Warming temperatures are impacting the hydrometeorological regime of Russian rivers in the zone of continuous permafrost

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Abstract. Large Arctic river basins experience substantial variability in climatic, landscape and permafrost conditions. However, the processes behind the observed changes at the scale of these basins are relatively poorly understood. While most studies have been focused on the 'Big 6' Arctic rivers – the Ob', Yenisey, Lena, Mackenzie, Yukon, and Kolyma – few or no assessments exist for the small and medium-sized river basins, such as the Yana and Indigirka River basins. Here, we provide a detailed analysis of streamflow data from 22 hydrological gauges in the Yana and Indigirka River basins with a period of observation ranging from 35 to 79 years up to 2015. These river basins are fully located in the zone of continuous permafrost. Our analysis reveals statistically significant ($p < 0.05$) positive trends in the monthly streamflow time-series during the autumn-winter period for most of the gauges. The streamflow increases in a stepwise pattern (post 1981) for 17 out of 22 gauges in September (average trend value for the period of record is 58% or 9.8 mm), and 15 out of 22 gauges in October (61% or 2.0 mm). The positive trends are seen in 9 out of 19 rivers which do not freeze in November (54%, 0.4 mm), and 6 out of 17 rivers which do not freeze in December (95%, 0.15 mm). Precipitation is shown to decrease in late winter by up to 15 mm over the observational period. Additionally, about 10 mm of precipitation that used to fall as snow at the beginning of winter now falls as rain. Despite the decrease in winter precipitation, no decrease of streamflow is observed during the spring freshet in May and June in the last 50 years (from 1966); moreover, 5 gauges show an increase of 86% or 12.2 mm in spring floods via an abrupt change in 1987-1993. The changes in spring freshet start date are identified for 10 gauges; the earlier onset in May varies from 4 to 10 days over the observational period. We conclude that warmer temperatures due to climate change are impacting the hydrological regime of these rivers via changes in precipitation type (rain replacing snow). Other factors such as melting of permafrost, glaciers, and aufeis, or changes in groundwater conditions are likely to contribute as well, however, no direct observations of these changes are available. The changes in streamflow can make a significant impact on the ecology of the zone of continuous permafrost, while the increasing freshwater fluxes to the Arctic Ocean can impact the Arctic thermohaline circulation.

Keywords. Yana and Indigirka Rivers, climate change, warming trend, autumn-winter streamflow increase, precipitation, permafrost, spring freshet

1 Introduction

Numerous studies have shown that river streamflow in Northern Eurasia and North America is increasing (Holland et al, 2007; Shiklomanov and Lammers, 2013; Rawlins et al., 2010). Most of them are focused exclusively on the "Big 6" Arctic rivers – the Ob', Yenisey, Lena, Mackenzie, Yukon, and Kolyma (Peterson et al. 2002; Holmes et al., 2013; Rood et al. 2017). Large Arctic river basins are characterized by a great variety of climatic, landscape and permafrost conditions and reported streamflow changes are not homogeneous in terms of different runoff characteristics and time scales. The mechanisms of the observed changes can hardly be understood on the large scale of the "Big 6".

Compared to large rivers, the changes of flow in small and medium rivers in cold regions have been studied much less. Tananaev et al. (2016) found that 30 small and medium-sized rivers out of 100 in the Lena River basin showed trends in mean annual flow. Significant changes have been recently reported for small and middle-sized rivers of northwestern Canada (Spence et al., 2015), Alaska (Stuefer et al., 2017) and the Canadian High Arctic (Lamoureux and Lafrenière, 2017) and attributed to climate change and permafrost disturbances. Further analysis of small river basins could reveal the mechanisms behind ongoing changes as at larger scales attributing changes can be problematic.

River runoff change estimates in North-Eastern Siberia are limited and contradictory. Magritsky et al. (2013) reported an increase in the total runoff of Yana and Indigirka during the period 1976-2006 by 1.5-3% compared to the period before 1976 and noted that the runoff of these rivers increased in summer and autumn by 20-25% and did not change in winter. According to Georgievsky (2016), on the contrary, there is an increase of Yana and Indigirka rivers winter runoff by 40% over the period 1978-2012 compared with the period 1946-1977, and an increase in the spring flood. Majhi and Daqing (2011) concluded that the Yana River monthly flow increases at the Jubileynaya gauge (224,000 km^2) for the period of 1972-1999 for June, August, September, October and April, while May, July and March monthly flow have decreased. Bring and Destouni (2014) reported an absence of any significant changes of the Yana and Indigirka streamflow accompanied by a decrease in precipitation of up to 38% for the period 1991–2002 compared to 1961–1991.

While some studies have examined flows at the outlet of the Yana and Indigirka river basins, estimation of streamflow changes of small and medium-sized rivers in the Yana and Indigirka river basins do not exist. The objective of this research is therefore a quantitative assessment of current changes of hydrometeorological regime within two large arctic river basins, with both basins completely located within the continuous permafrost zone, and which have long-term runoff observations along the main rivers and their tributaries at smaller scales.

In section 2 of this paper, we will present the study area. In section 3, we will describe the data to be examined and the methods that we will use. Results of the analysis will be presented in section 4, while these results will be put into context and potential causal factors influencing the results described in section 5. Finally, some conclusions will be drawn in section 6.

2 Study area

2.1 General description, relief

The Yana and Indigirka rivers are two of the few large Arctic rivers whose basins are completely located in the zone

of continuous permafrost (Figure 1). The terrain is mainly mountainous. There is high elevation in the Verkhoyansk (Orulgan, 2 389 m), Cherskiy (Pobeda, 3 003 m) and Suntar-Khayata (Mus-Khaya, 2 959 m) ranges, as well as wide river valleys. The average altitude of the research basins ranges from 320 to 1410 m and the elevations of the outlet gauges range from -1.55 to 833 m respectively. The lower parts of the Yana and Indigirka basin area are represented by the Yano-Indigirskaya Lowland. The average height of the lowland is above 30-80 m, with some parts of the lowland raised up to more than 500 m.

2.2 Climate

The study territory is the region where the Northern Hemisphere's 'pole of cold' is located. The absolute minimum there has reached record levels for the Northern Hemisphere: down as far as -71°C in Oymyakon and -68°C in Verkhoyansk (Ivanova, 2006). The research region's climate is distinctly continental. Long-time average annual air temperature ranges from -16.1°C (Oymyakon, 726 m, 1930-2012) to -13.1°C (Vostochnaya, 1288 m, 1942-2012). Minimum mean monthly temperatures are typically observed in January and can fall as low as -47.1°C (Oymyakon) and -33.8°C (Vostochnaya). Maximum average monthly temperatures are observed in July, averaging 15.7°C and 11.8°C for stations Yurty (590 m, 1957-2012) and Vostochnaya, respectively. Steady cold weather begins in the first week of October; spring starts in the second part of May or at the beginning of June, when seasonal snow cover starts to melt. Snow accumulation is relatively small and accounts for 25-30 cm depth. Annual average precipitation at Verkhoyansk meteorological station (137 m, 1966-2012) is about 180 mm, while at Vostochnaya (1966-2012) it is 280 mm. Most precipitation (over 60%) occurs in summer, with a peak in July of up to 70 mm per month (Vostochnaya, 1966-2012).

2.3 Soil, vegetation and landscapes

The research basins are situated in the transitional zone between forest-tundra and coniferous taiga (Figure 2). For high altitude mountain areas above 1900 m a.s.l., goltsy (bald mountain) and small glaciers with minimum and maximum area from 0.024 to 5.76 km^2 (GLIMS and NSIDC, 2005, updated 2017) are typical. Vegetation in this landscape is absent. Broken stone is present in the form of glacial frost-split boulders as well as diluvia soil of the valley slopes with admixed loam material. Below is the tundra, which is characterized by distribution of a tight and depressed layer of grass and moss with bushes, under which there is rock formation and some ice with admixtures. Most of the research areas are covered larch woodland with moss-lichen cover. In river valleys, grass-moss larch forest and swampy sparse growth forest are typical. Soil types at these landscapes are clayey podzol with partially decayed organic material underlain by frozen soil and bedrock. The updated map of permafrost landscapes (Fedorov et al., 2018) can be used for more detailed description of the studied basins.

2.4 Permafrost

In the studied river basins, permafrost thickness can reach over 450 m at watershed divides and up to 180 m in river valleys and depressions. There are highly dynamic cryogenic features such as retrogressive thaw slumps found in the Yana river basin that indicate on-going permafrost degradation processes (Günther et al., 2015). Permafrost temperature at a depth of zero annual amplitude in the studied region typically vary from -3 to -11 °C, and the active layer depth – from 0.3 to 2 m (Explanatory note …, 1991).

2.5 Hydrological regime and water balance

The hydrological regime is characterized by spring freshet, high summer-autumn rainfall floods and low winter flow. In winter, small and medium-sized rivers freeze thoroughly. Spring freshet starts in May-June (on average the 20th of May) and lasts approximately for a month and a half. In summer, glacier runoff, melting aufeis and snowfields contribute to streamflow.

The amount of precipitation at meteorological stations varies from 176 mm/year (ID 24261) to 279 mm/year (ID 24679). At the high altitude area, annual precipitation can reach up to 600 mm or more per year. Average annual precipitation at Suntar-Khayata station (2068 m) in 1957-1964 reached 690 mm with corrections for wind and wetting losses (Grave, 1964). Annual precipitation amount at the mountain peaks is estimated to be as high as 800 mm (Vasiliev, Torgovkin, 2002). The average annual flow at studied rivers varies from 58 mm (ID 3433, 18.3 km^2) to 362 mm (ID 3516, 16.6 km^2). This difference of a factor of six at two watersheds of similar area shows the impact of local conditions on runoff formation. Annual values of flow at the outlet gauges of the Indigirka (ID 3871, 305 000 km^2) and Yana (ID 3861, 224 000 km^2) rivers are 166 and 156 mm respectively. According to observational data (Makarieva et al., 2018a) annual evapotranspiration depends on the type of underlying surface and the distribution of landscapes over the catchment area. On average, it ranges from 90 mm in the goltsy landscape to 140 mm where there is sparse growth of larch trees (Lebedeva et al., 2017).

2.6 Groundwater and taliks

Since the whole Yana and Indigirka river basins are located in continuous permafrost, groundwater can be found in a seasonally developed active layer, underneath permafrost (supra-permafrost water) and in taliks (Shepelev, 2011). Depending on texture, infiltration and other soil properties, the active layer stores and transmits water to rivers in summer and early autumn. Water in the active layer could sustain recession river flow in autumn only until the freezing front reaches the permafrost table. Taliks with thicknesses of several meters typically exist under small and middle-sized rivers even if the rivers freeze in winter (Mikhailov, 2013). Through-taliks are typically found along the river channels with water depth exceeding 3-5 m. Rivers in continuous permafrost often lose water to channel taliks during summer and gain in winter (Arzhakova, 2001). Through-taliks are also associated with fractured deposits, with depth exceeding the permafrost thickness (Glotov et al., 2011). Rivers with lengths >800 km and basin area >75 000 km^2 typically do not freeze up and continue to flow over the winter. Year-round groundwater springs and winter flow of large rivers suggest suprapermafrost water contribution.

2.7 Aufeis and glaciers

Aufeis (naleds), which form at mountain foothills, as well as in sub-mountain and intermountain depressions, are another distinguishing feature of the region. According to Simakov and Shilnikovskaya (1958), the research area had 1 281 aufeis covering an area of about 2 082 km^2. In winter, the aufeis reduce both river and underground flow, and in the warm season, melted aufeis waters form an additional source of river runoff. Most flow from melting aufeis is observed in May-June. In most cases, the share of the aufeis component does not exceed 3-7% of annual river runoff (Reedyk et al., 1995; Sokolov, 1975), but in May its proportion may exceed 50% of the total runoff (Sokolov, 1975).

Few glaciers are found in the research area (GLIMS and NSIDC, 2005, updated 2017). The total area of glaciers is

about 2.2 km^2 at the Yana river and 436 km^2 (0.14% of the area) of the Indigirka river basin. At some studied basins, glaciers reach up to 0.38% of the basin area (ID 3488, Indigirka river – Yurty). The glacier runoff may exceed 3.8% of the overall annual streamflow and reach 6.1% of streamflow in July and August, as, for example, at the basin of the Agayakan river (the Indigirka basin), where glaciers cover over 1.35% of the catchment. On the slopes of the Suntar-Khayata and Cherskiy Ranges, perennial snow fields and rock glaciers are widespread (Lytkin, Galanin, 2016). They, along with the ice of the active layer and summer atmosphere precipitation, may represent a significant source of flow in the local rivers, however in this respect they are poorly studied (Zhizhin et al., 2012; Lytkin, Galanin, 2016).

3 Data and methodology

3.1 Data

Daily discharge series for 22 hydrological gauge stations of the Russian Hydrometeorological network in the Yana and Indigirka river basins were analyzed. Most of the stations have hydrological data until 2014-2015, but two of them ceased operation in 2007 and one (riv. Indigirka – Vorontsovo, ID 3871) in 1996. The median length of observations series is 62 years with minimum and maximum values reaching 36 and 80 years respectively (Table 1, Fig. 1). Ten out of the 22 catchments examined here have areas less than 10 000 km^2, with five of them being less than 100 km^2. Maximum catchment area is 305 000 km^2 (ID 3871). Average elevation above sea level of the examined catchments varies from 320 m (ID 3433) to 1 410 m (ID 3499). Thus, the study covers not only large, but also small and medium-sized rivers over a broad range of elevations and landscapes typical for the studied mountain region.

We used the values of monthly and annual flow (mm) and spring freshet start dates (counting days from the beginning of the year) used in the analysis were estimated based on daily discharge data for the entire observation period from 1936 up to and including 2014-2015. There are different ways to determine a freshet start date. For example, Lesack et al. (2013) defined the initiation of freshet discharge based on a threshold value of 3% increase in discharge per day. In this study where non-freezing and freezing rivers were investigated, a different approach was considered to be more appropriate. A day was defined as a freshet flood start date if its discharge reached or exceeded 20% of the average discharge value in the studied year. All the streamflow series were visually checked for the adequacy of this assumption.

The uncertainties associated with discharge determination change significantly from year to year and strongly depend on the computational methods used and frequency of discharge measurements. Possible errors in flow values shown in the database as reliable are as follows for all gauges: average annual flow errors do not exceed 10%, monthly flows errors are 10-15% for the open channel period and 20-25% for winter months. The errors of "approximate" flow, placed in the database in parentheses, can exceed the values indicated above by 2-3 times (State water cadastre, 1979). The errors for streamflow in large rivers may be slightly lower: monthly flow errors are 4-12% for the open channel period and 17% for winter months in the Lena River basin (Shiklomanov et al., 2006). Daily air temperature and precipitation data series, observed at thirteen weather stations (the elevation range varies from 20 to 1 288 m) located in the studied basins, over different periods from 1935 (but not later than 1966) to 2015 (some stations to 2012) were reduced to average monthly values series (Table 2). Monthly soil temperature under natural cover at different depths down to 320 cm from three weather stations over a period of 1966-2015 was also

analysed. Detailed description of soil temperature data sets and their quality control methods may be found in Sherstyukov (2012). Active layer thickness (ALT), used for the analysis, was estimated with polynomial interpolation of soil temperatures at depth (Streletskiy et al., 2015). The sources of the data are described in Makarieva et al. (2018b).

3.2 Methods

In this study, we applied the combination of widely used statistical methods for trend detection and assessment of their values in hydrometeorological data. General guidance with detailed description of different types of tests and their adequate application can be found in Kundzewicz and Robson (2004). Time series of runoff characteristics (monthly flow, estimated flood starting dates and maximum daily flows) and meteorological elements (monthly and annual values of air temperature and precipitation; soil temperature and ALT) were evaluated for stationarity, in relation to presence of monotonic trends, with Mann-Kendall and Spearman rank-correlation tests, at the significance level of $p < 0.05$ (Mann, 1945; Kendall, 1975; Lehmann, 1975). If both tests suggested a trend at the significance level $p < 0.05$, a serial correlation coefficient was tested at unity lag $r(1)$. With the serial correlation coefficient $r < 0.20$, the trend was considered reliable. In the case of $r \geq 0.20$, to eliminate serial correlation in the input series «trend-free pre-whitening» procedure (TFPW), described by Yue et al. (2002), was carried out. «Whitened» time-series were repeatedly tested with Mann-Kendall non-parametric test at the significance level $p < 0.05$. The Pettitt's test (Pettitt, 1979) was applied to look for the presence of a change point in time series at $p \leq 0.05$, the Buishand range test (Buishand, 1982) was used to search for numerous discontinuities at the same significance level. Trend values were estimated with the Theil-Sen estimator (Sen, 1968) and are given in the relevant data units along with the percentage change since the beginning of observations. Note that the trends are presented for the entire period of observations, and not for the period after the change point was identified, as there can be multiple trends within the period of observations. In some (specified) cases, the significance level was relaxed to the value $p > 0.05$.

4 Results

The results of the trend analysis are presented in Tables 3-8. The Tables have the same structure and designations. The cells filled with grey color correspond to statistically significant trends with $p<0.10$. If any value is bold, it has significance $p<0.05$; if a value is in italics, it has significance $0.05<p<0.10$. In Tables 4 (precipitation) and 7-9 (streamflow) each cell with significant trend contains three numbers: 1) the value of total change for the whole period of observations in the characteristic unit (for example, mm) 2) percentage of total change (%); 3) where available – the year of change point or letter "m" for monotonical trend. If there is neither year, nor "m", the Pettitt's test was not carried out due to too many gaps in the data. Statistically significant trend values are divided into 4 groups and marked with different colors accordingly: change points around 1966 – magenta, 1970-1985 – green, 1986-1995 – violet, 1996 and later – yellow. Monotonous trends and where change points were not available due to too many gaps in the data are in black. For streamflow, the year of change point marked with * indicates that the gauge has a long-term series of more than 70 years with change point in about 1966 and no significant trend after that period (last 50 years). In some cases, a second year of change point is given in brackets, as estimated with Buishand range test. We used the same colors as in Tables 3-8 in Figure 3 showing the percentage change in

monthly and annual streamflow and Figure 4, S12-S17 which presents the spatial patterns of the changes.

4.1 Air temperature

235   Increase in annual air temperature is statistically significant at all 13 studied stations (Table 3, Fig. S1) with an average cumulative value of about +2.1°C (from +0.16 to +0.46 and average +0.35°C per 10 years) for the historical period of observations (minimum, maximum and mean number of years correspond to 47, 80 and 63).

During the period from April to July, there is a significant air temperature trend at most of the weather stations of the region; average trend values in these months account for +3.0°C, 3.1°C, 1.9°C and 2.3°C correspondingly (Table

240   3). Positive air trend is observed in March in the mountainous part of the Indigirka River (five stations with elevation > 500 m). In August, air temperature has increased at three Yana basin stations and two lowland stations in the Indigirka basin accounting on average for 3.4 and 2.4 °C increase respectively. In September, air temperature has increased at two stations of the lower part of the Indigirka river basin by 2.3 °C on average. There are no significant trends in October at the Yana basin weather stations but the mean positive trend at five stations of the

245   Indigirka basin account for 3.7 °C in the same month. In November, at 7 stations of 13 across both basins, positive trends are statistically significant and reach on average 4.7 °C with a maximum value of 6.3 °C at Delyankir (ID 24691). Positive winter air temperature trends are significant at four weather stations in December, six – in January and at one station – in February. In March, the positive trend value is 3.6 °C on average for seven meteorological stations inthe mountainous part of the Indigirka River basin. Change point analysis was conducted for 9 stations out

250   of the 13 with full data series. Almost all changes occur through abrupt shifts rather than monotonic trends. Most change points are attributed to two periods: 1975-1985 and 1986-1996. The shifts in winter air temperature occurred at the beginning of the millennium (1999-2004).

4.2 Precipitation

255   Monthly precipitation analysis for 13 meteorological stations in the region, located at elevations from 20 to 1 288 m, 1966 – 2015 (some stations until 2012), has shown no evidence of a systematic positive trend (Table 4, Fig. S2).

On the contrary, at 6 weather stations out of 9 in the Indigirka basin, a statistically significant precipitation decrease is observed in January and at 3 stations in February. In the Yana basin, 2 stations have shown decrease of precipitation in December. Average statistically significant decrease in winter months ranges from -3.0 to -6.7 mm

260   per month or -44-92 %. In lowland areas which are close to the furthest most downstream gauges of the Yana and Indigirka rivers, reliable negative trends were identified in July (-73%, -23 mm) at Chokurdah (ID 21946, the Indigirka basin) and in August (-71%, -26 mm) at Kazachie (ID 21931, the Yana basin). It is unlikely that runoff from these areas significantly impacts the flow at the outlets of the Yana and Indigirka Rivers as most of the runoff is produced in the upper, mountainous parts of the basins. Positive trends in summer months are observed at two

265   stations of the Indigirka basin: + 44% (21 mm) at Vostochnaya (ID 24679) in June and +49% (22 mm) and +49% (15 mm) in June and September at Deputatsky (ID 24076) (Table 4). We evaluated cold season precipitation calculated as the sum from October to April. Two stations in the Yana River basin have shown a statistically significant (p<0.05) decrease of about 40% or 20 mm. Three stations in the Indigirka River basin experienced negative trends at the level of significance 0.05<p<0.08 with reduction of precipitation about -28% or 15 mm per

270   season. The change points for solid precipitation are estimated to occur between 1980 and 1996 with most of them

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occurring in 1986. A positive trend in warm period precipitation (May – September) is detected at Oymyakon (ID 24688), in the upstream parts of the Indigirka river, with values of 35% or 54 mm. Warm season precipitation has decreased by almost half (-48% or -60 mm) at the outlet of the Indigirka river (Chokurdah, ID 21946).

4.2.1 Rain – snow precipitation ratio

The state and timing of precipitation in May and September (which are the months when the 0 °C air temperature threshold is crossed) were analyzed. The results show that meteorological stations in the higher elevations (which are mostly located in the Indigirka river basin) exhibit a shift towards larger amounts of rain rather than snow in both studied months. In May, three stations show an upward trend for a larger fraction of rain ($p<0.05$). Vostochnaya (ID 24679, 1288 m) exhibits the strongest changes: mean share for the whole period is 0.43, with a trend value of 0.45. Oymyakon and Agayakan (ID 24684, 24688) have mean value of rain share equal 0.79 and on average increase by 0.16 (Table 5). In September, the mean share of rain fluctuates from 0.56 at Vostochnaya (ID 24679, 1288 m) to 0.79 at Agayakan and Oymyakon (ID 24684, 24688, 726 and 776 m). The trend value varies from 0.15 to 0.19 of increase in rain share for the whole period of observation at five stations (Table 5). In absolute values, the amount of rain increased on average by 60.7%, or 12.2 mm in total during the same period at six stations. Pettitt and Buishand tests for change points indicate an abrupt shift of precipitation regime in September in 1991-1993 for four stations.

4.3 Soil temperature and active layer thickness (ALT)

There are three meteorological stations with soil temperature data available for the entire historical period including the beginning of the 21st century with a total area of 529 000 km^2 – two in the Indigirka and one in the Yana river basin. We analyzed soil temperature at a depth of 80 cm and estimated maximum active layer thickness (Table 6). The analysis of changes in the number of days with positive soil temperature at the depth of 80 cm for 2001-2015 in comparison with the long-term mean value for 1971-2000 was also carried out. Positive soil temperatures at the depth of 80 cm at the described weather stations are observed from July to October.

Verhoyansk, ID 24266, 137 a.s.l., the Yana River basin Significant positive soil temperature trends at the depth of 80 cm in summer (from May to September), and negative ones in winter (from January to March) have been identified (Table 6, Fig. S3). On average, soil temperature at the studied depth increased by +3.4°C in summer months for the last 50 years. Maximum trend values are observed in July and August and account for +4.1 and 4.4 °C respectively. In winter, the corresponding temperature average dropped by -2.2 °C for the same period of observations. Winter trends should be viewed with some caution as there was a significant gap in the observations from 1985 to 1999. A change point estimated with Pettitt's test was identified around 1996-1999 in June–September and 2003 in May. Accordingly, ALT (mean = 170 cm) increased by 45 cm. It increased for 10 years (1997 to 2007) and was then stable for the next 8 years. The number of «warm» days at the depth of 80 cm has increased, on average, by 18 days over the last 15 years in comparison with the long-term mean value for 1971-2000 from 87 to 105 cm.

Oymyakon, ID 24688, 726 a.s.l., the Indigirka River basin In the uppermost part of the Indigirka river basin, significant negative soil temperature trends at the depth of 80 cm in summer are observed, along with positive trends in winter (Table 6, Fig. S3). In June – September, soil temperature at 80 cm depth dropped on average by -2.8°C and

increased by +4.8°C in October – April. The change of soil temperature occurs in an abrupt manner – the shifts in winter temperature are identified in 1977 (October), 1983 (November, April), 1990 (May) and 1994-1995 (December – February). In summer, the shift cannot be estimated due to the data gap from 1990-1999.

Due to the temperature decrease in summer, estimated ALT (mean = 165 cm) dropped by 77 cm over the period 1966-2015 (-1.5 cm a-1). The number of «warm» days has dropped by 32 days (from 103 to 71) over the period 2000-2015 in comparison with the previous 30-year period.

Ust-Moma, ID 24382, 196 a.s.l., the Indigirka River basin Statistically significant positive trends are identified for the period from May to November, and on average temperature increases by +2.1°C over 39 years (1977-2015) (Table 6, Fig. S3). The largest trends are observed in October and November and account for +3.0 °C and +5.9 °C respectively. The change points are estimated as occurring in 2001-2002 for August – November and 2006 for May – July. The trend in ALT (mean=127 cm) is insignificant. The number of «warm» days has increased, on average, by 39 days in 1977 to 2015 (from 57 to 96).

4.4 Streamflow

Positive statistically significant trends ($p<0.05$) in monthly streamflow were identified during two main periods: in autumn-winter and in the first month of a spring flood – in May for most of the river gauges (Fig. 3, Table 7-8). Most of the time series with significant trends are nonstationary, where changes are attributed to break points. Single and double change points are common for studied streamflow records and are described below.

4.4.1 Spring flow (May and June)

In May, a statistically significant increase in streamflow is observed at 12 of the 21 studied gauges. These 12 may be divided into two groups. The first group (Fig. S4, Group A) contains 7 gauges with basin areas from 8 290 to 89 600 km^2 characterized by a longer continuous series of observations beginning between 1937 and 1956. The shifts of streamflow occur in 1964-1966 and follow a similar behaviour. In most cases, a negative tendency changes to an insignificant positive one. Average trend rates are 79% or 8.9 mm for this group. If the assessment of trend is made for the last 50 years after the change point (1966-2015), no significant trend is detected in May for this group of gauges. The second group (Fig. S5, Group B) consists of 5 gauges with no significant trend, followed by breakpoints during the period from 1980 to 1999 and positive trends thereafter varying from 5.5 to 25.7 mm with average value of 12.2 mm (or from 64 to 103%, 86% in average). Minimum basin area for this group is 16.6 km^2, and the maximum is 52 800 km^2. No trends were identified in May at the Yana and Indigirka river outlet gauges for the periods 1972-2007 (ID 3861, 224 000 km^2) and 1936-1996 (ID 3871, 305 000 km^2) respectively. In June, a statistically significant ($p<0.05$) positive trend in streamflow is observed at 4 gauges of the Yana river (Fig. S6). One gauge exhibits a monotonic increase of flow in June for the last 50-60 years and the other 3 gauges have break points in 1983-1995. Average positive trend value is 40% or 16.4 mm. A small river in the Indigirka basin (ID 3510 – 644 km^2, $p<0.057$) has shown total decreased trend value during the last 70 years with a break point in 1967. The streamflow shifts from high mean with negative tendency to low mean with slightly positive tendency. If the analysis is made for the period 1967-2015, streamflow in June at this gauge does not present any detectable changes. Total negative trend value accounts for -61% or -14.2 mm.

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4.4.2 Summer-autumn floods (July – September)

In July, no statistically significant changes of streamflow occur in the Indigirka river basin. In the Yana River basin, two nested gauges show opposite tendencies (Table 7). The streamflow at gauge ID 3474 (8290 km^2) monotonically decreased by 38% (26 mm). At the same time gauge ID 3443 (52 800 km^2) experienced a total increase of streamflow of 17 mm or 36% with a breakpoint in 1995. In August, an increase in streamflow was identified at 7 out of 22 studied gauges with an average increase of 55% or 18 mm. Areas of the catchments, where discharge increases in August, vary from 644 to 89 600 km^2. Two nested gauges (ID 3507, 3489) have a monotonic increasing trend from the mid-1950s to 2015. The other, including two nested gauges of the Adycha river (ID 3443, 3445), exhibit the shift in 1982-1987 (Fig. S6, Fig.2).

In September, positive trends were identified at 17 out of 22 gauging stations (average value is 58% or 9.8 mm); three of those rivers are small ones (catchment areas are less than 100 km^2), the others are medium and large rivers (Table 7-8, Fig. S7, Fig. 2). This assessment includes a positive trend identified at the Indigirka river outlet gauge (ID 3871) for the shorter period 1936-1996. Some river gauges of the Yana River basin (ID 3478, 3479, 3483) have shown monotonic increase, other have change points mainly in the 1981-1982 period (nested gauges ID 3414 and 3424, 3443 and 3445); one gauge (ID 3430) exhibited the shift of mean in 1994. In the Indigirka river basin, seven gauges have a change point in 1992-1993 from which two of them with the length of time series of about 70 years have additional change points in 1965. The Indigirka river gauge (ID 3871) with the data series interrupted in 1996 has a change point in 1965 as well. One may assume that this gauge would show a positive shift in September around 1993 as did the other of its tributaries, if longer observation data were available.

4.4.3 Low flow (October – March)

In October, streamflow increases at 15 out of 22 gauges (on average by 61% or 2.0 mm) and in November at 11 out of 17 non-frozen gauges (on average by 54% or 0.4 mm) (Table 7-8, Fig. S7-S8). Most of the changes are abrupt. In October most of the step trends occur in 1987-1993 with several exceptions in 1982 and 2001-2002, in November – 1981-1999, mainly around 1994. In December, positive trends are found at 6 out of 15 non-frozen gauges (Table 7-8, Fig. S8, Fig. 2). Average positive trend magnitude is 95% or 0.15 mm. Change points occur from 1981 to 1994. A negative monotonic trend in December is found at gauge 3483 with the magnitude -54% or -0.04 mm. Decrease of streamflow at the Indigirka river at the Vorontsovo (ID 3871) is identified in December and January for the period 1936-1996 and accounts for 32 and 25% or -0.20 and -0.08 mm respectively with change points in 1964-1969 (Fig. S8-S9, Fig. 2). On the contrary, at the Yana river at Yubileynaya gauge (ID 3861) streamflow increases by 74% (0.12 mm) monotonically in December and by a step trend in 1981 in January amounting to 77% (0.03 mm) correspondingly. A positive trend is also found in the upstream part of the Yana river (ID 3414) in January with the magnitude by 161% or 0.04 mm in 80 years (change point in 1977) (Fig. S9, Fig. 2). In February, no trends are found at the Yana river basin where only 5 gauges stay unfrozen at this month of the year (Table 7). In March, streamflow trend at the Yana river at Yubileynaya (ID 3861) is negative with a change point around 1989 when monthly average value of 0.003 mm declines to zero. Positive trends are identified at two gauges of the Indigirka river (ID 3488, 3489) and one of its main tributaries, the Elgi river (ID 3507) with mean magnitude 74% (0.07 mm), 83% (0.02 mm) and 87% (0.08 mm) in February, March and April respectively (Table 8, Fig. S9). The change

points are 1981-1987 for ID 3489 and ID 3507 gauges, and 2002-2004 for ID 3488 gauge in those three months.

4.4.4 Annual flow

In the Yana river basin, statistically significant changes in annual streamflow are found at the Adycha river tributary. Maximum percentage and net flow changes accounting for +51% or +104 mm during 1960-2015 are observed at the Adycha river in Ust'-Charky (ID 3443) with basin area 51 100 km^2 with a step change in 1995. The change point at the nested lower gauge ID 3445 (basin area 89 600 km^2) occurred in 1987 with a total increase of flow of 42% or 82 mm for the period from 1937 to 2015 (Table 7, Fig. S10).

An increasing annual trend is also found at the gauges (ID 3478, 22.6 km^2 and ID 3479, 7570 km^2) with an increase of 73% or 79 mm with a shift in 1988 and monotonic growth by 48% or 34 mm correspondingly. Monotonic flow changes are observed at two nested gauges of the Yana River (ID 3414, 45 300 km^2 and ID 3861, 224 000 km^2) with the magnitudes of 22%, 24 mm and 39%, 60 mm correspondingly (Table 7, Fig. S10).

In the mountainous part of the Indigirka river basin, positive step trends in annual streamflow are found starting from 1993 at two gauges in the upstream of the Indigirka river (ID 3488, 3489) and its tributary, the Elgi river (ID 3507), with average magnitude of 27% or 49 mm. An increase in annual streamflow is also observed at the smallest basin from the analyzed set (ID 3516, 16.6 km^2) with a magnitude of 31% or 115 mm. Runoff in August and September have contributed the most of all months to the annual streamflow rate changes at these gauging stations (Table 8, Fig. S10).

4.4.5 Maximum daily streamflow

The analysis of maximum daily streamflow was carried out for the warm period from May to September. In general, the patterns of changes of maximum daily discharges replicate the change of monthly streamflow (Table S1). The main changes are observed in May with breakpoints around 1966, when negative trends change into an insignificant positive one. The percentage change in May for eight gauges averages 69% over the whole period of observations. In September, the break points in terms of maximum discharge occur around 1993 in the Indigirka and in 1976-1981 in the Yana River basin. The average increase in maximum discharge in September reaches up to 55% for 15 gauges.

4.4.6 Freshet onset dates

In the rivers with basin area less than 2 000 km^2, freshet starts in the middle of third week of May (May 11-18); for the larger rivers this date shifts to the middle of the fourth week (May 25, on average). Freshet starts 4-8 days earlier at the end of the time series compared to 50-70 years ago (the trends are statistically significant) in 8 rivers with the identified streamflow changes in May, as well as in 3 gauges for which monthly streamflow increase in May is statistically insignificant; two of these gauges have catchment areas smaller than 1 000 km^2 (Table 1). In the Indigirka River basin, 3 gauges have change points of freshet onset dates in 1967 and another 3 show a monotonical shift. In the Yana River basin, 4 gauges show a monotonical change to an earlier onset, with one gauge having a change point in 1978 and two in 1995-1997.

5 Discussion

5.1 Air temperature

Global land-surface air temperature has increased over the period 1979-2012 by 0.25-0.27 °C per 10 years (IPCC, 2014). According to Dzhamalov et al. (2012) the warmest decade in Russia was 1990–2000, while the highest temperature anomaly was recorded in 2007 (temperature anomaly of +2.06 °C), followed by 1995 (anomaly of +2.04 °C) and 2008 (anomaly of +1.88 °C). The Arctic has warmed at more than twice the global rate over the past 50 years. The greatest increase of more than 2 °C since 1960 occurred during the cold season (AMAP, 2017). Data from our study support these observations. Meanannual air temperature (MAAT) increases in the Yana and Indigirka river basins by about +2.1 °C (1966–2015). The values of trends assessed in this study (from +0.16 to +0.46 °C per 10 years) slightly exceed other observations. Interpolated MAAT trends between 1956 and 1990 in the studied region are from 0.15 to 0.30 °C per 10 years (Romanovsky et al., 2007). Kirillina (2013) reported an air temperature increase at the Verhoyansk, Ust'-Moma and Oymyakon meteorological stations from 1 to 2 °C in the warm season and from 1.6 to 1.9 °C in the winter season for the period 1941-2010. The different periods analyzed could partly explain the difference in estimated trends. As noted by Fedorov et al. (2014) and Kirillina (2013), there were several phases with different air temperature tendencies for continental regions of North-Eastern Siberia in the 20th and 21st centuries. The last warming phase started in the 1960s or 1970s and was preceded by three or four decades of cooling. The lowest trends of 0.16 to 0.30 °C per 10 years were identified at the stations with the longest MAAT time series that partly included the cooling phase: Ust-Charky, ID 24371 (1942-2015), Chokurdah, ID 21946 (1939-2015), Vostochnaya, ID 24679 (1942-2015) and Oymyakon, ID 24688 (1935-2015). It suggests that the actual MAAT trend for last 40 years is spatially homogenous for the Yana and Indigirka river basins. Trend values exceeding 0.3 °C/year are slightly higher than the global average and agree with other regional estimations of 0.03–0.05 °C/year (Pavlov and Malkova, 2009).

5.2 Precipitation

Although precipitation is projected to increase over the pan-Arctic basin, this is not always supported by ground meteorological data (Rawlins et al., 2010). Small and insignificant positive trends from 0.63 mm/year to 5.82 mm/year are reported for the 1951–2008 period for the high latitudes of the Northern hemisphere (60°N to 90°N) by IPCC (2014). Pan-Arctic cold season precipitation (October-May) increased by 3.6 mm per decade (1.5% per decade) over the period 1936–2009 (AMAP, 2017; Callaghan et al., 2011). Kirillina (2013) reported that precipitation in the region shows a positive trend with the exception of the Oymyakon meteorological station.

The presented analysis for 1966-2015 (2012 at some stations) has shown no evidence of a systematic positive trend in annual precipitation and even displays a negative trend of solid precipitation for several stations including Verhoyansk (ID 24266). Savelieva et al. (2000) reference the decrease of winter precipitation over the territory of Eastern Siberia to the changes in the location and intensity of the Siberian High and Aleutian Low before and after the 1970s. The complex topography of the Arctic region may cause considerable underestimation of precipitation as meteorological stations tend to be located in low elevation areas (Serreze et al., 2003). Analyzed precipitation data did not undergo wind correction which varies from 10% in summer to 80-120% in winter due to the effect of wind on gauge undercatch of snowfall (Yang et al., 2005). This study therefore confirms the high uncertainty of the spatial pattern of precipitation trends in cold regions (Hinzman et al., 2013).

5.3 Soil temperature

Permafrost temperatures have risen in many areas of the Arctic (AMAP, 2017). Long-term data on permafrost temperature from boreholes for the Yana and Indigirka basins is extremely scarce. Romanovsky et al. (2010) reported an increase of mean annual ground temperature (MAGT) in the eastern part of Northern Yakutia (including the Yana and Indigirka River basins) of up to 1.5°C over the last 20 years at 15 m depth. Pavlov and Malkova (2009) reported annual ground temperature linear trends of 0.02-0.03 °C/year for North-Eastern Russia. Air temperature increases in the May-July period at Oymyakon (ID 24688), however soil temperature dropped on average by -2.8°C (1966-2015) in summer. We suggest that the data of Oymyakon is not reliable as the decrease of soil temperature occurred in an abrupt manner which appears to be related to the replacement of an instrument (Fig. S11). Additionally, it is hypothesised that the increase of liquid precipitation should warm permafrost through advective heat transport.

Identified trends of air, soil temperature and precipitation at Verkhoyansk (ID 24266) and Ust'-Moma (ID 24382) stations agree with each other. At Verkhoyansk, soil temperature increase in May-September follows an air temperature upward tendency in April-August with one month delay. The soil temperature drop in winter may be caused by a decrease of snow depth (Sherstukov, 2008) due to a statistically significant decrease of precipitation in the cold season from October to April (Table 4). At Ust'-Moma, the soil temperature increase from May to November could be explained by a statistically significant air temperature rise for nine months out of twelve.

Detected trends from -0.05 to +0.12 °C/year at 80 cm depth in different months for 1966 (1977)-2015 at Verkhoyansk and Ust'-Moma show significant scatter compared to reported trends for the whole North-Eastern regions that vary from 0 to 0.03 °C/year. In Eastern Siberia and the Russian Far East, ALT generally increased between 1996 and 2007 but has since been more stable (AMAP, 2017), which is confirmed by the temporal patterns of ALT change at Verkhoyansk (ID 24266).

5.4 Streamflow

Streamflow significantly (p<0.05) increased at least in one month at 19 of the 22 analyzed gauges. Three small rivers (ID 3501, 84.4 km^2, 1120 m, 98 mm; ID 3480, 98 km^2, 570 m, 81 mm; ID 3433, 18.3 km^2, 320 m, 58 mm) do not show any significant changes in any studied streamflow metrics.

Analysis of the runoff data for the Yana and Indigirka river basins has shown statistically significant positive discharge trends in May and the autumn-winter period for the last few decades (accompanied by significant warming). Statistically significant increases are seen in 12 out of 22 gauges in May, 17 out of 22 in September, 15 out of 22 in October, 9 out of 19 in November, 6 out of 17 in December, 4 out of 12 in January, 3 out of 8 in February and 3 out of 7 in March. Note that the total number of gauges decreases below 22 in the period from November to April because the rivers freeze.

5.4.1 Autumn

September shows the most considerable change in hydrological regime. The increase of streamflow happened at basins of all sizes in 17 of the 22 studied gauges. In September, air temperature increased only at two, and precipitation increased only at one meteorological station out of 13.

In the Indigirka river basin, the increase in streamflow can be attributed to the shift of precipitation type in September. Investigating the correlation between monthly streamflow and precipitation in September for four small

500   watersheds (area <100 km^2) where meteorological stations are located nearby, we found that the correlation coefficient varies from 0.16 to 0.59 for liquid precipitation and from 0.14 to 0.60 for total precipitation (Table 9, Fig. S12). We could not explain the reasons for low correlation at gauge ID 3433 (Table 9). It is also worth noting that for gauge ID 3501, the correlation coefficient increases from 0.27 to 0.46 for total and liquid precipitation respectively.

505   The shift of precipitation from solid to liquid occurs starting from 1993 and manifests in a considerable increase of rain fraction in comparison with snow at the stations located in the mountains. The fact that the changes in streamflow are observed regardless of basin size and in general match the breakpoints of precipitation ratio shift indicates that it is climate rather than other possible factors (permafrost thaw, increased groundwater connectivity, etc.) which drives those changes. The average increase in streamflow reaches up to 9.8 mm, which is comparable

510   with the mean absolute increase of rain precipitation of 12.2 mm. In the Yana River basin, one would expect a similar linkage between precipitation and streamflow in autumn, but this cannot be confirmed due to the lack of meteorological stations in higher elevations.Spence et al. (2011) have shown that the trend towards more autumn rainfall in the northwestern subarctic Canadian Shield with no increase in total precipitation has been sufficient to cause late season peaks in discharge and higher winter low flows. Recessional curves of early autumn flood events

515   extend later into the autumn and winter seasons. The streamflow changes in October generally repeat the spatial pattern of changes in September but with lower magnitude. The hypothesis of Berghuijs et al. (2014) stating that a shift from a snow- towards a rain-dominated regime would likely reduce streamflow is contradicted by the results of this study for the rivers in the continuous permafrost zone.

5.4.2 Winter

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Upward trends in low flow are observed at Mackenzie River (Yang et al., 2015), at the Lena river and its tributaries (Tananaev et al., 2016) and in most of the Arctic (Rennermalm and Wood, 2010). The widely found hypothesis is that increased low flow indicates permafrost degradation, aquifer activation and better connectivity between surface and subsurface water. Increasing active layer thickness, enlarged infiltration and sub-surface water contribution to

525   winter discharge by deeper and longer flow pathways sustain increasing winter streamflow in permafrost environments (Karlsson et al., 2015, St. Jacques and Sauchyn, 2009; Tananaev et al., 2016).

Change points for low flow were detected in the 1980s, 1990s and 2000s. Similar change points are observed at the Lena River basin (Tananaev et al., 2016), where the major shifts in all nonstationary time-series occur in the 1990s, but when the data from adjacent decades are combined, the major changes in minimum discharge occur between

530   1985 and 1995, and in mean annual daily flow between 1995 and 2005.

The changes in November-December tend towards basins larger than 17 000 km^2 although many smaller ones do not freeze up until January. Glotova and Glotov (2015) attribute that to the fact that the fraction of groundwater contribution to middle- sized and large basins is higher than that to smaller ones in the continuous permafrost zone.

Gurevich (2009), Dzamalov and Potehina (2010) have substantiated the hypothesis that river ice cover regulates

535   ground water feeding into rivers in cold regions. The hypothesis is that in colder winters, with a significant thickness of ice, the total water discharge decreases in small river basins. In less severe winters, when the thickness of ice is lower, the underground contribution to streamflow in the river is higher by the end of winter.

Shiklomanov and Lammers (2014) report significant negative linear trends for the outlet gauges of the Lena,

Yenisey and Yana Rivers where decreases in maximum ice thickness over 1955–2012 reached up to 73, 46 and 33 cm respectively. Average values of maximum ice thickness for the same rivers were about 180, 105 and 153 cm respectively for the period 1955-1992. 10-days series of river ice depth for the Lena River at Tabaga for the period 1955-2015 were analyzed based on Mann-Kendall test at the significance level of $p < 0.05$. Negative statistically significant trends were identified in March and April with Theil-Sen estimator. The depletion of river ice depth intensifies from March to April and decreases by 27 to 49 cm, or 20-35% (Copernicus Climate Change Service, project #C3S_422_LOT1_SMHI). However, Shiklomanov and Lammers (2014) have found that the relationship between annual maximum ice thickness and mean river discharge over the November–April period has shown no significant correlation: the highest correlation coefficients were found for the Yenisey (r = −0.63) and Lena rivers (r = −0.54).

5.4.3 Freshet

The increases in monthly streamflow in May occur in an abrupt manner. At seven gauges (area >=8 290 km^2) out of 12, the shift of flow happened around 1966, and was accompanied by two consequent years (1967, 1968) with extraordinarily high streamflow in May. Monthly flow in May 1967 and 1968 exceeded the monthly average by 3.8 – 6.5 times. Moreover, at 9 gauges out of 22 it was the highest flow through the whole period of observations. At the other six gauges, streamflow was the second highest among the observations with three of them differing by less than 5% from the historical maximum, with the other 3 from 11 to 27% lower.

No significant trends were detected for the period after the change point (1967-2015). The changes of spring freshet start date were identified at 10 gauges with streamflow changes in May. Trend value varies from 4 to 10 days earlier. This agrees with Savelieva et al. (2000) who stated that the final frost in spring has been 12–15 days earlier than the mean value in Yakutia. Smith (2000) estimated the time shift of start date of spring ice-cover events for the outlet of the Indigirka river at Vorontsovo (ID 3871) as 8.1 days for the period of observations 1937-1992.

Another five basins have shown the shift of flow in May during the period from 1980 to 1999. In 4 cases out of 5, that shift can be attributed to an earlier freshet. Yang et al. (2014, 2015) documented increases in May flows for the Mackenzie and Yukon Rivers, related to earlier melting of snow. An earlier start of freshet agrees with identified significant air temperature increases in May at 9 out of the 13 meteorological stations in the region. However, in contrast to the Lena river basin, where strong warming in spring led to an advance of snowmelt season into late May and resulted in a lower daily maximum discharge in June (Yang et al., 2002; Tan, 2011), at the study gauges, streamflow has not reduced in June (except ID 3510).

5.4.4 Maximum flow

According to recent projections, the annual maximum river discharge could almost double by the mid-21st century at the outlets of major Siberian rivers (Shkolnik et al., 2017). Existing assessments of maximum flow changes across cold regions do not fully confirm future projections. Shiklomanov et al. (2007) found no widespread significant change in spring maximum discharge, except for the Lena River, among the 139 gauging stations in the Russian Arctic. Tananaev et al. (2016) reported trends in maximum discharge only in nine time series (negative at three and positive at six gauges) out of the 105 in the Lena River basin. The Ob' and Lena rivers showed uncorrelated changes in spring peak with those aggregated from small natural watersheds located within these larger river basins

(Shiklomanov et al., 2007). There are significant negative trends (p < 0.1) over 1950-2001 from aggregated maximum discharge for the Kolyma river basin (Shiklomanov et al., 2007). The outcomes from this study support these results; we found no significant changes in maximum flow in any of our analysed river basins.

5.5 Water balance

5.5.1 Precipitation and streamflow relationship

Positive discharge trends in the Arctic have been established in recent years (McClelland et al., 2006; Peterson et al. 2002, 2006; Shiklomanov and Lammers, 2013). Increasing precipitation has been suggested as the one of the drivers of increasing streamflow (Dyurgerov and Carter, 2004; McClelland et al. 2004). Bring et al. (2016) project long-term streamflow increases over the Yana and Indigirka rivers by 50% during the 21st century by combining information from global climate model runs of multiple scenarios. The findings of this study largely contradict this, with an increase of streamflow reported at most of the gauges despite no substantial change in the absolute amount of precipitation. We estimate that 10 mm of snow is lost in September as rain draining directly into streamflow. Adding the decrease of precipitation in February-March months, the decrease of snow water equivalent during winter may reach up to 15-20 mm in total. Curiously though, no evident decrease of streamflow is observed during freshet or summer months.

Inconsistent trends in discharge and precipitation have also been reported for other Arctic rivers. In some cases there is an opposite sign in the direction of runoff changes from that in precipitation (Karlsson et al., 2015). Berezovskaya et al. (2004) have shown that the patterns in increasing trends of runoff from Siberian Rivers cannot be resolved from the apparent lack of consistent positive trends in the considered precipitation datasets.

Milliman et al. (2008) suggest that a fluctuating climate in the Yana River watershed precluded delineating a statistically significant change in either precipitation or discharge, but concluded that the Indigirka River basin had a statistically significant decrease in precipitation and non-significant increase in runoff.

5.5.2 Evapotranspiration

The issue of increasing streamflow in the absence of increasing precipitation may be explained by decreased evapotranspiration. By increasing the active layer depth and thus potentially lowering the water table, evapotranspiration might decrease, leading to increases in runoff (McClelland et al. 2004). Milliman et al. (2008) proposed that decreased evapotranspiration due to earlier snowmelt and the changes in water storage within the drainage basins could be a potential source of excess streamflow. Based on modelling results, Stieglitz et al. (2000) showed that as warming occurs mostly during winter months it does not lead to an increase in evapotranspiration.

On the other hand, Rawlins et al. (2010) argue that evapotranspiration is increasing. This is supported by reanalysis data for the pan-Arctic domain. According to model simulations, evapotranspiration has a significant trend of 0.11 mm yr^{-2} (VIC model, 1950 – 1999), while annual total evapotranspiration from LSMs model also shows a positive trend (0.40 mm yr^{-2}) (Rawlins et al., 2010). A longer growing season, observed as a result of climate warming in the 20th century, is likely to result in continued upward trends in evapotranspiration (Huntington 2004).

5.6 Cryosphere

5.6.1 Thawing permafrost

620 Permafrost temperature in Russia has been increasing and the active layer has been deepening for the last 20-30 years (Romanovsky et al., 2010; Sherstyukov and Sherstyukov, 2015). Subsurface ice melting along with air temperature increase, widespread over the studied area (Brown et al., 1998; Yang et al., 2002), can contribute to the streamflow increase (Frey and Mclelland, 2009). Though McClelland et al. (2004) argue that if water released from thawing permafrost was making a significant contribution to the observed increase in annual discharge from Eurasian Arctic rivers, one might expect that watersheds with the most permafrost cover would show the largest increase in runoff, but no such pattern is apparent.

625 An analysis using satellite based gravimetry at the Lena basin suggest that the storage of water in these areas has increased over the past decades (Velicogna et al., 2012; Muskett and Romanovsky, 2009), but the causes of this phenomenon are not clear (Velicogna et al., 2012). One reason may be the permafrost degradation, because warming in the active layer will cause greater connectivity between surface and subsurface water (Walvoord and Kurylyk, 2016) and talik development (Yoshikawa and Hinzman, 2003; Jepsen et al., 2013). Most groundwater discharge 630 occurs through areas overlying open taliks so they play the important hydrogeological role in accommodating preferential pathways acting to either recharge the deeper regional aquifer from the supra-permafrost system or facilitating discharge from the deeper aquifer (Bense et al., 2011; Walvoord et al., 2012; Lamontagne-Hallé, 2018). An easier flow of groundwater may increase the discharge of groundwater into the rivers (Ge et al., 2011; Walvoord et al., 2012; Michelle et al., 2016; Lamontagne-Hallé, 2018). However, this phenomenon only holds if sufficient 635 water is available to replenish the increased discharge. Otherwise, there will be an overall lowering of the water table in the recharge portion of the catchment (Ge et al., 2011). Michelle et al. (2016) suggest that permafrost loss is more likely to contribute to baseflow increases in discontinuous permafrost than in continuous permafrost, where permafrost tends to be cold and thick. The results of this study have shown that baseflow is increasing in the zone of continuous permafrost as well.

640 **5.6.2 Glaciers, rock glaciers and aufeis**

Another possible contribution to streamflow increase could be the meltwater from glaciers, at least in the Indigirka river basin where glaciers take up to 0.12% of the total basin area. Dyurgerov and Carter (2004) studied glacier retreat and their input into increased streamflow of the Arctic Rivers. Bliss et al. (2014) assessed the global-scale 645 response of glacier runoff to climate change based on scenario modelling, and have proposed that the Canadian and Russian Arctic region exhibits steady increases of glacier runoff consequently changing the hydrological regime.

Under the current climate, the glaciers of the region melt more intensively in July and August so their input to streamflow would be expected during those months. In the headwaters of the Indigirka river (ID 3488, 51 100 km^2) the area occupied by glaciers is the highest among the studied rivers and amounts to 0.30% of the basin area, 650 however no significant trend of streamflow is observed in July and August. The next-most downstream gauge of the Indigirka River (ID 3489, 83 500 km^2) exhibits a monotonical increase of streamflow in August from 1944 to 2015 which is mainly explained by increasing streamflow of its tributary, the Elgi River (ID 3507) where no glaciers are found. Huss and Hock (2018) estimated the hydrological response to current and future glacier mass loss; according to their simulations, annual maximum input of glacier runoff to streamflow in the Indigirka River basin was passed 655 in the period 1980-2010 and is expected to decline in the future. It will also be accompanied by the change of timing of glacier runoff. In the Indigirka River basin, glacier runoff is expected to increase by 20-40% in June and drop by

20% on average in other months (Huss and Hock, 2018).

Liljedahl et al. (2017) have found that in Jarvis Creek (634 km^2), (a sub-basin of the Tanana and Yukon Rivers), the excess discharge sourced from mountain glaciers has not only increased headwater streamflow, aquifer recharge, and storage but has also increased aquifer capacity – all with the final effect of increasing winter discharge in lower gauges. Ananicheva (2014) estimated the loss of glacier ice volumes for the Suntar-Khayata and Chersky Ranges as 1.7 and 1.4 km^3 for the period of 1945-2003 and 1970-2003 respectively. 1.7 km^3 in 58 years would give an additional inflow of 0.35 mm per year which is comparable with the increase of streamflow in the Indigirka River (ID 3489) in November and December for the same period. The fact that the change points of the increase of streamflow in late autumn – early winter occurred about 10-18 years earlier at downstream gauge (ID 3489) in comparison with headwater gauge (ID 3488) does not contradict this hypothesis. But the same pattern of more early change points at a downstream gauge is observed at nested gauges of the Adycha river (ID 3443, 3445) where glacier impact would be negligible due to their tiny area in this catchment (about 1.35 km^2 in total).

The melt of rock glaciers and aufeis, which are widespread in the study area, may have a similar effect of additional water input. According to Lytkin and Galanin (2016), 540 rock glaciers are identified within the Suntar-Khayata Range with a distribution density of 8.4 objects per 100 km^2.

The assessment of aufeis area conducted for the Indigirka River basin based on recent Landsat imagery analysis has shown that the number of aufeis fields increased by 35% but the total area decreased by 1.6 times (Makarieva et al., 2019a) in comparison with the data by Simakov and Shilnikovskaya (1958). Current aufeis area share for the studied watersheds in the Indigirka River basin ranges from 0.26 to 0.80% (Makarieva et al., 2019a), though historical estimations are higher. For example, Tolstikhin (1974) estimates that relative aufeis area averages from 0.4 to 1.3%, reaching 4% in the basins of some rivers. Due to changed conditions of aufeis functioning in the current warmer climate, they may contribute to the observed increase of streamflow in May and June at several studied gauges due to more active melting.

5.6.3 Geotectonic conditions

A significant positive trend of annual streamflow was identified only for four gauges. Arzhakova (2001) emphasizes that river Elgi (ID 3507, the Indigirka river basin) and river Adycha (ID 3443, 3445, the Yana river basin) cross tectonic dislocation zones. The area is characterized by modern seismotectonic activities (Imaeva et al., 2016). Taliks, which form within faults and excessive jointing zones, supply rivers even in extreme winter conditions (Romanovsky, 1983). Glotov et al. (2011) proposed that in particular years during sublittoral seismic activity periods, winter streamflow fluctuations in the Kolyma River may depend on geotectonic extensions and compressions which occur in the region via river bed through-taliks. Savelieva et al. (2000) pointed to redistribution of the water budget between the upper (thaw layer) water and ground water beneath the permafrost. According to Savelieva et al. (2000), the increases of temperature and thickness of the permafrost active layer may enhance the water inputs from the seasonal thaw layer into the ground waters beneath the permafrost through tectonic trenches and the lake's talik zone.

5.7 Overall impacts to the ecosystem

This study has identified increases in runoff in rivers discharging to the Arctic Ocean. Increasing volumes of

freshwater flows to the Arctic Ocean could lead to a significant weakening of the thermohaline circulation, changing sea stratification and sea ice formation (Arnell, 2005; Lique et al., 2016, Weatherly and Walsh, 1996). The total volume of water being discharged from the Yana and Indigirka rivers is around 84 km^3 (about 1.7% of total freshwater discharge to the Arctic). As a result, changes in these two basins are unlikely to impact the Arctic by themselves, but noting that even subtle changes of river streamflow may have large implication on the ocean-climate system (Miller and Russel, 2000). However, if the changes in hydroclimate seen in these basins are being felt across other Arctic basins, impacts on the Arctic Ocean could be significant.

Approximately 85% of the total terrestrial runoff to the Arctic Ocean is supplied by rivers draining from Russia (Aagaard and Carmack, 1989). Moreover, Makarieva et al. (2019b) have shown that most runoff of the Indigirka River is generated in mountainous areas and not from the coastal plains. Therefore, the analysis of this database including the mountainous upstreams of the Yana and Indigirka rivers, is particularly timely.

Forman and Johnson (1996) have previously identified the assessment of volume, timing, and natural variability of Russian river discharge as being a major priority in Arctic science. In particular, the Indigirka is one of the two largest rivers flowing into the East Siberian Sea (Anderson et al, 2011) and thus changes in flows from the Indigirka river have the potential to impact on acidity, nutrients and carbon cycling in this sea (Semiletov et al, 2016).

In terms of ecological impacts, increases in discharge, velocity, temperature, and concentration of suspended materials exert important effects on primary production and food-web dynamics in rivers and estuaries (Scrimgeour et al., 1994). Flooding associated with increased discharge is a primary control on the exchange of sediment and organic carbon between rivers and Arctic floodplains (Smith and Alsdorf, 1998).

6 Conclusions

Analysis of data from the Yana and Indigirka river basins has shown increases in annual air temperature for the region of around 2.0 °C over the last 50 years (1966-2015). Much of this increase has occurred in the late autumn and spring. Precipitation has shown a decrease in the late winter (February-March) and exhibits little change in other seasons. However, the increases in air temperature have led to a shift in the rain-snow ratio, with more rain at the expense of snow in May and September in mountainous areas. In total, snow loss can be estimated at around 20-25 mm, half of which now falls as rain and the other half as a decrease in late winter precipitation. The increase in air temperature is also reflected in soil temperature and the length of the thaw season.

Despite the slight decrease in overall precipitation, analysis of daily discharge data for 22 gauging stations in the Yana and Indigirka river basins (1936-2015) has revealed, at most of the stations, statistically significant (p< 0.05) positive trends in monthly streamflow during the autumn-winter period (September through December) and in the spring flood (May-June). Changes in spring flow are also seen through the spring freshet occurring 4 to10 days earlier over the period of record. Total annual flow has increased significantly in the upstream tributaries of the Yana and Indigirka rivers.

Most of the increases in streamflow are seen via break points, rather than showing a monotonic increase over the entire period of record. The structure of the timing of these changes is very complex; however, in general, the changes occur in the Yana River basin 10 years before the Indigirka River basin. Changes in winter streamflow are seen in the larger river basins (lower-elevation gauges) before they are seen in the smaller river basins. Analysis of monthly data is required in order to identify these changes, as in many cases, changes in annual flow are not

significant. Additionally, analysis of other datasets such as monthly precipitation and temperature is required in order to develop hypotheses regarding the potential causes of these changes in streamflow.

Increases of streamflow in the autumn-winter period are likely mainly caused by a shift in precipitation from snow to rain in September, with consequent increases in streamflow in that month, continuing into October and later months. Decreased depth of river ice and better connection of surface and ground water due to deepening of active layer and prolonging of freeze-free period may also be causing higher winter flow.

There are no changes seen in spring discharge in the last 50 years (from around 1966) except at several upstream, mountainous gauges in both studied river basins. Curiously, snow losses and the earlier timing of the spring freshet in May do not lead to a decrease of streamflow in June. This additional input of water is likely related to the regional warming trend impacting more intensive melting of the cryosphere elements such as permafrost, glaciers, and aufeis. It is difficult to directly attribute changes in streamflow to definite causes and it is almost certainly a consequence of a complicated interplay between different changing water storages and pathways in warming permafrost. The possibility also exists of additional water input via precipitation higher in the mountains, but this hypothesis cannot be verified with current observational data. The observed changes agree with reported positive trends in arctic river discharge albeit with low confidence (IPCC, 2014) and the importance of local factors in streamflow response to climate change over Siberia (AMAP, 2017). Increased streamflow may also cause changes to the Arctic Ocean through an increased freshwater flux and decreased thermohaline circulation.

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Table 1 Characteristics of runoff gauge stations

Index	River – gauge	Period	Basin area (km²)	Outlet catchment elevation (m)	Average catchment elevation (m)	Average annual flow (mm)	The average date of the beginning of the runoff (the number in May)
	Yana River basin						
3414	Yana – Verkhoyansk	1936-2015	45300	125	740	112	21
3424	Sartang – Bala	1957-2015	16700	136	700	94	19
3430	Dulgalaakh – Tomtor	1956-2015	23900	145	930	143	20
3433	Khoptolookh –Verkhoyansk	1968-2014 (gap in 1987)	18.3	133	320	58	11
3443	Adycha – Ust'-Charky	1960-2015	52800	259	960	203	19
3445	Adycha – Yurdyuk-Kumakh	1937-2015	89600	108	880	192	21
3474	Charky - 3.5 km upstream of the mouth	1949-2007 (gap in 1990)	8290	274	1030	242	19
3478	No name (Gnus) - 0.2 km upstream of the mouth	1953-2007	22.6	279	520	115	15
3479	Borulakh – Tomtor	1956-2014	7570	175	540	71	18
3480	Turagas – 1.2 km upstream of the mouth	1969-2014 (gap in 2004, 2012)	98	187	570	81	13
3483	Bytantay – Asar	1945-2015	40000	80	750	123	24
3861	Yana - Yubileynaya (Kazachye)	1972-2007	224000	-1.55	728	156	27
	Indigirka River basin						
3488	Indigirka – Yurty	1956-2015	51100	578	1330	155	19
3489	Indigirka – Indigirskiy	1944-2015	83500	482	1250	168	21
3499	Suntar river – riv. Sakharinya mouth	1956-2015	7680	828	1410	189	22
3501	Sakharinya –stream mouth	1957-2014	84.4	833	1120	98	31
3507	Elgi – 5.0 km upstream of the river Artyk-Yuryakh mouth	1946-2015	17600	594	1140	210	23
3510	Artyk-Yuryakh – 3.5 km upstream of the mouth	1946-2014	644	591	900	89	18
3516	Dunai (Ambar-Yuryuete) – Rempunkt	1964-2014	16.6	494	1060	362	11
3518	Nera – Ala-Chubuk	1945-2015	22300	568	1150	174	21
3527	Blizhniy – 0.3 km upstream of the mouth	1945-2014	23	578	900	108	18
3871	Indigirka - Vorontsovo	1936-1996	305000	3.41	760	166	29

Table 2 Characteristics of meteorological stations

Index	Meteorological station	Latitude	Longitude	Elevation, m
	Yana River basin			
21931	Kazachye	70.75	136.22	20
24261	Batagay-Alyta	67.80	130.38	494
24266	Verkhoyansk	67.55	133.38	137
24371	Ust-Charky	66.80	136.68	273
	Indigirka River basin			
24382	Ust-Moma	66.45	143.23	196
24585	Nera	64.55	143.12	523
24588	Yurty	64.05	141.88	590
24679	Vostochnaya	63.22	139.60	1288
24684	Agayakan	63.33	141.73	776
24688	Oymyakon	63.27	143.15	726
24691	Delyankir	63.83	145.60	802
24076	Deputatskiy	69.33	139.67	275
21946	Chokurdah	70.62	147.90	53

Table 3 Changes of monthly and annual air temperature (value, year of change point)

Index	Period	1	2	3	4	5	6	7	8	9	10	11	12	Avg	*CPY
						Yana River basin									
21931*	1961-2015	2.8	0.7	2.9	**4.1**	**3.1**	2.0	1.4	**3.0**	1.7	1.8	3.0	2.1	**2.2**	**0.40**
24261	1966-2012	*3.1 m*	-3.3	-0.1	1.7	**3.1 m**	2.3	2.2	2.4	-0.2	0.5	3.6 2000	-0.1	**1.4 m**	**0.30**
24266*	1969-2015	**5.6**	2.1	0.0	**2.3**	**3.8**	**1.7**	**3.2**	**2.1**	0.5	0.6	1.9	**4.5**	2.1	**0.45**
24371	1942-2015	**3.5 1990**	0.7	1.0	**3.4 1967**	**3.3 1970**	0.8	*1.5 m*	0.3	-0.4	0.7	**4.1 1982**	1.9	**1.8 1982**	**0.24**
						Indigirka River basin									
21946	1939-2015	1.4	0.4	1.4	2.8	1.1	0.4	**1.5 1986**	*2.1 2001*	**2.9 1979**	**4.4 1993**	**4.7 1993**	2.5	**2.3 1987**	**0.30**
24076	1960-2015	**4.6 1992**	1.8	2.5	*3.7 2002*	*3.1 2004*	0.9	1.8	**2.0 1994**	**1.6 m**	1.7	3.2	3.1	**2.5 1987**	**0.45**
24382	1938-2015	**5.1 1975**	**3.0 1978**	**4.1 1983**	**4.5 1980**	**3.5 1987**	1.1	**2.2 1986**	1.4	1.3	**4.5 1987**	**6.3 1983**	**5.2 1978**	**3.6 1987**	**0.46**
24585*	1966-2012	-1.6	0.1	**4.0**	1.4	1.8	**2.2**	1.7	0.7	0.3	1.5	**4.7**	**2.9**	**1.7**	**0.36**
24588	1957-2015	2.4	0.1	*3.3 2000*	1.0	1.2	1.4	*1.6 m*	1.0	0	2.1	**3.8 m**	2.4	**1.8 1979**	**0.31**
24679*	1942-2015	1.7	-0.9	**2.5**	**1.9**	**2.8**	**1.9**	1.0	-0.6	-0.7	0.5	2.3	1.2	**1.2**	**0.16**
24684	1957-2015	1.3	-0.3	*3.0 1999*	1.1	1.9	**2.0 1988**	**2.1 1990**	1.2	0.6	1.1	**5.7 1983**	3.2	**2.1 1979**	**0.36**
24688	1935-2015	**3.7 1973**	0.8	**4.1 1988**	**2.8 1969**	**2.7 1970**	**2.1 1985**	**1.6 1993**	0.7	0.5	1.4	1.4	1.8	**2.0 1979**	**0.25**
24691	1966-2015	1.6	-0.5	*4.0 1999*	1.3	1.9	1.4	**2.2 1987**	1.0	0.3	**3.1 1993**	**6.2 1983**	**5.0 1994**	**2.3 1993**	**0.46**

1030 The cells filled with grey color and bold fonts correspond to statistically significant trends with p<0.10. If any value is bold it has significance p<0.05; if the values is in italics it has significance 0.05<p<0.10. First figure means trend value (°C), second (if available) means the year of change point. Letter "m" is for monotonical trends. Some stations marked with * had many gaps and it was not possible to assess the change point. CPY (°C $(10y)^{-1}$) is for average change of temperature per 10 years. Statistically significant trends values are divided into 4 groups and marked with
1035 different colors accordingly: change points 1985 and before – green, 1985-1995 – violet, 1996 and later – yellow. Monotonous trends and where change points were not available due many gaps are in black.

Table 4 Changes of monthly, seasonal and annual precipitation (mm, %, change point year), 1966-2015

Index	Period	1	2	3	4	5	6	7	8	9	10	11	12	Year	Cold (10-4)	Warm
							Yana River basin									
21931	1966-2015	2.5	-1.4	3.0	0.0	-0.7	10.0	-12.9	**-26.0 -71**	-6.3	-1.5	4.5	1.1	-36.2		
24261	1966-2012	-1.7	-1.8	-1.2	-4.5	5.3	8.1	17.9	6.5	2.0	-4.2	-0.3	**-3.5 -67**	32.6		
24266	1966-2015	-2.9	-2.9	-1.3	-3.1	2.2	5.8	3.0	5.1	7.3	-3.9	-1.9	-5.0	9.0	**-19.3 -36 1979**	
24371	1966-2015	-1.3	-1.7	-0.7	-4.6	1.8	13.9	5.7	8.5	5.5	-4.8	-2.5	**-4.2 -63 1985**	10.8	*-23.6 -46 1996*	
							Indigirka River basin									
24382	1966-2015	**-6.7 -92 1986**	**-4.8 -71 m**	-2.9	-1.0	4.3	5.2	3.3	7.1	4.1	0.0	0.8	-4.3	11.8	*-16.0 -29 m*	
24585	1966-2015	**-4.2 -58**	-2.6	1.2	-0.8	-0.2	5.5	-8.9	5.5	14.6	2.7	2.9	-3.0	15.5		
24588	1966-2015	**-4.3 -68**	-1.5	0.0	-2.8	1.7	-12.1	-8.8	2.8	-0.2	-1.7	-1.7	-1.9	-26.6	*-14.9 -26*	
24679	1966-2015	**-4.0 -90**	**-3.3 -121**	-2.1	-0.4	1.3	**20.7 44**	-28.3	-3.2	13.8	-1.7	-0.1	-1.0	41.6	*-13.0 -30*	
24684	1966-2015	-2.4	-0.6	1.8	0.3	-1.6	2.1	-9.0	-4.5	3.9	0.5	2.7	-1.1	13.7		
24688	1966-2015	**-4.4 -60 1980**	**-3.0 -44 1994**	-1.3	-0.6	0.5	7.5	0.1	9.7	8.5	-1.0	3.0	-4.5	40.9		**53 34 m**
24691	1966-2015	**-5.5 -62 1987**	-3.6	1.1	1.7	-3.5	9.2	-2.8	12.3	5.8	3.0	3.5	-3.8	15.9		
24076	1966-2012	-2.0	-2.6	1.6	-3.8	3.1	**21.8 49**	9.4	23.7	**15.3 49**	5.0	4.0	-1.9	58.5		
21946	1966-2012	-5.3	-4.8	2.8	0.0	-2.1	14.4	**-22.9 -73**	-11.5	-1.7	5.6	5.0	3.3	-42.9		**-48 -60**

The cells filled with grey color correspond to statistically significant trends with p<0.10. If any value is bold, it has
1040 significance p<0.05; if a value is in italics, it has significance 0.05<p<0.10.
First and second figures mean trend value (mm and %), third (if available) is for the year of change point. Letter

"m" is for monotonical trends. If there is neither year, nor "m", the Pettitt's test was not carried out due to many gaps in the data. Statistically significant trends values are divided into 4 groups and marked with different colors accordingly: change points 1985 and before – green, 1985-1995 – violet, 1996 and later – yellow. Monotonous trends and where change points were not available due many gaps are in black.

Table 5 Characteristics of rain and snow share in precipitation regime in May and September, 1966-2012 (the table contains only the data of stations with the changes)

Station ID	24679	24684	24688	24076	24585	24679	24684	24688	24691
Month		May				September			
Significance *p*	<0.01	0.01	0.01	0.15		0.18	0.05	0.03	0.09
Mean share of rain (dimensionless)	0.43	0.78	0.79	0.63		0.56	0.79	0.79	0.74
Trend value (dimensionless)	**0.45**	**0.15**	**0.17**	0.19		0.18	**0.15**	**0.15**	*0.18*
Significance *p*	0.004	0.17	0.07	0.03	0.09	0.06	0.02	0.01	0.32
Mean amount of rain (mm)	8.7	12.0	10.3	19.3	25.5	53.6	19.4	18.3	20.5
Trend value (%)	79.0	39.9	62.8	68.1	61.0	57.6	60.3	77.7	39.3
Trend value (mm)	**6.9**	4.8	*6.5*	**13.1**	*15.5*	*10.4*	**11.7**	**14.2**	**8.1**
Pettitt's test significance *p*	0.03	0.06	0.23			0.32	0.14	0.12	
Pettitt's test change year	1973	1971	**1987**			1979	**1992**	**1993**	
Buishand test change year	**1986**	1971	2006			**1991**	**1992**	**1993**	**1993**

Table 6 Changes of soil temperature at 80 cm depth and maximum active layer thickness (ALT)

	1	2	3	4	5	6	7	8	9	10	11	12	ALT	D
				24266 Verkhoyansk, Yana River basin, 1966-2015										
N	31	31	33	33	48	50	49	49	50	49	49	34		
M	-16.8	-18.9	-18.6	-14.3	-6.6	-1.4	2.1	2.9	1.3	-0.5	-5.8	-12.4		
T	*1.8*	**-2.3**	**-2.4**	1.2	**3.3**	**2.5**	**3.8**	**3.7**	**1.7**	0.2	0.6	-1.2	**45**	18
Y					2003	1999	1996	1996	1998					
				24688 Oymyakon, Indigirka River basin, 1966-2015										
N	47	45	44	46	35	38	40	41	43	48	46	47		
M	-16.1	-17.5	-17.4	-13.8	-5.3	-1.0	2.3	3.1	1.5	-0.2	-4.9	-11.7		
T	**7.6**	**6.3**	**5.0**	**2.5**	-1.8	**-2.3**	**-4.2**	**-3.5**	*-1.0*	**0.7**	**4.5**	**7.3**	**-77**	-32
Y	1995	1995	1990	1983						1977	1983	1994		
				24382 Ust'-Moma, Indigirka River basin, 1977-2015										
N					34	38	38	38	38	39	38			
M					-7.3	-2.5	0.3	1.0	0.3	-1.5	-6.7			
T					**1.7**	*1.1*	**1.1**	**1.0**	**1.0**	**3.0**	**5.9**		6	40
Y					2006	2006	2006	2001	2001	2001	2002			

*N – the number of values in analyzed series; M, °C – mean temperature; T, °C[1] – temperature trend Sen's estimate; Y – change point (year); ALT (cm) – change of maximum active layer thickness; D – change in the number of days with positive soil temperature at the depth of 80 cm, 2001-2015, comparing to the long-term mean value for 1971-2000. The numbers of row T in **bold** font and filled with grey color are significant values of trends at p<0.05 level. Values in italic font marked by have the level of significance 0.05<p<0.10. The numbers in decreased font are not significant trends. Empty cells refer to the series with significant number of gaps where the assessment of change points were not possible.

Statistically significant trends values are divided into 4 groups and marked with different colors accordingly: change points 1985 and before – green, 1985-1995 – violet, 1996 and later – yellow. Monotonous trends and where change points were not available due many gaps are in black.

Table 7 Changes of monthly and annual streamflow (mm, %, change point year) and freshet onset dates. The Yana River basin

ID	Period	Area, km²	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Freshet onset dates
3478	1953-2007	22.6	NA	NA	NA	NA	6.9	14.0	12.9	13.0 50 1981	7.1 54 m	0.12 31 1987	0.00	0.00	79 69 1988	5.8
3479	1956-2014	7570	NA	NA	NA	NA	5.6	12.8 64 m	4.6	8.3 54 1987	5.5 67 m	0.1	0.0	NA	38	
3474	1949-2007	8290	NA	NA	NA	NA	7.5 54 1964*	-6.7	-26 -38 m	8.7	8.4	4.5 78 1991	0.3	0.0	-7	10
3424	1957-2015	16700	0.0	NA	NA	NA	2.9	7.3	-5.5	0.4	5.7 53 1982	0.8 54 1987	0.1	0.0	9	4.5 m
3430	1956-2015	23900	0.0	NA	NA	NA	5.5 64 1999	12.6	-2.2	0.4	7.6 50 1994	2.0 72 1982	0.4 77 1981	0.1 149 1981	20	7.1 1997
3483	1945-2015	40000	0.0	0.0	NA	NA	3.6 71 1966*	3.4	1.8	9.0	5.7 46 m	1.3 74 2001	0.31 74 1998	-0.04 -54 m	24	
3414	1936-2015	45300	0.04 161 1977	0.0	0.0	0.0	4.3 60 1965*	7.6	3.2	5.5	5.8 46 1982	1.0 51 1993	0.3 77 1994	0.1 126 1994	24 22 m	6.5 1978
3443	1960-2015	52800	0.0	NA	NA	0.0	15.5 79 1987 (1990)	18.6 28 1995	17.4 36 1995	27.0 62 1986	19.0 83 1981	3.3 96 1992	0.2 44 1994	0.0	104 51 1995	6.8 1995
3445	1937-2015	89600	0.0	0.0	0.0	0.0	12.4 83 1966*	17.9 28 1988	7.4	24.7 63 1982	15.7 69 1981	2.1 54 1992	0.5 54 1987	0.1 75 1987	82 42 1987	4.3 m
3861	1972-2007	224000	0.03 79 1981	0.0	-0.004 -153 1989	0.0	-0.8	16.2 40 1983	9.4	9.2	7.8	4.4 118 1993	0.4 118 m	0.12 75 1982	60 40 1983	

The cells filled with grey color correspond to statistically significant trends with p<0.10. If any value is bold it has significance p<0.05; if the values is in italics it has significance 0.05<p<0.10.

First and second figures mean trend value (mm and %), third (if available) is for the year of change point. Letter "m" is for monotonical trends. Statistically significant trends values are divided into 4 groups and marked with different colors accordingly: change points around 1966 – red, 1970-1985 – green, 1986-1995 – violet, 1996 and later – yellow. Year of change point marked with * indicates that the gauge has long-term series more of than 70 years with change point in about 1966 and no significant trend after that period (last 50 years). In some cases second year of change point is given in brackets, it was estimated with Buishand range test.

Table 8 Changes of monthly and annual streamflow (mm, %, change point year) and freshet onset dates. The Indigirka River basin

ID	Period	Area, km²	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Freshet onset dates
3516	1964-2014	16.6	NA	NA	NA	0.0	25.7 78 1989	12.4	-9.1	18.3	36.8 111 1992	1.6 107 1992	0.0	0.0	115 32 1993	
3527	1945-2014	23	NA	NA	NA	NA	3.9	-11.1	10.9	6.4	8.8 87 1965 (1993)	0.0	NA	NA	21	4.2 m
3510	1946-2014	644	NA	NA	NA	NA	5.2	-14.2 -61 1967*	5.3	14.0 65 1982	6.3 61 1993	0.1	0.0	NA	21	
3499	1956-2015	7680	NA	NA	NA	NA	6.8 103 1996	11.6	-17.6	-2.6	9.9 49 1993	3.3 70 1993	0.43 52 1994	0.0	26	5.4 m
3507	1946-2015	17600	0.03 59 1985	0.02 91 1985	0.02 86 1985	0.01 57 1985	15.3 106 1964*	4.0	2.9	23.4 53 m	16.5 76 1993	2.1 61 1990	0.6 88 1988	0.1 80 1987	81 39 1995	7.6 1967
3518	1945-2015	22300	0.0	NA	NA	NA	11.8 90 1966*	-12.3	-3.2	3.9	9.1 51 1965 (1993)	0.9 34 1966*	0.2 47 1994	0.0	14	3.9 1967
3488	1956-2015	51100	0.1	0.10 54 2003	0.11 87 2004	0.10 56 2002	7.6 97 1980	9.9	-4.4	7.6	12.5 59 1993	2.3 45 2002	0.4 25 1989	0.0	43	5.1 m
3489	1944-2015	83500	0.06 64 2006	0.10 86 1977	0.10 120 1983	0.14 159 1981	7.4 92 1966*	-0.6	-6.0	13.2 34 m	11.4 55 1993	1.4 34 1993	0.4 28 1982	0.3 63 1983	33 19 1995	4.6 1967
3871	1936-1996	305000	-0.08 -25 1964*	-0.01	0.01	0.01	0.2	0.3	-6.3	4.3	11 49 1965	0.7	-0.1	-0.2 -32 1969	8.1	

All designations are the same as in Table 6.

Table 9 Correlation coefficient of monthly streamflow and total and liquid precipitation in September at small watersheds

| Meteorological station, index	Elevation, m	Gauge index	Average basin elevation, m	Basin area, km^2	Period	Correlation coefficient	
						total	liquid
Indigirka River basin							
Nera, 24585	523	3516	1060	16.6	1966-2012	0.53	0.51
Agayakan, 24684	776	3501	1120	84.4	1966-2015	0.27	0.46
Yana River basin							
Ust-Charky, 24371	273	3478	520	22.6	1966-2007	0.60	0.59
Verkhoyansk, 24266	137	3433	320	18.3	1967-2015	0.14	0.16

1080
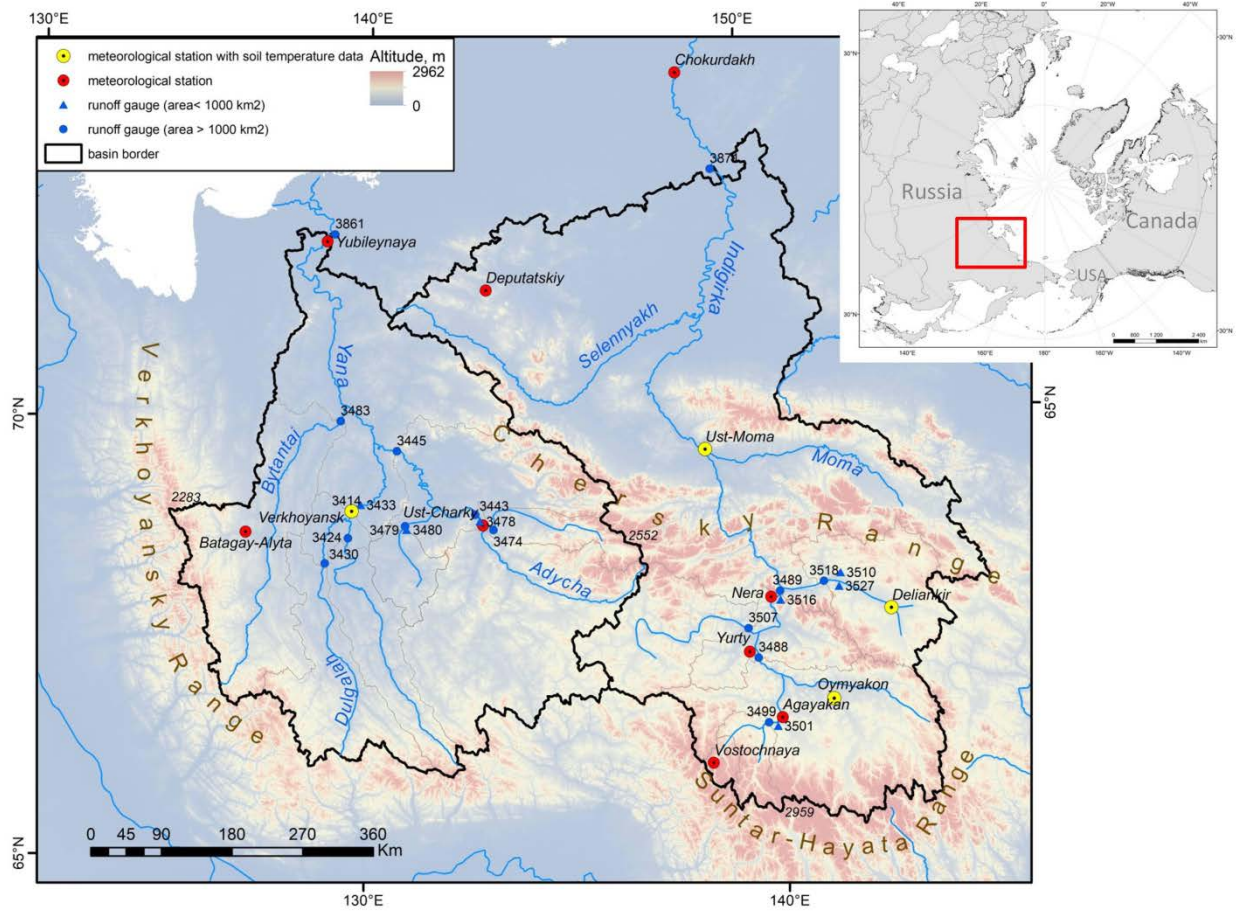
**Figure 1: Meteorological stations and hydrological gauges within the study basins**
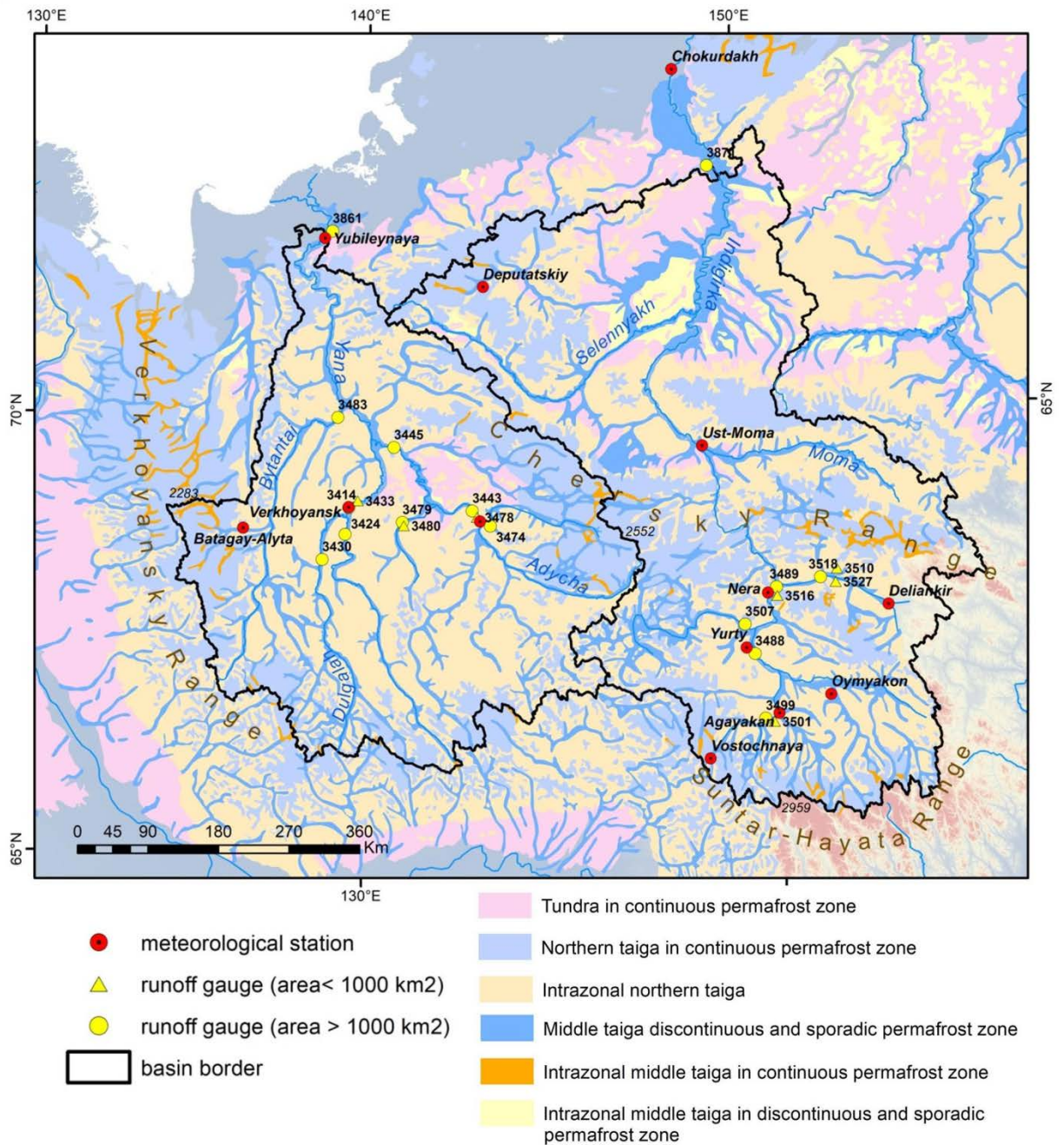
Figure 2: Landscape distribution within the study basins according to Permafrost-Landscape Map of the Republic of Sakha (Yakutia) on a Scale 1:1,500,000 (Fedorov et al., 2018)
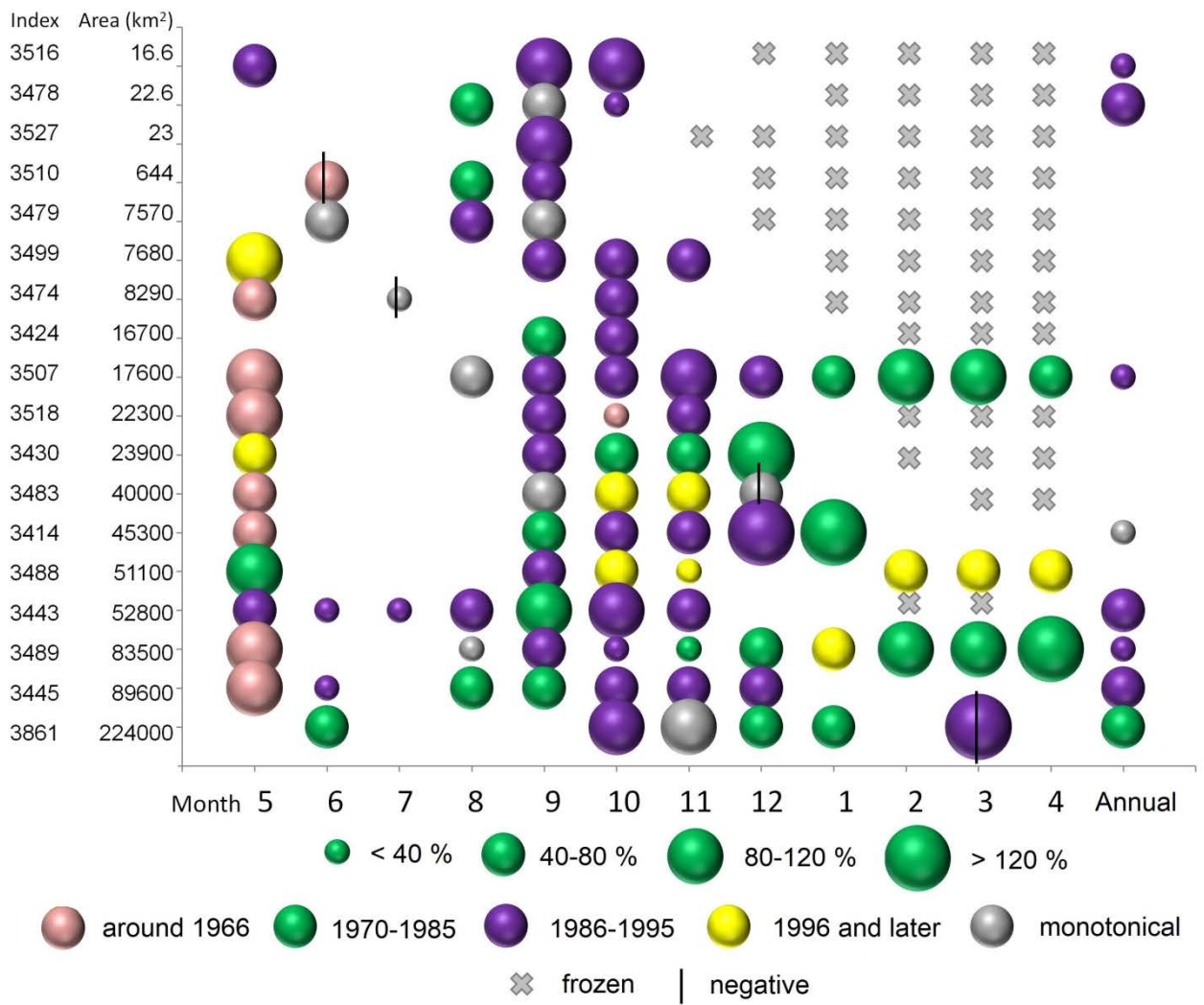
Figure 3: Change in monthly streamflow represented as a %, along with the period in which that change occurred. Data are for both Yana and Indigirka river basins and are sorted in order of basin area.

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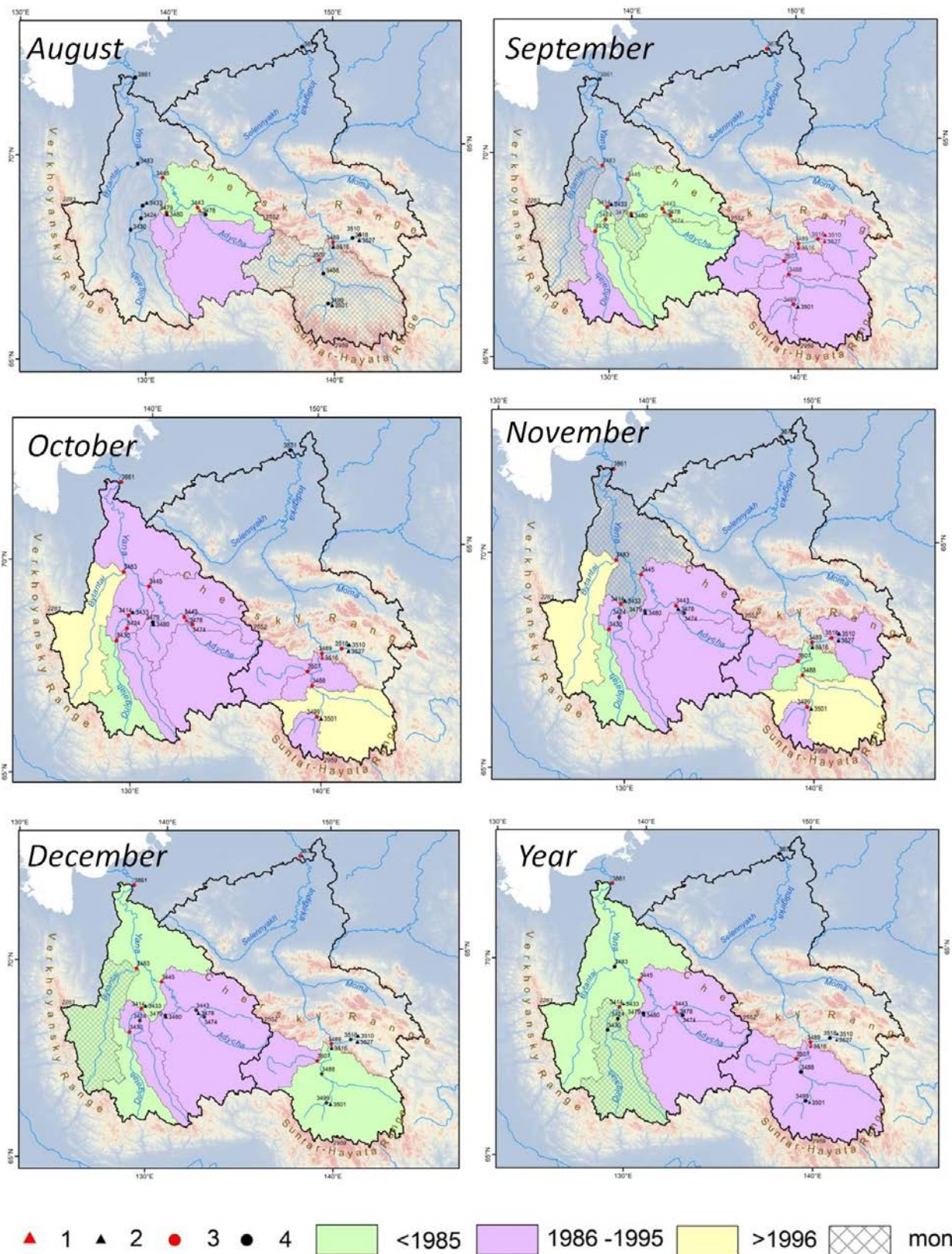
Figure 4: The periods of changes of streamflow in August, September, October, November, December and annually. Red and black colours indicate the presence and absence of the trends, respectively. The triangles and circles indicate the basin area of less and more 1000 km² , respectively. Detailed figures for each month can be found in Supplementary (Fig. S13 – S18).

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