Changes in the Behavior of Long-Term Waterflow Variations in the Middle Part of Yakutia under the Global Warming Conditions

R N Shpakova

1Moscow State Institute of International Relations (MGIMO), Regional Governance and National Policy Department, prospect Vernadskogo, 76, bldg. 1, Moscow 119454, Russia

E-mail: production2003@mail.ru

Abstract. Currently, not only the expected future climatic changes but also the associated changes in the long-term waterflow regime are popular research objectives. However, such studies, as a rule, are focused on large water bodies of a regional or even subplanetary significance. Also, the estimates obtained for the expected changes in the waterflow regime are of the most common nature. They are certainly important in terms of assumptions on the main trends in the development of the situation with water resources on a macro-regional scale but do little in assessing the risks of water use or even living safety (if people live near a water body) in the foreseeable future in respect of relatively small and medium-sized water bodies. The study identifies and evaluates the specifics of the waterflow regime response to global warming for rivers, the basins of which are compactly located within a single natural and climatic zone - the middle part of Yakutia. This approach allows adequately comparing the parameters of changes in the behavior of long-term waterflow variations for different rivers. For all rivers in the middle part of Yakutia, a significant increase in water content has been detected after 1987 (taken as the year preceding the start of the climate warming period), however, for the rivers of the western part of the region, this increase is associated not with a change in the behavior of long-term waterflow variations but with the onset of a high-water phase of a long-term natural cycle there. An increase in the annual waterflow variations was recorded for almost all rivers. Changes in the behavior of long-term waterflow variations after 1987 led to the loss of stationarity of the annual waterflow time series in the overwhelming majority of cases. It has been established that for rivers located in the middle part of Yakutia, a change in the behavior of long-term waterflow variations, which is presumably associated with global warming, can manifest itself in two main forms: a) in some cases, extremely high annual waterflow against the background of the typical regime of long-term variations - 1-2 cases (for the period from 1987 to 2018) lasting 1-3 years; b) the onset of a relatively long (5 years or more) period with an increased annual water content against the background of a violated of the cyclical behavior of long-term water content variations, which is typical for a given river. Herewith, for the rivers of the western region zone, the absence of pronounced changes in the behavior of long-term waterflow variations has been detected.
1. Introduction
The increase in the number of dangerous hydrological events, the probability of which has been forecasted in connection with developing global warming, seems to become a fait accompli. Such events should be foreseen to prevent or significantly mitigate the damage they cause. Flooding residential areas and settlements are almost always a social and environmental emergency [1]. These situations are especially dangerous when the increase in water content is atypical for a given place and has not had precedents before.

The study is devoted to identifying violations of the behavior of long-term waterflow variations in central Yakutia - part of the Republic of Sakha (Yakutia) territory between latitudes 60° N. and the Arctic Circle (66°33’ N). To a certain extent, the study is a continuation of the research performed for water bodies in the subpolar zone of Yakutia [2]. Violations of the behavior of long-term variations here mean a disturbance of the time series stationarity, the occurrence of previously unobserved, pronounced cases of extreme deviations from the long-term average value in this series, a significant change in the type of long-term variations, i.e. the emergence or, on the contrary, the disappearance of a cyclical component, and a significant change in the duration of cycles.

The disturbance of the stationarity of long-term variations of hydrological characteristics cannot be currently questioned. The ongoing climatic changes have already led to significant changes in the water regime in a number of large regions [3]. Herewith, some studies indicate that global warming will continue in the foreseeable future. In particular, according to the study by Hiyama Tetsuya et al. [4], by 2050, the air temperature will rise by another 2-3 °C. Similarly, other researchers believe that global warming will progress [5, 6]. It is assumed that the territory of Russia (especially the Arctic and subarctic regions) will be among those with the most intense warming effect [7].

Regarding the assumed changes in the annual waterflow, the prevailing opinion is that the greatest increase in the annual waterflow will take place in the northern hemisphere and Siberian rivers (from more than 8 % at the beginning to 17 % at the end of the 21st century) [7]. An increase in the waterflow is also expected for Yakutia rivers, primarily, the Lena River [8, 9].

Considering these prospects, it is not difficult to assume that the response of water bodies to climate changes will continue (and, probably, intensify). In this regard, the general rule is an increase in the waterflow in cases where the increased evaporation does not exceed an increase in precipitation [7].

Magritsky [10] gave estimates of current waterflow changes caused by climatic changes for the lower Lena and Vilyuy basin rivers running near the study area. Georgiadi and Kashutina have concluded that climatic changes in the waterflow are especially intense in the Arctic Ocean basin, particularly, in the Lena River basin [11].

The above studies give the most common assessment of the expected changes in the water content of rivers but not an answer to the question of the nature of these changes in terms of frequency, duration, the amplitude of deviation from the norm, etc. Partly, this question can be answered by studying the current changes in the behavior of annual waterflow variations when steady warming has been observed for a long time – more than thirty years.

Shpakova et al. [12] established a common long-term tendency towards an increase in the average annual waterflow for the Yakutia rivers over the past 50 years, although without a separate assessment of the waterflow response during active warming. In another work [2], the change in the behavior of long-term waterflow variations for rivers of the subpolar zone of Yakutia adjacent to the region considered herein has been studied, according to which, such a change is different: either the complete absence of any response or the occurrence of extremely high annual waterflow against the background of the typical long-term variation regime in some cases.

A part of the territory considered herein was included in the study by Yumina and Tereshina [13], in which the relationships between changes in the water regime and those in individual meteorological characteristics (air temperature, precipitation) were established.
2. Materials and methods
Long-term data on the average annual waterflow from 8 streamflow measuring stations of the state meteorological service (Roshydromet), located within the selected region have been used (Fig. 1).

The monitoring points chosen are watersheds of various sizes (Table 1). The monitoring period at the stations ranges from 38 to 86 years and ends in 2018. For comparability, the annual waterflow data were given in a form normalized with respect to the mean long-term value.

![Figure 1. Schematic Map of the Water Bodies, Waterflow Monitoring Points, and Meteorological Stations in the Region of Middle Yakutia.](image)

| Monitoring Point         | Catchment Area (km²) | Monitoring Period  |
|--------------------------|----------------------|--------------------|
| Vilyuy, Suntar           | 202,000              | 1927 – 2018        |
| Markha, Malykay          | 89,600               | 1947 – 2018        |
| Nyuya - Kurum            | 32 600               | 1934 – 2018        |
| Sinyaya - Tongulakh      | 11 600               | 1972 – 2018        |
| Buotama - Brolog         | 12 200               | 1935 – 2018        |
| Tangnary - Chay          | 5 760                | 1964 – 2018        |
| Kengkeme – Vtoroy Stanok | 3 550                | 1946 – 2018        |
| Indigirka - Ust-Nera     | 83 500               | 1948 – 2018        |

Despite the rather small number of waterflow monitoring points, their location allows covering the entire territory of the middle part of Yakutia.

All water bodies chosen for research have a natural regime, except for the Vilyuy River: 430 and 575 km from the Suntar streamflow measuring station upstream of the river, there are objects of the Vilyuy HPP cascade. However, according to the above-mentioned study by Yumina and Tereshina [13], the regulation of the Vilyuy River waterflow having a significant impact on the annual flow distribution, at the same time, did not affect the total average water content in Vilyuy and the behavior...
of long-term waterflow variation: the stations located downstream of the HPP showed statistically significant changes in the annual waterflow in neither the mean value nor the variance. Therefore, this object was included in this study as a natural regime object.

3 meteorological stations were chosen for the primary study of climatic waterflow factors, for each of which, long-term air temperature series were considered. To determine the long-term dynamics of average annual temperatures, the meteorological stations were chosen approximately at the same latitude and distributed evenly throughout the region (Table 2).

| Meteorological Stations | Latitude (E) | Longitude (N) | Elevation above Sea Level (m) |
|-------------------------|--------------|---------------|------------------------------|
| Suntar                  | 62°10’       | 117°38’       | 130                          |
| Yakutsk                 | 62°00’       | 129°40’       | 98                           |
| Oymyakanon              | 63°15’       | 143°09’       | 740                          |

To determine changes in the statistical characteristics of the time series under the conditions of a radical climatic change, the start moment of this change with the subsequent division of the time series into periods before and after this moment should be defined. In [2], such a moment was determined for the polar zone of Yakutia as 1988. For the region of Central Yakutia, using 1987 as a turning point is optimal (see Fig. 2). In all figures below, this date is marked with a vertical straight line for ease of analysis.

![Figure 2](image-url)

**Figure 2.** Change in Average Annual Air Temperature According to the Yakutsk Meteorological Station. The Tendency Change after 1987 is Clear.

It is important to note that the same year was determined as the start date of climate-related changes in the water regime for the region chosen for this research and in the study by Yumina and Tereshina [13]. These authors used the residual mass curve method to determine this date. Thus, the
date was obtained by two independent techniques and can be estimated as quite correct. In this regard, it should also be noted that according to the study by Min Xu et al. [14] performed for the Ob River basin belonging to the territory of the Siberian macroregion and located in relative proximity to the area considered herein, the approximate start date of significant climate change is 1990, which is obviously close to that for the region studied.

The check for the presence (absence) of a significant change in the river regime under the changing climatic conditions was based on estimating the stationarity of the time series of the annual waterflow until the start of pronounced warming, i.e. 1987, and the complete time series from the start to the end of the monitoring period - 2018. The estimation of the time series stationarity was reduced to testing statistical hypotheses about the constancy of the mathematical expectation and the variance using Fisher's and Student's tests at a 5 % test significance [15]. The homogeneity (stationarity) of mean values was estimated using the Student's test by comparing the calculated t values and the critical statistical t* ones. The hypothesis of homogeneity (stationarity) of variances was adopted using the Fisher’s test at a given significance α, if the calculated F criterion value is less than the critical F* one for the given degrees of freedom corresponding to the sizes of samples n1 and n2, each of which is approximately half of the time series.

3. Discussion of results

According to the Yakutsk meteorological station data, the transition from stationarity to an upward tendency after 1987 is quite pronounced (Fig. 2). For the Suntar and Oymyakon meteorological stations, this transitional moment is not so pronounced due to the cyclical nature of variations in the average annual air temperatures at these points. However, in the average annual air temperature fluctuation plots for these points (not shown here due to the limited paper volume), it could be seen that the local maximum of the average annual air temperature growth period came on the end of the 80s of the 20th century, after which, a phase of decline was supposed to last until the middle of the first decade (Oymyakon) or the end of the second decade (Suntar) of the 21st century, while maintaining the natural behavior of long-term variations. In fact, the upward tendency has continued and is observed now.

Table 3 provides data on the average long-term air temperature from the Suntar, Yakutsk, and Oymyakon meteorological stations.

| Meteorological Stations | Average long-term air temperature from the start of observations until 1987 | Average long-term air temperature for 1988-2018 | Change in average long-term temperature |
|-------------------------|-------------------------------------------------|---------------------------------|-------------------------------------|
| Suntar                  | -7.8                                            | -6.3                            | +1.5                               |
| Yakutsk                 | -10.2                                           | -8.1                            | +2.1                               |
| Oymyakon                | -16.4                                           | -15.0                           | +1.4                               |
| Average                 | -11.5                                           | -9.8                            | +1.7                               |

As can be seen from Table 3, on average for the region, since 1987, the average annual temperature has increased by 1.7 °C. The intensity of warming was about 0.55 °C over 10 years.

The increase in average temperature in the western and eastern parts of the region is similar, and for the central part (m/st Yakutsk), it is significantly higher - 0.6-0.7 °C. It is important to note that the climate becomes harsher from west to east: the average long-term temperature in Oymyakon is 8.7 °C lower than in Suntar.

The general nature of changes in the behavior of long-term waterflow variations can be judged by the data in Table 4.
Table 4. Change in the Average Annual Waterflow and Waterflow Variability for the Monitoring Periods before and after 1987.

| Monitoring point          | Average waterflow for the period from start monit. 1987 to the of 1988 | Change (%) | Variability index for the period from start monit. 1987 to the of 1988 | Change (%) |
|---------------------------|---------------------------------------------------------------|------------|---------------------------------------------------------------------|------------|
| Vilyuy, Sunar             | 0.93                                                          | +23.7      | 0.063                                                               | 0.093      |
| Markha, Malyk            | 0.92                                                          | +19.6      | 0.078                                                               | 0.083      |
| Nyuya - Kurum            | 0.89                                                          | +32.6      | 0.054                                                               | 0.189      |
| Sinyaya - Tongulakh      | 0.90                                                          | +17.8      | 0.288                                                               | 0.368      |
| Buotama - Brolog         | 0.92                                                          | +21.7      | 0.096                                                               | 0.197      |
| Tangnary - Chay           | 0.70                                                          | +74.3      | 0.330                                                               | 0.496      |
| Kengkeme – Vtoroy Stanok | 0.72                                                          | +90.3      | 0.413                                                               | 2.029      |
| Indigirka - Ust-Nera     | 0.95                                                          | +12.6      | 0.008                                                               | 0.032      |
| Average value             | +36.6                                                         |            |                                                                     | +147.3     |

Data in Table 4 allow drawing the following conclusions about changes in the behavior of long-term waterflow variations. After 1984, there was a significant increase in water content in almost all water bodies of the territory considered. On average for 1988-2018, the increase in the average annual waterflow was 36.6 %. On small rivers, the growth reaches 70-90 %. The increase in the water content of rivers with a catchment area of more than 30,000 km² averaged 22.1 %.

The smallest growth of 12.3 % came on a point in the eastern part of the region analyzed - the Indigirka River, Ust-Nera.

After 1987, the annual waterflow variability also increased significantly, on average, by 147.3 %. An increase in the average annual waterflow variability was recorded in all water bodies of the region studied. For some objects, this value exceeded 300 %. No relationship has been established between the increase in the average annual waterflow variability and the water body size: for large rivers (with a catchment area of more than 30,000 km²), the average increase in the variability was 151 %, which was slightly different from the average increase in variability for the entire region. In the geographical aspect, it may be highlighted that the degree of increase in the average annual waterflow variance reduces towards the northwestern part of the region (Tongulakh, Chay, Sunart, and Malykay points).

The estimates of the waterflow series stationarity have changed radically (Table 5).

Table 5. Stationary Waterflow Data and Characteristics of Changes in Long-Term Waterflow Variations.

| Monitoring point | Evaluation of stationarity of the waterflow series from the start of the monitoring period until 1987 | Evaluation of stationarity of the entire waterflow series for the entire monitoring period | The time frame when the waterflow series exhibited the elements that disturbed the series stationarity |
|------------------|--------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| Vilyuy, Sunart   | Stationary                                                                                        | Non-stationary                                                                                   | -                                                                                                 |
| Markha, Malyk    | Stationary                                                                                        | Non-stationary                                                                                   | -                                                                                                 |
| Nyuya - Kurum    | Stationary                                                                                        | Non-stationary                                                                                   | 1998, 2008                                                                                        |
| Sinyaya          | Stationary                                                                                        | Stationary                                                                                      | 2007                                                                                             |
| Tongulakh        | Stationary                                                                                        | Stationary                                                                                      | 2007                                                                                             |
Only two hydrological points - Tangnary, Chay, and Kengkeme, Vtoroay Stanok were characterized by non-stationarity of the annual waterflow series from the very beginning of monitoring due to the small size of the streamflow and the associated increased role of the random factor, as well as the relatively short monitoring period. For the rest of the stations, the annual waterflow series were estimated as stationary up to 1987. Estimation of stationarity for the entire monitoring period has shown that only one point – Sinyaya, Tongulakh, corresponds to stationarity parameters. Consequently, for 1988-2018, the rivers have undergone changes in the behavior of long-term variations, which have ‘canceled’ stationarity at most objects.

In general, three types of water body responses to changing climatic conditions can be distinguished.

The first type is typical for rivers in the western and northwestern parts of the Middle Yakutia region. This area is represented by the basins of the Upper Vilyuy and Markha Rivers. Despite the stationarity disturbance statistically revealed in some waterflow observations, after 1987, there were no violations of the main type of long-term waterflow variations in this area, which had a rather pronounced cyclical component. On Vilyuy, after 1987, high-water years with a water content of up to 1.4 norms became characteristic with a sufficient regularity (about 1 time over 10 years); in one case, the water content exceeded 1.6 norms (Fig. 3). However, this did not disrupt the overall sinusoidal trend.

These changes cannot be reliably attributed to the warming period. Fig. 3 shows that the Vilyui River water content variation period is approximately 80 years. From the beginning of the 70s of the last century, a high-water phase has started, which continues to this day. The previous high-water
phase remained mainly outside the observation period (it ended at the end of the 20s of the last century). Probably, in the past, there were the same long-term water regime variations as during the current cycle observed from the end of the 20th century to this day. By the way, just the peculiarities of the long-term variations in the objects of this part of the region considered explain the increase in the average water content after 1987 (Table 4) – a high-water cycle of long-term variations comes on this period. Herewith, attention still should be paid to the extremely high waterflow in 2008, which exceeded 2 norms and the maximum waterflow limit according to the long-term behavior of variations customary for this object.

The second area is the southwestern and central parts of the region. A characteristic feature is the occurrence of the so-called ‘bursts’ – short-term periods with extremely high water content after 1987 (Fig. 4).

For most water bodies, there was one such ‘burst’, and two those for the Nyuya River, in 1998 and 2008-2009 (Fig. 4). The usual duration of such an extreme period is 1–2 years. For one river – Kengkeme – such a ‘burst’ lasted three years – from 2006 to 2008. The water content of the river in such a period increases to 2.5-4.0 norms and 1.6-1.8 of the maximum annual waterflow in the previous period.

Finally, the third area is the eastern part. Here, almost until 2014, no significant changes in the behavior of long-term variations were observed at all (Fig. 5).
This object peculiarity was the alternation of 13-15-year periods of increased water content and 6-7-year periods of low water content. At the end of the 1990s, another period of increased water content began, and by the middle of the second decade of the 21st century, this period should have ended with a transition to a period of decreased water content. Instead, the period of increased water content did not end but, on the contrary, intensified: in all the next five years – 2014-2018, the water content was significantly higher than the maximum water content in the previous periods of increased water content.

4. Conclusion
Under the conditions of active warming, the start of which we attributed to 1988, in all rivers in the middle part of Yakutia, a general increase in water content by an average of 36.6 % was recorded, reaching 70-90 % for small rivers. The variability of the annual waterflow increased significantly - by 147.3 %.

On most rivers in the region, excluding two small water bodies, long-term series of annual waterflow before the onset of stable warming are assessed as stationary. Subsequent changes in the behavior of long-term variations within 1988-2018 led to the loss of monitoring series stationarity (except for one series) in terms of both the mathematical expectation and variance.

It should be noted that the waterflow variations in the western part of central Yakutia (the Vilyuy River at the Suntar and Markha streamflow measuring stations) were within the range of sinusoidal variations typical for this region both before 1987 and after. No changes in the behavior of these variations were detected, except for a single case in 2008 on Vilyuy at the Suntar streamflow measuring station, which was expressed in about 15 % excess of the local maximum assumed according to the existing long-term variation pattern.

In most water bodies of the region under consideration, changes in the behavior of long-term annual waterflow variations were manifested in the cases of extremely high annual waterflow in 2006-2007; in the southwestern part (the Nyuya River) another case of such a ‘burst’ was in 1998. The annual waterflow in such cases exceeded the norm by 2.5-2.8 times and the previous historical maximum by 1.6 times (for small rivers, up to 1.8 times). It should be noted that the waterflow, assessed as extremely high, may occur for 2 (rarely 3) years in a row.
In the eastern part of the considered region of central Yakutia (the Indigirka, Ust-Nera rivers), the change in the behavior of long-term annual water flow variations was as follows: instead of the onset of a low water content period, according to the previously established long-term regularity, the high-water period grew into one of extremely high water content: for 5 years in a row, the average annual water flow exceeded historical maximums, in some years, 1.2–1.3 times.

Considering the results previously obtained in [2], a general conclusion can be drawn that on the rivers of the rest of Yakutia and its neighboring regions, cases of extremely high water content can be expected in one of the options described above. This is possible for both rivers on which such cases have not yet been recorded and repeatedly those where extreme water content has already occurred. For settlements located near water bodies, such manifestations may have a high degree of danger since they are spontaneous and atypical for a given area given the experience of all past years.

5. References
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