Trend analysis of Icelandic discharge, precipitation and temperature series*

Jóna Finndís Jónsdóttir[1,2], Páll Jónsson[1] and Cintia B. Uvo[2]

[1]Hydrological Service, National Energy Authority, Grensásvegi 9,108 Reykjavík, Iceland.
E-mail: *jfj@os.is*
[2]Department of Water Resources Engineering, Lund University, Sweden

Nordic Hydrology **Vol 37 No 4–5 pp 365–376** © IWA Publishing 2006

Received 30 January 2006; accepted in revised form 2 June 2006

Abstract This study is a part of a Nordic co-operative research project, Climate and Energy, funded by Nordic Energy Research and the Nordic energy sector. The project has the objective of a comprehensive assessment of the impact of climate change on Nordic renewable energy resources including hydropower, wind power, biofuels and solar energy. In this paper, the long term variability of precipitation, temperature and discharge of Icelandic rivers is analyzed with respect to trends. Trend is tested for two periods: 1941–2002, since the longest Icelandic discharge records reach 60 years back in time, and 1961–2000, so that a larger set of discharge records could be included, as only a few Icelandic discharge records extend more than 40 years back in time. An eventual trend in the time series is analyzed using the Mann–Kendall test. The test is applied to the time series of both annual and seasonal values, and also to the timing and volume of the maximum daily discharge in spring and autumn, respectively. The main conclusions from the study are that, despite significant increase in measured precipitation, discharge in non-glacial rivers has not increased. Meanwhile, spring temperatures have a negative trend and spring floods, therefore, are larger and delayed.

Keywords Discharge; Iceland; precipitation; temperature; time series; trends

Introduction

Hydropower is the main source of electricity production is Iceland. In 2004, 82.7% of all electricity was generated by hydropower (7131 GW) (Pálsson and Jónasson 2005). According to ongoing studies of the effects of climate change on discharge and therefore hydropower, discharge may increase substantially and its seasonality may change during the next 100 years (Beldring *et al.* 2006). Both variations and changes in discharge affect the generation of hydropower. This study is meant to provide to the energy sector information on whether trends appear in the records of precipitation, temperature and discharge in Iceland.

The Icelandic Low is typically situated between Iceland and southern Greenland (Serreze *et al.* 1997). It represents one of the centers of action in the atmosphere of the Northern Hemisphere (Hurrell *et al.* 2003) and greatly influences the climate in Iceland, by affecting predominant wind directions and precipitation, and causes frequent changes in weather through its cyclonic activity. Meanwhile, oceanographic conditions also affect the climate in Iceland considerably (Einarsson 1984). Variations in precipitation are large within the country. It is generally higher in the south than in the north and highest on the glaciers and highest mountains (Eyþórsson and Sigtryggsson 1971).

*Paper presented at the 15th Northern Research Basins Symposium/Workshop (Luleå to Kvikkjokk, Sweden), 29 August–2 September, 2005.

doi: 10.2166/nh.2006.020

The rivers in Iceland are of three origins: direct runoff, groundwater fed and glacial rivers. There are vast areas of post-glacial lava where the permeability of the ground is high and the groundwater aquifers filter out the effects of short term variations in precipitation on river runoff. Approximately 50% of the country is above 500 m a.s.l. and glaciers cover 11% of the country. Therefore, precipitation is stored as snow or ice between seasons and sometimes between water years depending on temperature.

Trends in Icelandic discharge series have earlier been studied by Hisdal *et al.* (1995). Trends in meteorological series have been studied and recent findings are discussed by Hanna *et al.* (2004) and Jónsson and Miles (2001). Trends are, however, very dependent on the period analyzed. This work expands the analyses made previously by analysing different time periods. The dependence on the studied period may partly be explained by decadal variability in the time series. Figure 1 shows the annual time series of the river Hvítá at Kljáfoss (Figure 2) which is a clear example of such decadal variability.

In a study by Hisdal *et al.* (1995), regionally averaged series of annual and seasonal discharge assembled from seven discharge gauges in Iceland were analyzed for the period 1950–1990. Regional series showed no significant trend in annual runoff and a regional series from glacial rivers showed no change either in seasonal runoff. A non-glacial regional averaged series showed a positive trend in the spring and summer season, but a negative trend in the winter season. A trend study by Hisdal *et al.* (submitted) has analysed the discharge in the Nordic countries. There, the trends found in the Icelandic discharge are put into a Nordic perspective, while here the trends seen in three variables are compared and discussed.

Long time series of sea level pressure in Iceland, from 1820–2002, show no significant overall trends (Hanna *et al.* 2004). However, Jónsson and Miles (2001) show that, in recent decades, the low pressure period, that usually ends around mid-February, has extended into March. This lengthening of the low-pressure season can be linked to the contribution of the Icelandic Low to the positive trend in the North Atlantic Ocean index since the 1960s (Jónsson and Miles 2001).

Hanna *et al.* (2004) reveal that, according to most station records, the temperature in Iceland has been increasing in all seasons during the period 1871–2001. However, there has not been a simple linear trend towards higher temperatures through the whole series. Records show that the temperatures increased most rapidly during the 1920s, especially during the spring. The years 1965–1983 show a cooling, while during the years 1984–2004 the mean temperature has been increasing again, especially after 1995 (Hanna *et al.* 2004).

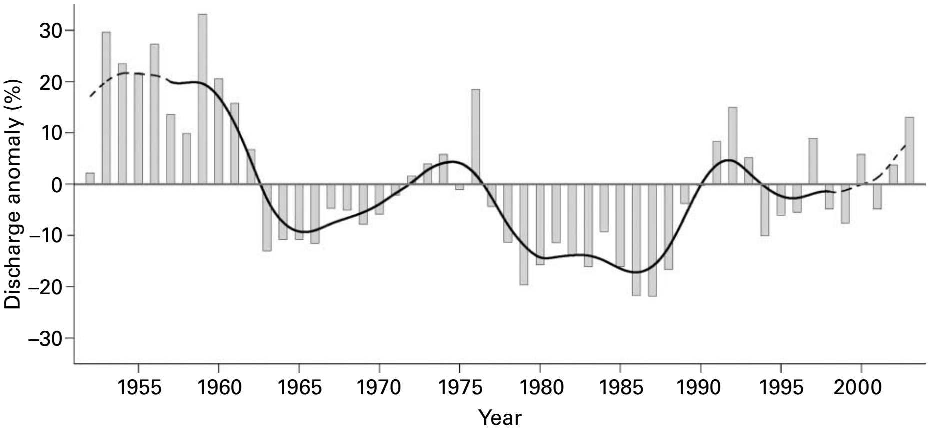

Figure 1 Annual deviations from mean discharge at Hvítá, Kljáfoss. Columns show annual values while the line represents Gauss filtered values ($\sigma^2 = 3$)

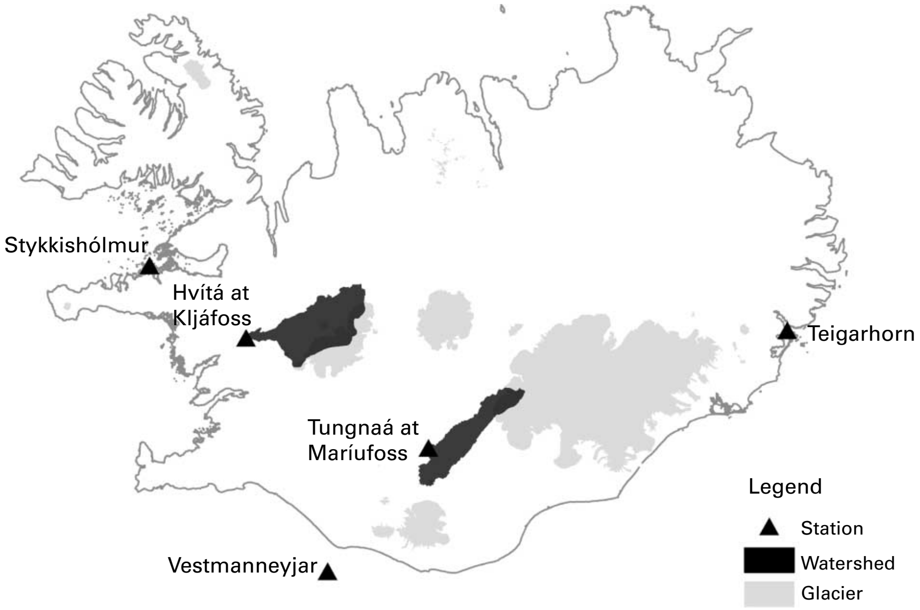

Figure 2 Location of places mentioned in the paper

Hanna *et al.* (2004) analyzed the longest precipitation records in Iceland, 1881–2002. Those records are from Stykkishólmur, Vestmannaeyjar and Teigarhorn (Figure 2). The annual series show a positive trend in precipitation over the period 1881–2002, but only in Vestmannaeyjar the record has a statistically significant annual trend, accompanied by a significant trend in the spring and summer.

The objective of this study is to identify trends and show the relations between trends seen in the three variables – precipitation, temperature and discharge – for identification of whether discharge has changed and why. The length of time series as well as the period analysed influences the results of a trend study: therefore, in this study, common periods were selected for all three variables and both seasonal and annual trends were studied with a Mann–Kendall trend test.

Data

Series of monthly precipitation, temperature and discharge were analyzed and compared. In accordance with the study by Hisdal *et al.* (submitted), two periods were analyzed, 1941–2002, since the longest Icelandic discharge records reach 60 years back in time, and the period 1961–2000, to include a larger set of discharge records. Very few Icelandic discharge records extend more than 40 years back in time. Seasonal values of meteorological variables and discharge are according to the four season division: autumn, Sep–Nov (SON), winter, Dec–Feb (DJF), spring, March–May (MAM) and summer, June–Aug (JJA). For discharge, the spring season is defined as April–June (AMJ).

Precipitation

Monthly values of precipitation were collected from the database of the Icelandic Meteorological Office (IMO). The time series were tested for non-homogeneity with a standard non-homogeneity test (SNHT, Alexandersson 1986) for the time period 1941–2002 and 1961–2000 annual values. Only time series that appeared homogeneous during that time period were used in this study. Of the selected time series, 28 span the shorter period 1961–2000 while 12 series span the period 1941–2002. All time series have less than 10%

missing values that were replaced by the long-term average for the specific month. Figure 3 shows the location of the weather stations from which precipitation records were used. The location of the stations are all below 400 m a.s.l. and 22 of the 28 stations are below 100 m a.s.l.: the stations away from the coast are on higher ground.

Temperature

Monthly values of temperature were extracted from the database of the IMO. The time series were tested for non-homogeneity with the SNHT and only used if they appeared homogeneous. The 18 time series selected have a good geographical coverage and they all, except for two, span both time periods. Figure 4 shows the location of the weather stations from which temperature records were used.

Discharge

Monthly discharge data series were obtained from the Hydrological Service of the National Energy Authority in Iceland. The stations were selected according to the length of their time series and excluded if they did not fulfil SNHT homogeneity conditions. Ten time series were selected spanning the period 1961–2000. Two time series available during 1941–2002 were not tested with the SNHT due to lack of series for comparison. Four records had some missing monthly values; they were replaced by watershed model results (Halldórsdóttir and Gröndal 2001; Vatnaskil 2001, 2002).

For the analysis of floods, a spring flood is defined as the maximum daily discharge between March 1 and July 16, and an autumn flood is defined as the maximum daily discharge between July 17 and November 30. Figure 5 shows the location of the discharge stations from which records were used.

Methods

SNHT

A standard normal homogeneity test – SNHT (Alexandersson 1986) – was used to test the homogeneity of precipitation, temperature and discharge series, annual values, for the periods 1961–2000 and 1941–2002. The test is purely statistical. It is based on the assumption that the ratio between the time series of a precipitation/discharge station being tested and a time series from a neighbouring reference station is fairly constant in time and a break in one of the series will then be revealed if this ratio has a definite change. The details of the tests are described in Alexandersson (1986).

Mann–Kendall test

The Mann–Kendall (Salas 1993) nonparametric test was used to detect trends in the datasets. According to Zhang and Zwiers (2004), the trend test may, however, reject the null hypothesis of no trend more often than specified by the significance level, in the case of serially correlated data. Many of the discharge series appear to have a significant autocorrelation at the time lag of one year. Therefore, prior to applying the Mann–Kendall test, the discharge series were pre-whitened according to a procedure found in Appendix A of Wang and Swail (2001) as recommended by Zhang and Zwiers (2004). Furthermore the method of evaluating the trend line parameters described by Wang and Swail (2001) is used here.

Results and discussion

The results of the trend analysis are shown in Table 1 and Figures 3–6. The figures show trends significant at the 95% confidence level with large signs. Small signs show trends with low significance, 70% confidence level. These two significance levels are used to identify all series that imply possible trends, while only the series with large signs should be regarded as having

Table 1 Results from the trend study, number of significant trends and the range of the estimated change per decade

	Time period 1941–2002				Time period 1961–2000			
Variable	**Sign. negative trends**	**Sign. positive trend**	**Change per decade, i.e. range**	**Nr. of series**	**Sign. negative trends**	**Sign. positive trend**	**Change per decade, i.e. range**	**Nr. of series**
Precipitation–annual		5	4–5%	12		5	4–7%	28
DJF		3	4–7%	12		1	7–12%	28
MAM				12		1		28
JJA		3	4–5%	12	2		−9%	28
SON		2	4–7%	12		5	8–15%	28
Temperature–annual	3		−0.1°C	16		2	0.2–0.3°C	18
DJF				16				18
MAM	3		−0.1–0.2°C	16	1		−0.2°C	18
JJA	5		−0.1–0.2°C	16		10	0.2–0.6°C	18
SON				16		3	0.2–0.3°C	18
Discharge–annual		1	4%	2				10
DJF				2				10
MAM		1	6%	2				10
JJA		1	5%	2		2	6–7%	10
SON				2				10
Timing of spring flood				2		1	5 days	10
Timing of autumn flood				2	2		−8–15 days	10
Volume of spring flood		1	7%	2	1	1	−15%, 13%	10
Voluma of autumn	1		−9%	2				10

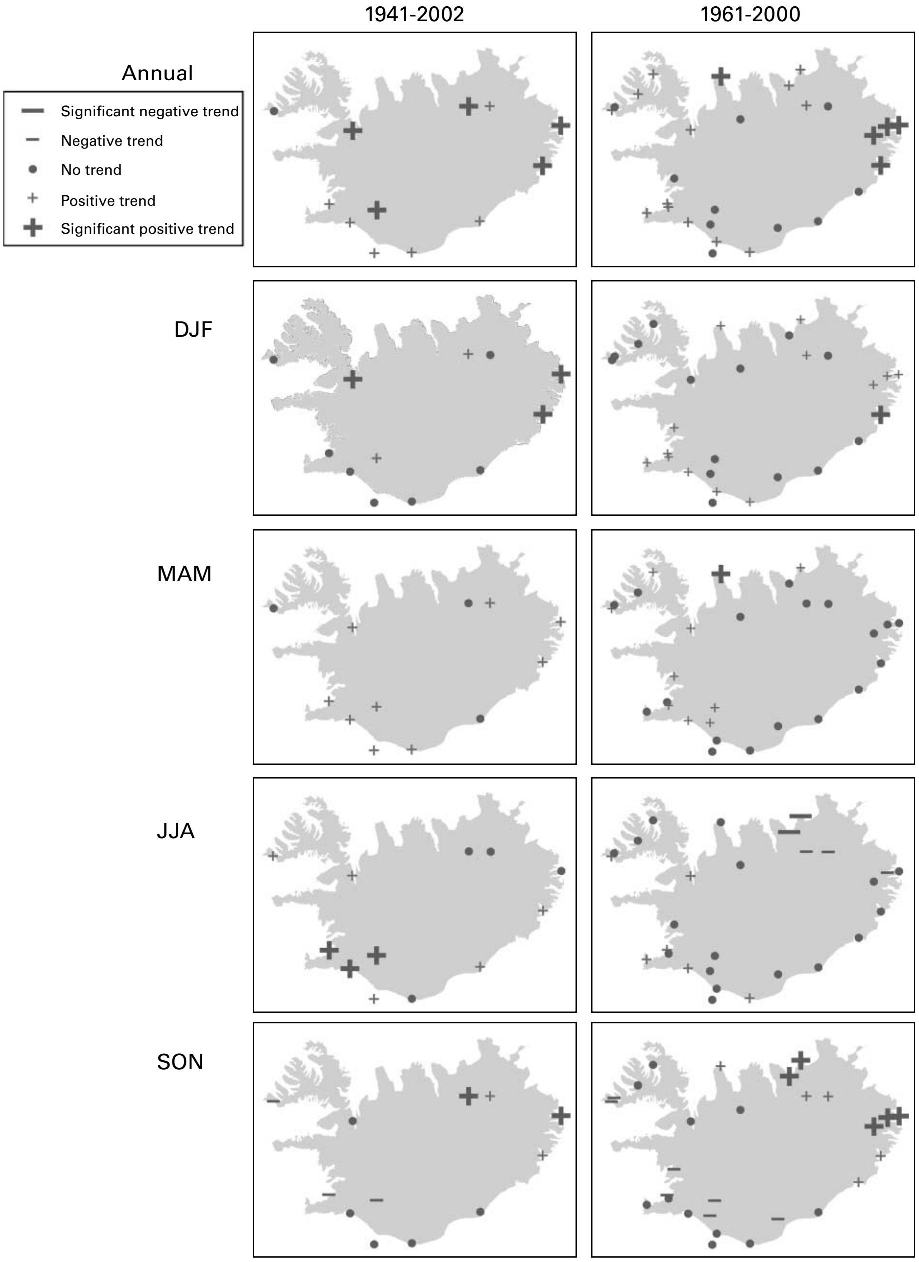

Figure 3 Trends in annual and seasonal precipitation

significant trends. A plus (+) denotes a station with a positive trend while a minus (−) denotes a station with a negative trend. Small grey dots show stations with no apparent trend.

Annual precipitation has increased during both periods. Trends in annual and seasonal precipitation are shown in Figure 3. The stations with a significant trend show a trend of 4–8% increase of precipitation per decade for the period 1941–2002 but a 4–15% increase per decade for the period 1961–2000. The winter (DJF) and autumn (SON) show stronger positive trends than the other seasons and the north-eastern part of the country shows

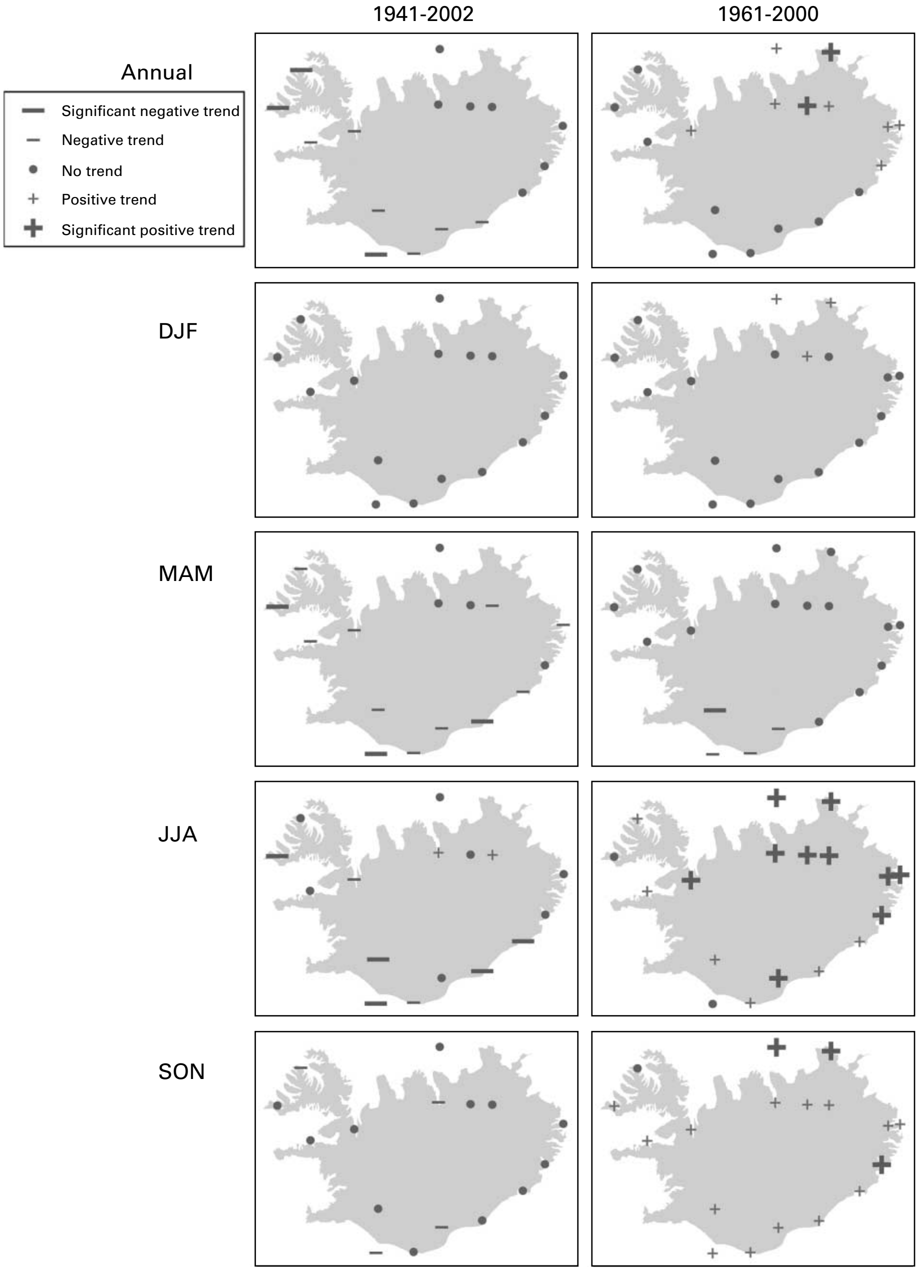

Figure 4 Trends in annual and seasonal temperature

stronger trends than other parts of the country. Significant negative trends appear only in the north-eastern part of the country for the 1961–2000 summer season (JJA).

Since decadal variations in temperature during the last century have been high, and the 1940s and 1950s were warm compared to the late 1960s and 1970s, trend analysis of these two periods 1941–2002 and 1961–2000 give quite different results (Figure 4). For the longer period 1940–2002 annual temperature has decreased while for the shorter period annual temperature has increased. The stations with a significant trend show a trend of 0.1–0.2°C decrease of temperature per decade for the period 1941–2002 but 0.2–0.6°C

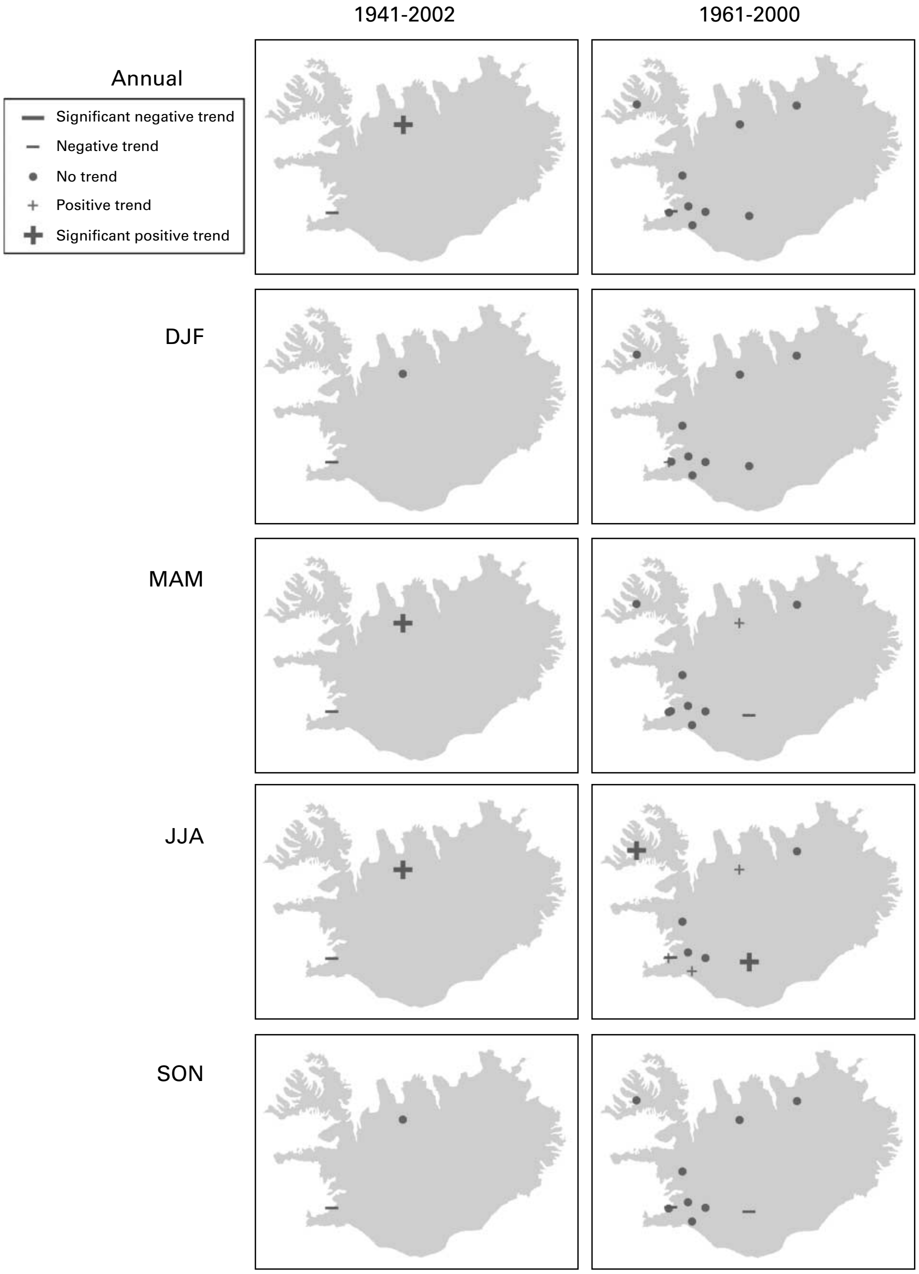

Figure 5 Trends in annual and seasonal discharge

increase per decade for the period 1961–2000. Spring (MAM) is the only season with a consistent negative trend in both periods, coinciding with the trend in the lengthening of the low pressure period discussed by Jónsson and Miles (2001). Summer and autumn account for most of the annual temperature increase during 1961–2000, the summer having particularly high increase in temperature, up to 0.6°C per decade, where series of other seasons do not reach higher than 0.3°C per decade.

Autocorrelation with a time lag of one year is significant in many of the Icelandic discharge series. Therefore, a pre-whitening procedure was performed on the discharge

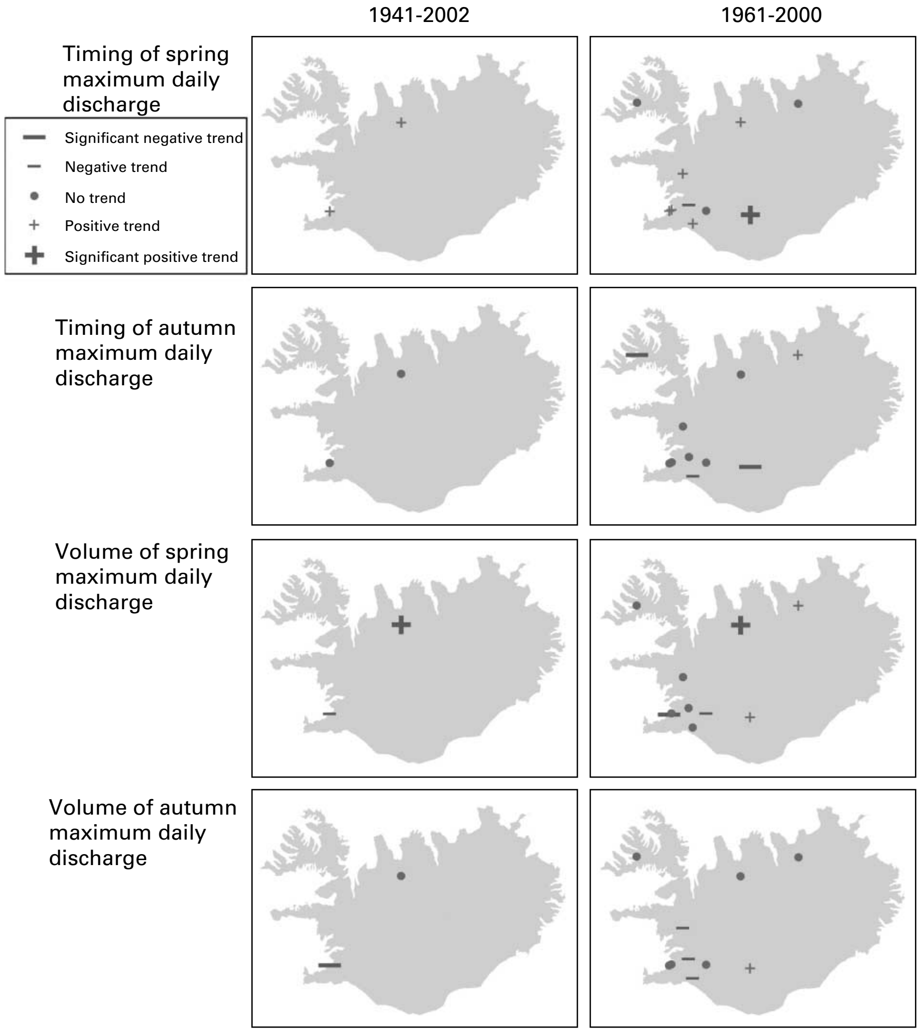

Figure 6 Trends in spring and autumn floods

series depending on its autocorrelation coefficient as discussed in the methods chapter. Using this method instead of applying the Mann–Kendall test to the original series reduced the number of series where a significant trend was identified.

Discharge series show almost no significant trends (Figure 5). The few stations that do, show a 4–6% change per decade for the period 1941–2002 and a 6–7% change per decade for the period 1961–2000. Only two series are available during the longer period, and they show opposite trends in all seasons. For the period 1961–2000 trends in the summer season (JJA) are most clear; for the summer season two stations have significantly increased runoff. The reason for the increased summer runoff can be attributed to cooler spring temperatures (Figure 4). The snow melt in watersheds at high elevations appears to become increasingly delayed from the spring to the summer.

The effect of this cooling in the spring also appears in the trend analysis of timing and volume of spring floods (Figure 6). The timing of spring flood is delayed 5 days per decade for some stations. The volume of spring maximum daily discharge has also increased in some of the series in relation to the delay of the spring flood. No clear trends appear in the autumn floods (Figure 6) except for two watersheds where the melt of the snow pack and glacier extends into the period of autumn floods. River Tungnaá at Maríufoss (Figure 2) is one of those rivers. The delay of spring flood is shown in Figure 7 as well as the increasing tendency towards late snow melt floods to be higher than late autumn floods caused by autumn precipitation.

The trend in precipitation is strongest in the northern and eastern part of the country during autumn and winter. In these parts of the country much of the precipitation falls as snow during autumn and winter and, as explained by Haraldsdóttir *et al.* (2001), precipitation is generally underestimated by precipitation gauges in wind and for temperature below 0°C. Positive precipitation trend during 1961–2000 may, therefore, to some extent be attributed to the positive temperature trend during the same period and, therefore, presumably a higher ratio of rain to snow, and a better catch of precipitation at the stations. Wind shields on precipitation gauges reduces the underestimation of precipitation but wind shield installation occurred on most gauges during the period 1950–1960 (Jónsson 2003) and may, therefore, explain some of the trends seen in precipitation during 1941–2002. These two explanations for positive precipitation trends along with the lack of corresponding increase in annual discharge implies that the trend may not be found in actual precipitation but only measured precipitation.

Annual temperature has increased in Iceland in the period 1961–2000, similarly as in the other Nordic countries (Kuusisto 2004) while spring is the only season with a consistent negative trend in both periods, coinciding with the trend in lengthening of the wintertime low pressure period discussed by Jónsson and Miles (2001). The increased annual temperature has not lead to significantly increased discharge in the rivers investigated. If, however, rivers with large glacial components would have been included, the results would probably have been different as increased temperature enhances melting. The cooling of spring temperatures, however, have led to delayed spring floods and increased volume of maximum daily discharge. Possibly both because the snow accumulation period extends longer into the year and because of a greater chance of a sudden warming when the spring is delayed and, therefore, faster melting of the snow pack. These results are different from results in the other Nordic countries; there spring floods occur earlier than before (Hisdal submitted). This difference in results may be connected to the upward trend in the North Atlantic Oscillation in recent years and its opposite correlations to temperature in Iceland to temperature in Northern Europe (Hurrell *et al.* 2003).

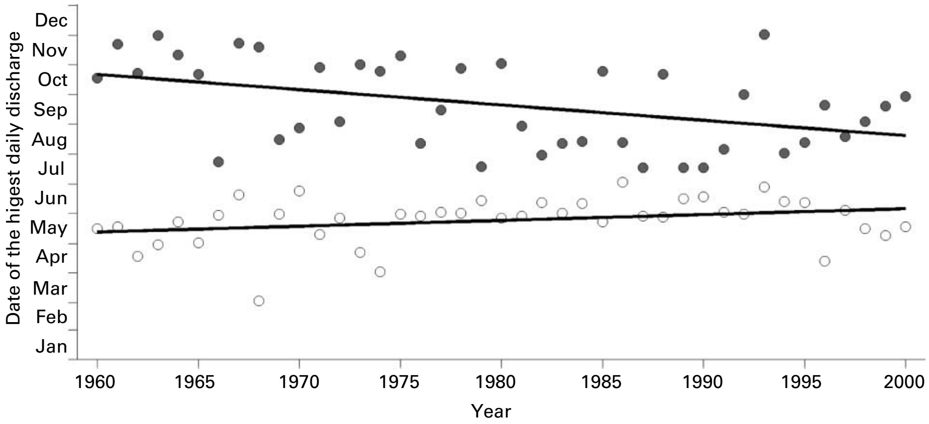

Figure 7 Time of spring and autumn maximum daily discharge at V96, Tungnaá, Maríufoss

These results agree with earlier trend studies for somewhat different time periods, Hanna *et al.* (2004) found a positive trend in annual precipitation and temperature and Hisdal *et al.* (1995) found no trends in annual discharge.

Summary and conclusions

The Mann–Kendall test was used to investigate trends in the precipitation, temperature and rivers discharge for the periods 1941–2002 and 1961–2000, both annually and seasonally. A significant increase was observed in annual precipitation and especially autumn and winter precipitation for both periods while temperature trends for the two periods do not agree because of large decadal variations. Still both periods show cooling of the spring season and the shorter period shows warming during the summer and autumn season. Discharge series do generally not reflect the trends seen in the precipitation series. Only summer discharge has increased during 1961–2000, probably caused by cooling spring season and delay of snow melt into the summer season. The analysis of spring floods also reflect the cooling of the spring season where spring floods are delayed in most of the watersheds and their volume tends to increase.

The main conclusions from the study are that, despite significant increase in measured precipitation, discharge in non-glacial rivers has not increased. Meanwhile, spring temperatures have a negative trend and spring floods, therefore, occur later than before and they are larger.

Acknowledgements

This analysis was made within the framework of the Nordic Climate and Energy project (CE) and the Icelandic national project Climate and Energy (VO). The CE project is funded by the Nordic Energy Research and the Nordic energy sector. The VO project is funded by the Icelandic National Energy Fund, the National Power Company, The National Energy Authority and the Hydrological Service. Information on these projects can be found at their websites: http://www.os.is/ce and http://www.os.is/vvo. Cintia B. Uvo thanks the Swedish Research Council and the Swedish International Development Cooperation Agency – SIDA for financing.

References

Alexandersson, H. (1986). A homogeneity test applied to precipitation data. *J. Climatol.*, **6**(6), 661–675.

Beldring, S., Andréasson, J., Bergström, S., Jónsdóttir, J.F., Rogozova, S., Rosberg, J., Suomalainen, M., Tonning, T., Vehviläinen, B. and Veijalainen, N. (2006). *Mapping Water Resources in the Nordic Region Under a Changing Climate*. Climate and Energy report CE-3.

Einarsson, M.A. (1984). Climate of Iceland. In in H. van Loon (Ed.), *World Survey of Climatology* vol 15 *Climates of the Oceans*, Elsevier, Amsterdam, 673–697.

Eyþórsson, J. and Sigtryggsson, H. (1971). In in E. Bertelsen, *et al.* (eds), *The Climate and Weather of Iceland (precipitation map by Adda Bára Sigfúsdóttir). The Zoology of Iceland*, Munksgaard, Copenhagen.

Halldórsdóttir, S.G. and Gröndal, G.O. (2001). *Vatnafar á Glámu. 1. Rennslislíkön*. National Energy Autority report OS-2001/007.

Hanna, E., Jónsson, T. and Box, J.E. (2004). An analysis of Icelandic climate since the nineteenth century. *Int. J. Climatol.*, **24**(10), 1193–1210.

Haraldsdóttir, S.H., Ólafsson, H., Durand, Y., Mérindol, L. and Giraud, G. (2001). SAFRAN-Crocus snow simulations in an unstable and windy climate. *Ann. Glaciol.*, **32**, 339–344.

Hisdal, H., Holmqvist, E., Jónsdóttir, J.F., Jónsson, P., Kuusisto, E., Lindström, G. and Roald, L.A. (submitted). Has streamflow changed in the Nordic countries? *Climate Res.*

Hisdal, H., *et al.* (1995). *Historical Runoff Variations in the Nordic Countries*, NHP, OsloNHP report 37.

Hurrell, J.W., Kushnir, Y., Ottersen, G. and Visbeck, M. (2003). An overview of the North Atlantic Oscillation. In in J.W. Hurrell, Y. Kushnir, G. Ottersen and M. Visbeck (Eds.), *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, American Geophysical Union, Washington, DC, 1–35.

Jónsson, T. (2003). *Langtímasveiflur II - Úrkoma og úrkomutíðni*, Icelandic Meteorological Office, ReykjavíkInternal Report VÍ-ÚR10.

Jónsson, T. and Miles, M.W. (2001). Anomalies in the seasonal cycle of sea level pressure in Iceland and the North Atlantic Oscillation. *Geophys. Res. Lett.*, **28**(22), 4231–4234.

Kuusisto, E. (2004). *Climate, water and energy: a summary of a joint Nordic project 2002-2003*, Climate, Water and Energy, CWE-4, Reykjavík.

Pálsson, O. and Jónasson, T. (2005). *Energy Statistics in Iceland*, Orkustofnun, Reykjavík.

Salas, J.D. (1993). Analysis and modeling of hydrologic time series. In in D.R. Maidment (Ed.), *Handbook of Hydrology*, McGraw-Hill, New York, chapter 19.

Serreze, M.C., Carse, F. and Barry, R.G. (1997). Icelandic low cyclone activity: climatological features, linkages with the NAO, and relationships with recent changes in the northern hemisphere circulation. *J. Climate*, **10**, 453–464.

Verkfræðistofan Vatnaskil (2001). *Skjálfandafljót. Rennslislíkan*. National Energy Authority report OS-2001/029 (in Icelandic).

Verkfræðistofan Vatnaskil (2002). *Þjórsár-Tungnaársvæði. Rennslislíkan*. Vatnaskil Consulting Engineers report 00.01 (in Icelandic).

Wang, X.L.L. and Swail, V.R. (2001). Changes of extreme wave heights in Northern Hemisphere oceans and related atmospheric circulation regimes. *J. Clim.*, **14**(10), 2204–2221.

Zhang, X.B. and Zwiers, F.W. (2004). Comment on "Applicability of prewhitening to eliminate the influence of serial correlation on the Mann-Kendall test" by Sheng Yue and Chun Yuan Wang. *Wat. Res. Res.*, **40**(3), W03805.