1. Comments from referees

Short comments from the scientific community

Y. Zhang states that this is an important analysis in a data-sparse region and recommends looking at ecohydrological implications more closely, particularly whether warming increases vegetation cover during Autumn. He also suggests adding an inset to Figure 1 to put the basins into regional context.

Reviewer #1

Reviewer #1 states that the content is within the scope of The Cryosphere and is well structured. They provide numerous suggestions to improve the manuscript by utilizing stronger visuals to communicate results, more thoroughly explaining the novelty of the study, improving sentence structure and grammar, and by using more precise language.

Reviewer #2

Reviewer #2 states that the central research question addresses an important topic and that the paper provides a valuable in-depth examination of the two basins using relevant data and appropriate methods. Their detailed comments focus on improving the communication of results, agreeing with reviewer #1 that the material in some of the tables should be displayed as figures.

2. Author’s response

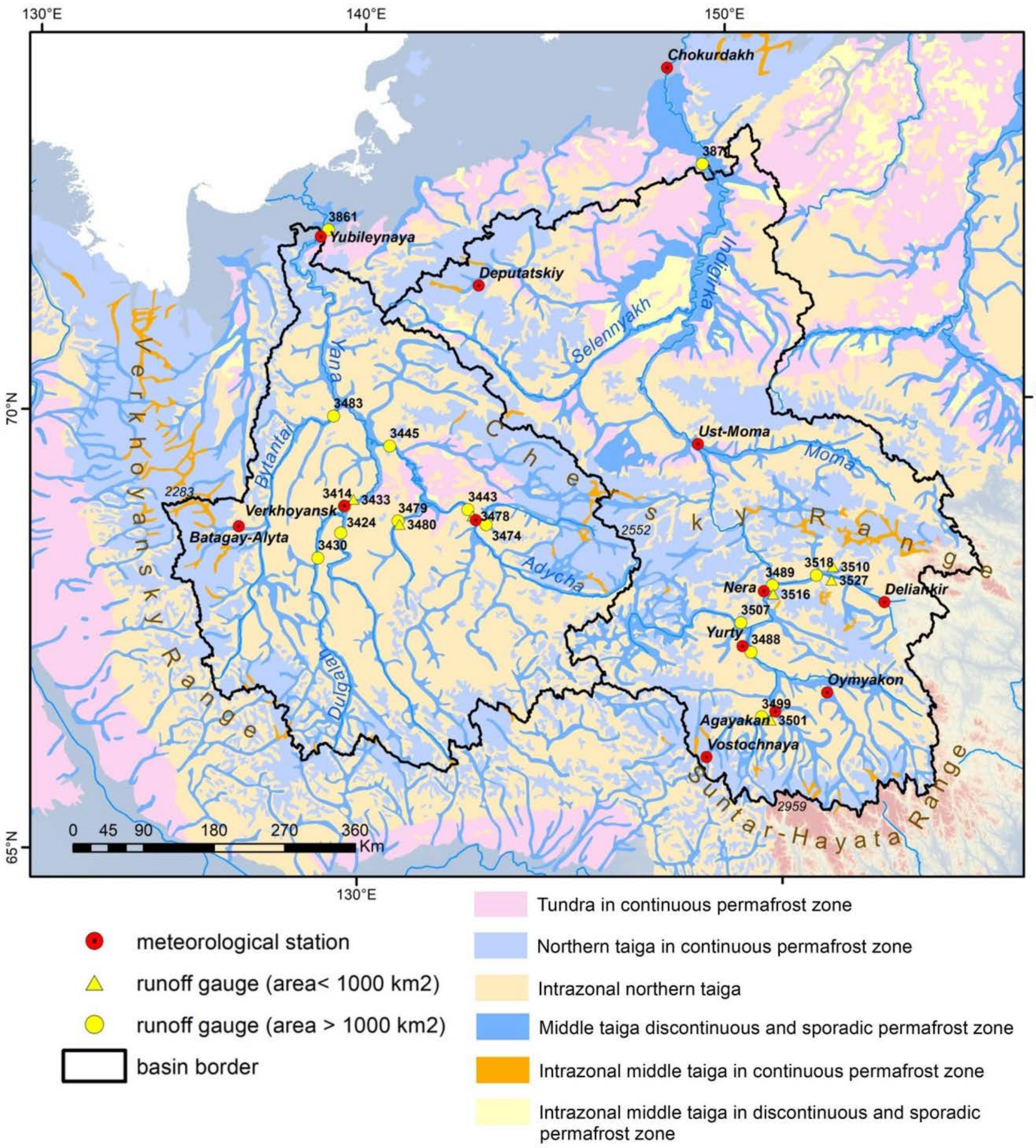
We thank all three reviewers for their positive comments on the manuscript, and their detailed comments to help improve the manuscript. Their numerous, detailed comments will make the manuscript much better overall. We agree that some of the material currently presented in tables should also be presented in figures to assist with interpretation and have made those changes. We have also incorporated the vast majority of individual comments as detailed below.

3. Author’s changes in manuscript

Zhang comments

Comment: It will be great if the authors look more at ecohydrological implication. I have not seen any data relating to vegetation. What is vegetation condition there? Does temperature warming increase vegetation coverage during Autumn?

Response: There is a brief description of the vegetation in Section 2.3. Also, we added a Figure which shows the spatial distribution of vegetation. We did not look into vegetation changes with climatic changes yet, but this is a good suggestion. It would be interesting to look at long term trends in vegetation, and we will follow this up. However, changes in monthly temperature occur in July. So it is unlikely to increase vegetation coverage in autumn.



Comment: It would be good to add a zoom out figure into Figure 1, where once can find where the two basins are.

Response: Inset has been added to Figure 1. It shows the location of the basins within the Arctic region as a whole.

Reviewer #1

Stronger visuals:

Comment: In the final paragraph of the introduction, you mention that a study of this kind has never been done. This would be more convincing if you provided a map that shows the study region in context, with sites of other studies labelled. Make it clear that this study is new, and in a region where a study like this is important and required.

Response: Inset has been added to Figure 1 which shows the study basins in the regional context of the Arctic as a whole. We have modified the text to make it clear that analysis of data for these basins is new. That is, the new part of this study is that we look into the changes of the rivers of different scale in two basins of large rivers which lie fully in the continuous permafrost zone. All other big rivers are situated in different zones (discontinuous, sporadic, no permafrost). We were unable to include a map showing the location of all other studies as we do not have GIS information for these other studies.

Comment: Section 2.1: Refer to a figure that shows what you describe.

Response: Reference to Figure 1 added to Section 2.1. Reference to Figure 2 is added to Section 2.3

Comment: Section 2.3: It could be helpful to see the stations plotted over land category.

Response: Yes, we added a new map showing the landscapes as new Figure 2.

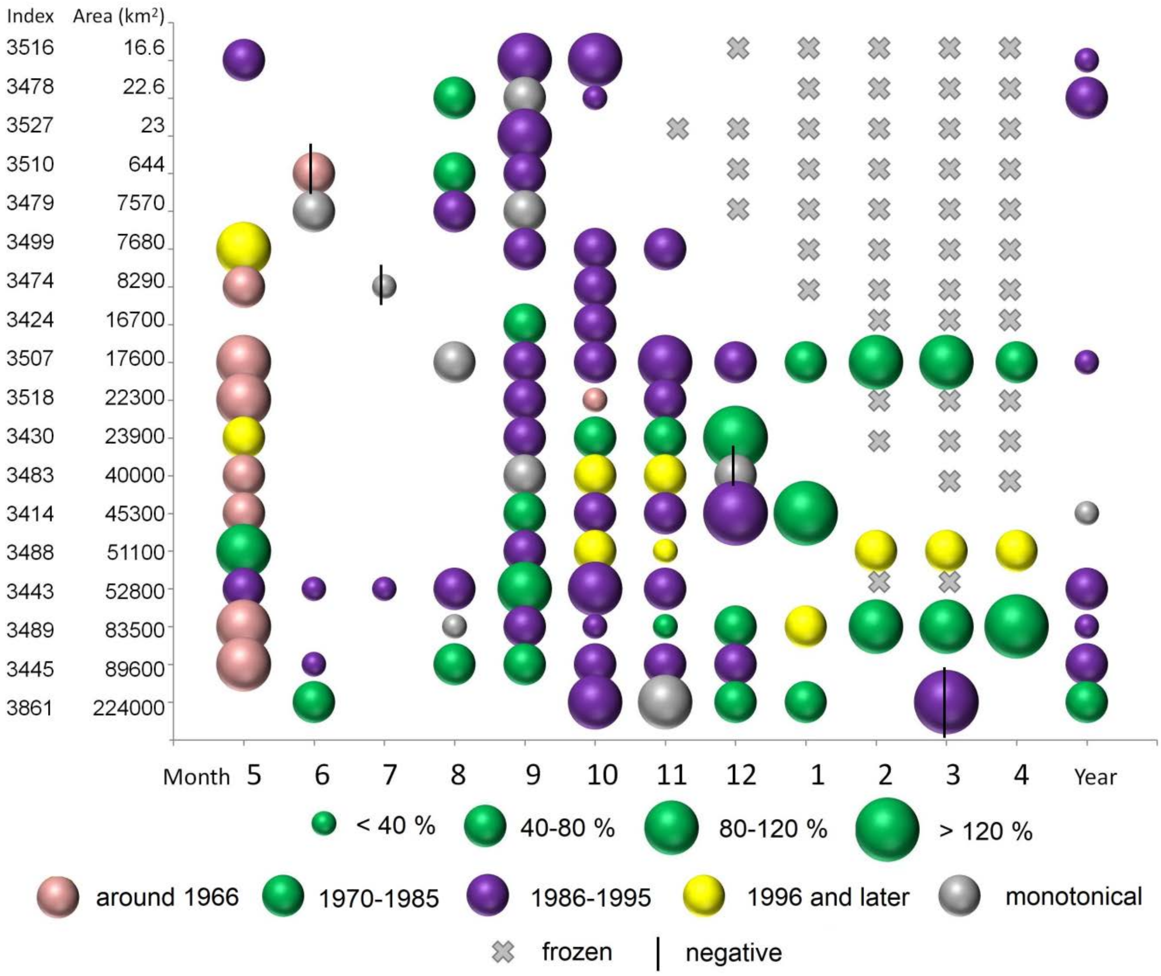
Comment: Section 3.1: Histograms or kernel density estimation may be helpful in expressing some of this information. ie: y-axis: frequency, x-axis: catchment size, or elevation above sea level, or length of series, etc.

Response: As we have only 22 gauges we believe that presenting these data in tabular form in Table 1 is more useful for the reader.

Comment: Tables 3-8 are hard to interpret as a reader. Express this information in graphical form, either instead of or in addition to the tables. The green and brown colours are also hard to see as a colour-blind person. You could label the rows instead.

Response: Extra rows added to Tables 1, 2, 3, and 4 to make it clear which rows correspond to Yana Basin and which to Indigirka Basin in order to remove the issue for colour-blind readers.

An additional figure has been added to the manuscript to represent the changes of monthly and annual stream flow, but the Tables have been retained to provide the reader with the actual numbers as we think that presenting the actual numbers is important.



Comment: Of the figures that are shown in the supplementary information, why were those specific stations chosen?

Response: These stations show the best examples of the behaviour we are describing, and so were therefore included in the paper. The figures were moved to the supplementary section at the request of the Editor on the stage of submitting the paper as they felt there was too much information in the paper itself.

Comment: Section 4.2.1: Refer to a figure that shows what you describe.

Response: This section describes the changes of rain versus snow in May and September. We think the information in Table 5 is sufficient. It is not clear how a figure would make this clearer..

Comment: Section 4.4.1: Where do these subclusters exist in space?

Response: We examined the characteristics of the catchments within the groups and looked into various aspects which could aggregate them in a cluster and could not find any common features, either spatially or with regard to other catchment characteristics, eg size, aspect, latitude, altitude etc.

Comment: Section 4.4.5: Is this information displayed somewhere in a table or figure?

Response: We added an additional table to the supplementary material which provides these data.

Further Discussion:

Comment: Line 221: Why was twenty percent chosen as the threshold? Is this robust? Do spring rain events ever falsely trigger this threshold?

Response: The authors derived that 20% threshold by experimenting with different values. To verify that it was working as expected, we checked every gauge for every year visually to confirm the correctness of the date. We also introduced more explanation in the text as the following

"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, 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 up for the correctness of such assumption."
We also added this publication to the reference list

Lesack, L. F. W., P. Marsh, F. E. Hicks, and D. L. Forbes (2013), Timing, duration, and magnitude of peak annual water-levels during ice breakup in the Mackenzie Delta and the role of river discharge, Water Resour. Res., 49, 8234–8249, doi:10.1002/2012WR013198.

Comment: 2. Section 3.2: What assumptions underpin these statistical tests? Can you briefly justify their use here? What are limits to applying these tests?

Response: In this study, we applied the combination of widely used statistical methods for the trend detection and assessment of their values in hydrometeorological data. We really do not think it is necessary to describe those methods in this paper. General guidance with detailed description of different types of tests and their adequate application can be found in Kundzewicz and Robson (2004). We added this reference and the changed the text in the beginning of the Section 3.2.

Kundzewicz and Robson, 2004. Change detection in hydrological records—a review of the methodology. Hydrological Sciences Journal des Sciences Hydrologiques 49: 7–19

Comment: Line 246: "proved" or "suggested"?

Response: Changed to "suggested"

Comment: Line 278: Why was change point analysis not conducted for all thirteen stations?

Response: Because some stations had many gaps in the data which didn't allow for change point test.

Comment: Does the variability of the variables studied change after a change point?

Response: That's a very good question. We didn't study that issue in the current paper, but will look at it further in the future.

Comment: Line 505: How can you draw conclusions about trends in winter precipitation if there are uncertainties of over one hundred percent?

Response: Uncertainties in snow volumes due to wind are well known, we do not have the wind data to correct the precipitation. Therefore, we draw our conclusions on the data we have, giving the reader an understanding of the related uncertainties.

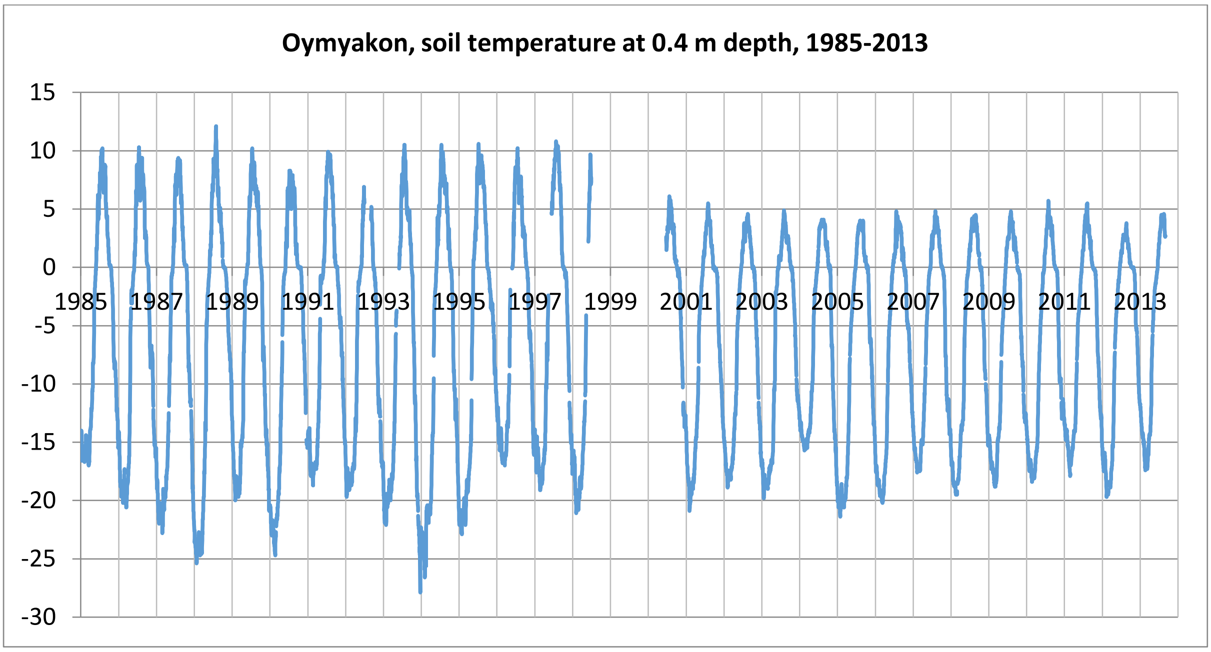
Comment: Line 515: Why is it controversial?

Response: We actually meant multidirectional trends of soil temperature at Oymyakon and Verhoyansk stations. As the issue with Oymyakon data is clarified (see following comment) the data is not controversial. We eliminated this phrase.

Comment: Line 517: What is the mechanism that would cause an increase in liquid precipitation to cause soil temperature to drop? I would think that liquid precipitation would warm permafrost through advective heat transport, so please explain to me why I would be wrong.

The data have shown that the monthly soil temperature at 0.8 m depth dropped on average by -2.8°C (1966-2015) in summer, at the same time air temperature increased and the amount of liquid precipitation increased. We think that the decrease of soil temperature happens due to increase of late summer liquid precipitation which may cause the saturation of clayish soil and the increase of ice content which would take longer to melt in summer. But we have looked at the data more carefully and investigated the temperature at 0.4 m depth. The figure shows that those radical changes happened in two years – from 1999 to 2001 which seems impossible without any artificial reason. Therefore, we conclude that the data is wrong. We made the following changes in the text

Lines 552-557: “Air temperature increases in May-July period at Oymyakon station, soil temperature dropped on average by -2.8°C (1966-2015) in summer. Therefore we suggest that the data of Oymyakon station is not reliable as the decrease of soil temperature has happened in abrupt manner which would not be possible without artificial reasons. Additionally, the increase of liquid precipitation would warm permafrost through advective heat transport.”



Comment: Line 520: You say that the trends agree with each other. Explain the mechanisms that cause you to conclude that they agree.

Response: The section about soil temperature at Verkhoyansk and Ust'-Moma stations was revised as follows. Lines 560-566:

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

Comment: Line 546: Is there a correlation between streamflow to liquid precipitation fraction that you could use to bolster your argument?

Response: We studied the correlation between monthly streamflow and precipitation in September for 4 small watersheds (area < 100 km^2) where meteorological stations are located nearby (Table 9). 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, Figure S11). We could not explain the reasons of low correlation at gauge 3433 (Table 9). It is also worth noting that for gauge 3501, the correlation coefficient increases from 0.27 to 0.46 for total and liquid precipitation respectively.

We also added more information about that issue in Discussion Section 5.4.1 Autumn

Table 9 Correlation coefficient of monthly streamflow and precipitation in September at small basins

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

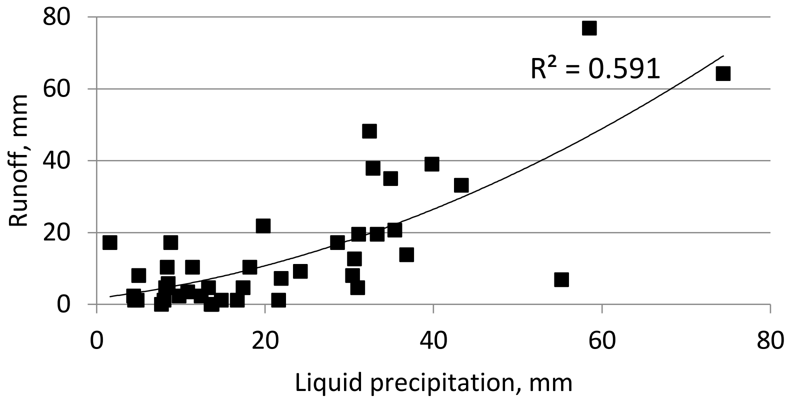


Fig.S11 Dependence of streamflow on liquid precipitation in September, Ust-Charky meteorological station – gauge 3478

Comment: Section 5.4.3: Are trends in freshet related to elevation of the station? Are changes occurring faster at higher elevations?

Response: No. there are no correlations with either the elevation neither the area of the basin.

Comment: Section 5.5.2: You should focus this section to discussing your results. You mention a longer growing season, but is agriculture significant in your study region? Is the reanalysis data for the study region? You say that “Rawlins et al. (2010) argue that evaporation is growing”; do you mean evapotranspiration is increasing?

Response: We believe that the discussion session is a useful place to put our results in the context of previous findings. This is what we are attempting to do here.

The changes of growing season length affect native vegetation as much as agricultural plants. Therefore this issue is within the scope of the discussion.

Yes, we clarified the sentences as follows:

Lines 681-682: “On the other hand, Rawlins et al. (2010) argue that evapotranspiration is increasing. This is supported by reanalysis data for the pan-Arctic domain.”

Comment: Section 5.6.2: In addition to contributing to total streamflow, glaciers tend to reduce the year to year variability of summer streamflow. This is because in hot/dry summers, increased melting partially compensates for reduced rain, while in cool/wet summers, reduced melting partially compensates for increased rain. You could also investigate the year to year variability of July/August total streamflow to further investigate if/where glaciers are important in these basins.

Response: This is an interesting point, but is beyond the scope of the current paper. We will consider it in future exploration of the data.

Comment: Section 5.7: How does the input from these rivers into the Arctic Ocean compare in magnitude to input from other rivers (such as the Big 6 that you mention earlier)? If the input from your study is much less, then it is harder to link your results to ocean circulation.

Response: Added a comparison of Yana and Indigirka flows to the total inflow to the Arctic Sea to the paper, along with a discussion of potential impacts on the East Siberian Sea and two new references.

Comment: Line 727: You say that increases in air temperature are reflected in soil temperature and length of the thaw season. Is it? You have soil temperature stations that behave differently than each other and I am not convinced that you can conclude that increases in air temperature are reflected in the soil temperature. I am not saying that the increased temperature isn't reflected in the soil temperature, only that you need to be more clear, explicit, and convincing in your discussion.

Response: As the issue with Oymyakon data is clarified (see the reply for the 8 question above) we may conclude that the increases in air temperature are reflected in soil temperature and length of the thaw season. We corrected the text at lines 785-786: "The increase in air temperature is also reflected in soil temperature and the length of the thaw season."

Comment: Line 757: Your study does not investigate how the changes are impacting large scale features in Arctic ecosystems, and so you cannot conclude that "these changes are having large-scale effects on the Arctic ecosystem". Keep your conclusions within the scope of your results and discussion.

Response: Agree. Deleted

Response: Line 758: This is your first mention of how your study relates to the livelihood of northern peoples. Don't introduce new information in your conclusion, and again, keep your conclusions within the scope of your results and discussion.

Comment: Agree. Deleted.

Other:

Comment: In the introduction, it is hard to mention the dynamics of major Arctic rivers without mentioning glaciers. Briefly consider the analysis of large-scale basins, including Mackenzie, Yukon, and Ob, for example as presented in "Global-scale hydrological response to future glacier mass loss" by Huss and Hock, 2018.

Response: We added a short consideration of the glacier runoff issue. Lines 55-59:

"There are also the studies of glacier retreat and their input into increased streamflow of the Arctic Rivers (Dyurgerov and Carter, 2004). Bliss et al. (2014) assessing global-scale response of glacier runoff to climate change based scenario modelling have proposed that Canadian and Russian Arctic exhibits steady increases of glacier runoff and affect hydrological regime."

Following the comment we also added some more discussion in Section 5.6.2 Glaciers,..

"Huss and Hock (2018) estimated 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 have been passed in the period of 1980-2010 and 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% in average in other months (Huss and Hock, 2018)."

Comment: Line 85: What are the "other complex hydrological consequences" you refer to?

Response: We clarified "other complex hydrological consequences".
"Permafrost degradation could cause greater connectivity between surface and subsurface water (Walvoord and Kurylyk, 2016), talik development (Yoshikawa and Hinzman, 2003; Smith et al., 2005; Jepsen et al., 2013) and other complex hydrological consequences, such as land-cover changes that can alter basin runoff production in permafrost region (Quinton et al., 2011), and the changes in the wetland-dominated basins that characterize the southern margin of permafrost (Connon et al., 2014)."

Comment: In the final paragraph of the introduction, it would improve clarity if you give more details about what you will do. I.e.: "This study is structured as follows: in Part II, we will [blank]. In Part III, we will [blank]" etc. Make it clear what your methods will be and how they will achieve the goal you state.

Response: Added overview of the paper at the end of the Introduction.

Comment: Line 119: What is meant by "record"? Is it a regional record? A global record?

Response: The temperature reaches record levels for the Northern Hemisphere. Clarified.

Comment: Line 120: How is "cold" defined?

Response: Pole of cold is defined where minimum temperature is observed. It is a widely-used term.

Comment: Line 134: How is "small" defined?

Response: Added minimum and maximum values of glaciers area. ") and small glaciers with minimum and maximum area defined as 0.024 and 5.76 km^2 (GLIMS and NSIDC, 2005, updated 2017) are typical"

Comment: Line 153: "deglaciation waters" should be "glacier runoff". Also, melt from glaciers, aufeises, and snowfields contribute to streamflow, not rainfall. Be precise with language.

Response: Corrected

Comment: Line 175: Does "they" refer to taliks or to rivers?

Response: We meant rivers. Corrected to "Taliks with thicknesses of several meters typically exist under small and middle-sized rivers even if the rivers may freeze in winter."

Comment: Line 185: A more up to date reference would be better, if possible. I suspect the number of aufeises and their area has changed since the 1970's.

Response: There is the study of the aufeis changes in the region. It is in review at the moment. The updated assessments and the reference were added.

Makarieva, O., Shikhov, A., Nesterova, N., and Ostashov, A.: Aufeis of the Indigirka river basin (Russia): the database from historical data and recent Landsat images, Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-99, in review, 2018.

Comment: Line 186: How does a basin have 4% aufeis if you say that the area share ranges from 0.4 to 1.3 percent?

Response: We wrote that area averages from 0.4 to 1.3. 4% is very high value which is found only for some rivers.

Comment: Line 198: Glacier modelling has changed since the 1970's, and so a more up to date reference would be better.

Response: We carried out a literature search and didn't find any newer assessments of glacier runoff input to streamflow for the studied rivers.

Comment: Section 2: Are there dams in the region? Are these rivers modified or used by humans in any way (ie: agriculture, municipal water supply)?

Response: No, there are no dams in the region. The water can be used for water supply but all the gauges were checked for the information if the streamflow was modified. In this study we used the streamflow which was not modified by any human use.

Comment: Section 3.2, and then throughout the study: Trends describe a slope, and in a time series, should be in units of [y-axis unit like mm or C]/time. You need to be more clear about if you are referring to slope of trendline, total difference over period (and how this is calculated), and how percentage change since the beginning of observations is calculated. How do you account for the fact that different stations have different length of observations when you compute the total change over period of observation? Throughout the manuscript you need to be much clearer about what you mean when you refer to trends, total changes, and their units.

Response: Because each station has a different length available we are unable to calculate changes over a consistent time period. Most of our results are presented in the form of total change over the whole period. We published the database and give the link to it in the paper, so everyone can explore the data in the way it will be useful to his/her studies.

In Section 3.2, we describe how the total changes from the beginning of the observations were estimated:

Trend values were estimated with 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 $p > 0.05$.

Comment: Line 288: Do you mean per month or per year? It is unclear what this sentence means.

Response: Corrected. Average statistically significant decrease in winter months ranges from -3.0 to -6.7 mm per month or -44-92 %.

Comment: Line 299-301: It sounds like you are talking about a total decrease over the period of observation, but you refer to it as a “decrease” and “trend”. Be more clear about what you are talking about.

Response: Corrected.

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 season.

Comment: Line 337: What is meant by “Change point in increasing tendency”?

Response: Deleted “increasing tendency”

Comment: Line 387: How can you note a negative tendency if no trends are statistically significant?

Response: Deleted “negative tendency”

Comment: Line 408: What is a “trend rate”? The units then provided are neither trends nor rates.

Response: Corrected.

In October, streamflow increases at 15 out of 22 gauges (in average by 61% or 2.0 mm) and in November at 11 out of 17 non-frozen gauges (in average by 54% or 0.4 mm) (Table 7-8, Fig. S7-S8).

Comment: Line 458: How are “small” and “large” rivers defined?

Response: We clarified the text. In the rivers with basin area less than 2000 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).

Comment: Section 4.4.6: Causal links should be explored in discussion, not in results. This causality needs to be further explored as well, and not just presented as fact.

Response: We agree. We eliminated the sentence “Air temperature increase in the last decades has led to significantly earlier freshet starting dates” in this section. Section 5.4.3 contains the discussion of casual links of changes of freshet onset dates.

Comment: Line 471: What is meant by “highest temperature”?

Response: The word anomaly was missing. The sentence is corrected.

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).

Comment: Line 476: What is meant by “average cumulative value”?

Response: Average cumulative value was corrected to average annual value.

The annual air temperature increase in Yana and Indigirka river basins with average annual value about +2.1 °C (1966–2015) and trends from +0.16 to +0.46 °C per 10 years slightly exceeds other observations.

Comment: Line 488: “relatively homogeneous”; relative to what?

Response: 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 slightly outnumber globally reported ones and agree with other regional estimations of 0.03–0.05 °C/year (Pavlov and Malkova, 2009).

Deleted “relatively”.

Comment: Line 543: Say the number of stations, not “more than 3/4”

Response: Corrected. “more than 3/4” changed for 17.

Comment: Line 544: How do you conclude that precipitation has increased at ten stations if nine trends are insignificant?

Response: Corrected. In September, air temperature and precipitation increased only at 2 and 1 meteorological stations out of 13 respectively.

Comment: Line 583: You mention decreases in maximum ice thickness, but this means little without mentioning the mean maximum ice thickness for context.

Response: We added average maximum ice thickness for the rivers.

“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 (Vuglinsky, 2000).”

Comment: Line 593: What is meant by “changes”? Change in daily streamflow? Be explicit.

Response: Corrected. The changes of monthly streamflow in May occur in an abrupt manner

Comment: Line 594: What does “extraordinarily high” mean?

“Extraordinarily high” means that out of 22 gauges, at 9 of them monthly streamflow in one of those years was historically highest, at other 6 gauges streamflow was the second highest among the observations with three of them differing less than 5% from historical, other 3 – from 11 to 27%.

We added that information as the following:

Lines 636-639

“Monthly flow in May 1967 or 1968 exceeded 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 other 6 gauges streamflow was the second highest among the observations with three of them differing less than 5% from historical maximum, other 3 – from 11 to 27%."

Comment: Line 601: What does "in most cases" mean when you are talking about five basins? The phrase "can be attributed" is used without explicitly showing why it can be attributed.

Response: We corrected for "Another 5 basins have shown the shift of flow in May during the period from 1980 to 1999. In 4 cases of 5 that shift can be attributed to earlier freshet."

Comment: Line 671: 0.30% of what? Be clear.

Response: Corrected. "In the headwaters of the Indigirka river (ID 3488, 51100 km^2) the glaciers share is the highest among studied rivers and amounts up to 0.30% of the area share… "

Comment: Line 685: How is "tiny" defined?

Response: We defined "tiny".

"But the same pattern of more early change points at 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 (about 1.35 km^2 in total)."

Comment: Lines 687-688: Why are rock glaciers described in terms of number per 100 km2, while aufeises are described in terms of percentage of basin area?

Response: Because this is the only information which was found in the literature.

Sentence Structure, Grammar, and Technical Comments:

Comment: Line 20-21: Do the 9 out of 19 rivers refer to freezing rivers?

Response: Clarified the sentence.

"In November and December, increases are seen in 9 out of 19 rivers which do not freeze in November (54%, 0.4 mm) and 6 out of 17 rivers non-freezing in December (95%, 0.15 mm), respectively."

Comment: Line 52: "agree" should be "agrees" since it refers to "change", not "changes"

Response: Corrected.

Comment: Line 87: "assessment" should be "assessments" and "is" should be "are"

Response: Corrected.

Comment: Line 109: "Mainly the terrain is mountainous" should be "The terrain is mainly mountainous"

Response: Corrected.

Comment: Line 120: Do you mean to say "changes" or "ranges"?

Response: Ranges. Corrected.

Comment: Line 207: ", two" should be ", but two"

Response: Corrected.

Comment: Line 224: “values” or “errors”? Additionally, how do you know the errors of these measurements?

Response: We mean errors. Corrected. Also we have given additional reference on possible errors of streamflow values.

“In general the uncertainties associated with discharge determination significantly change from year to year and strongly depend on the computational methods used and frequency of discharge measurements (Shiklomanov et. al, 2006). 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 large rivers streamflow may be slightly lower: monthly flows errors are 4-12 % for the open channel period and 17 % for winter months in the Lena River basin (Shiklomanov et al., 2006).”

Comment: Lines 289-291: Restructure this sentence so that its format is the same when describing the trends in July and August.

Response: Corrected

Comment: Line 297: The phrase “was carried out” is passive. Use active phrases instead. I.e.: “We evaluated cold season precipitation: : :”. Passive phrasing happens multiple times throughout the manuscript.

Response: I am not sure what the reviewer is getting at here. Passive text is common in the scientific literature. No change made.

Comment: Line 302: “Positive trend” should be “A positive trend”. This type of error occurs multiple times throughout the manuscript.

Response: Corrected at multiple places in the manuscript.

Comment: Line 303: “the values” should just be “values”.

Response: Corrected.

Comment: Line 338: “from by” is a typo.

Response: Corrected.

Comment: Line 340: “for the last fifteen years” or “over the last fifteen years”?

Response: Corrected.

Comment: Line 342: Have “along with” clause at the end of the sentence.

Response: Moved ‘along with’ to end of sentence as suggested.

Comment: Line 344: “in average” should be “on average”

Response: Corrected.

Comment: Line 353: “account for the increase by” is unclear. Do you mean “on average, temperature increases by”?

Response: Yes. Corrected.

Comment: Line 366: It is more clear to say “observed at twelve of the twenty-one studied gauges.”

Response: Corrected.

Comment: Line 375: missing units when mentioning the minimum area.

Response: Corrected.

Comment: Line 379: “monotonical” should be “monotonic”

Response: Corrected.

Comment: Line 473-474: “the anomaly” should be “anomaly”

Response: Corrected.

Comment: Line 489: Remove the comma

Response: Corrected.

Comment: Line 525: “comparative” should be “compared”

Response: Corrected.

Comment: Line 531: “at least in at least” is a typo.

Response: Corrected.

Comment: Line 574: “larger” should be “larger than”

Response: Corrected.

Comment: Line 576: “the continuous permafrost” should be “regions of continuous permafrost”, or “the continuous permafrost zone”

Response: Corrected.

Comment: Line 614: “driver” should be “drivers”

Response: Corrected.

Comment: Line 661: There is a font change, although this could be an issue of the PDF and not the manuscript.

Response: Corrected.

Reviewer #2

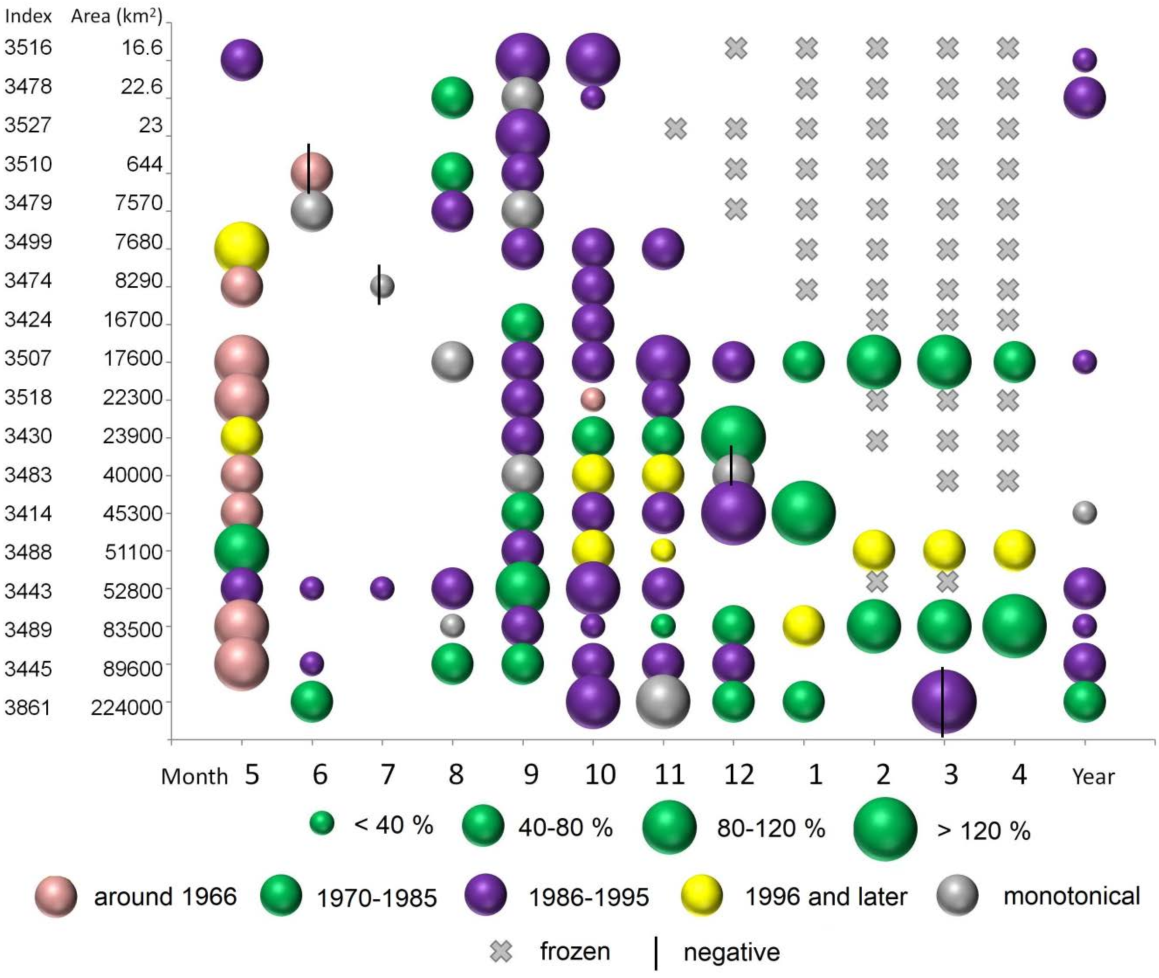
Major comments

Comment: Some of the most important findings in this study are shown in tables that are very complicated to interpret for a reader, e.g Table 3, 4, 6, 7, and 8. I urge the authors to display the information in figures, which is a more effective way to communicate data to the average reader (see any textbook about data visualization). I do not have the time to analyze these tables as they are currently designed, but I would be happy to provide a complete review of the findings if the authors provide a revised version where the data is shown in a more accessible format.

Response: An additional figure was added to the manuscript to represent the main results of the paper – the assessment of changes of monthly and annual stream flow. However, the Tables have been retained to provide the reader with the full set of actual numbers. We agree that our tables need some effort to understand them, but they also have a lot of information about the percentage and absolute value of the change for the whole period and the year of abrupt change.

We added the description of general structure of the tables at the beginning of the Section 4 before the description of the results to assist in interpreting them.

"The results of trend analysis are presented in the Tables 3-9. 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 many gaps in the data. Statistically significant trends 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 many gaps are in black. For streamflow the 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. We used the same colors as in the Tables 3-8 in Figure 3 showing the percentage change of monthly and annual streamflow and Figure 4 which presents spatial patterns of change periods."



Comment: The majority of the figures in the supplementary material are key to study and need to be moved to the main manuscript. Additionally, many figures are only showing a sample. This sample should be motivated, or even better – show all the data.

Response: These stations show the best examples of the behaviour we are describing, and so were therefore included in the paper. The figures were moved to the supplementary at the request of the Editor at the stage of submitting the paper.

Comment: The figure captions can be improved throughout. It should be possible to understand the figures without having to read the manuscript text. Provide more contexts in all captions.

Response: We provided more explanations in all captions.

Comment: I suggest the authors expand their analysis of the spatial pattern of the changes within these two catchments by preparing effective maps. It would help the reader understand if there are spatial clustering and local coherence in trends and changes in various variables.

Response: We try to present spatial analysis at Figures 3 and 4. Figure 3 shows the total changes of monthly streamflow in (%) and the periods of changes. The gauges are sorted by basin area.

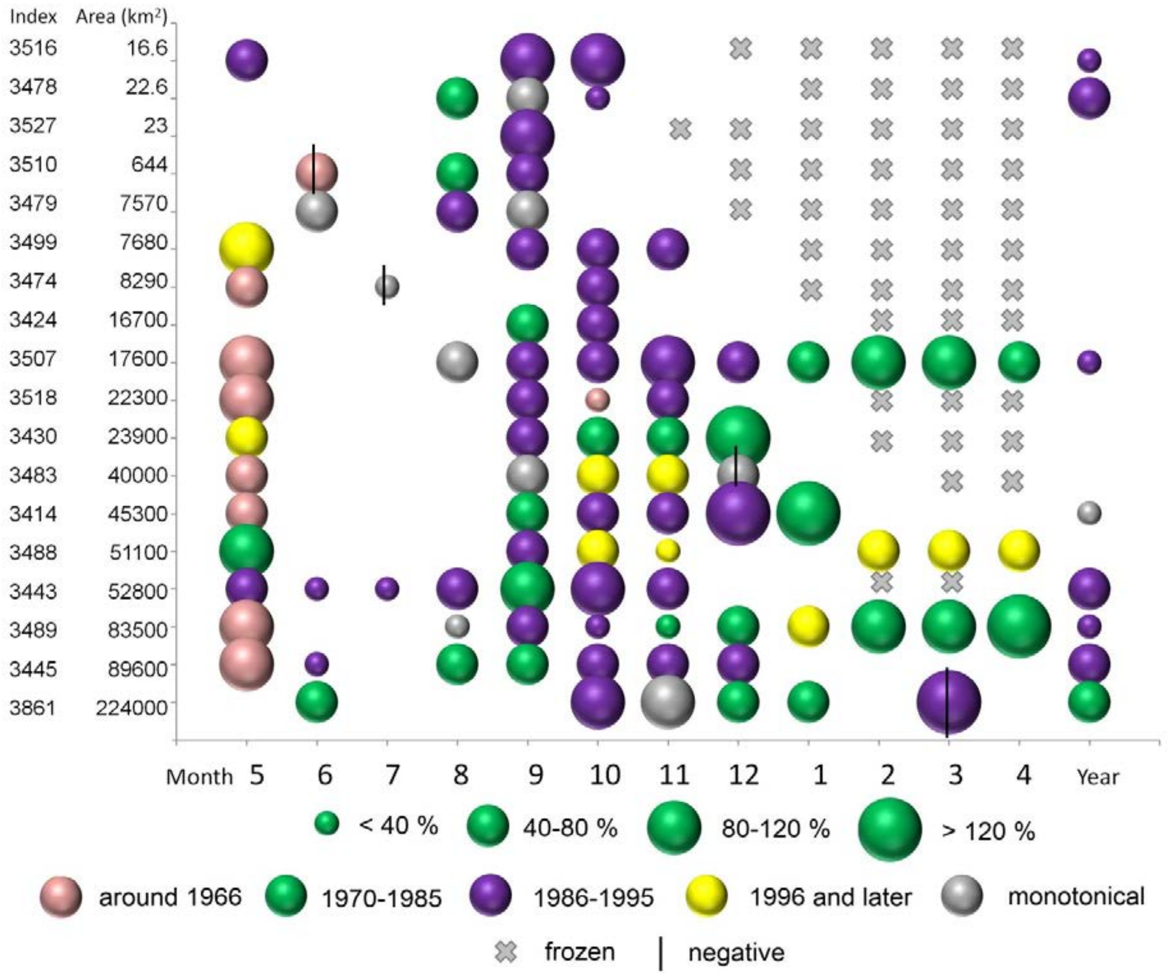


Figure 3: The total changes of monthly streamflow in (%) and the periods of changes. The gauges are sorted by basin area.

Figure 4 presents the periods of changes of streamflow in August, September, October, November, December and annually. Red and black colours indicate the presence and absence of trends, respectively.

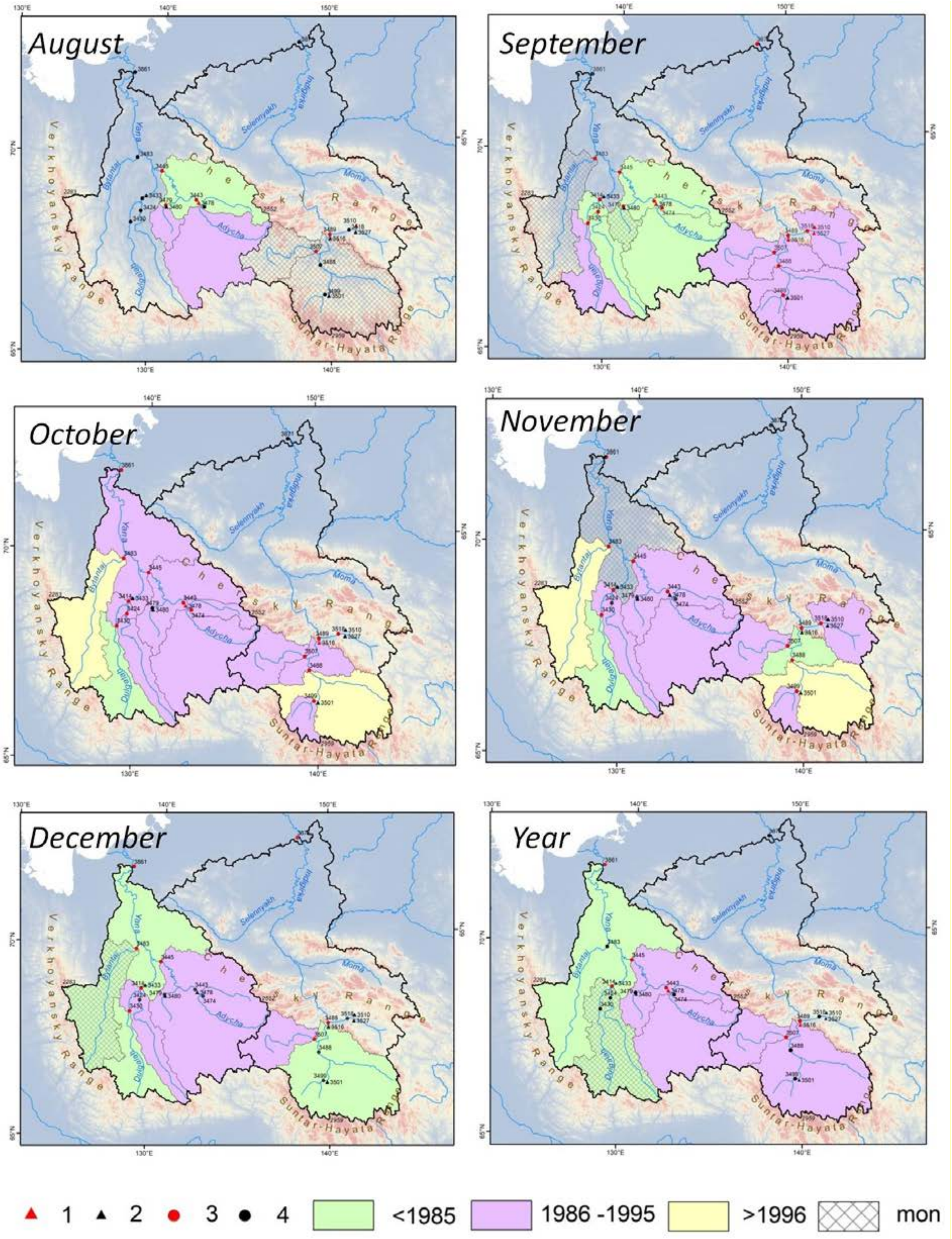


Figure 4: The periods of changes of streamflow in August, September, October, November, December and annually. Red and black colours indicate the presence and absence of the trends, respectively. The triangles and circles indicate the basin area of less and more 1000 km^2, respectively.

Minor comments

Comment: Study Area. Some references are missing, e.g. the sections 2.3, 2.5, and 2.6 lack references about key statements.

Response: We added additional references in the section 2.3

GLIMS and NSIDC: Global Land Ice Measurements from Space glacier database. Compiled and made available by the international GLIMS community and the National Snow and Ice Data Center, Boulder CO, U.S.A., doi:10.7265/N5V98602, 2005, updated 2017.

Fedorov, A.N.; Vasilyev, N.F.; Torgovkin, Y.I.; Shestakova, A.A.; Varlamov, S.P.; Zheleznyak, M.N.; Shepelev, V.V.; Konstantinov, P.Y.; Kalinicheva, S.S.; Basharin, N.I.; Makarov, V.S.; Ugarov, I.S.; Efremov, P.V.; Argunov, R.N.; Egorova, L.S.; Samsonova, V.V.; Shepelev, A.G.; Vasiliev, A.I.; Ivanova, R.N.; Galanin, A.A.; Lytkin, V.M.; Kuzmin, G.P.; Kunitsky, V.V. Permafrost-Landscape Map of the Republic of Sakha (Yakutia) on a Scale 1:1,500,000. Geosciences, 8, 465. 2018.

Section 2.5

Grave N., Gavrilova M., Gravis G., Katasonov E., Klyukin N., Koreysha G., Kornilov B., Chistotinov L. The freezing of the earth's surface and glaciation on the ridge Suntar-Hayata (Eastern Yakutia). Nauka, Moscow. 1964 (in Russian)

Hydrological Yearbook: Volume 8. Issue. 0-7. The basin of the Laptev and East-Siberian seas to the Kolyma river, Yakutsk Department of Hydrometeorology, Yakutsk, 1936-1980.

State water cadastre: Annual data on the regime and resources of surface terrestrial waters. Volume 1. Issue 16. The Lena River basin (middle and lower course), Khatanga, Anabara, Olenka, Yana, Indigirka, Yakutsk Department of Hydrometeorology, Yakutsk, 1981-2007.

Section 2.6

Shepelev, V.V.: Suprapermafrost waters in the cryolithozone. Novosibirsk. Geo. 2011, 169 pp (in Russian)

Mikhailov, V. M.: Floodplain taliks of North-East of Russia. Novosibirsk. Geo. 2013, 244 pp. (in Russian)

Methods

Comment: Clarify if a separate test of stationary was applied or if stationarity was determined with Mann-Kendall and Spearman rank.

Response: The stationarity of the time series was checked with respect to: 1) a monotonous trend (Mann-Kenndall and Spearman) and 2) abrupt changes (Pettitt's and Buishand tests).

Comment: Explain why both Mann-Kendall and Spearman rank were used to determine trends.

Response: In most cases the interpretations of Kendall's tau and Spearman's rank correlation coefficient are very similar. Two tests were selected mostly selected to check and compare the results because no statistical test is perfect even when all test assumptions are met; more than one statistical test is good practice (Kundzewicz and Robson, 2004. Change detection in hydrological records—a review of the methodology. Hydrological Sciences Journal des Sciences Hydrologiques 49: 7–19).

Comment: Explain the serial correlation better. Why and how was it applied? More details are needed.

Response: Serial correlation increases the number of errors of the first kind when checking for the presence of a trend, overestimating the significance of the assessment, and the probability of finding a trend where there is none in reality increases. On the other hand, the presence of a stationary trend overestimates the value of the autocorrelation coefficient. The method proposed in [Yue et al., 2002] and known as trend-free pre-whitening (TFPW) was used to increase the reliability of statistical trend assessment. At the first step, the linear component is subtracted from the time series, the coefficient of which is determined by the Theil-Sen method. In the second step, the time series is decorrelated by subtracting from it the component corresponding to the first-order AR (1) autoregressive process. Then the two series are summarized, after which the values of the rank correlation indicators are determined for the final series.

Comment: Use either autocorrelation or serial correlation term to make it easier for the reader to follow along.

Response: Used serial correlation. Corrected.

Comment: More context for the Pettitt's test and the Buishand range test would be welcomed.

Response: The Pettitt's test and the Buishand range test are widely used to identify change points in series of hydrometeorological data. The Pettit test for a change in the median of a series with the exact time of change unknown is based on ranks, which implies that it is less sensitive to outliers. The Buishand test is used to detect a change in the mean by studying the cumulative deviation from the mean, it assumes a normal distribution of data.

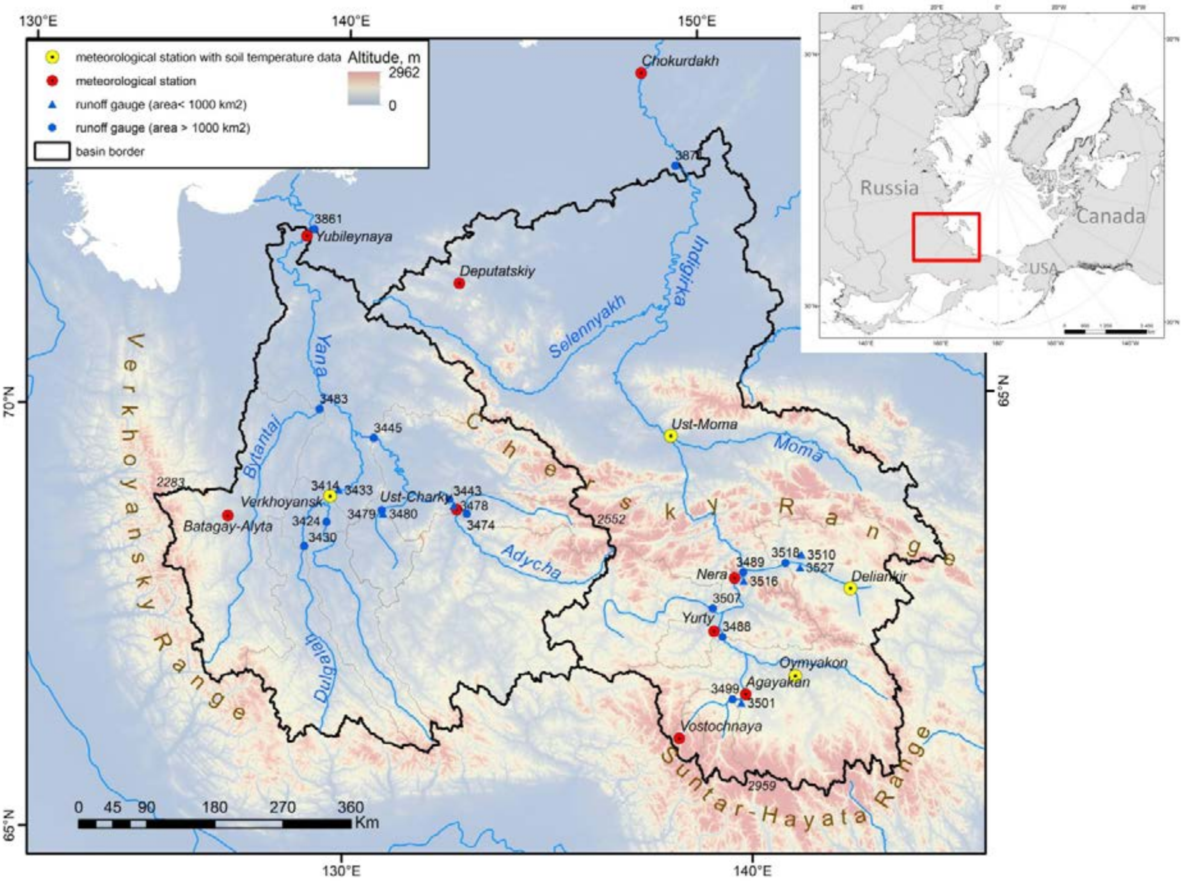
Results

Comment: The stations are referred to as numbers in tables 3 and up, but by name in the text (e.g. the section about precipitation). Please choose one or the other, it is too much to ask for the reader to cross-reference with table 1 and 2.

Response: Corrected.

Comment: Figure 1: Add an inset map that shows the study area in a larger context (e.g. Siberia)

Response: Change made to Figure 1 as requested.



Comment: Figure 2: The symbol size is too small. It is very difficult to see what the changes are. Additionally, the symbology needs to be better explained. Consider removing the background elevation map, which clutters the map and makes it more difficult to interpret.

Response: We moved the detail from parts of Figure 2 to the Supplementary material. We also improved the captions better explaining the symbology. We think the elevation map is important for interpretations of streamflow changes.

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

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Abstract. Analysis of streamflow data was conducted for 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 located completely in the zone of continuous permafrost. The main result is the presence of statistically significant ($p < 0.05$) positive trends in monthly streamflow in the autumn-winter period for most of the gauges. Streamflow increases via break points (post 1981) for 17 of the 22 gauges in September (average trend value for the period of record is 58%, or 9.8 mm), and 15 of 22 in October (61%, or 2.0 mm). In November and December, increases are seen in 9 out of 19 rivers which do not freeze in November (54%, 0.4 mm) and 6 out of 17 ~~non-freezing~~ rivers non-freezing in December (95%, 0.15 mm), respectively. Average annual air temperature increases at all 13 meteorological stations of the region by 1.1-3.1 °C over the course of the period 1966-2015. Despite this, the active layer thickness trends are contradictory: it shows an increase of 45 cm, decrease of 77 cm, and no significant trend at the three stations with available soil temperature data. Precipitation decreases in late winter by up to 15 mm over the period of record. Additionally, about 10 mm of precipitation which 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 flood via an abrupt change in 1987-1993. Changes in spring freshet start date were identified for 10 gauges. The trend value varies from 4 to 10 days earlier in May over the period of record. 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 to these changes in streamflow, but no direct observation of these changes are available. Overall, these changes are likely to have a significant impact on the ecology of the zone of continuous permafrost. Increasing freshwater fluxes to the Arctic Ocean could also impact the Arctic thermohaline circulation. Hydrometeorological data used in this study is combined in a single archive and available at https://doi.pangaea.de/10.1594/PANGAEA.892775.

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; White et al., 2007; Shiklomanov and Lammers, 2009, 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; Rawlins et al., 2009; Holmes et al., 2013; Rood et al. 2017). Reported streamflow changes are not homogeneous in terms of different runoff characteristics and time scales. While basin-averaged annual and seasonal discharges of the Lena River basin for the period from 1936 to 1995 were increasing (Rawlins et al., 2009), spring peak discharges show no significant changes within the same time frame (Shiklomanov et al., 2007).

Large Arctic river basins are characterized by a great variety of climatic, landscape and permafrost conditions and the mechanisms of the observed changes could hardly be understood on the large scale of the “Big 6”. Although climate model simulations project increased net precipitation over the pan-Arctic watershed, this is not always supported by ground meteorological data analysis (Rawlins et al., 2010). Runoff change does not necessarily coincide with precipitation and potential evaporation changes (Gao et al., 2016) but usually agrees with increase of air and soil temperature. In some cases there is an opposite change direction in runoff from that in precipitation (Karlsson et al., 2015). There are also the studies of glacier retreat and their input into increased streamflow of the Arctic Rivers (Dyurgerov and Carter, 2004). Bliss et al. (2014) ~~assessing~~assessed the global-scale response of glacier runoff to climate change based scenario modelling, and have proposed that the Canadian and Russian Arctic region exhibits steady increases of glacier runoff and ~~affect~~consequently hydrological regime.

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 rises 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.

Bring et al. (2016) projected long-term streamflow increases over the Yana and Indigirka rivers by 50% during the 21st century by combining information from model runs of multiple scenarios. These estimates agree with other existing projections (Kuzin and Lapteva, 2015; Shkolnik et al., 2017).

Compared to large rivers, the flow of small and medium rivers in cold regions has been studied much less. Tananaev et al. (2016) found that thirty 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), Finland (Ashraf et al., 2017), Alaska (Stuefer et al., 2017) and 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.

Although air temperature rise and associated permafrost degradation have been reported for the whole Arctic and subarctic territories (Nelson, 2003; Frauenfeld et al., 2004), local anomalies could differ due to specific environmental settings. Three periods with different air temperature tendencies were reported for continental regions of North-Eastern Siberia: warming period 1916-1945, cooling period 1946-1975 and modern warming period that started in 1976 (Kirillina, 2013). Analysis of Kirillina (2013) precipitation in the region shows a positive trend with the exception of the Oymyakon meteorological station.

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) but reported changes are spatially heterogeneous and do not necessarily follow air temperature trends. Permafrost degradation could cause greater connectivity between surface and subsurface water (Walvoord and Kurylyk, 2016), talik development (Yoshikawa and Hinzman, 2003; Smith et al., 2005; Jepsen et al., 2013) and other complex ~~hydrological~~ consequences ~~consequences (Quinton et al., 2011; Connon et al., 2014).~~ such as land-cover changes that can alter basin runoff production in the permafrost region (Quinton et al., 2011), and ~~the~~ changes in the wetland-dominated basins that characterize the southern margin of the permafrost- region (Connon et al., 2014).

Existing assessments of maximum and minimum flow across the cold regions ~~is~~ are contradictory. Minimum flow decrease is reported for the Tibetan Plateau (Gao et al., 2016) and Finland (Ashraf et al., 2017) but an increase is 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). 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 Kolyma river basin (Shiklomanov et al., 2007). According to recent projections, the annual maximum river discharge could almost double by the mid-21st century in the outlets of major Siberian rivers (Shkolnik et al., 2017).

While some studies have examined flows at the outlet of the Yana and Indigirka river basins, ~~E~~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~~ – the Yana and Indigirka~~, 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 describe 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). ~~Mainly t~~The terrain is mainly mountainous. There is a high elevation of 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 values of the outlet gauges from -1.55 to 833 m respectively. The lower parts of the Yana and Indigirka basin area are presented by the Yano-Indigirskaya Lowland. The average height is above 30-80 m. Some places of the lowland are 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 ~~changes~~ 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 station (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 defined as 0.024 and 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 with 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 (Makarieva et al., 2019)~~.~~ The updated map of permafrost landscapes (Fedorov et al., 2018) can be used for more detailed description of the studied basins.

2.4 Permafrost

Permafrost distribution controls the hydrological regime, especially baseflow formation and ratio of maximum to minimum discharge (Niu et al., 2016). 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, 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, ~~deglaciation waters~~glacier runoff as well as ~~ones from~~ melting aufeis~~es~~ and snowfields ~~add to rainfalls~~contribute to streamflow (Hydrological Yearbooks, 1936-1980; State Water Cadastre, 1981-2007).

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 the value of 690 mm with the 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~~; Hydrological Yearbook, 1983~~).

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). The difference by six times 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, 305000 km^2) and Yana (ID 3861, 224000 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 at the goltsy landscape to 140 mm at the 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 before the freezing front reaches the permafrost table. Taliks with thicknesses of several meters typically exist under small and middle-sized rivers even if ~~they~~ the rivers may 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, 2015). Rivers with lengths >800 km and basin area >75 000 km^2 typically do not freeze up and 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) ~~T~~the research area ha~~s~~d ~~about~~ 1,281 ~~10,000~~ aufeis~~es~~ covering an area of about ~~more than 14~~2,0~~00~~82 km^2. ~~(Sokolov, 1975).~~ Recent assessment of aufeis area conducted for the Yana and Indigirka River basins based on recent Landsat imagery analysis has shown that the number of aufeis increased up to 1,796 but the total area decreased to 1,713 km^2 (Makarieva et al., 2018c).

The aufeis area share for the studied ~~river~~ watersheds in the Indigirka River basin ranges from 0.26 to 1.15% (Makarieva et al., 2018c), though previous estimations~~s~~ are higher: relative aufeis area ~~basins~~ averages from 0.4 to 1.3%, reaching 4% in the basins of some rivers (Tolstikhin, 1974). For example, the aufeis area at the Suntar river (ID 3499) reaches 58 km^2, ~~(~~0.8% of the basin~~)~~ (Makarieva et al., 2018c) while in the Charky river basin (ID 3478) it is 113 km^2, ~~(~~1.4%~~)~~ (Tolstikhin, 1974).

In winter, the aufeis~~es~~ reduce river stream and underground flow, and in the warm season, melted aufeis waters form an additional source of river runoff. Most significant 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 (3488, Indigirka river – Yurty). The glacier runoff may exceed 3.8% of the overall annual runoff and reach 6.1% of runoff 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 (USSR surface waters…, 1972).

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 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 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 (Indigirka river at Vorontsovo) 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 22 examined catchments 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 (riv. Indigirka – Vorontsovo). Average elevation above sea level of the examined catchments varies from 320 m (Khoptolooh stream – Verkhoyansk) to 1 410 m (riv. Suntar – riv. Sakhariniya mouth). 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 daily discharge data for the entire observation period from 1936 up to and including 2014-2015, published in Hydrological Yearbooks (Hydrological Yearbooks, 1936-1980; State Water Cadastre, 1981-2007) and available for the period 2008-2015 on the website of the Automated information data system for state monitoring of water bodies (AIS SMWB) (URL: https://gmvo.skniivh.ru, reference date: 01.03.2018).

Monthly and annual flow (mm) and spring freshet start dates (counting days from the beginning of the year) were analyzed here. 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 ~~considered~~ 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 ~~up~~ for the adequacy~~correctness~~ of ~~such~~this assumption.

In some cases when daily discharge data was not available, monthly values of flow were adopted from State Water Cadastre (1979, 1987).

In general the uncertainties associated with discharge determination significantly change from year to year and strongly depend on the computational methods used and frequency of discharge measurements (Shiklomanov et. al, 2006). 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 ~~streamflow~~ may be slightly lower: monthly flow~~s~~ 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 temperatures and precipitation data series, observed at thirteen weather stations (the elevation range varies from 20 to 1288 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 temperatures under natural cover at different depths down to 320 cm from three weather stations over a period of 1966-2015 were also ~~analyzed~~analysed. Detailed description of soil temperature data sets and their quality control methods may be found in Sherstyukov (2012a; 2012b). Active layer thickness (ALT), used for the analysis, was estimated with polynomial interpolation of soil temperatures at depth (Sherstyukov, 2009; Streletskiy and Sherstyukov, 2015).

The source of the meteorological and soil temperature data is All-Russian Research Institute of Hydrometeorological Information – World Data Centre (http://meteo.ru/data). Combined monthly hydrometeorological data used in this study is available in Makarieva et al. (2018b).

3.2 Methods

In this study, we ~~used~~ applied the combination of widely used statistical methods for ~~the~~ trend~~s~~ detection ~~assessment of trends presence~~ 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). ~~as described by Tananaev et al. (2016).~~ 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 ~~proved~~ 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 ~~autocorrelation~~ 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 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 ~~the~~ 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~~s~~ 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 many gaps are in black. For streamflow, the year of change point marked with * indicates that the gauge has a long-term series of more ~~of~~ 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, it was estimated with Buishand range test. We used the same colors as in ~~the~~ Tables 3-8 in Figure 3 showing the percentage change of monthly and annual streamflow and Figure 4, S12-S17 which presents the spatial patterns of change periods.

4.1 Air temperature

Annual air temperature increase 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 3). Positive air trend is observed in March in the mountainous part of the Indigirka River (5 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 5 stations of the Indigirka basin accounting for 3.7°C in the same month. In November, at 7 stations of 13 in both basins positive trends are statistically significant and reach on average 4.7 °C with a maximum value of 6.3°C at Delyankir station (ID 24691).

Positive winter air temperature trends are significant at 4 weather stations in December, 6 – in January and at 1 station – in February. In March, the positive trend value is 3.6 °C on average for 7 meteorological stations of the mountainous part of the Indigirka River basin.

Change point analysis was conducted for 9 stations out of 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

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 ~~period~~ months ~~accounted for the~~ ranges from -3.0 to -6.7 mm 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 station (ID 21946, the Indigirka basin) and in August~~ station~~ (-71%, -26 mm) at Kazachie~~ station (-71%, -26 mm) ~~ (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 formed in upper mountainous parts of the basins.

Positive trends in summer months are observed at two stations of the Indigirka basin – + 44% (21 mm) at Vostochnaya station (ID 24679) in June and +49% (22 mm) and +49% (15 mm) in June and September at Deputatsky station (ID 24076) (Table 4).

We ~~The~~ evaluat~~ion~~ed ~~of~~ cold season precipitation calculated as the sum from October to April~~ was carried out~~. 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 ~~of~~ about -28% or 15 mm per season~~ at the level of significance 0.05<p<0.08~~. The change points ~~in decreasing tendency~~ for solid precipitation are estimated from 1980 to 1996 with most of them occurring in 1986.

A ~~P~~positive trend in warm period precipitation (May – September) is detected at Oymyakon station (ID 24688), the upstreams of the Indigirka river, with ~~the~~ values of 35% or 54 mm. Warm season precipitation has decreased by almost half (-48% or -60 mm) at the outlet of Indigirka river (Chokurdah station, 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 mostly are 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 station (ID 24679, 1288 m) exhibits the strongest changes: mean share for the whole period is 0.43, trend value is 0.45. The stations 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 station (ID 24679, 1288 m) to 0.79 at Agayakan and Oymyakon stations (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 5 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 6 stations. Pettitt and Buishand tests for change points indicate an abrupt shift of precipitation regime in September during the 1991-1993 period at 4 stations.

4.3 Soil temperature and ALT

There are three meteorological stations with soil temperature data available for the entire historical period including the beginning of the 21st century for studied territory with 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., 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 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.

Change point ~~in increasing tendency~~ estimated with Pettitt's test was identified around 1996-1999 in June–September and 2003 in May. Accordingly, ALT (mean = 170 cm) increased ~~from~~ by 45 cm. It has grown in 10 years (1997 to 2007) and is stable for the last 8 years. The number of «warm» days at the depth of 80 cm has increased, on average, by 18 days ~~for~~ 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., Indigirka River basin In the uppermost part of the Indigirka river basin~~, along with~~ meaningful negative soil temperature trends at the depth of 80 cm in summer are observed, along with~~,~~ positive trends in winter ~~are observed~~ (Table 6, Fig. S3). In June – September soil temperature at 80 cm depth dropped ~~in~~ 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 in the period of 1966-2015 (-1.5 cm a-1). The number of «warm» days has dropped by 32 days from 103 to 71 in the period 2000-2015 in comparison with the previous 30-years period.

Ust-Moma, ID 24382, 196 a.s.l., Indigirka River basin Statistically significant positive trends are identified for the period from May to November, and on average temperature increases ~~account for the increase~~ by +2.1°C in 39 years (1977-2015) (Table 6, Fig. S3). Maximum values of trends are observed in October and November and account for +3.0°C and +5.9°C respectively. The change points are estimated as 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 Runoff

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. ~~2~~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 twelve of the twenty-one studied gauges~~observed at 12 gauges of the 21 studied ones~~. Those twelve may be divided into two groups.

The first group (Fig. S4, Group A) contains 7 gauges with basin areas from 8290 to 89600 km^2 characterized by a longer continuous series of observations beginning from 1937 to 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, maximum is 52800 km^2. No trends were identified in May at the Yana and Indigirka river outlet gauges for the periods 1972-2007 (ID 3861, 224000 km^2) and 1936-1996 (ID 3871, 305000 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~~al~~ increase of flow in June for the last 50-60 years and 3 other gauges have break points in 1983-1995. Average positive trend value is 40% or 16.4 mm.

The small river in the Indigirka basin (ID 3510 – 644 km2, $p<0.057$) 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.

4.4.2 Summer-autumn floods (July – September)

In July, no statistically significant changes of streamflow occur in the Indigirka river basin~~, but in general one may note a negative tendency (Table 8)~~. 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 (52800 km^2) experienced total increase of streamflow by 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 by 55% or 18 mm. Areas of the catchments, where discharge increases in August, vary from 644 to 89600 km^2. Two nested gauges (ID 3507 and ID 3489) have a monotonic increasing trend from mid-50s to 2015. The other, including two nested gauges of the Adycha river (ID 3443, ID 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, 7 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 positive shift in September around 1993 as 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 (~~o~~in average by ~~trend rate is~~ 61% or 2.0 mm) and in November at 11 out of 17 non-frozen gauges (~~o~~in average ~~value is~~ 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).

In contrary, at the Yana river at Yubileynaya gauges (ID 3861) streamflow increases by 74% (0.12 mm) monotonically in December and by step trend in 1981 in January amounting to 77% (0.03 mm) correspondingly. A ~~P~~positive trend is also found at the upstreams of the Yana river (gauge 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 in Yubileynaya is negative with 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 tributary, 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 3488 station in those three months.

4.4.4 Annual flow

In the Yana river basin, statistically significant changes of 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 51100 km^2 with a step change in 1995. The change point at the nested lower gauge ID 3445 (basin area 89600 km^2) occurred in 1987 with a total increase of flow by 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 by 73% or 79 mm with 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, 45300 km^2 and ID 3861, 224000 km^2) with the magnitudes by 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 by 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 most significantly 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). Main changes in May are observed with breakpoints around 1966 when negative trends reverse into an insignificant positive one. The percentage change in May for 8 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 between 1976-1981 in the Yana River basin. Average increase of maximum discharge in September reaches up to 55% for 15 gauges.

4.4.6 Freshet onset dates

In the ~~small~~ rivers with basin area less than 2000 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). ~~Air temperature~~

~~increase in the last decades has led to significantly earlier freshet starting dates.~~ Freshet starts 4-8 days earlier than 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 have monotonical shift. In the Yana River basin 4 gauges have monotonical change to earlier onset, 1 gauge has a change point in 1978 and 2 – 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 (~~the~~ temperature anomaly of +2.06 °C), followed by 1995 (~~the~~ anomaly of +2.04 °C) and 2008 (~~the~~ 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 supports these observations. The annual air temperature increase in Yana and Indigirka river basins with average ~~cumulative~~ annual value about +2.1 °C (1966–2015) and trends from +0.16 to +0.46 °C per 10 years slightly exceeds 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 air temperature increase at the Verhoyansk, Ust'-Moma and Oymyakon meteorological stations from 1 to 2 °C in warm season and from 1.6 to 1.9 °C in winter season for the period 1941-2010.

The different period of analyzed data 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 from 0.16 to 0.30 °C per 10 ~~/~~years were identified at the stations with longest MAAT time series that partly included the cooling phase: Ust-Charky 24371 (1942-2015), 21946 Chokurdah (1939-2015), 24679 Vostochnaya (1942-2015) and 24688 Oymyakon (1935-2015). It suggests that the actual MAAT trend for last 40 years is spatially ~~relatively~~ homogenous for the Yana and Indigirka river basins. Trend values exceeding 0.3 °C/year~~,~~ slightly outnumber globally reported ones 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. 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 1936–2009 (AMAP, 2017; Callaghan et al., 2011c).

The presented analysis for 1966-2015 (to 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. 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 1970s. At the same time Kononova (2013) reported increase of winter sum for Verhoyansk for 1981-2007.

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 may vary from 10% in summer to 80-120% in winter due to the effect of wind on gauge undercatch of snowfall (Yang et al., 2005). The study confirms high uncertainty of spatial pattern of the 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) up to 1.5°C over the last 20 years at the 15 m depth.

Pavlov and Malkova (2009) reported annual ground temperature linear trends of 0.02-0.03 °C/year for North-Eastern Russia. ~~The soil temperature data for the studied region is controversial.~~

~~Although a~~Air temperature increases in May-July period at Oymyakon station, soil temperature dropped on average by -2.8°C (1966-2015) in summer. Therefore we suggest that the data of Oymyakon station is not reliable as the decrease of soil temperature ~~has happened~~occurred in an abrupt manner which ~~would not be possible without artificial reasons~~appears to be related to the replacement of an instrument. Additionally, it is hypothesised that the increase of liquid precipitation sh~~w~~ould warm permafrost through advective heat transport.

~~Partially it could be the consequence of liquid precipitation increase which increased by up to 53 mm (or 36%) in the warm season (May – September). However, precipitation has been growing monotonically and an abrupt drop of soil temperature occurred between 1987 and 2000.~~

Identified trends of air, soil temperature and precipitation at Verkhoyansk and Ust'-Moma stations agree with each other. At Verkhoyansk soil temperature increase in May-September follows air temperature upward tendency in April-August with one month delay. The s~~S~~oil temperature drop in winter may be caused by decrease of snow depth (Sherstukov, 2008) ~~.~~due to identified statistically significant decrease of precipitation in cold season from October to April (Table 4). At Ust'-Moma soil temperature increase from May to November could be explained by 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 stations show significant scatter compared~~ative~~ 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 station.

5.4 Streamflow

Streamflow significantly (p<0.05) increased at least in ~~at least~~ one month at 19 gauges of the 22 analyzed. Three small rivers (ID 3501 84.4 km^2, 1120 m, 98 mm; ID 3480 – 1.2 km upstream of the mouth, 98 km^2, 570 m, 81 mm; ID 3433, 18.3 km^2, 320 m, 58 mm) do not show any significant changes of 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 in12 out of 22 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 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 of hydrological regime. The increase of streamflow happened at basins of all sizes in 17 ~~more than ¾ of the~~ of the 22 studied gauges. In September, air temperature and precipitation increased only at 2 and 1 meteorological stations out of 13 respectively.~~. Although precipitation increased at 10 stations out of 13 in September, only one trend among them is statistically significant.~~

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 4 small 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.S11). We could not explain the reasons for~~of~~ low correlation at gauge 3433 (Table 9). It is also worth ~~to note~~noting that for gauge 3501, the correlation coefficient increases from 0.27 to 0.46 for total and liquid precipitation respectively.

The shift of precipitation from solid to liquid ~~It~~ occurs starting from 1993 and manifests in a considerable increase of rain fraction in comparison with snow at meteorological stations located in the mountains. The fact that the changes of streamflow are observed at the gauges regardless of basin size and in general match the breakpoints of streamflow rise and precipitation ratio shift indicate that it is climate rather than other possible factors (permafrost thaw, increased groundwater connectivity, etc.) which drives those changes. Average magnitude of streamflow trend reaches up to 9.8 mm, which is comparable 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 because of the lack of meteorological stations in higher elevations this cannot be confirmed.

Spence et al. (2011) have shown that the trend towards more autumn rainfall in the northwestern subarctic Canadian Shield with no sign of significant total precipitation increase has been sufficient to cause late season peaks in discharge and higher winter low flows. Recessional curves of early autumn flood events extend into later autumn and winter season. 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

Upward trends of low flow are observed 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 winter discharge by deeper and longer flow pathways sustain increasing winter streamflow in permafrost environments (Karlsson et al., 2015, Niu et al., 2016; St. Jacques and Sauchyn, 2009; Tananaev et al., 2016).

Change points for low flow were detected in 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 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) attributes that to the fact that the fraction of groundwater contribution to middle- sized and large basins is higher than to smaller ones in the continuous permafrost zone.

Markov and Gurevich (2008), Gurevich (2009), Dzamalov and Potehina (2010) have substantiated the hypothesis on a regulatory impact of river ice cover in the regions with long-lasting winter on ground water feeding into rivers. It suggests that in colder winters, with a significant thickness of ice, the total water discharge decreases in small river basins. In less severe winters, there is a decrease in the thickness of river ice and the preservation of higher runoff of the underground streamflow in the river 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 (Vuglinsky, 2000). 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 reaches the rates from 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 November–April has shown no significant correlation: the highest correlation coefficients were found for the Yenisey (r = −0.63) and Lena (r = −0.54).

5.4.3 Freshet

~~All~~ The changes of monthly streamflow ~~changes~~ in May occur in an abrupt manner. At 7 gauges (area >=8290 km^2) out of 12, the shift of flow happened around 1966, it was accompanied by two consequent years (1967, 1968) with extraordinarily high streamflow in May. Monthly flow in May 1967 and~~or~~ 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 6 gauges, streamflow was the second highest among the observations with three of them differing by less than 5% from the historical maximum, the other 3 – from 11 to 27%.

No significant trends are detected for the period after the change point (1967-2015) alone. The changes of spring freshet start date were identified at 10 gauges with streamflow changes in May. Trend value varies from 4 to 10 earlier days. 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 magnitude of 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 5 basins have shown the shift of flow in May during the period from 1980 to 1999. In 4 cases of 5 ~~, in most cases,~~ that shift can be attributed to earlier freshet. Yang et al. (2014, 2015) documented increases in May flows for the Mackenzie and Yukon Rivers, respectively related to earlier melting of snow. Earlier start of freshet agrees with identified significant air temperature increase in May at 9 out of 13 meteorological stations in the region. But 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 have not reduced in June (except ID 3510).

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, 2009). Increasing precipitation has been suggested as the one of the drivers of increasing streamflow (Dyurgerov and Carter, 2004; McClelland et al. 2004).

The findings of this study largely contradict this, with an increase of streamflow reported at most of the gauges despite no substantial change in 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. 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 the Indigirka River basin had a statistically significant decrease of 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 ~~ration~~ is increasing~~growing~~. This is supported by reanalysis data for the pan-Arctic domain. According to model simulation, evapotranspiration has a significant trend of 0.11 mm yr^{-2} (VIC model, 1950 – 1999), 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

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 (USSR surface waters resources, 1972; 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.

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 increase the flow of groundwater and, consequently, the discharge of groundwater into the rivers will be increased too (Ge et al., 2011; Walvoord et al., 2012; Michelle et al., 2016; Lamontagne-Hallé, 2018). However, this phenomenon only holds if sufficient 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.

If the permafrost is degraded, talik zones can be relieved. Most groundwater discharge 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). Permafrost thaw can also generate rapid landscape changes. An example may be thermokarsting and plateau subsidence (Quinton et al., 2011) that in turn influence surface water storage, routing, and runoff (Connon et al., 2014; Michelle et al., 2016).

5.6.2 Glaciers, rock glaciers and aufeis~~es~~

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.

In current climate the glaciers of the region melt more intensively in July and August so their input to streamflow would be intuitively expected during those months. . In the headwaters of the Indigirka river (ID 3488, 51100 km^2) the glaciers share is the highest among studied rivers and amounts up to 0.30% of the basin area, however no significant trend of streamflow is observed in July and August. The next downstream gauge of the Indigirka River

(ID 3489, F = 83500 km^2) exhibits 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 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 have been passed in the period of 1980-2010 and expected to decline in the future.~~The glaciers of the region melt more intensively in July and August so their input to streamflow would be intuitively expected during those months~~, 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% in average in other months (Huss and Hock, 2018). ~~In the headwaters of the Indigirka river (ID 3488, 51100 km^2) the glaciers share is the highest among studied rivers and amounts up to 0.30%, however no significant trend of streamflow is observed in July and August.~~

~~However,~~ Liljedahl et al. (2017) have found that in Jarvis Creek (634 km^2), (a subbasin 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 losses 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 by order is comparable with the increase of streamflow in the Indigirka River (ID 3489) in November and December together for the same period. The fact that the change points of the increase of streamflow in late autumn – earlier 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 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 (about 1.35 km^2 in total).

The melt of rock glaciers and aufeis~~es~~, 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 Suntar-Khayata Range with a distribution density of 8.4 objects per 100 km^2.

The aufeis~~es~~ account for 0.01 – 0.5% of relative basin areas in the studied territory (Shepelev, 2016).

5.6.3 Geotectonic conditions

A significant positive trend of annual streamflow was identified only for four gauges. Arzhakova (2001) emphasizes that riv. Elgi (ID 3507, the Indigirka river basin) and riv. Adycha (ID 3443, 3445, the Yana river basin) cross tectonic dislocation zones. The studied 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; Piguzova, 1989). The correlation between streamflow and sub-permafrost waters is also confirmed by Glotov et al. (2011), who assumed that in particular years, the Kolyma river winter runoff losses at cross sections downstream in comparison with cross sections upstream depending on the current extensive extensions and compressions of underflow through talik space during sublittoral seismic activity periods. 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 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 of 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, noting however that ~~E~~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~~s~~ 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 the Russian Federation (Aagaard and Carmack, 1989), therefore analysis of this database covering the Yana and Indigirka rivers, is particularly timely. Forman and Johnson (1996) have previously identified the 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 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 is the decrease in late winter precipitation. The increase in air temperature is also reflected in soil temperature and the length of the thaw season~~ with increases at two stations and decreases at one other~~.

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 to 10 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 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 aufeises.

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). ~~These changes are having large-scale effects on the Arctic ecosystem, impacting the ecology in the zone of continuous permafrost as well as impacting the livelihood of northern peoples.~~ 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 (km^2)	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**

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 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 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)

	24679	24684	24688	24076	24585	24679	24684	24688	24691
	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, km^2	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 **(1956)**	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 **(1941)**	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** **(1999)**	*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 **(1953)**	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, km^2	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** **67** **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** **1999**	0.0	43	**5.1** **m**
3489	1944-2015	83500	**0.14** **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 precipitation in September at small watersheds

Meteorological station, index	Elevation, m	Gauge index	Average basin elevation, m	Basin area, km^2	Period	Correlation coefficient with precipitation	
						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

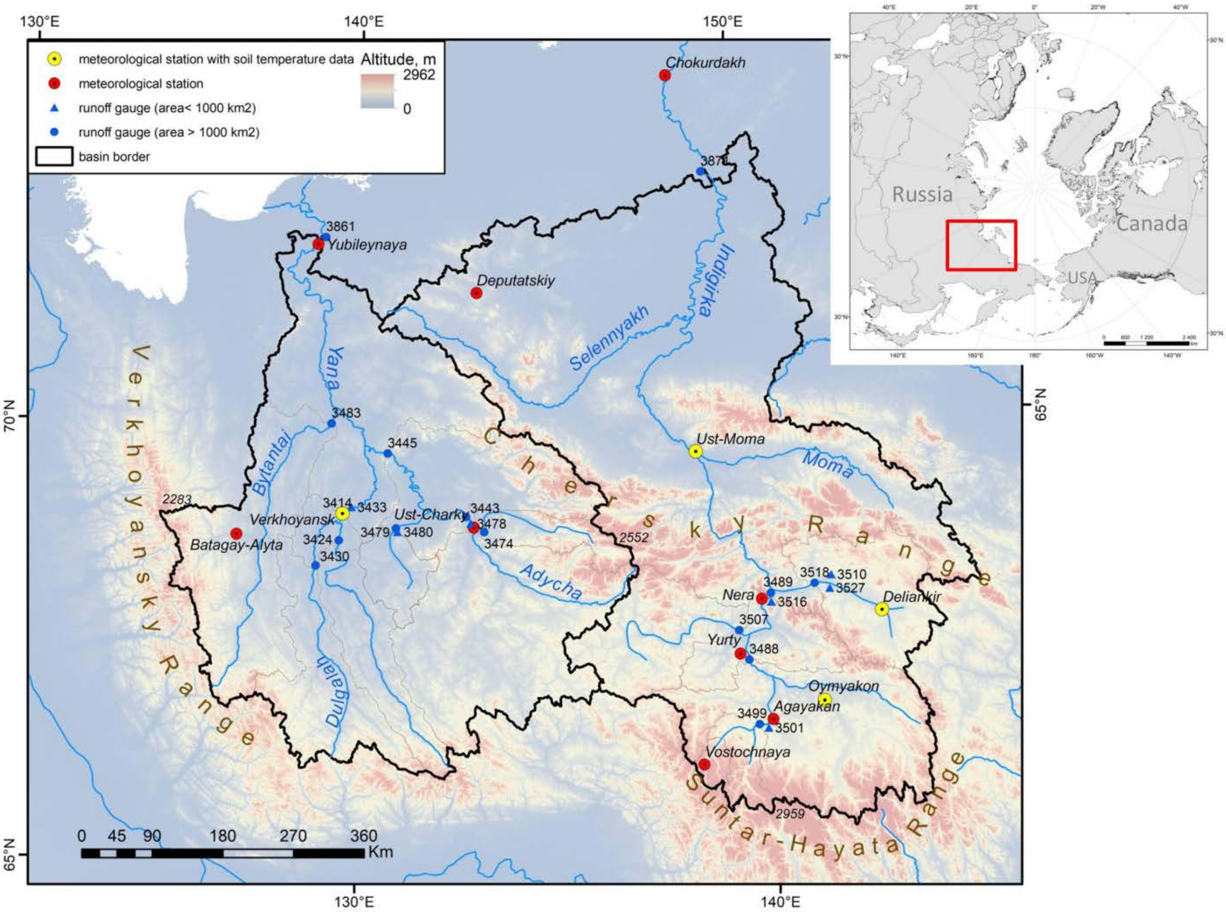

Figure 1: Meteorological stations and hydrological gauges within the study basins

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)

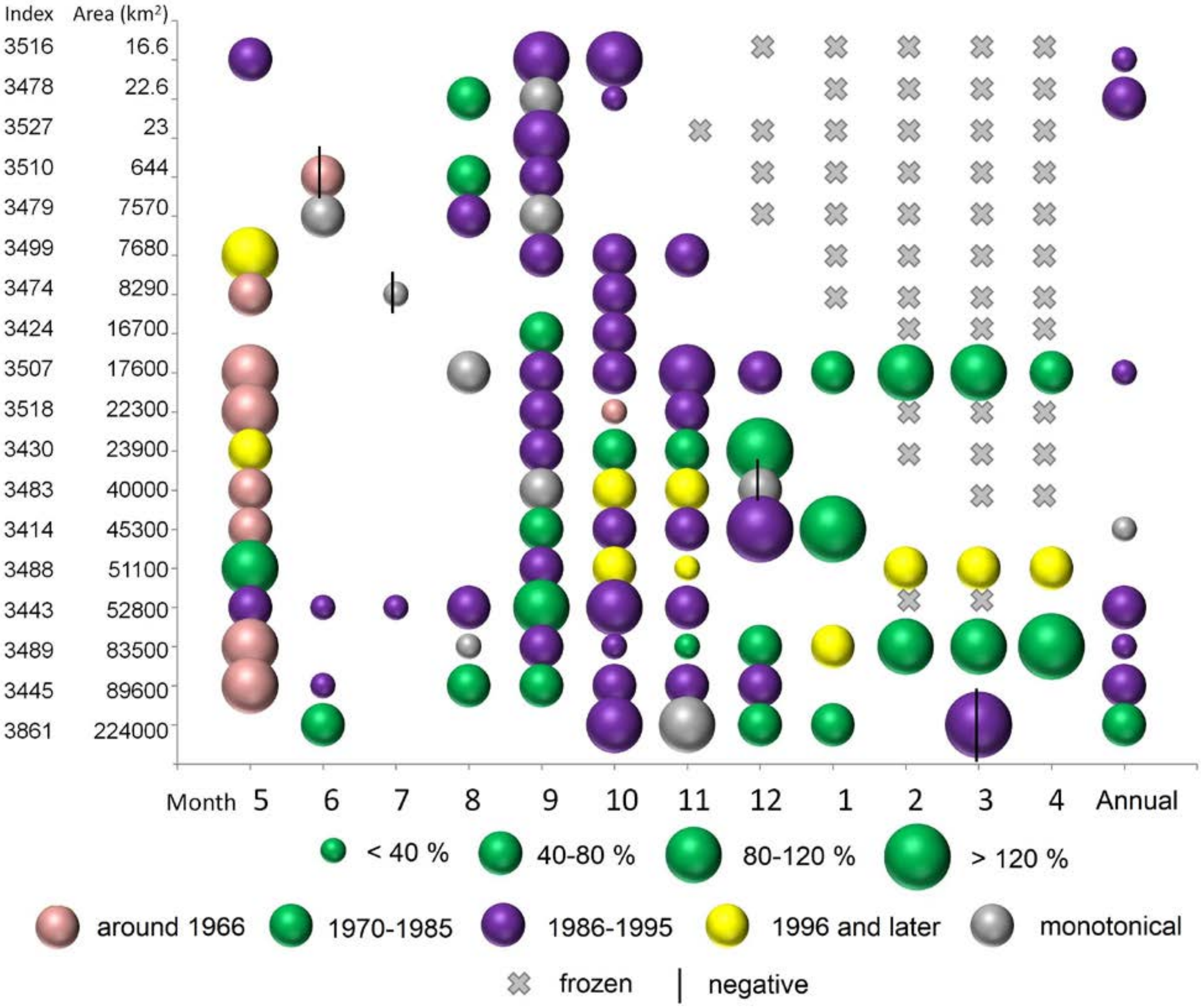

Figure 3: Change in monthly streamflow represented as a %, along with the period in which that change occurred. Data are for both Yana and Indigirka river basins and are sorted in order of basin area.

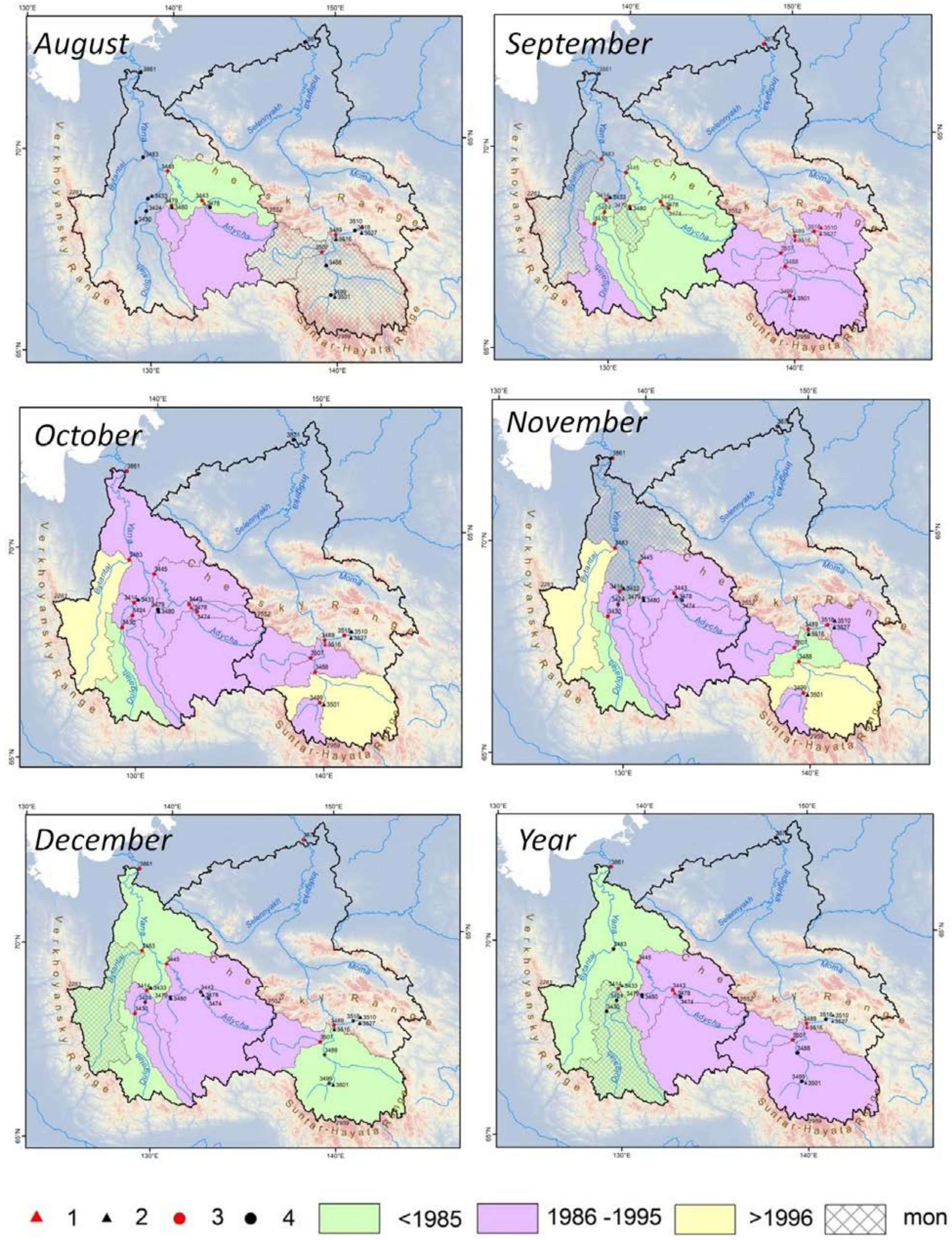

Figure 4: The periods of changes of streamflow in August, September, October, November, December and annually. Red and black colours indicate the presence and absence of the trends, respectively. The triangles and circles indicate the basin area of less and more 1000 km^2, respectively.