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Stationarity analysis of runoff time series in Arctic basins

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Abstract

In the world, climate change happened regionally and globally, rapidly and gradually. Also it has great impacts on atmosphere, hydrosphere and biosphere. From the inter-annual and long-term variation in hydrology, it reflects generally the influence of climate changes. The river runoff plays an important role in the hydrological cycle. Therefore, the study of long-term runoff time series is of great significance. In this thesis, runoff time series are analyzed. There are many characteristics in runoff time series, such as homogeneity, stationarity, trend, periodicity and persistence. The main purpose of this thesis is to analyze the stationarity of river runoff time series in basins. Four river basins around the Arctic ocean are collected for this thesis: the Mackenzie River, the Ob River, the Yenisei River and the Lena River. To study inter-annual and long-term changes of river runoff, the period from 1930 to 2000 is selected. In order to analyze clearly, the time series are investigated on four aspects: trend, amplification, break points and seasonal stationarity. In relation to the overall process of the analysis, we primarily analyzed the mean and maximal river runoff. Through analysis, it can be drawn a conclusion. The runoff of these four rivers is generally stable over the whole studied period. Moreover, for a given month, the change of river runoff is basically stable. There are many factors affecting the river runoff, such as precipitation, snow melting and human intervention, which have impacts on the results of this thesis. In order to study the stability of the time series of the river runoff, analysis of the influence factors is required.

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Chapter 1

Introduction

Background. Global climate is changing rapidly, with unexpected consequences (Houghton et al., 2001). The Arctic is a central component of the global climate system. Increasing temperatures in recent decades have been linked to a wide variety of changes in the Arctic (Serreze et al., 2000). The hydrological cycle is an important research direction because of its major influence on the global climate change. The hydrological cycle is the process of transporting water through the atmosphere, land areas and oceans (Hendriks, 2010). It consists of evaporation, precipitation, surface runoff, infiltration into the groundwater, groundwater flow and discharge into the oceans (Maidment et al., 1992). Discharge is one of the most significant variables utilized for observing the hydrological cycle. It can be computed from the water level at the gauging station and the measured velocity of the flow, essentially called runoff. Figure 1.1 depicts the river discharge in Arctic basins. The Arctic Ocean receives a large amount of fresh water from river runoff relative to its area, compared to other oceans. There are five major rivers that flow into the Arctic, the Mackenzie and Yukon in North America, and the three largest in Asia, the Ob, Yenisei and Lena Rivers (Perovich et al., 2011). In this thesis we study the runoff time series of the rivers Ob, Yenisei, Lena and Mackenzie.

A time series is a series of data points listed in time order. If a random variable r is indexed to time, usually denoted by t, the observations $r(t), t \in T$ is called a time series. Most commonly, a time series is a sequence taken at successive equally spaced points in time. Thus, it is a sequence of discrete-time data r_t. They are used for example in statistics, pattern recognition, weather forecasting and largely in any domain of applied science and engineering involving temporal measurements. Time series analysis is required in order to extract meaningful statistics and other characteristics of the data. In hydrology, most variables are observed in time series. Furthermore it is used for building mathematical models to generate synthetic hydrological records, to forecast hydrological events, to detect trends and shifts in hydrological records and to fill in missing data and extend records (Salas, 1993). The principal aim of it is, to describe the history of movements in time of some variables (e.g. runoff at a given site). Properties of time series are of great significance in planning, designing and evaluating of water resource systems.

There are many characteristics to be investigated in hydrological time series, e.g. homogeneity, stationarity, trend, periodicity, and persistence. Homogeneity implies that the data in the series have a time invariant mean. Non-homogeneity arises due to changes in the method of data collection and/or the environment in which it is done (Fernando and Jayawardena, 1994). According to Jayawardena(2014)'s opinion: Stationarity means that the statistical properties of the series computed from different samples do not change except due to sampling variations (Jayawardena, 2014). A time series is said to have trends, if there is a significant correlation (positive or negative) between the observations and time. Periodicities in natural time

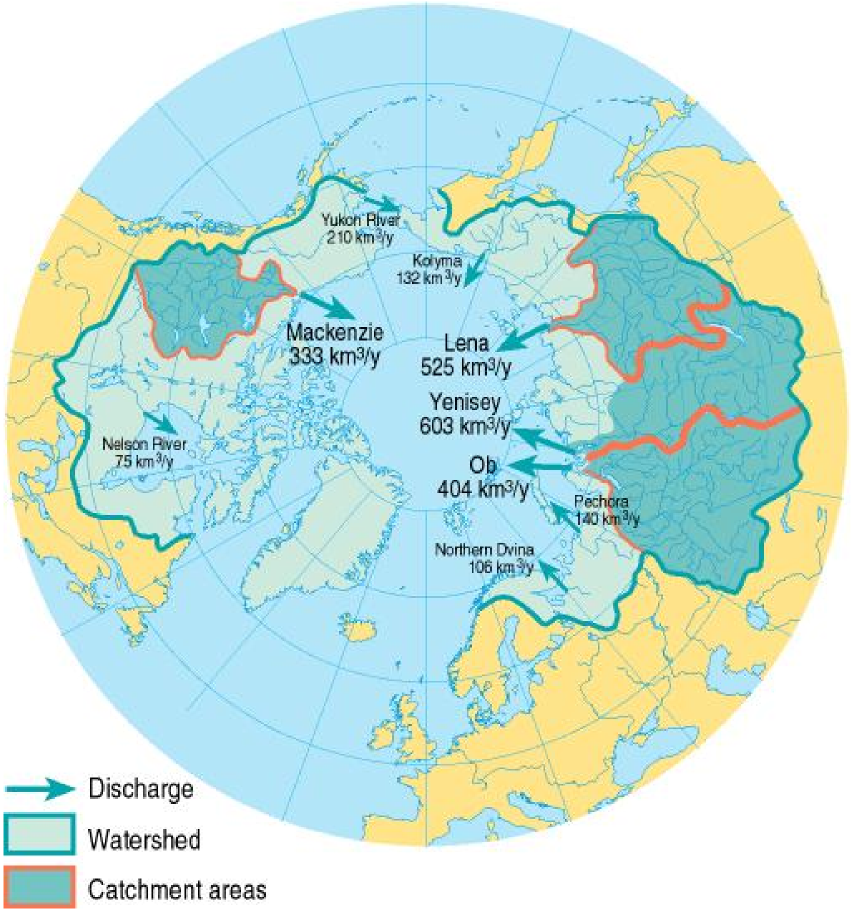


Figure 1.1: *An example of river discharge in Arctic basins (Rekacewicz, 1997)*

series are generally due to astronomical cycles such as earth's rotation around the sun (Kite, 1989). Persistence is the tendency for the magnitude of an event to be dependent on the magnitude of previous events, a memory effect. For example, the tendency of the process of low stream flows following low stream flows and high stream flows following high stream flows can be considered synonymous with autocorrelation (O'Connell, 1977).

Motivation. In the hydrological cycle, precipitation, evaporation and runoff mainly reflect seasonal behavior. The time series with seasonal variation are usually relatively stable. However, they are affected by some factors, such as climate change and human activities, resulting in the instability of these time series. The impact of these factors is slow and long-term. Sometimes, the data in some years is unstable. But this phenomenon is maybe accidental and can not directly determine if the time series is stable. Therefore, we need to use long-term data to see the stability of the time series. The river runoff data is usually a few decades or even centuries. Therefore, its stability can be studied because of enough data. The river runoff data reflects the hydrological phenomenon and it is an important indicator of natural climate change. It is of great significance to analyze natural phenomena and agricultural development by studying the long-time variation of hydrological time series. Through the analysis of the stability of the long-term river runoff time series in the Arctic Ocean, it is possible to further understand the changes that have taken place before, such as climate change. Future changes can also be predicted based on the stationarity analysis.

Outline. In this thesis, a stationarity analysis will be provided. It aims at river runoff time series in four different basins: the Mackenzie River, the Ob River, the Yenisei River and the Lena River. Its content will be divided into four chapters. In the first chapter, the background and purpose of this thesis were introduced. The second consists of the fundamental information about this thesis. Firstly, the definition of time series stationarity was explained in detail. Secondly, structure of data and researched rivers were introduced. Lastly, the statistical methods used in this thesis were assessed. The third chapter is mainly relating to data processing and analyzing. In this chapter, the stationarity of river runoff time series in four cases are discussed. The last chapter concluded with the results of the stationarity analysis of river runoff time series in the different basins.

Chapter 2

Fundamentals

2.1 Time series stationarity

Stationarity means that the statistical parameters of the series computed from different samples do not change except due to sampling variations. A time series is said to be strictly stationary if its statistical properties are time-invariant. In other words, if a time series has a constant mean and variance, it is a stationary time series, as shown in Fig. 2.1. These properties are described as follows:

$$\begin{cases} \mathrm{E}(x) &= \mu \\ \sigma(x)^2 &= c \end{cases} \tag{2.1}$$

A less strict type of stationarity which is known as called weak stationarity or second-order stationarity, is that in which the first- and second-order moments depend only on time differences (Chen and Rao, 2002). For example, there is a time series and divides it into two time intervals, i.e., $\mathbf{x} = [\mathbf{x}_1, \mathbf{x}_2]$. It is a weak stationary time series when

$$\begin{cases} \mathrm{E}(\mathbf{x}_1) = \mu_1, \quad \sigma^2(\mathbf{x}_1) = c_1 \\ \mathrm{E}(\mathbf{x}_2) = \mu_2, \quad \sigma^2(\mathbf{x}_2) = c_2 \\ \mu_1 \approx \mu_2 \end{cases} \tag{2.2}$$

In fact, strictly stationary time series does not exist. Essentially, the length of time series, which can be observed are limited, like hydrological time series. Hence, weakly stationary time series are practically considered as stationary time series. A stationary time series cannot have any trend or periodic component. In contrast, if a series does not have a constant mean or variance, it is not stationary. Figures 2.2, 2.3 and 2.4 show three typical examples of non-stationary time series. In case 1, the time series has a significantly increasing trend. In contrast, the time series has a stable average but the variance of it has an increasing trend in case 2. In case 3, there are break points, but the mean of the time series is invariant with time changing.

2.2 Datasets

2.2.1 Structure of data

The initial set of data is from the Global Runoff Data Centre (GRDC). Nowadays, the Global Runoff Data Base comprises discharge data of more than 9200 gauging stations from all over the world. On behalf of the runoff in this thesis, the Global Runoff Data Centre (GRDC) maintains the Arctic Runoff Data Base (ARDB). It is an international archive of data up to 200 years

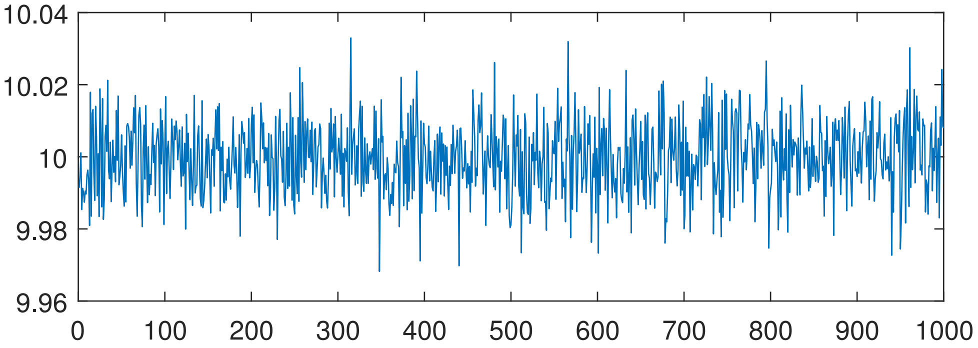


Figure 2.1: *Stationary time series*

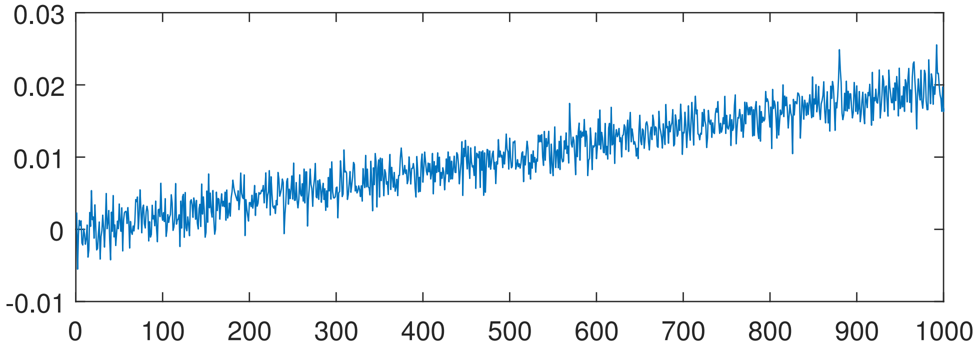


Figure 2.2: *Non-stationary time series case 1: trend*

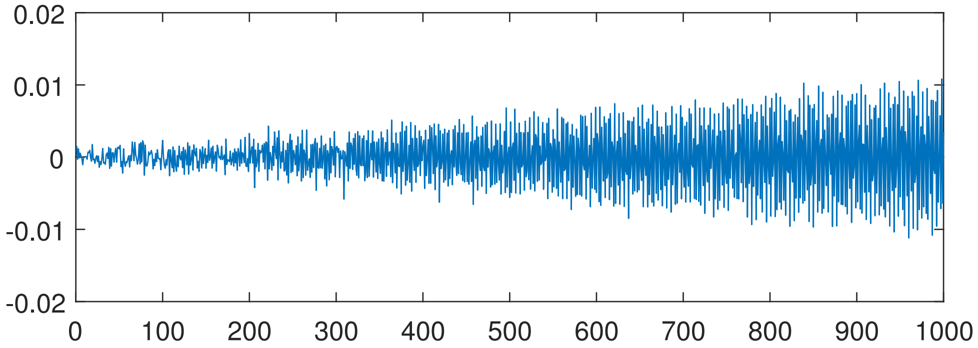


Figure 2.3: *Non-stationary time series case 2: time-variable variance*

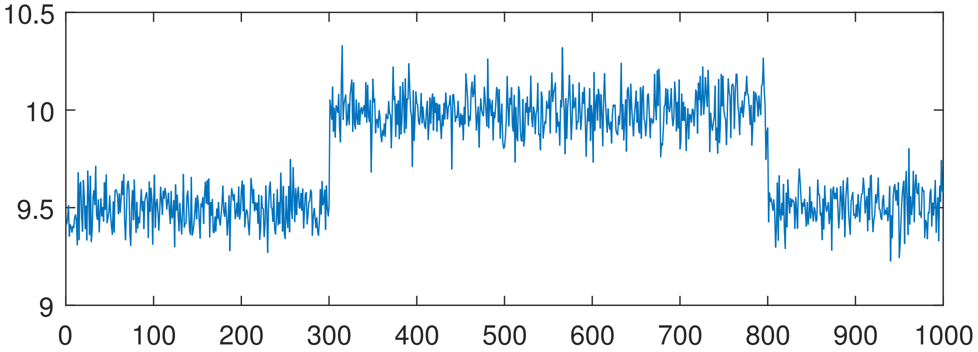


Figure 2.4: *Non-stationary time series case 3: time-variable mean*

old, fosters multinational and global long-term hydrological studies. There are many gauging stations for every river basin. However, with regard to the analysis of runoff for the whole basin, the outlet of every basin is selected. As present in Fig. 2.5, GRDC station 6742201 is the outlet gauging station of the whole blue river basin. Monthly runoff values used in the thesis are computed from these outlet stations of the four Arctic river basins. The data are in units of m^3/s. Then discharge of the basins can be obtained with runoff at outlet gauging station multiplied by time. Discharge is given in units of volume and runoff is referred to in units of volume per time. While the height of discharge is in units of mm/month called as runoff in this thesis are easier for the study, the conversion of the original data is needed. The dataset also provides the area of the catchments in units of km^3, which is required in the conversion. As the heights are relatively small in units of m, the units of heights are converted into mm in order to facilitate the analysis of the later chapters. The conversion is made as follows:

$$r = \frac{Q \times t}{A} \tag{2.3}$$

with r_i being the monthly runoff, i.e., the height of discharge, Q being the river runoff, t being the second per month and A being the area. The runoff data which is converted from discharge will be applied in this thesis.

Figure 2.5: *An example of a outlet gauging station (GRDC, 2011)*

2.2.2 Rivers under investigation

In this thesis, the following four rivers are analyzed: Ob, Yenisei, Lena and Mackenzie river. Ob, Yenisei and Lena river are the three great Siberian rivers that flow into the Arctic Ocean. The Ob River is a major river in western Siberia, Russia, and is the world's seventh longest river. It forms 25 km southwest of Biysk in Altai Krai at the confluence of the Biya and Katun rivers. The Yenisei River is the central one of the three great Siberian rivers. The maximum depth of the Yenisei is 24 m and the average depth is 14 m. The Lena River is the easternmost of the three great Siberian rivers. It is the 11th longest river in the world and has the 9th largest watershed. The Mackenzie River is the largest and longest river system in Canada. The river's main stem runs 1,738 km in a northerly direction to the Arctic Ocean. It is the largest river flowing into the Arctic from North America. The time series of runoff data of the Ob River is from January 1930 to December 1999, covering 70 years. For the Yenisei River, it is from January 1936 to December 1999, covering 64 years. The runoff data of the Lena River covers 2 years more than the Yenisei River. It is from January 1935 to December 2000. In addition, the time series of the Mackenzie River is from January 1973 to December 1996, covering 24 years. Figure 2.6 shows a map of catchments used in the thesis and the four rivers are also represented by table 2.1.

Table 2.1: *Longitude λ, latitude ϕ and area A of the catchments in the dataset.*

Catchment	λ [°]	ϕ [°]	A [km^2]
Ob	66.53	57.25	2926321
Yenisei	86.50	58.00	2454961
Lena	127.65	61.50	2417932
Mackenzie	-133.74	60.00	1666073

Figure 2.6: *Map showing the distribution of catchments used in the sample dataset in the world. (JE, 2015)*

2.3 Statistical methods

2.3.1 Mean

The arithmetic mean is defined as

$$\bar{r} = \frac{1}{n}\sum_{i=1}^{n} r_i \tag{2.4}$$

with r_i being the values of the time series and n being the length of the time series. In terms of monthly mean, it can be described as follows:

$$\tilde{r}_t = \frac{1}{n}\sum_{i=1}^{n} r_{t,i} \tag{2.5}$$

where the value of n is the number of years, t is a certain month and $r_{t,i}$ is the value of the certain month runoff in each year. As an example shown in Fig. 2.7, the left side is the original runoff time series of the Mackenzie River from 1981 to 1990 and the right side consists monthly mean runoff of this river during the period.

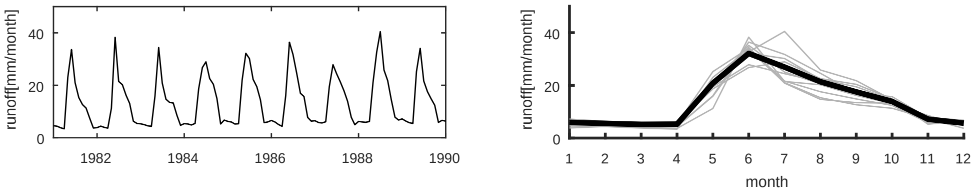


Figure 2.7: *An example of monthly mean*

The seasonal variation has a great influence on the hydrological time series. Therefore, the monthly mean is very important for the stability analysis of runoff time series. For the four rivers in the datasets, monthly averages will be calculated. The value average is used to report central tendencies and as a basis for the further analysis. As it is greatly influenced by outliers, other parameters (e.g., Root-mean-squares) are needed to analyze the datasets.

2.3.2 Root-mean-squares

For a set of n discrete runoff values $r_1, \ldots, r_n$, the root-mean-squares (RMS) is

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} r_i^2} \tag{2.6}$$

with n being the number of the months in the time series. RMS is used as a basis for the determination of other parameters (e.g., cyclostationarity). Through RMS, we can only know the change of river runoff. However, to know the magnitude of its changes, the relative

RMS(RRMS) is introduced in this thesis for analyzing the extent of the runoffs' change with the following formula.

$$\mathrm{RRMS} = \frac{\mathrm{RMS}(r - \bar{r})}{\mathrm{RMS}(r)} \tag{2.7}$$

with $\bar{r}$ being the mean of runoff values.

2.3.3 Cyclostationarity

The cyclostationarity plays an important role in studying the stability of each complete time series runoff data. Therefore it gives an overall concept for stability of the runoff. The cyclostationarity measurable metric is defined as

$$\gamma = 1 - \frac{\mathrm{RMS}(\delta_r)}{\mathrm{RMS}(r)} = 1 - \sqrt{\frac{\sum (r - \tilde{r})^2}{\sum r^2}} \tag{2.8}$$

δ_r is the difference between the runoff and its monthly mean

$$\delta_r = r - \tilde{r} \tag{2.9}$$

with $\tilde{r}$ being the monthly mean runoff. If the cyclostationarity measurable metric equals 1, it means that the runoff of the river with the change of the year is perfectly stable. The closer the measurable metric is close to 1, the better the stability of the time series is.

2.3.4 Trend estimation

Trend estimation is a statistical technique to aid interpretation of data. It can be used to make and justify statements about tendencies in the data and to describe the behavior of the observed data. In this thesis, it is useful to determine if the runoff has an increasing or decreasing trend. For trend detection, there are two methods used in this thesis, the parametric trend test and the non-parametric trend test: Mann-Kendall test (*Non-Parametric Tests against Trend.*, n.d.; Kendall, 1962). For the latter method, the magnitudes of linear trends are determined using Sen's estimator of slope. The method of the parametric trend test is least-squares regression used in this thesis. The least-squares regression can be used when data is independent and normally distributed. The Mann-Kendall (MK) test can be used when data sets contain non-detects and results are not impacted by the magnitude of extreme values as with regression tests. The Mann-Kendall test is commonly employed to detect trends in series of climate data or hydrological data (e.g., runoff time series).

Least-squares regression The method of least squares is a approach in regression analysis to make a trend line for a time series. Least squares means that the overall solution minimizes the sum of the squares of the errors made in the results of every single equation. If r is linearly related to t, i.e., it comprises a linear combination of the parameter t, the linear trend can be described as follows:

$$r = a_0 + a_1 t \tag{2.10}$$

Letting $\mathbf{A} = [1,\ t]$ and $\mathbf{x} = \left[\begin{smallmatrix} a_0 \\ a_1 \end{smallmatrix}\right]$, then it can be rewritten as

$$\mathbf{r} = \mathbf{A}\mathbf{x} = \left[\begin{smallmatrix} 1 & t \end{smallmatrix}\right] \left[\begin{smallmatrix} a_0 \\ a_1 \end{smallmatrix}\right] \tag{2.11}$$

In this case the least square estimate a_0 and a_1 is given by

$$\mathbf{x} = \left[\begin{smallmatrix} a_0 \\ a_1 \end{smallmatrix}\right] = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{r} \tag{2.12}$$

Then can the trend line be drawn out as shown in Fig.2.8.

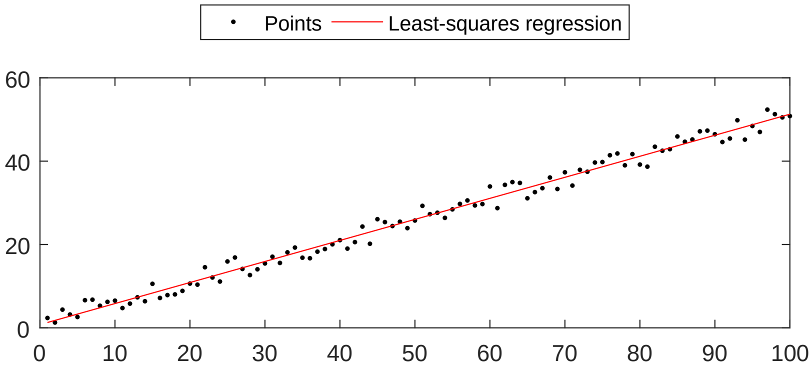


Figure 2.8: An example of least-squares regression

The Mann-Kendall (MK) test The Mann-Kendall test uses the runoff data to test the null hypothesis of the randomness of data against trend. According to Mann, the null hypothesis H_0 states that the runoff data $(r_1, r_2, \ldots, r_n)$ are a sample of n independent and identically distributed random variables. The alternative hypothesis H_1 of a two-sided test is that the distribution of r_i and r_j are not identical for all $i, j \leq n$ with $i \neq j$. The test statistic S is defined as

$$\mathrm{S} = \sum_{i \geq j} \mathrm{sgn}(r_i - r_j) \tag{2.13}$$

Mann showed that under H_0 the distribution of S is normal in the limit as $n \to \infty$. Given the possibility that there may be ties in the values of r, Kendall obtained the mean and variance of S under the assumption of no trend as

$$\begin{cases} \mathrm{E(S)} & = & 0 \\ \sigma^2(\mathrm{S}) & = & \frac{n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)}{18} \end{cases} \tag{2.14}$$

where t is the extent of any given tie and $\sum_t$ denotes the summation over all ties. The runoff data used in this thesis was to have no tied groups. Thus, the variance is

$$\sigma^2(S) = \frac{n(n-1)(2n+5)}{18} \tag{2.15}$$

Both Mann and Kendall derived the exact distribution of S for $n \leq 10$ and showed that even for n=10 the normal approximation is excellent, provided one computes the standard normal variate Z by using the following equation

$$Z = \begin{cases} \frac{S-1}{\sigma(S)}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sigma(S)}, & S < 0. \end{cases} \tag{2.16}$$

Thus, in a two-sided test for trend at a significance level of α, the H_0 should be rejected if $|Z| \geq z_{\frac{\alpha}{2}}$, where $F_N(z_{\frac{\alpha}{2}}) = 1 - \frac{\alpha}{2}$, F_N being the standard normal cumulative distribution function. That is, at the confidence level α, the time series data has a significant upward or downward trend. A positive value of Z indicates an upward trend and a negative value of Z indicates a downward trend. When absolute value of Z is bigger than or equal 1.28, 1.64, 2.32, man can respectively say the significance are 90%, 95% and 99% in the test.

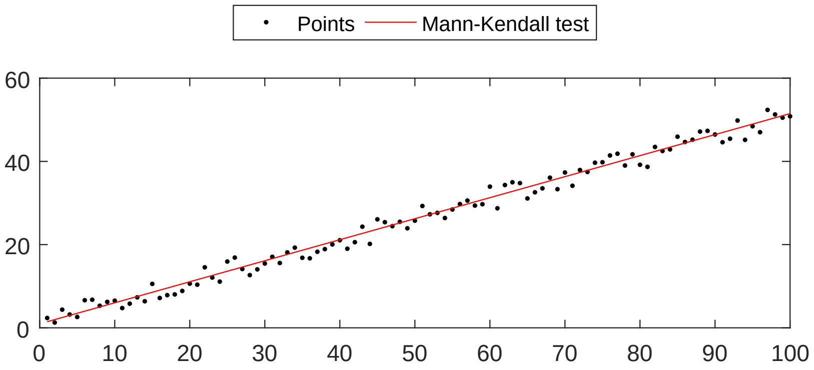


Figure 2.9: *An example of Mann-Kendall test*

Sen's estimator of slope If a linear trend is present, the true slope can be approximated by using a simple non-parametric procedure developed by Sen (Sen, 1968). This procedure is not greatly affected by gross data errors or outliers and can be used for records with missing values. The computational procedures are as follows. First, compute the slope estimates of N pairs of data, Q,

$$\mathrm{Q} = \frac{r_j - r_k}{t_j - t_k} \quad , \tag{2.17}$$

where r_j and r_k are data values at times t_j and t_k, respectively, with $t_j \geq t_k$. The median of these N values of Q is Sen's estimator of slope. If there is only one datum in each time period, then $N = \frac{n(n-1)}{2}$, where n is the number of time periods. The median of the N slope estimates is obtained in the usual way, that is, the N values of Q are ranked by $\mathrm{Q}_1 \leq \mathrm{Q}_2 \leq \ldots \leq \mathrm{Q}_{N-1} \leq \mathrm{Q}_N$ and

$$a = \begin{cases} \mathrm{Q}_{\frac{N+1}{2}}, & N = 2k+1 \\ \frac{1}{2}[\mathrm{Q}_{(\frac{N}{2})} + \mathrm{Q}_{(\frac{N+2}{2})}], & N = 2k. \end{cases} \tag{2.18}$$

with a being Sen's estimator and k being integer. Then can the trend line be drawn out.

Fig.2.9 shows the method of Mann-Kendall test. From the comparison between the method of Mann-Kendall test and that of least-squares regression, it can be seen that the trend lines of the two method are very similar. In this thesis, the two trend tests are used to analyze the runoff time series in Arctic basins.

Chapter 3

Data analysis

In this chapter, the stationarity of river runoff time series are analyzed on four aspects. According to the three typical instability time series which are described in the second chapter, the first three following cases in this chapter are analyzed on the basis of the typical classification: trend, amplification and break points. As this thesis studies hydrological time series, it is necessary to analyze inter-monthly variation within a year, i.d., seasonal stability. That is the fourth case, which will be explained in the next section.

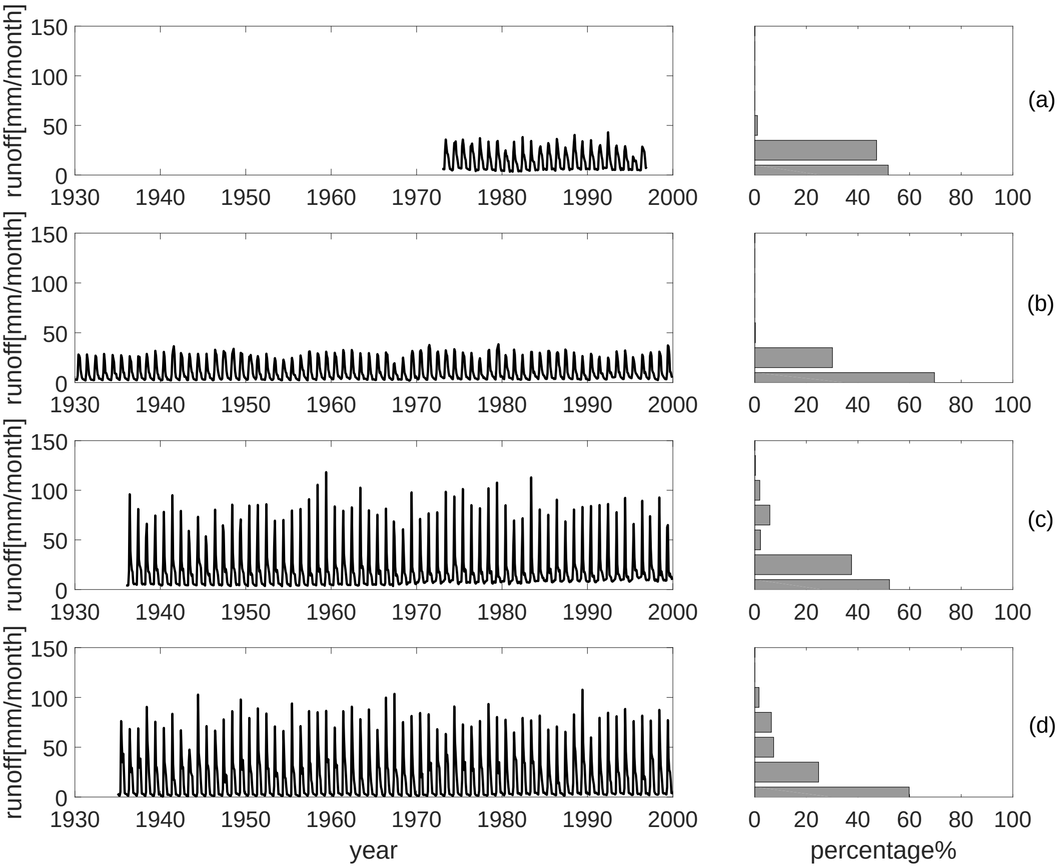


Figure 3.1: All raw data of the Mackenzie River(a), Ob(b), Yenisei(c) and Lena(d) and histogramm of them

In figure 3.1, the left shows all runoff time series of these four rivers and its probability distribution is on the right side of this figure. It describes the overall situation of raw runoff data of the four rivers during the all selected time period 1930-2000. It is obviously that the raw runoff of Yenisei and Lena are more than that of Mackenzie River and Ob. For the Mackenzie River and Ob River, all raw runoff of them are low than 50 mm/month. On the contrary, some runoff of Yenisei and Lena are even more than 100 mm/month. On the right side of the figure 3.1, it is clear to see the different runoff segments accounted for in the proportion of the total data in the histogram. We can see that although the Yenisei and Lena River have some runoff data greater than 100 mm/month, more than eighty percent of the total runoff are less than 50 mm/month. In figure 3.2, these four colored lines represent respectively the statistical distributions of the annual mean runoff time series for each river basin. It gives a comparison of the changes in the annual mean runoff of the four rivers. The annual mean runoff of the Ob and Lena River are very similar. About 3 mm/month runoff value in the two total runoff data accounts for the largest proportion which is more than 15 percent, while the maximum annual runoff data is about 5 mm for the Yenisei and Mackenzie River. Through these figures , a general knowledge of the four rivers runoff is presented.

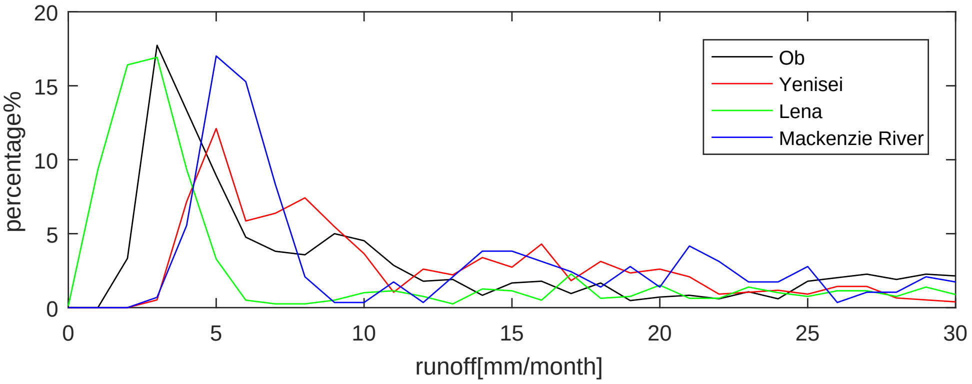
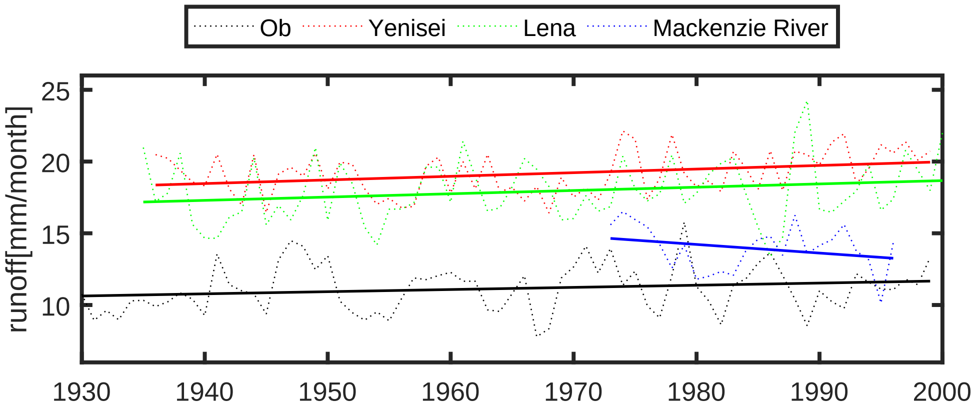


Figure 3.2: *Annual mean of the Mackenzie River, Ob, Yenisei and Lena*

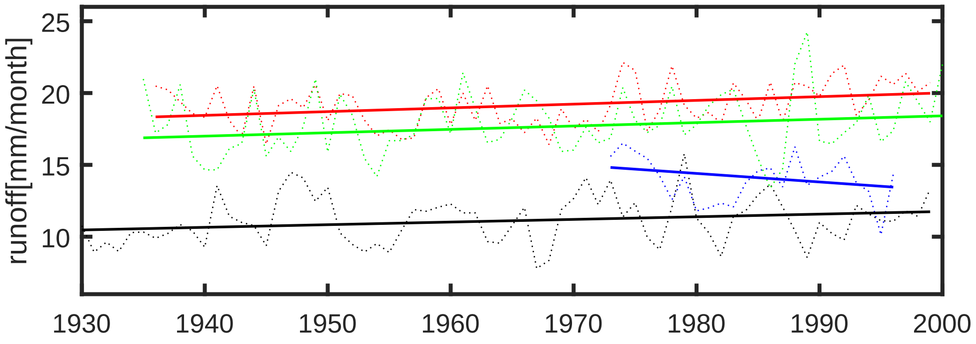
3.1 Analysis of trend

In the first case, trends of the four river runoff time series are analyzed based on case 1, which was indicated in figure 2.2.

The most important element to reflect the change of trend is the change in the mean. Therefore, mean runoff is mainly analyzed in this section. In figure 3.3, these dashed lines represent annual mean runoff time series for each river basin. As the same time, these solid lines represent their trends of annual mean runoff. It provides information about annual mean of all known river runoff data for the four rivers over the period from 1930 to 2000. Of these rivers, the annual mean runoff of the Yenisei River is similar to that of the Lena River. The two runoffs are in the approximately 18 mm/month. Some of the annual mean runoff for the Lena River reaches 25 mm/month. However, the annual runoff curve of the Yenisei River is above that of the Lena River. Simultaneously, the mean runoff of the Mackenzie River are near by 15 mm/month and that of the Ob River are nearly 10 mm/month. In general, the annual mean runoff of the Yeni-



(a) Least-squares regression



(b) Mann-Kendall test

Figure 3.3: *Comparison of annual mean trend test by two different method*

sei River and the Lena River more substantial than that of the Ob River and the Mackenzie River.

For the stability of the annual mean runoff, trend test plays an important role on the analysis. There are two methods used for trend analysis: parametric trend test and non-parametric trend test: Mann-Kendall test. The method of the parametric trend test is least-squares regression used in this thesis. For the latter method, the magnitudes of linear trends are determined using Sen's estimator of slope. Figure 3.3 respectively depicts the trend of the annual mean runoff in the two trend test. As for the Mann-Kendall trend test, the curve of the Yenisei River and the Lena River are higher than that of the Mackenzie River and the Ob River.

Table 3.1: *Trend for each curve of annual mean: linear regression and Mann-Kendall test*

annual mean		Mackenzie	Ob	Yenisei	Lena
Linear regression	Trend [mm/month/year]	-0.06	0.02	0.03	0.02
	Variation of trend [mm]	-1.4	1.1	1.6	1.5
Mann-Kendall	Confidence level (95%)	→	↗	↗	↗
	Trend [mm/month/year]	-0.06	0.02	0.03	0.02
	Variation of trend [mm]	-1.4	1.3	1.7	1.6

According to table 3.1, the overall trends show an increase for the Ob River, the Yenisei River and the Lena River over 1930-2000. However, the trends are very small,respectively only 0.02 mm/month/year, 0.03 mm/month/year and 0.02 mm/month/year. From a mathematical point of view, they do have trends. But from a practical point of view, these trends are very small compared to the actual runoff data. Therefore, it can be neglected even though there is a trend in statistics.In contrast, as for the Mackenzie River, the variation of trend is a decrease. However, it is stable and has no significant trend from the trend test at confidence level 95%. In the two figures, the difference between this two trend test is quite small and can be negligible. For the calculation of the trend, the results is the same. Only the variation of trend has a little difference. Therefore, in the back of this thesis, non-parametric Mann-Kendall trend test is used for all related to the trend.

Based on the trend analysis of annual mean runoff, it comes to a conclusion. The annual mean runoff of the four rivers (Ob, Yenisei, Lena and Mackenzie) are generally stable and have no noticeable trend.

3.2 Analysis for amplification

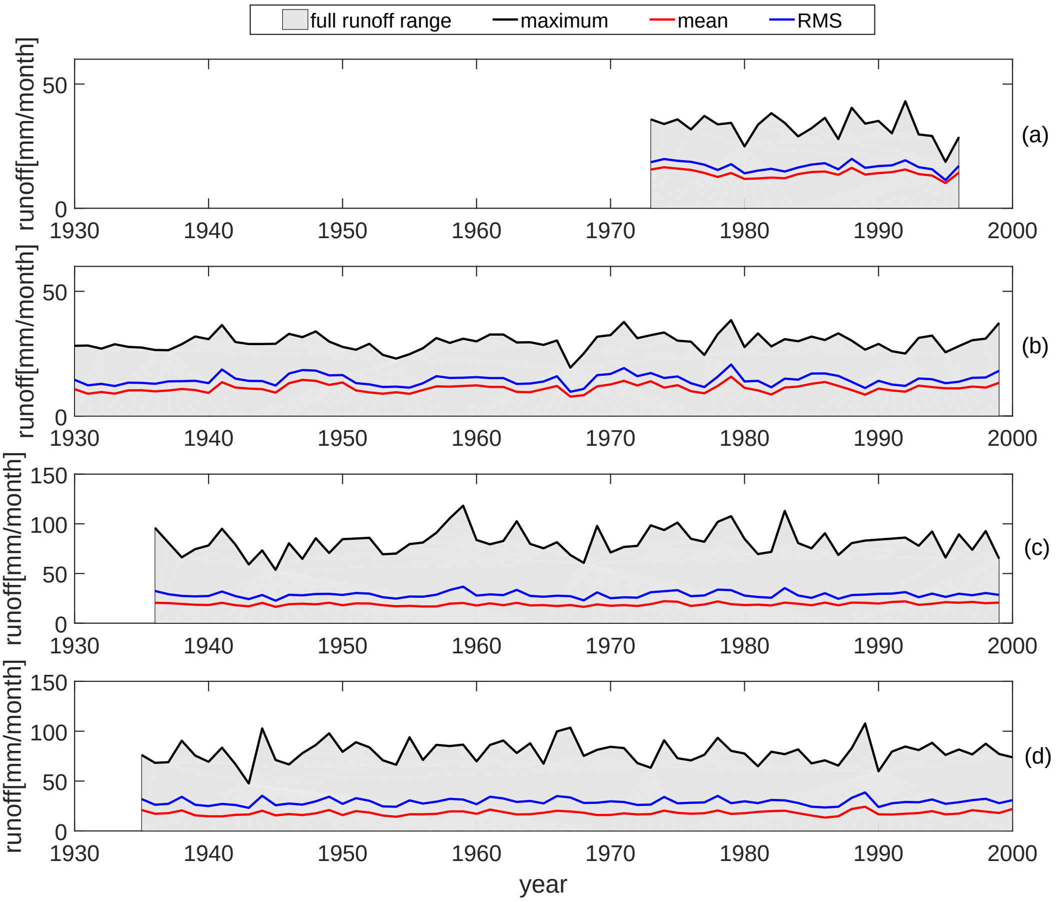


Figure 3.4: Annual mean, maximum, RMS of the Mackenzie(a), Ob(b), Yenisei(c) and Lena River(d)

In order to study changes in the annual mean runoff, the RMS values are firstly calculated for the analysis. To know the extent of the annual mean runoff changes, the relative behavior of RMS is used for the analysis, i.e. the quotient of RMS $(r - \bar{r})$ and RMS (r) with r being raw runoff data and $\bar{r}$ being annual mean runoff. Table 3.2 provides the information about RMS $(r - \bar{r})$, RMS of all raw runoff and relative RMS(RRMS). As for the quotient, 10% is set as a boundary value to determine the stability of annual mean runoff.

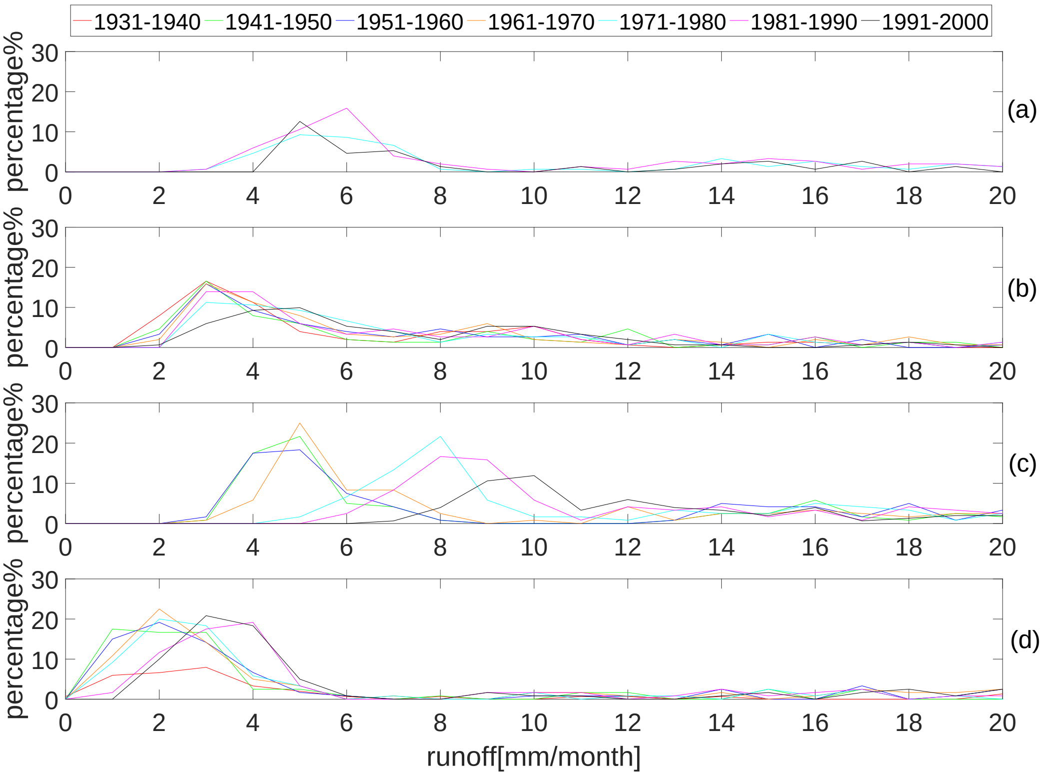


Figure 3.5: *River runoff every ten years for the four rivers: Mackenzie River(a), Ob(b), Yenisei(c) and Lena(d)*

From the table 3.2, it is clear that the relative RMS of the three rivers (Mackenzie, Yenisei and Lena) are less than 10%. For the Ob River, its RRMS is 11.3%, which is bigger than 10%. However, the relative RMS of the annual mean runoff is just 11.3%, which is close to 10%. Compared to RMS of the all raw runoff, the RMS values of annual mean runoff are apparently smaller than that of its all raw data. Table 3.2 shows the comparison of the two sets of data. This point illustrates the change of the runoff is not big in a year.

From the aspect of RMS, it is known that the annual mean runoff of the three rivers (Mackenzie, Yenisei and Lena) are stable and that of Ob river is generally stable. Although they fluctuate in different years, they are still within the range.

In addition to the relative RMS of annual mean runoff, in the second case, the maximum and variance of the river runoff time series are analyzed for the analysis of amplification. The stability of the time series is determined in this section according to the case 2, which is shown in figure 2.3. In case 2: the variance of average becomes bigger; maximal value has an increasing trend. At the same time, the minimum shows a downward trend. In this thesis river runoff time series is analyzed. The value of river runoff is almost zero in dry season e.g. in January.

Table 3.2: *RMS($r-\bar{r}$), RMS(r), RMS of all raw runoff and all maximal runoff and relative RMS of them*

		Mackenzie	Ob	Yenisei	Lena
All raw runoff	RMS ($r-\bar{r}$) [mm/month]	1.6	1.7	1.5	2.2
	RMS (r)[mm/month]	17.0	14.7	28.8	29.3
	RRMS·100%	9.3%	11.3%	5.2%	7.4%
	RMS($\bar{r}$)[mm/month]	14.0	11.3	19.2	18.1
All maximal runoff	RMS ($r-\bar{r}$) [mm/month]	5.2	3.4	13.0	11.1
	RMS (r)[mm/month]	33.2	29.9	83.3	80.0
	RRMS·100%	15.5%	11.3%	15.6%	13.9%

Therefore, it's not necessary to consider the change of minimum because the minimum is close to zero.

In figure 3.4, these black lines in these graphs indicate the maximal runoff of the four rivers and these red lines represent annual mean runoff of them. In addition, RMS values of these four rivers are showed by these blue lines and the shadow parts indicate the full runoff range of them over these years. The maximum of all known river runoff data of the four rivers over the period from 1930 to 2000 are picked out and represented in the form of curves in figure 3.4. It is intuitively seen that the difference between the mean and the maximum runoff of the Yenisei and Lena River is large, indicating that the runoff of the two rivers fluctuates much.

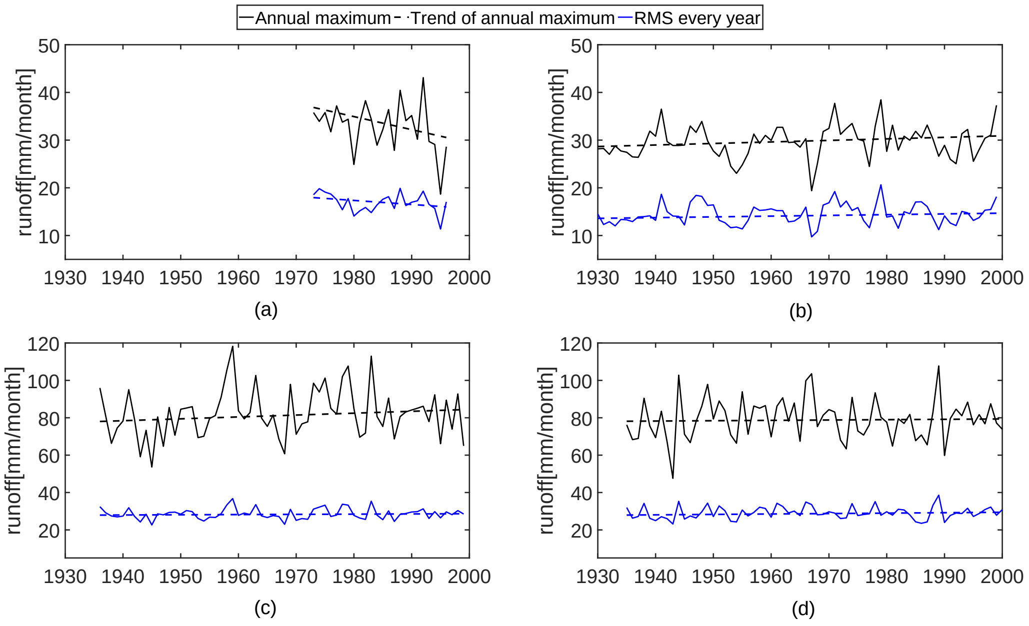


Figure 3.6: *Annual maximum and annual RMS: Mackenzie(a), Ob(b), Yenisei(c) and Lena(d)*

In fig. 3.5, based on the sample of every decade, this figure draws the distribution of the river runoff with seven kinds of colors during these different periods corresponding to the four river basins. It shows vividly the river runoff every ten years for the four rivers. In general, most of the river runoff values are in the range of 15 mm/month. From the distribution, as for the Ob River, it shows a slight shift since 1991. That means, the runoff of the Ob River has a gradual increase over these years. The growth of the mean runoff is about from 3.5 mm/month to 5 mm/month. However, for the Yenisei River, it shows an obvious shift from 1931 to 2000 from the distribution. Hence, its river runoff has a significant trend, especially between 1960 and 1980, roughly from 5 mm/month to 8 mm/month. With regard to the Lena River, there is a slight shift in last twenty years. Therefore, the runoff of this river has a tendency to increase, but not significant as the Yenisei river. In general, the runoff of the Ob, Yenisei and Lena River have a overall increasing trend over time, which are the three great Siberian rivers, all flow into the Arctic Ocean. The increasing trend may be due to global warming. Compared to the other three rivers, the overall runoff of the Yenisei River is the largest and it has the most obvious increasing trend. The Yenisei River is the largest river flowing to the Arctic Ocean. Therefore, it is the most affected by climate change. This may be the cause of the above-described-phenomenon.

To determine the change of annual maximal runoff statistically, the RMS values of annual maximum and the relative behavior of RMS are calculated as the same as annual mean. Table 3.2 provides the information about RMS $(r - \bar{r})$, RMS of all maximal runoff and the relative RMS. Compared to the annual mean river runoff, the RMS values of annual maximum are apparently much bigger than that of its annual mean. The range of fluctuation for annual mean runoff is between 5 mm and 25 mm while its of annual maximum fluctuates up to nearly 120 mm/-month, for the Yenisei River, the maximal runoff in the whole years is 118.3 mm/month in June 1959 and its RMS value of annual maximal runoff is 83.3 mm/month, the largest of the four rivers. As for the Ob River, its maximal runoff is near 30 mm/month. With regard to the relative RMS, 10% is set as a boundary value to determine the stability of annual maximal runoff. From the table 3.2, it's apparent that the relative RMS are all more than 10%. Compared the relative RMS of annual mean, the RRMS of the Ob River is almost unchanged. From this point, it can be seen that the variation of annual mean and maximum of the Ob River are considerably the same. From the aspect of RMS, it is known that the annual maximal runoff of the four rivers are generally stable.

Table 3.3: *Trend for each curve of annual maximal runoff*

annual maximum	Mackenzie	Ob	Yenisei	Lena
Confidence level (95%)	$\longrightarrow$	$\nearrow$	$\longrightarrow$	$\longrightarrow$
Trend [mm/month/year]	-0.27	0.03	0.10	0.02
Variation of trend [mm]	-6.6	2.2	6.4	1.2
RMS [mm/month]	33.2	29.9	83.3	80.0

In addition to the relative RMS, the trend of annual maximum is analyzed to determine its stability. In figure 3.6, these solid black lines draw the annual maximal runoff of these four rivers and these dashed black lines show their corresponding trends. In addition, the annual RMS values are represented by the solid blue lines and their trends are indicated by those blue dashed lines. It depicts the trend of the annual maximal runoff. In this section, the non-parametric Mann-Kendall trend test is used to draw the trend line of annual maximum. The overall trends show just an increase for the Ob River (0.03 mm/month/year) at confidence level 95%. As previously mentioned in the trend section of this chapter, from a mathematical point of view, it does have an increasing trend. But from a practical point of view, this trend is very small compared to the actual runoff data. Therefore, it is a stable process even though there is a tiny increasing trend for the Ob River. However, the annual maximal runoff of the other three rivers have no significant trend which are shown in table 3.3. Based on the trend analysis of annual maximal runoff, it comes to a conclusion: the annual maximal runoff of the Ob River is generally stable. At the same time, the annual maximal runoff of the other three rivers (Mackenzie River, Yenisei and Lena) are stable and have no significant trend.

Table 3.4: *Trend for each curve of RMS every year*

RMS	Mackenzie	Ob	Yenisei	Lena
Confidence level (95%)	⟶	⟶	⟶	⟶
Trend[mm/month/year]	-0.08	0.02	0.01	0.02

In addition, it is also necessary to study the variance of annual mean over the period 1990-2000. RMS is an indicator of variation in variance, so RMS value can be analyzed instead of variance. Figure 3.6 also depicts the change of annual RMS for the river runoff.

As for the RMS values every year, it shows no significant trend for the four rivers according to the trend test. They are illustrated in table 3.4. That means the variance of annual mean runoff of the four rivers have no significant change.

Through the above analysis of the maximal river runoff and the variance of the annual mean runoff, it can be concluded: for the time series of river runoff in basins (Mackenzie River, Ob, Yenisei and Lena),the variances of average river runoff are generally stable. At the same time, the annual maximal runoff of these four rivers have no significant trend. However, the runoff of the Ob, Yenisei and Lena River have a overall increasing trend over time from the distribution, may be due to global warming. Compared to the other three rivers, the overall runoff of the Yenisei River is the largest and it has the most obvious increasing trend from 1931 to 2000.

3.3 Analysis for break points

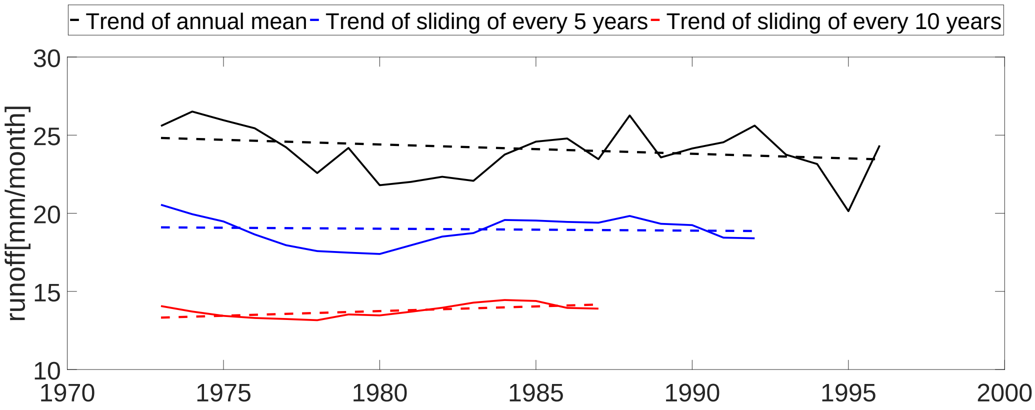


Figure 3.7: *Trend of the Mackenzie River*

In the third case, for break points of analysis, the moving average of the river runoff time series is analyzed. Using case 3, which is shown in figure 2.4, the sliding average of the time series should be determined. In case 3: the average value has no change over a wide range. Nonetheless, there are break points in a small range.

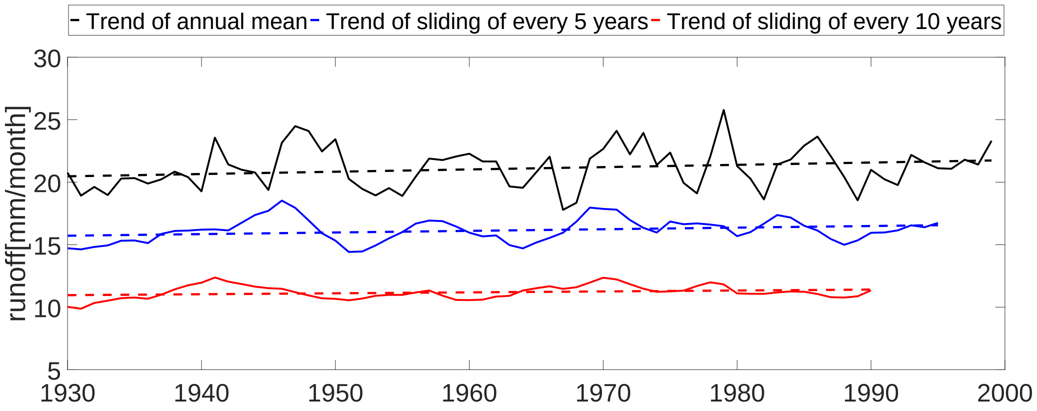


Figure 3.8: *Trend of the Ob River*

In the figure 3.7, 3.8, 3.9 and 3.10, these solid black lines draw the annual mean runoff of these four rivers and these dashed black lines show their corresponding trends. In addition, the sliding mean runoff of every 5 years are represented by the solid blue lines and their trends are indicated by those blue dashed lines. Additionally, these solid red lines draw the sliding mean runoff of every 10 years of these four rivers and these dashed red lines show their corresponding trends. The annual mean runoff and sliding mean runoff of every five and ten years for the four rivers from 1930 to 2000 are successively calculated and successively represented in the form of curves in these figures.

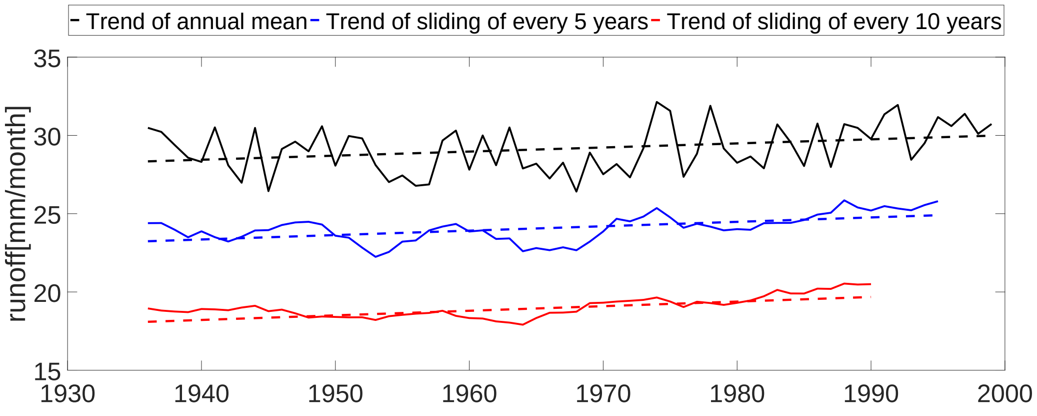


Figure 3.9: *Trend of the Yenisei River*

In order to see the variation of the three trends more clearly in the four graphs, the curves of the set of annual mean runoff data are overall shifted up by 10 mm/month. At the same time, the curves of the sliding mean of every five years runoff data are overall shifted by 5 mm/month. Compared to the annual mean runoff, the curves of sliding mean are gradually flatter.

From these four figures, the first thing is obvious that the trend of annual mean runoff and sliding mean runoff of every five years are different for the Mackenzie River compared to the other three rivers. There are no significant trend for annual mean and sliding mean of every 5 years as for the Mackenzie River. In this thesis, only the runoff data from 1973 to 1996 are collected for the Mackenzie River. The shorter time series of runoff results in only 24 years. Therefore, the trends can not be well demonstrated.

For the Lena River, significant inter-annual variability exists in runoff rates, with a range of nearly 11 mm/month between the annual maximum (24.3 mm/month in 1989) and minimum (13.4 mm/month in 1986) runoff rates.

Table 3.5: *Trend and RMS values for each curve in the three figures of annual mean, sliding mean of every 5 and 10 years*

		Mackenzie	Ob	Yenisei	Lena
Confidence level (95%)	annual mean	→	↗	↗	↗
	every 5 years	→	↗	↗	↗
	every 10 years	↗	↗	↗	↗
Trend [mm/month/year]	annual mean	-0.06	0.02	0.03	0.02
	every 5 years	-0.01	0.01	0.03	0.03
	every 10 years	0.06	0.01	0.03	0.02
Variation of trend [mm]	annual mean	-1.4	1.3	1.7	1.6
	every 5 years	-0.2	0.9	1.7	1.6
	every 10 years	0.9	0.5	1.6	1.3
RMS [mm/month]	annual mean	14.0	11.3	19.2	18.1
	every 5 years	13.9	11.2	19.1	17.8
	every 10 years	13.8	11.2	19.0	17.8

According to the non-parametric Mann-Kendall test and Sen's estimator of slope, the overall trends of annual mean runoff show an increase for the Ob River (0.02 mm/month/year), the Yenisei River (0.03 mm/month/year) and the Lena River (0.02 mm/month/year) over 1930-2000 (confidence level 95%).

In addition to the annual mean runoff, there are all increasing trend for these three rivers. As for the trend of the sliding mean runoff of every five years, the trend of runoff in these cases gradually becomes flatter. It shows also the increase for the Ob River (0.01 mm/month/year), the Yenisei River (0.03 mm/month/year) and the Lena River (0.03 mm/month/year) and no significant trend is found for the Mackenzie River. For every ten years, the trends show an increase for the all four rivers (the Mackenzie River: 0.06 mm/month/year, the Ob River: 0.01 mm/month/year, the Yenisei River: 0.03 mm/month/year, the Lena River: 0.02 mm/month/year) in the confidence level 95%. But all trend values are small. As previously mentioned in the trend section, from a mathematical point of view, they do have an increasing trend. But from a practical point of view, this trend is significantly small compared to the actual runoff data. Therefore, it can be neglected even though there is a tiny trend. These statistical information about variation of trend for annual mean runoff and sliding mean runoff are presented in table 3.5.

Table 3.5 also gives information of RMS values. The values of RMS describe the mean runoff and degree of dispersion of the runoff for the four rivers in the three cases (annual, sliding 5

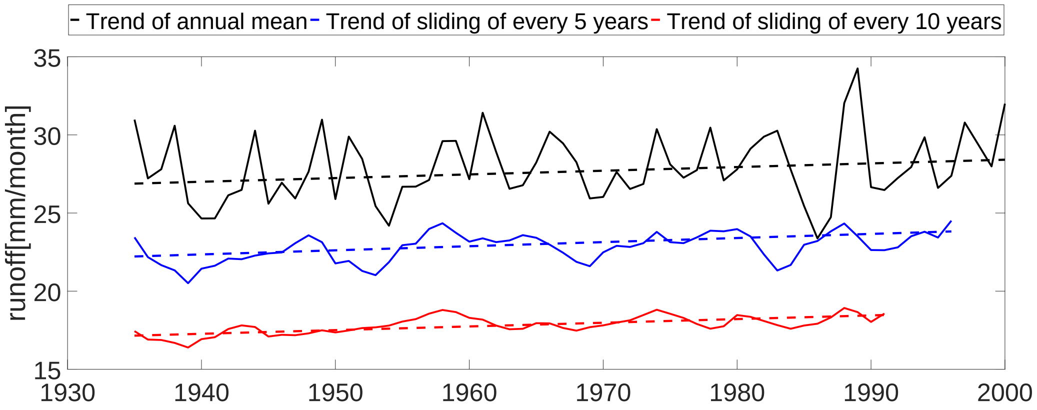


Figure 3.10: *Trend of the Lena River*

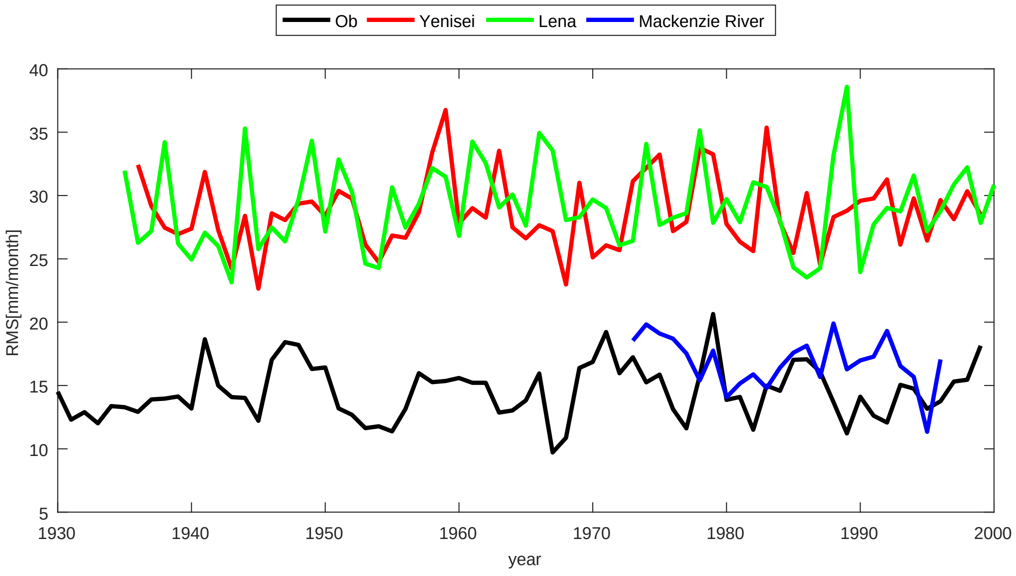
years and sliding 10 years). From this Table, we can get information about extreme changes of these four rivers. For the Mackenzie River and Yenisei River, the RMS values of annual mean, sliding mean of every 5 and 10 years decrease respectively. In other words, there are no extreme changes on these two rivers. However, as for the Ob River, the RMS values of every 5 and 10 years are constant, both are 11.2 mm/month. It is probably that the Ob River has some extreme changes such as 1940-1950 and 1960-1970. The analysis of the Lena River is the same as the Ob River. Therefore, it is also concluded that there are some extreme changes of the Lena River such as 1980-1990.

Table 3.6: *Trend in every ten years*

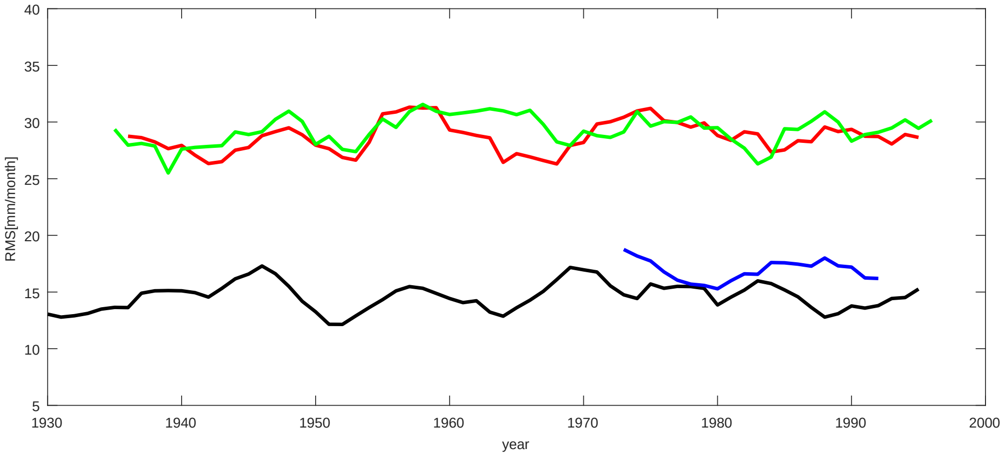
Trend[mm/month/year]	Mackenzie	Ob	Yenisei	Lena
1931-1940	-	0.12 ⟶	-	-
1941-1950	-	0.15 ⟶	-0.00 ⟶	0.21 ⟶
1951-1960	-	0.37 ↗	-0.05 ⟶	0.12 ⟶
1961-1970	-	0.03 ⟶	-0.25 ⟶	-0.33 ⟶
1971-1980	-	-0.29 ⟶	0.11 ⟶	0.08 ⟶
1981-1990	0.25 ↗	0.08 ⟶	0.05 ⟶	-0.19 ⟶
1991-2000	-	-	-	0.40 ↗

In figure 3.11, these black, red, green and blue lines represent respectively the RMS values of these four river basins. From this figure, it is visually to see annual RMS, sliding RMS of every 5 years and every 10 years. It shows that annual RMS of the Yenisei River and the Lena River are bigger than that of the Mackenzie River and the Ob River. The RMS values of the Yenisei River and the Lena River are in the neighborhood of 30 mm/month while that of the Mackenzie River and the Ob River are round 15 mm/month. In the three figures, the curves becomes constantly more flatter and the changes of RMS are gradually becomes smaller for the four rivers. It also confirms the flatter trends which mentioned previously.

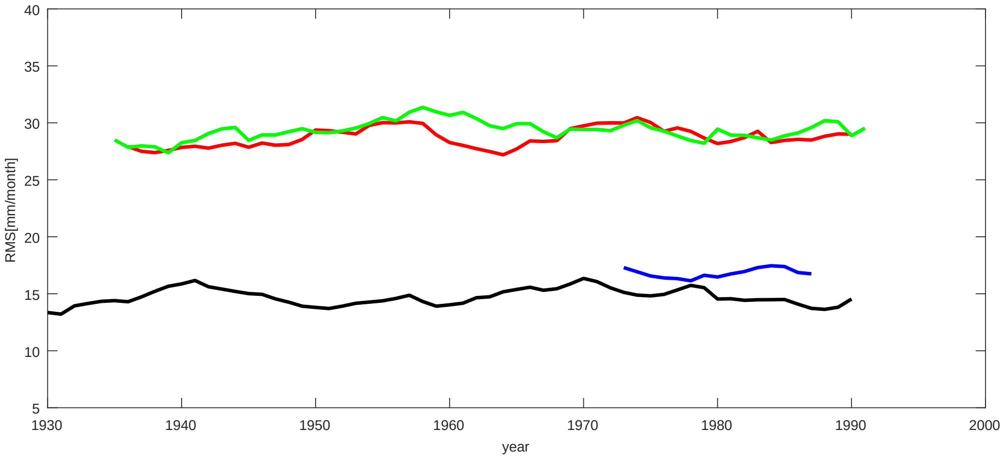
In figure 3.12, these thin lines represent respectively the annual mean runoff of these four rivers. In addition, their corresponding trends are indicated by these thick lines. It depicts annual



(a) Annual RMS



(b) Sliding RMS of every 5 years



(c) Sliding RMS of every 10 years

Figure 3.11: *Annual RMS and sliding RMS*

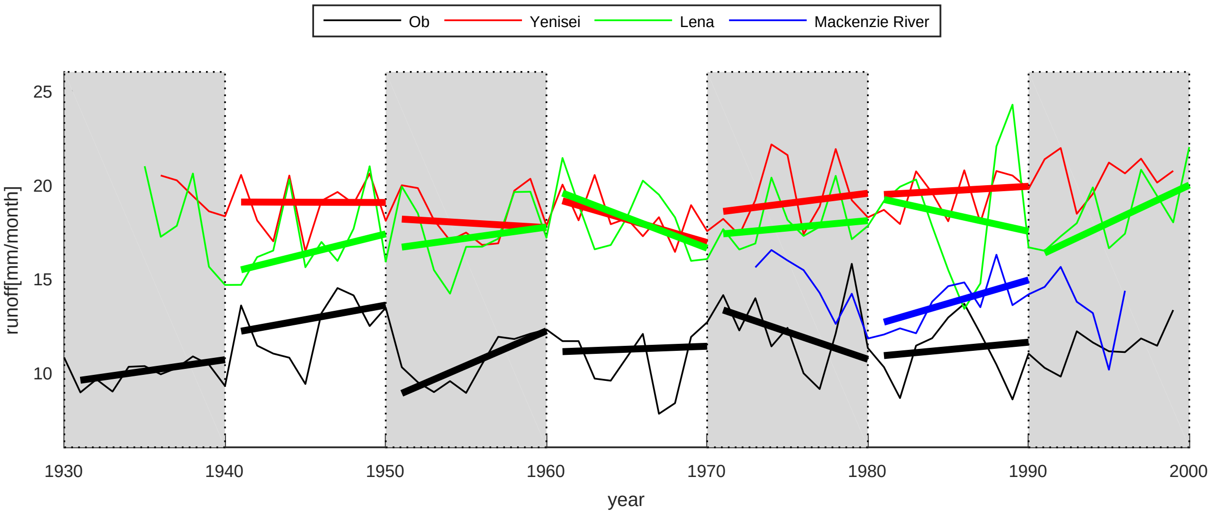


Figure 3.12: *Annual mean and trend of every 10 years*

mean and trend of every 10 years for the four rivers. As can be seen, the trends in every ten years are mostly not significant. However, there are also increasing trends for the Mackenzie, Ob and Lena River. This confirms what said before, there are extreme changes for the Ob and Lena River. As for the Mackenzie River, only the runoff data from 1973 to 1996 are collected. The shorter time series of runoff results in only 24 years. Therefore, there is only one trend of ten years. The trends of every ten years in this section can not be well demonstrated. In addition, table 3.6 and 3.7 illustrate statistically the trends in figure 3.12 during the time period 1931-2000. As can be seen, the trends of the Ob river from 1951 to 1960 (0.37 mm/month/year) and of the Lena River from 1991 to 2000 (0.40 mm/month/year) are much bigger than the trends' value previously calculated. This is more powerful to explain the extreme change of the Ob and Lena River.

Table 3.7: *Variation of trend in every ten years*

Variation of trend [mm]	Mackenzie	Ob	Yenisei	Lena
1931-1940	-	1.2	-	-
1941-1950	-	1.5	-0.0	2.1
1951-1960	-	3.7	-0.5	1.2
1961-1970	-	0.3	-2.5	-3.3
1971-1980	-	-2.9	1.1	0.8
1981-1990		0.8	0.5	-1.9
1991-2000	2.5	-	-	4.0

Through the above analysis, it is concluded: For the Mackenzie River and Yenisei River, there are no extreme changes on these two rivers. However, as for the Ob River, it has probably some extreme changes such as 1951-1960. The analysis of the Lena River is the same as the Ob River. It is also concluded that there are some extreme changes of the Lena River such as 1991-2000.

3.4 Seasonal stationarity analysis

For the hydrological time series, precipitation has a great influence on river runoff, which mainly changes with the seasons. In the case of a certain basin area, the greater the precipitation, the greater the river runoff.

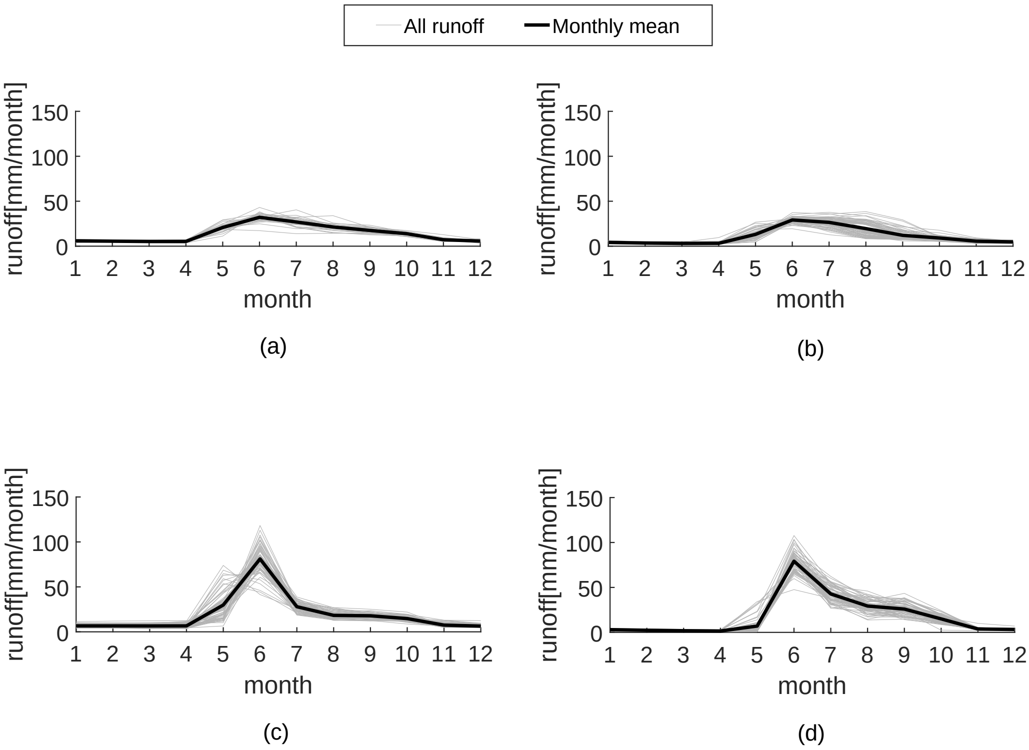


Figure 3.13: All runoff and monthly mean for the Mackenzie River(a), Ob(b), Yenisei(c) and Lena(d)

In this thesis, the river runoff time series are analyzed. Therefore, it is very significant to analyze inter-monthly variation with a year to determine the stability of the time series. In figure 3.13, these gray lines represent all collected runoff of these four rivers and these black lines indicate the corresponding monthly mean of them. The monthly mean of all known river runoff data of the four rivers over the period from 1930 to 2000 are calculated and represented in the form of curves in this figure. In winter, the river will generally be in the frozen state. However, in order to maintain the smooth flow channel when people living near the river, mostly people will break the ice on the river. Such as the Yenisei River is taken this measure in the winter.

From figure 3.13, there is an interesting point that the Yenisei River in addition to the normal peak runoff in June, there is a small runoff peak in May. It is probably because of some special climatic factors, such as ice melting and human activities. In figure 3.14, the solid lines represent the monthly mean runoff of these four river basins and the shadow parts are the corresponding

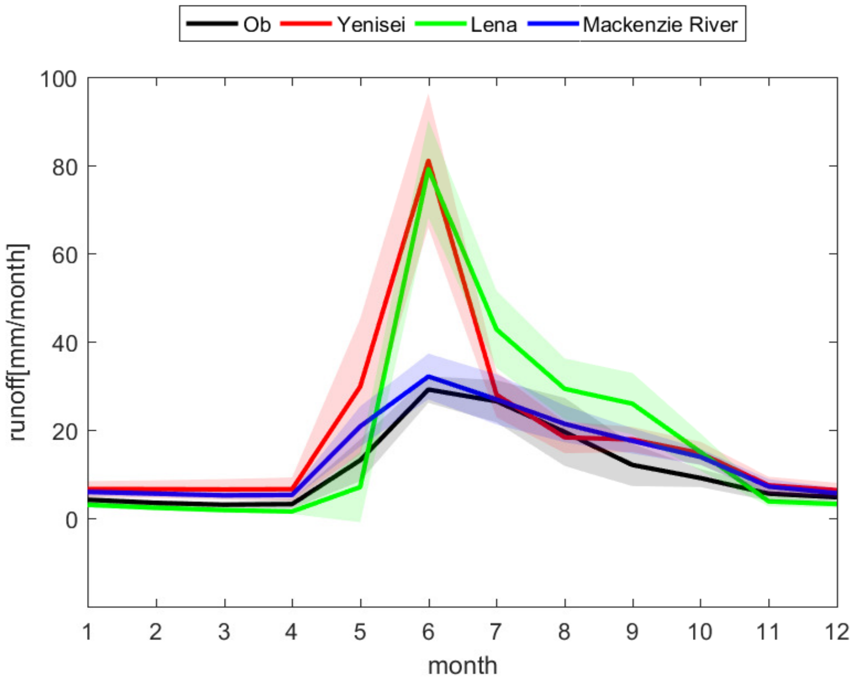


Figure 3.14: *Monthly mean and standard deviation of the Mackenzie River, Ob, Yenisei and Lena*

standard deviation of them. From this figure, it shows monthly mean and standard deviation over the whole years of the four rivers. Obviously, these four rivers in the winter are basically no runoff. For the Yenisei and Lena River, the mean peak runoff in June is substantially the same.

The river runoff data are divided into 12 months runoff data from January to December. Then sufficient information are acquired from the typical annual cycle. In the cold months, runoff is small and there can be no runoff at all (E.g. the Ob and Lena). Runoff begins to increase in April or May when snow begins to melt. In general, it reaches the runoff peak in June with a rapid rate. There are differences in the monthly runoff for the Mackenzie, Ob, Yenisei and Lena. With runoff peaks in June for the four rivers, the peaks are much sharper in the Yenisei and Lena as compared with the Mackenzie and Ob. The rapid melt of the snow has a increase to sharp runoff peaks when it becomes warm enough in June.

Table 3.8: *Cyclostationarity of the four rivers' runoff*

	Mackenzie	Ob	Yenisei	Lena
Cyclostationarity	0.82	0.76	0.77	0.81

In figure 3.15, the white grids represent the maximal river runoff for each basin over observed years. All years collected in this thesis, maximal river runoff are substantially in June. Especially for the Lena, all of total runoff peaks of the Lena occurs in June, as in this figure. This can be attributed to the precipitation over much of the area peaks in summer. From autumn through spring, most of the precipitation is stored as snow. By contrast, the months of the

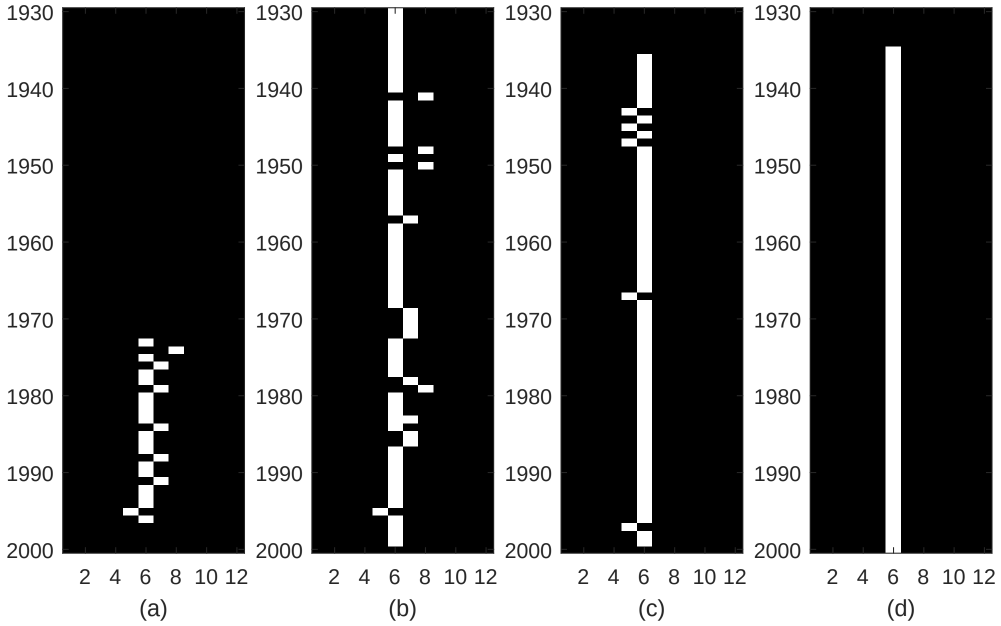


Figure 3.15: *Seasonal pattern of all runoff of the Mackenzie River(a), Ob(b), Yenisei(c) and Lena(d)*

runoff peaks are not stable. Some of the runoff reach their peak in August over the past years. For the Yenisei, some runoff reaches the peaks in May.

There are gray lines representing monthly mean runoff every five years of these four rivers and black lines indicating the monthly mean in all years of them in figure 3.16. It demonstrates monthly mean runoff of all years and every five years for the four rivers. Compared with figure 3.13, the curve of five-year average is closer to the curve of monthly mean. That means essentially, with monthly change, changes in river runoff is substantially stable.

In addition, the cyclostationarity also plays an important role in studying the stability of river runoff. It gives an overall concept for stability of the runoff. If the cyclostationarity measurable metric equals 1, it means that the river runoff is perfectly stable. That is to say, it has perfectly stable seasonal behavior. The closer the cyclostationarity to 1, the better the stability of the river runoff .To detect the stationarity in seasonal performance, the cyclostationarity is calculated. Table 3.8 shows the cyclostationarity values for the four rivers. They are almost 0.8, which close to 1. In other words, it reflects stable seasonal behaviors for the runoff of the four river basins.

After the analysis, the runoff of the four river basins show stable seasonal behavior in most years. In general, the river runoff reaches the peaks in June, even though some reaches the peaks in May or in August.

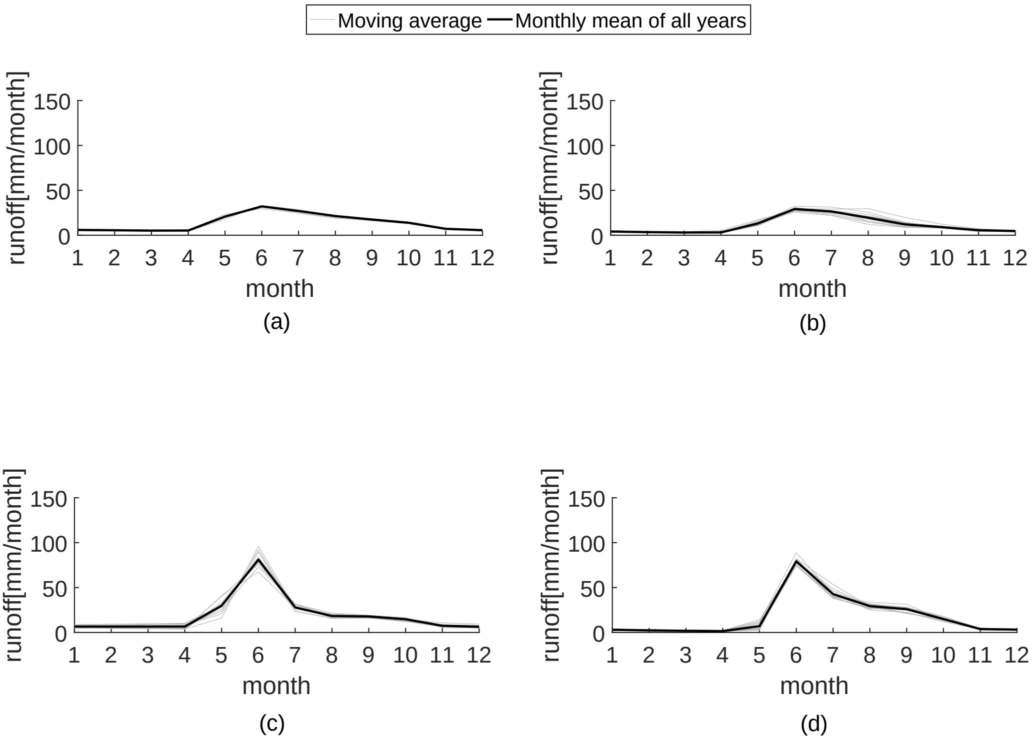


__Figure 3.16:__ Monthly mean in all years and every five years of the Mackenzie River(a), Ob(b), Yenisei(c) and Lena(d)

Chapter 4

Conclusion and discussion

In this thesis, time series from 4 different basins (the Mackenzie River, the Ob River, the Yenisei River and the Lena River) are analyzed in order to assess the stationarity of river runoff. As for the range of river runoff time series, the period from 1930 to 2000 is selected and analyzed. To investigate the stationarity of runoff time series, the trend in a statistical way, cyclostationarity and root-mean squares of the series are estimated. From the analysis, we get the conclusions as follows:

As for the Mackenzie River, its annual mean runoff is stable and has no noticeable trend based on trend test. From the annual maximal runoff and its variance, we can see that there is no obvious fluctuation through decades. Beside that, there are no extreme changes in the runoff time series of the Mackenzie River. Because its RMS values of annual mean, sliding mean of every 5 and 10 years decrease respectively. At last, to detect the stationarity in seasonal performance, the monthly mean is estimated and compared with monthly runoffs in each year. From the cyclostationarity, it reflects stable seasonal behaviors. In general, most of its runoff reaches peak in June.

For the Ob River, even though there is a trend for annual mean runoff in statistics, it can be neglected, compared to the whole runoff observations over 70 years. In fact, its annual mean runoff has no distinct trend and it is a stationary process. From the distribution of runoff, it shows a slight shift since 1991. That means, the runoff of the Ob River has a gradual increase over these years. Its trend of annual maximum is also small and negligible. Regarding these results it can be said, that the annual maximal runoff and its variance are stable. From the trend of sliding mean, the Ob River has some extreme changes such as 1951-1960. As for the seasonal stationarity, they show stable seasonal behaviors in most years.

Different from the Mackenzie and Ob River, the Yenisei River has a larger runoff every year, even more than 100 mm/month. We can neglect the trend of annual mean runoff, because the statistical trend is significantly small compared to the whole runoff over these years. In other words, the annual runoff of this river is stable without noticeable trend. However, it shows an obvious shift from 1931 to 2000 from the runoff distribution. Hence, the river runoff has a significant trend, especially between 1960 and 1980. With stable maximal runoff and RMS, there are no extreme changes for the Yenisei River. At last, it is also generally stationary in seasonal behavior from the cyclostationarity, although some runoffs reach peaks in May.

Statistically, the trend of annual mean runoff of the Lena River is negligible even though there is a tiny trend over these years. That is to say, the annual runoff of this river is generally stable and has no noticeable trend. From the distribution, there is a slight shift in the last twenty years. Therefore, the runoff of this river has a tendency to increase, but not as significant as the

Yenisei river. Its annual maximal runoff and annual RMS are stable. After evaluation, there are some extreme changes of this river between 1991 and 2000. From the view of seasonal stability, it reflects quite a stable seasonal behaviors with high cyclostationarity. The river runoff reach their peak in June every year.

After analysis of the runoff time series, it can be concluded that the river runoff of the four rivers are generally stationary with annual cycle. Moreover, it is seasonal stationary, according to obvious and stable seasonal behaviors in each year. However, there are still some unstable changes and extreme events in some years. That might be related to climate change, for example, ice melting and global warming, or human activities. Because of the limitation of the observations, the river runoff time series might not accurately reflect inter-annual and long-term variation. Nevertheless, the stationarity analysis is still helpful for predicting the changes of river runoff in the Arctic basins, and meaningful to investigate the influence of climate change in Arctic region. Therefore, further research and analysis are necessary in the future on the causes of unpredictable changes and the hydrological relationship among these river basins around the Arctic ocean.

Bibliography

Chen, H.-L. and Rao, A. R. (2002), 'Testing hydrologic time series for stationarity', *Journal of Hydrologic Engineering* 7(2), 129–136. DOI: 10.1061/(ASCE)1084-0699(2002)7:2(129).

Fernando, D. and Jayawardena, A. (1994), Generation and forecasting of monsoon rainfall data, *in* 'Proc. of the 20th WEDC conference. Colombo, Sri Lanka', pp. 310–313.

GRDC (2011), 'Global runoff data centre (2011): Watershed boundaries of grdc stations / global runoff data centre. koblenz, germany: Federal institute of hydrology (bfg).'.

Hendriks, M. (2010), *Introduction to physical hydrology*, Oxford University Press.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K. and Johnson, C. (2001), 'Climate change 2001: the scientific basis'.

Jayawardena, A. (2014), *Environmental and hydrological systems modelling*, CRC Press.

JE, V. (2015), 'Effects of permafrost thaw on arctic aquatic ecosystems. biogeosciences, 12, 7129-7167'.

Kendall, M. G. (1962), 'Rank correlation methods'. DOI: 10.1234/12345678.

Kite, G. (1989), 'Use of time series analysis to detect climatic change', *Journal of Hydrology* 111(1), 259–279. DOI: http://dx.doi.org/10.1016/0022-1694(89)90264-3.

Maidment, D. R. et al. (1992), *Handbook of hydrology.*, McGraw-Hill Inc.

Non-Parametric Tests against Trend. (n.d.).

O'Connell, P. (1977), 'Arima models in synthetic hydrology, mathematical models for surface water hydrology'.

Perovich, D., Meier, W., Tschudi, M., Farrell, S., Gerland, S. and Hendricks, S. (2011), 'Arctic report card: Update for 2015, sea ice'.

Rekacewicz, P. (1997), 'Arctic watersheds ocean watershed, catchment areas and annual runoff (km3/year)', `http://www.grida.no/prog/polar/bsc/fig3.htm`.

Salas, J. D. (1993), 'Analysis and modeling of hydrologic time series', *Handbook of hydrology* 19, 1–72.

Sen, P. (1968), 'Estimates of the regression coefficient based on kendall's tau', *Journal of the American Statistical Association* 63(324), 1379–1389. DOI: 10.1080/01621459.1968.10480934.

Serreze, M., Walsh, J., Chapin, F., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W., Morison, J., Zhang, T. and Barry, R. (2000), 'Observational evidence of recent change in the northern high-latitude environment', *Climatic Change* 46(1-2), 159–207. DOI: 10.1023/A:1005504031923.