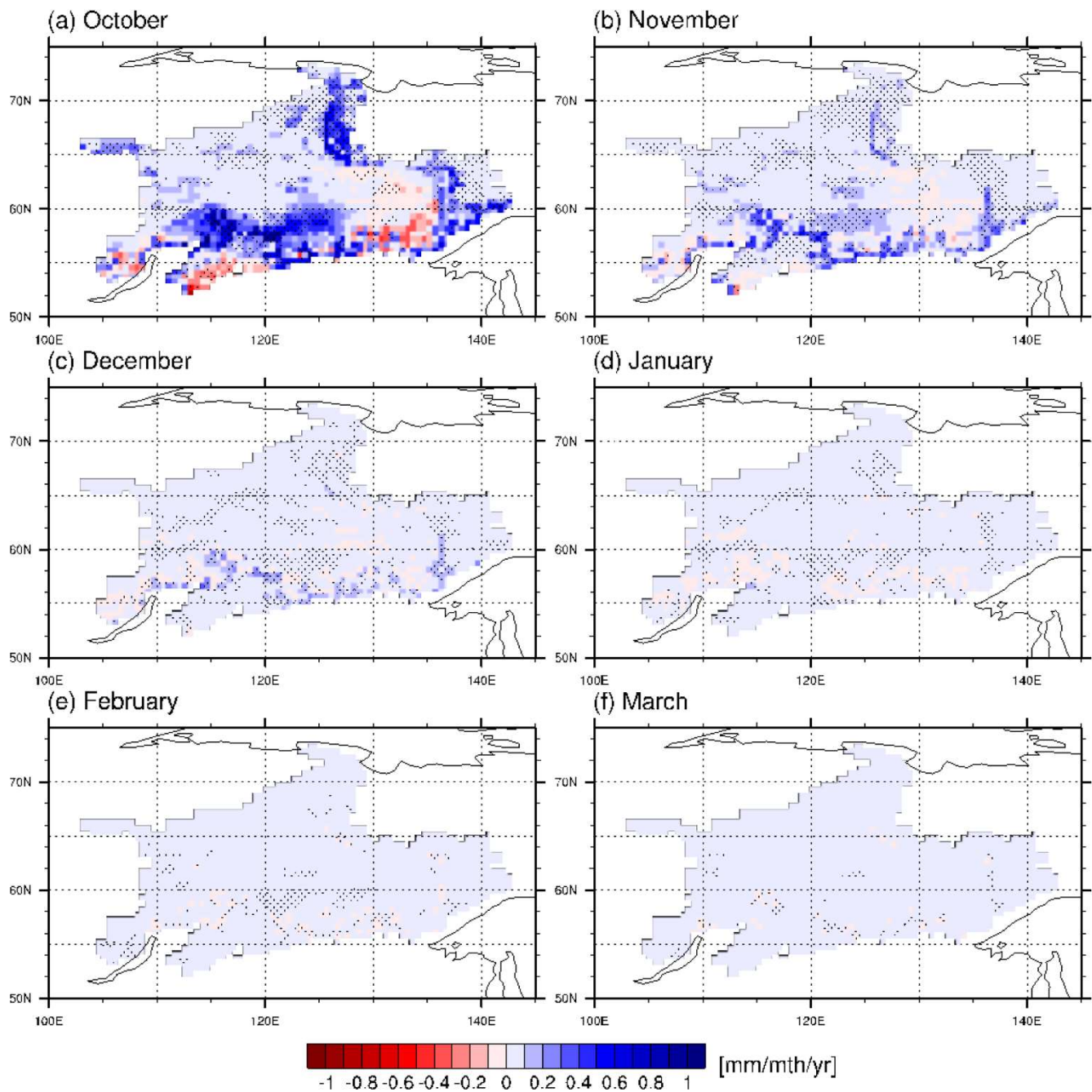


Fig. 7. Distributions of linear trend in baseflow in cold season (from October to March) from 1979 to 2016. The dotted areas represent statistically significant results at the 95% confidence level in the trend analysis from the Mann-Kendall test.

regional distributions suggest that soil moisture in the northern part of the basin, where soil freezing occurs relatively early in comparison with southern parts of the basin (Supplementary Fig. 8), is linked to autumnal baseflow prior to the freezing of the active layer.

Fig. 9c shows a scatter plot of the trend of winter baseflow in the relationship between the linear trends of soil moisture within the active layer and ALT. The pattern shown in Fig. 9c is similar to that shown in Fig. 9a, although the trend values of winter baseflow are lower than the autumnal values. However, some of the winter baseflow showed a strong trend of increase ($>2.0 \text{ mm mth}^{-1} \text{ yr}^{-1}$) in the area of concentrated positive trends (Fig. 9c). We also identified regions with positive trends in the three variables (Fig. 9d). The regions that showed consistently increasing trends in the three variables were distributed widely in the upper parts of the basins of the Lena and Aldan rivers, where the

landscape is underlain by discontinuous permafrost (Fig. 1) and autumnal baseflow is also increased (Fig. 9b). This indicates that the increase in winter discharge of the Lena River is primarily the result of the increase in winter baseflow in upper parts of the basin.

To confirm the above model-based analysis on the detection of the source region in relation to winter river discharge, trend analysis was applied to the observed monthly discharges in the cold season (October–March) observed at 26 river stations in the Aldan River basin during 1979–2016 (Table 1). The months and gauges when rivers freeze-up to the bottom and have zero flow every year were excluded from the analysis. The analyzed results revealed various regimes of discharge at the stations with positive/negative monthly trends (Supplementary Table 1). Interestingly, statistically significant change in monthly discharge occurred mostly between the mid-1990s and mid-2000s. This

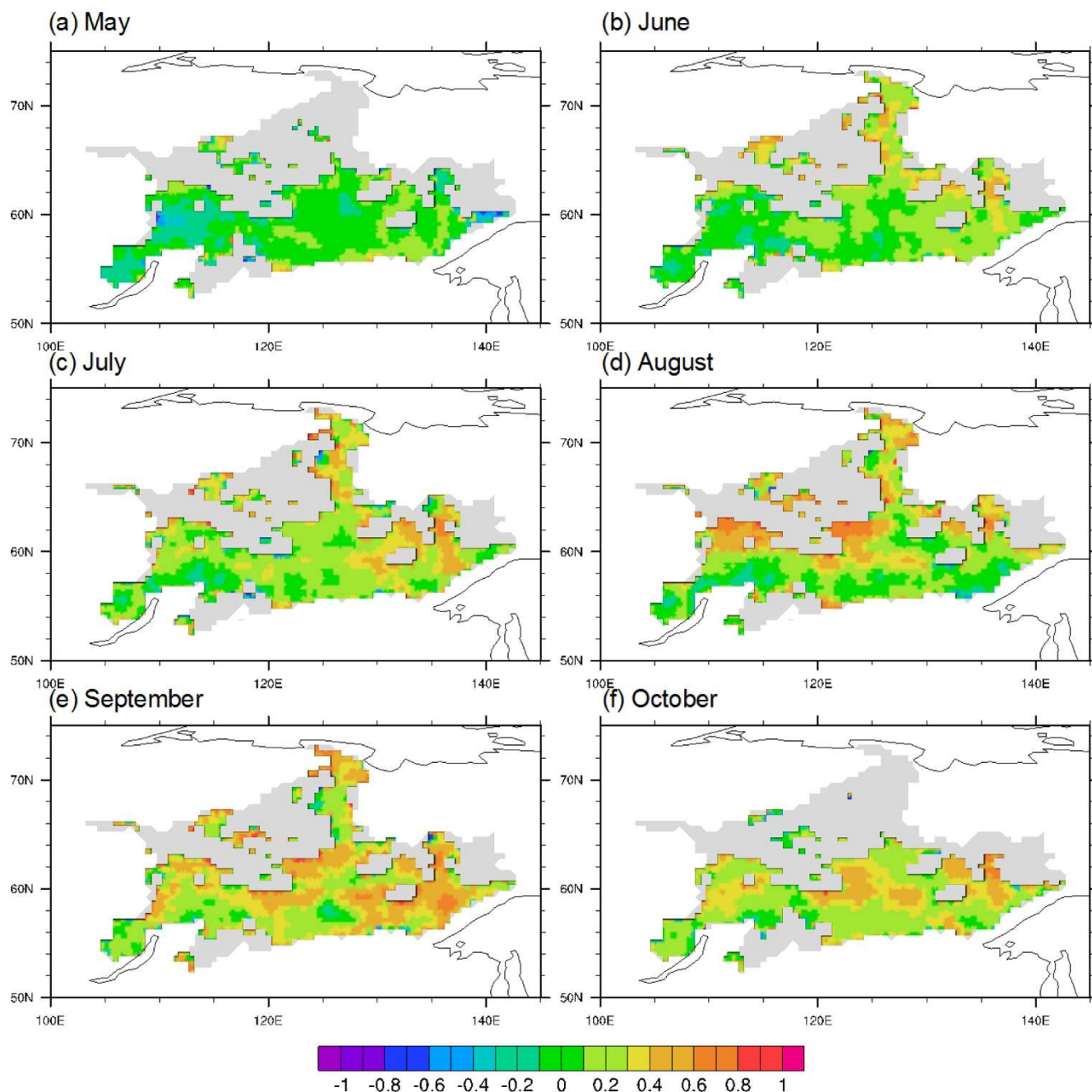


Fig. 8. Distributions of lag correlations in interannual variations between monthly soil moisture in the active layer and winter baseflow. The gray shading represents the basin mask.

could be associated with the increase in net precipitation in the same period (Hiyama et al., 2016). Positive trends were identified in 57 months (45.6 %) among the total of 125 months of the cold season, except those with zero flow caused by complete freeze-up of stream water. Insignificant trends were found in 66 months (52.8 %) and negative trends were detected in only 2 months (1.6 %). Significant increases in monthly discharge during October–January were observed at approximately half of the non-frozen gauges. In February and March, one-third of the gauges showed positive trends. The regime in which winter discharge recorded positive trends over 3 months or more in the 6 cold months was found at 10 stations (Table 1). Thus, this analysis broadly supports the robustness of the model-based results presented above.

3.4. Trend of river ice thickness

Warming air temperatures likely affect river ice processes (i.e., breakup, freeze-up, and thickness) that are closely associated with winter river discharge. An increase in river ice thickness means conversion of discharging water to ice and resultant decrease in river discharge, although the ice is subsequently added to river discharge in spring. Conversely, a decrease in ice thickness represents a potential contribution to increased river discharge. To examine the impact of changing river ice thickness on winter river discharge, the river ice volume of the Lena River basin was calculated based on model-simulated ice thickness and river width and length of individual grids. Fig. 10 displays the trend of the simulated monthly averaged river ice volume of the Lena River basin during the study period, indicating a trend of decrease in all months. The decrease of ice volume was greatest

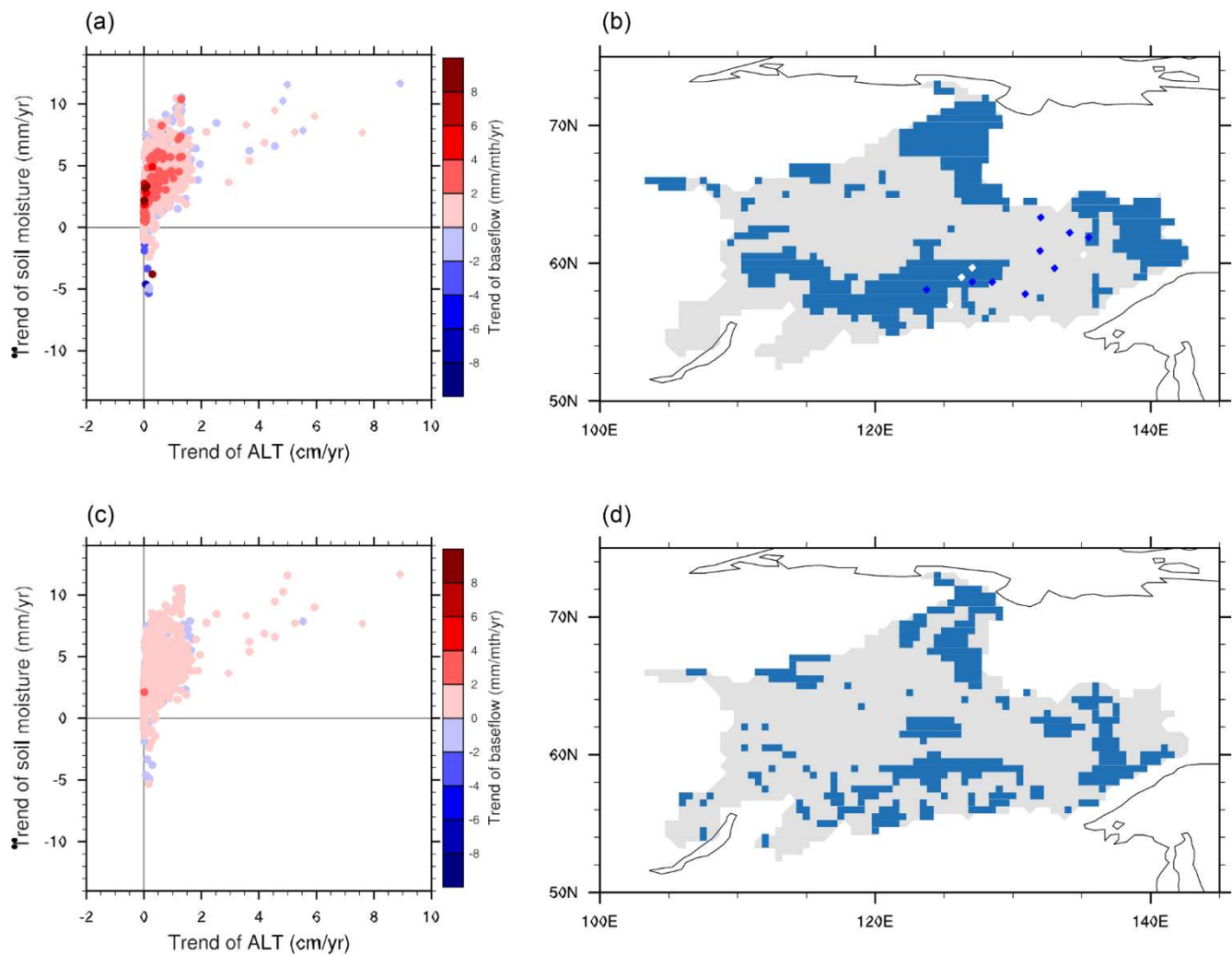


Fig. 9. Box plots represent relationship between linear trends of soil moisture within the active layer and ALT, with linear trend of baseflow in (a) autumn (SON) and (c) winter (DJF) from 1979 to 2016. Geographical distributions showing linear trend for soil moisture within the active layer, ALT, and the baseflow in (b) autumn (SON) and (d) winter (DJF) for the study period. The blue colors in (b) and (d) configure regions showing positive trends in ALT (0–10 cm yr⁻¹), soil moisture (0.1–10 mm yr⁻¹), and baseflow (0.1–8 mm mth⁻¹ yr⁻¹), and the gray in the base maps represents the basin mask.

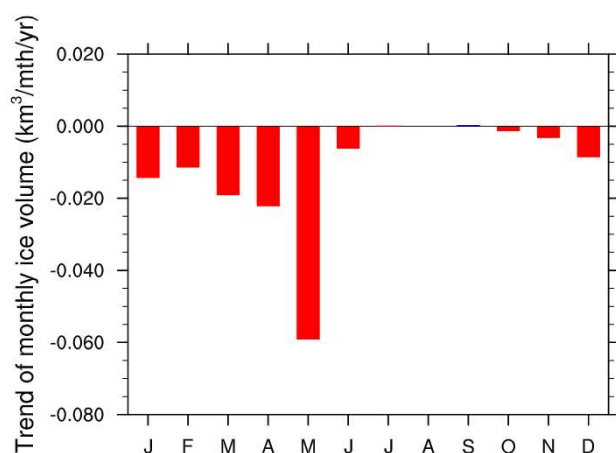


Fig. 10. Trends of CHANGE-simulated monthly mean river ice volume in the Lena River basin during the study period. The ice volume was calculated based on the simulated river ice thickness, river width, and channel length in individual grids and integrated over the entire Lena River basin.

in May, which reflects decreased ice growth during the entire winter. The decreased ice volume is primarily attributable to the impact of warming air temperatures (Park et al., 2016b; Shiklomanov and Lammer, 2014). The increased snow depth is likely to further reinforce the ice-thinning trend (Park et al., 2016b).

3.5. Sensitivity simulations

Four sensitivity simulations, described in section 2.4, were conducted to investigate the influence of the warming climate on hydrological variables. Increased air temperature induced a baseflow decrease in autumn and winter, particularly in the southern mountainous regions (Fig. 11a, b) where the baseflow was originally large (Supplementary Fig. 6). Seasonally, the increased air temperature induced strong summer discharge decreases at the two stations, especially in June, whereas ET in the entire Lena River basin increased considerably (Supplementary Fig. 9), causing soil drying. This temperature-driven discharge decrease, influenced by larger ET, lasted until autumn. These results indicate that, when only air temperature increased, the Lena River discharge decrease was likely caused by higher ET. In the fourth simulation, the precipitation increase likely alleviated the ET-induced soil drying and offset the river discharge decrease. Indeed, the ET-induced river discharge decrease in summer was absent from the fourth simulation results, but

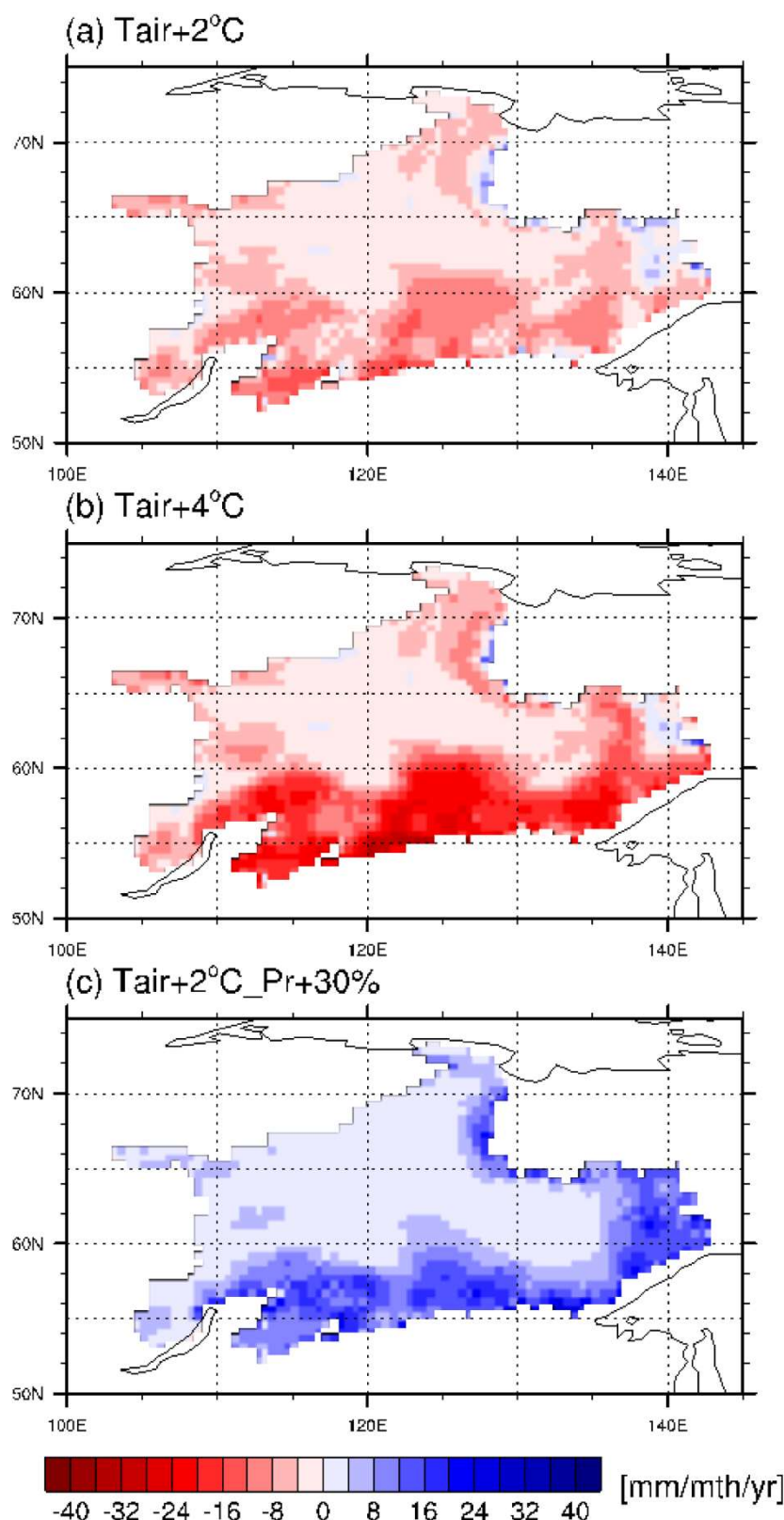


Fig. 11. Deviations of winter baseflow increased with (a) 2°C in air temperature, (b) 4°C in air temperature, and (c) 2°C in air temperature combined with a 30% precipitation increase against the control run.

the influence of precipitation on river discharge was visible during the cold season when the absolute ET value was low (Supplementary Fig. 9). Increased precipitation also induced a large spring discharge increase.

Increased air temperature resulted in thinner river ice in the Lena

River basin, as shown by the anomalous simulated ice volumes (Supplementary Fig. 9f). The ice volume decrease was particularly large in early spring when air temperature was originally warm. This indicates that the temperature-driven ice volume decrease likely affected the early

spring river discharge increase, in conjunction with the earlier snowmelt enhanced by the warmer air temperature. In autumn and winter, the largest ice volume decrease was calculated in the fourth simulation because the precipitation-induced snow insulation increase also decreased river ice thickness (Park et al., 2015b).

4. Discussion

4.1. Impact of climate change on winter discharge

Using observational data and modeling results, this study analyzed the trends of seasonal and interannual discharge in the Lena River basin, focusing particularly on the discharge in the cold season, including the implications regarding warming permafrost on changing hydrological processes. Observational data of soil temperature have indicated warming of permafrost over eastern Siberia, including the Lena River basin (Fedorov et al., 2014b). The model-simulated ALT also showed increasing trends throughout the Lena River basin during the study period (Supplementary Fig. 5). The increased ALT has the physical property of being able to hold much more soil moisture within the active layer; thus, the active layer water storage capacity increases. The ALT-derived larger storage needs additional net precipitation for saturation of soil moisture. In the storage process, moisture in the surface soil layers is primarily used for ET while simultaneously percolating downward (Park et al., 2021). CHANGE-simulated increasing trends of summer ET in the Lena River basin were particularly large in late spring and early summer (Supplementary Fig. 2). Increasing ET enhances soil moisture loss, inducing active layer drying. The ET-derived dry soil likely reduces the opportunity for soil moisture in the active layer to be connected to subsurface runoff or baseflow. Interestingly, the monthly trends of river discharge observed at the inner river stations were negative in June and July (Supplementary Fig. 1c, d) despite increasing precipitation (Supplementary Fig. 2). These negative trends were probably associated with higher ET. Early summer ET in the Lena River basin is, indeed, larger than precipitation (Park et al., 2008). Under the increasing air temperature conditions, similarly, ET-driven discharge decrease in the Lena River basin was amplified (Supplementary Fig. 9). Larger precipitation could temporarily compensate the ET-driven soil drying and baseflow decrease, as calculated in the fourth simulation (Supplementary Fig. 9). The model also simulated increasing trends for autumn ET (Supplementary Fig. 2). However, autumn ET values were generally smaller, because of lower vegetation activity and lower atmospheric demand (Park et al., 2008). Conversely, autumn precipitation increased during the study period (Supplementary Fig. 2). This larger net precipitation became a source of soil moisture, thereby influencing baseflow in autumn (Fig. 9a, b) and winter (Fig. 9c, d). These results clearly demonstrate the essential contribution of climate-induced precipitation increase to baseflow, as illustrated by the clear relationship between net precipitation (Fig. 5) and baseflow (Fig. 7).

The warming climate likely alters precipitation regime characteristics, for example through a larger rainfall fraction or duration (Yang et al., 2002; 2007). Higher soil moisture caused by increased precipitation in the warmer autumn season is characterized by higher heat capacity which, in turn, delays soil freezing in later months, thereby lengthening the period of strong correlation between soil moisture and baseflow. Satellite remote sensing data also indicate delayed freezing of the soil surface in autumn caused by recent global warming effects (Park et al., 2016a). While the soil surface begins to freeze, snow accumulates on the surface. Snow water is then completely decoupled from runoff processes occurring in the soil system during the cold season. Recent climate change resulted in a thicker snow depth in the southern mountainous regions (Park et al., 2015) identified as the source area of increased baseflow (Fig. 9) and in a delayed freezing of the active layer

(Supplementary Fig. 8). Snow cover provides greater insulation that likely delays soil freezing, thereby maintaining baseflow. However, baseflow variations caused by the thicker snow cover have not been fully studied in the context of cold season hydrological processes.

Snow also covers river ice that forms in October or November in the Lena River basin. This further limits river ice growth during the winter season, in conjunction with increasing air temperature (Park et al., 2016b). In 1955–2012, climate warming caused a marked thinning of river ice (by 73 cm) at the Kusr station (Shiklomanov and Lammers, 2014). Yang et al. (2002) found a negative correlation ($r = 0.73$) between winter streamflow and river ice thickness at the Kusr station, suggesting that the warming climate induces a decrease in river ice production and an increase in the winter streamflow. Similarly, Gurvich (2009) analyzed changes in air temperature, river ice thickness, and river discharge for 16 monitoring stations in the Aldan River basin, and reported that winter air temperature was correlated positively with winter discharge. Warmer winter temperatures weakened the influence of river ice on discharge, causing discharge to increase. These results suggest that river ice is a key storage component affecting winter streamflow. Our simulation results also showed a clear thinning of river ice during the cold season over the study period (Fig. 10), implying a contribution of river ice to winter river discharge variations.

4.2. Impact of permafrost thawing on winter discharge

An ALT increase is an indicator of permafrost thawing but is not directly related to river discharge. However, our analysis clearly indicated that the climate-induced ALT increase was correlated with baseflow increase in the cold season (Fig. 9). This correlation was also influenced by soil water storage in the active layer. Permafrost is also associated with soil water storage dynamics. Permafrost below the active layer acts as a barrier that prevents water from percolating deeper. Thus, inflowed water from the surface soil layers eventually accumulates in the soil layers close to the permafrost table, stabilizing soil moisture at a high level that can affect baseflow (Jorgenson et al., 2010). In this study, we identified the southern mountainous regions as the major baseflow source area during the cold season (Fig. 9b, d). The southern regions, underlain by continuous and discontinuous permafrost, were characterized by a thicker active layer in which higher autumn net precipitation (Fig. 5), thus higher soil moisture (Fig. 6), was stored, contributing to the baseflow increase (Fig. 7). This finding is generally consistent with recent studies reporting that permafrost thawing is linked to discharge increase during the cold season (Han and Menzel, 2022; Smith et al., 2007; Walvoord and Striegl, 2007; Wang et al., 2021) through increased groundwater storage within the active layer (Walvoord and Kurylyk, 2016).

An ALT increase is not always concurrent with a baseflow increase. For example, in the upper parts of the Lena River basin around Lake Baykal, the ALT is larger than 3 m (Supplementary Fig. 5a) but lag correlation between interannual variations of monthly soil moisture in the active layer and of winter baseflow is low (Fig. 8). During the study period, decreasing trends were calculated for soil moisture in the active layer, ALT, and baseflow in the upper Lena River basin around Lake Baykal during the cold season. When the thicker active layer associated with a warmer climate dries, inflowed net precipitation is preferentially converted to soil moisture and baseflow decreases. This hypothesis was confirmed by comparing the control run with the two sensitivity simulations, in which the increased air temperature induced a considerable decrease in autumn and winter baseflow, particularly marked in the southern mountainous regions (Fig. 11a, b) where the baseflow was originally large (Supplementary Fig. 6d). On the other hand, our results indicated regional inconsistency between ALT and baseflow trends. They clearly showed that an ALT increase does not systematically

correspond to an increase in soil water storage within the active layer. Net precipitation affects soil water storage and influences baseflow. Analyzed net precipitation variations showed considerable regional complexity, with a marked increase in the southern mountainous regions (Fig. 5) inducing a baseflow increase (Fig. 7). This suggests that the Lena River discharge increase was caused by the combined climate-induced effects of localized larger net precipitation and permafrost thawing.

Permafrost is ice-rich frozen soil mixed with ground ice such as Yedoma and ice wedges. Warming of permafrost temperature or increasing of the ALT likely enhance the melting of ground ice, contributing to the wetted active layer. In situ observations found thawing of the upper ice-rich permafrost following warming of the climate and resultant expansion of thermokarst lakes in tundra (Liljedahl et al., 2016) and boreal forested (Fedorov et al., 2014a; Ulrich et al., 2017) regions within the Lena River basin. Observational data analysis indicated significant correlation between the warming permafrost temperature and increasing river discharge in the cold season in the upper parts of the Lena River basin underlain by discontinuous permafrost (Tananaev et al., 2016), and eventually in the Aldan River basin underlain by continuous permafrost (Han and Menzel, 2022). The observational results suggest a possible contribution to increased baseflow from ground ice melting associated with permafrost warming. Modeling the change in ground ice is currently beyond the capability of CHANGE simulations.

4.3. Model uncertainty

Inadequate hydroclimatological data from the Lena River basin, including lack of actual ET and long-term permafrost observations, limit the scope of analysis of the hydrological response to changes in climate and permafrost in this region. This study used the CHANGE model to resolve this problem. Model simulations were conducted using three different atmospheric forcing datasets and the results presented differences in the amounts of simulated river discharge between the forcing datasets as well as in comparison with observations (Figs. 3 and 4). The differences were mainly attributable to the difference in precipitation between the three forcing datasets (Park et al., 2020). Although numerous internal feedbacks and the complexity of the CHANGE model prevent us from determining clear reasons for its limited performance, we discuss here its intrinsic limitations as a one-dimensional model. CHANGE has a rough spatial resolution of $0.5^\circ \times 0.5^\circ$, inappropriate to represent water movements (e.g., lateral flow) occurring in the complex mountain topography of the upper Lena and Aldan River basins where baseflow production is large. Furthermore, the TRIP2 model used to simulate river discharge is a storage-based, grid-cell-wise routing model dependent on spatially effective subgrid parameters. These are estimated independently from topographic data and from the model-simulated water storage, without possibility for parameter tuning based on the observed discharge data. Slater et al. (2007) compared simulations of five land surface models with observations from the four major Arctic river basins. They established that model hydrographs were often out of phase, peaking too early from the spring maximum discharge. In terms of model performance, simpler hydrological models (e.g., HBV; Bergström and Lindström, 2015) occasionally yield comparable agreement with observations. However, CHANGE can reproduce a wide range of physical phenomena, particularly for high-latitude processes. Thus, it is potentially better adapted to investigate the influence of permafrost on river discharge. Furthermore, simulated ALT spatial distribution and trends were comparable for the three forcing datasets, despite differences in absolute values (Supplementary Fig. 5). The consistency between all simulations indicated satisfactory agreement with observations. Overall, simulation results obtained with the WATCH forcing dataset do not preclude meaningful analysis of the impacts of changing hydroclimatological processes and permafrost on winter river discharge in the Lena River basin.

5. Conclusions

This study focused on the increasing trend in winter river discharge in the Lena River basin and examined the impact of global-warming-induced changes in net precipitation, soil moisture, ALT, and baseflow, as well as their interrelations, based on model-simulated results for the 38-year period 1979–2016. Net precipitation showed an increasing trend in summer, which was especially significant in lower parts of the Lena River basin and upper parts of the basins of the Lena and Aldan rivers, resulting in higher soil moisture in the active layer. Lag correlation analysis between net precipitation and soil moisture exhibited higher positive correlations in the warm season (July–September) in the same regions, indicating that net precipitation was stored as soil moisture. Moreover, the maximum values of ALT recorded in August and September revealed increasing trends over the entire basin during the study period, meaning that the deepened active layer could store more soil moisture. Trend analyses also identified increasing baseflow in the cold season in lower parts of the Lena River basin and in upper parts of the basins of the Lena and Aldan rivers. Lag correlation analysis revealed that winter (DJF) baseflow was highly correlated with soil moisture of the previous late summer (August and September). These results synthetically explain the connectivity of the soil moisture increase associated with global warming, which is strongly implicated with net precipitation and the ALT, to the increase in winter discharge in the Lena River basin. Furthermore, warming air temperatures reduced the river ice thickness, thereby also contributing to the increase in winter discharge.

Our results revealed that the upper parts of the basins of the Lena and Aldan rivers are major source areas for the increased winter river discharge, which was verified by correlation analyses among the ALT, soil moisture, and baseflow in the cold season. Interestingly, the regions contributing to the increase in autumnal baseflow are located in the lower and upper parts of the Lena River basin, whereas the contribution to winter baseflow was relatively large in the upper parts of the basins of the Lena and Aldan rivers that are underlain by continuous and discontinuous permafrost. In conclusion, the increases in winter river discharge of the Lena River could be the result of increased groundwater flow associated with higher storage capacity caused by the deepened active layer and thawing permafrost in the upper parts of the basins of the Lena and Aldan rivers. These results suggest that the contribution of thawing permafrost to winter discharge will further increase under the effects of further climate change. However, quantitative assessment on the contribution of permafrost-sourced water to the increasing discharge remains a subject for future research.

Data availability

Three different gridded climatic datasets are available at; WATCH, <https://doi.org/10.24381/cds.20d54e34>, CRUNCEP, <https://rda.ucar.edu/datasets/ds314.3/>, and Princeton, <https://hydrology.princeton.edu/data/pgf.php>. The GRDC dataset is also available at https://www.bafg.de/GRDC/EN/04_spcltdbss/41_ARDB/arcticHycos.html?nn=201698.

The following data that support the findings of this study are also available from the corresponding author upon reasonable request; the vertical soil texture fractions for sand, silt, and clay, which was derived from the IGBP Soil Data System, monthly discharge data at 26 gauges in the Aldan River basin (Table 1) which was operated by the Russian Hydrological Service (Roshydromet), and the soil temperature data in the Lena River basin (Table 2) which was installed by the Melnikov Permafrost Institute.

CRediT authorship contribution statement

Tetsuya Hiyama: Conceptualization, Funding acquisition, Methodology, Formal analysis, Validation, Visualization, Writing – original

draft, Writing – review & editing. **Hotaek Park:** Conceptualization, Funding acquisition, Methodology, Formal analysis, Software, Validation, Visualization, Writing – review & editing. **Kota Kobayashi:** Formal analysis, Visualization. **Liudmila Lebedeva:** Data curation, Investigation, Validation, Writing – review & editing. **David Gustafsson:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhydrol.2022.128797>.

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