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HYDROLOGICAL VARIABILITY AND GENERAL CIRCULATION OF THE ATMOSPHERE

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ABSTRACT

Observed long term variability in Icelandic time series of riverflow is quite regular and significant. Its relation to variation in time series of climatic variables is very important, since it can give indications of the possible effects of proposed climatic changes due to increased concentration of CO_2 and other gases in the atmosphere.

Standard meteorological variables, such as temperature and precipitation, are often not very suitable variables for studies of such relations, since they are point measurements, that often depend on e.g. topography. Furthermore, they are difficult to predict from general circulation models.

In this paper an attempt is made to relate hydrological variables to meteorological variables derived from the height of the 500 mb pressure level above Iceland. This approach might overcome the problems discussed above, and could also take advantage of the fact that these variables are more easily predicted by general circulation models.

1. INTRODUCTION

Climatic variability and climatic change is one of the main themes of scientific inquiry at present. Due to anthropogenic changes of the environment, climate is expected to change with global consequences. International agencies have organized global effort in the area of science and technology with great emphasis on meteorology, climatology and hydrology.

The past was held to be the key to the future, but in the face of the prospect of dramatic changes in nature, this might not be as true as before. Nevertheless, the variability of natural phenomena as manifested in historical data, might still give valuable clues. Studying the phenomenological aspects of natural processes hopefully gives us a deeper insight into the changes that the future will bring about.

The first part of the paper gives an overview of the general circulation of the atmosphere and its relation to climatic variability and change, based mostly on the works by Lamb (1966, 1972, 1977), Willett and Sanders (1959) and Rudloff (1967). Next, the focus is on a long term variation of the hydrological processes, as manifested in the discharge of three Icelandic rivers. Finally, the relationship between variations in runoff and time series based on the height of the 500 mb pressure level above Iceland is studied as well as the relation between runoff and wind strength, direction and air temperature, measured at ground levels.

2. *GENERAL CIRCULATION OF THE ATMOSPHERE*

The incoming radiation from the sun is highly variable, depending upon latitude. The outgoing radiation from the Earth is also quite variable, depending upon e.g. the surface albedo. This together causes considerable temperature difference between the equator and the polar areas amounting to tens of centigrades for static atmosphere and ocean. This temperature gradient is the *primus motor* of the general circulation of both the atmosphere and the oceans. The rotation of the Earth as well as its topography modulates these global hydrodynamical systems.

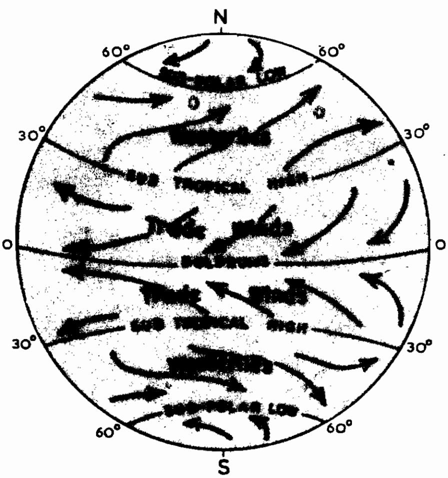


Fig. 1. General distribution of sea level pressure and wind zones over the world. (From: H.H. Lamb (1972).)

The prevailing surface wind systems of the Earth are shown in a simplified form in Fig. 1. The air mass at the equator rises, with mostly light and variable winds. This region is called the doldrums. On either side of it are the trade-wind regions, which are the easterlies, persistent but not very strong. On either side of the trade-winds are the sub-tropical low-pressure areas but between the 30-60 degrees latitude are the westerlies, which are strong, but variable. In the polar regions are the polar easterlies, but in the zone between the moist, warm tropical air and the dry, cold polar airmasses are the sub-polar low pressure areas and the main polar front. The polar fronts themselves are unstable and often move in waves which can develop into low pressure systems or frontal cyclones.

The height of the 500 mb pressure level reveals the pressure gradients and wind systems in the troposphere. It lies at the height of 5-6 km, which is around the middle of the troposphere. On contour maps of the *average* 500 mb pressure level, the main structures of the weather systems can be seen on a global scale. Depending on the time interval averaged over, various structures can be observed, reflecting anything from instantaneous weather patterns to long term climatic patterns.

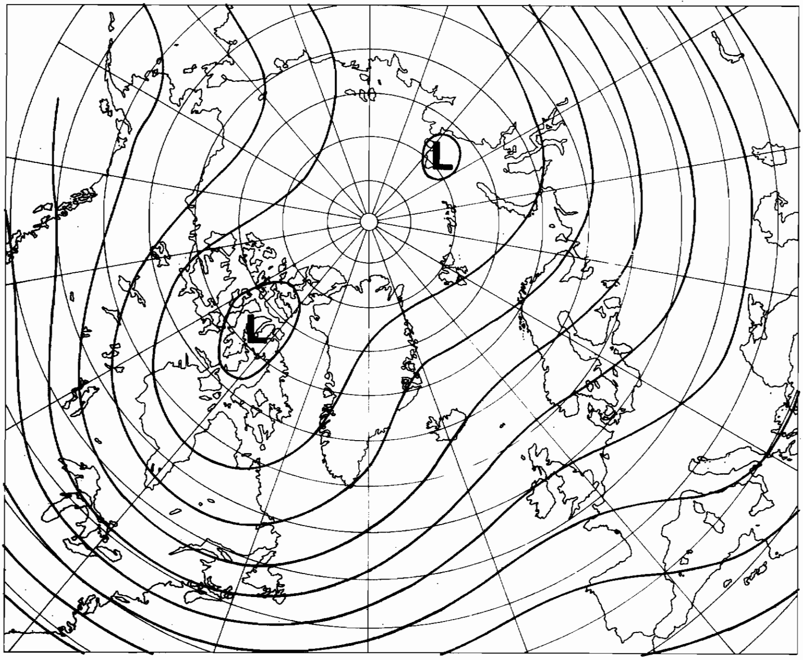


Fig. 2. Average height of the 500 mb pressure level for January over the Northern hemisphere for the period 1949-1973. (From: Deutscher Wetterdienst.)

A contour map of the 500 mb pressure level over the Northern hemisphere, for the month of January, averaged over the years 1949-1973, is shown in Fig. 2. The contours and the gradient of the 500 mb pressure level have nearly the same significance as isobars and pressure gradients, at the 5-6 km level. The wind tends to blow along the contours, counter-clockwise around the low pressure regions on the Northern hemisphere and vice versa on the Southern hemisphere. The wind strength is inversely proportional to the spacing of the countour lines. The course of the upper westerly winds or polar vortex is, therefore, counterclockwise around the polar region with the strongest wind off the East coasts of the continents due to elongations of the polar trought. This causes the long term upperly wind direction over Iceland and Scandinavia to be south-westerly.

Changes in weather and climate are reflected in changes of the general circulation of the atmosphere. For the circumpolar vortex of upper westerly winds, these changes can be classified into several categories as follows:

1. Changes in the strength of the circulation.
2. Changes in the latitude of the main flow.
3. Changes in the wavelength of the main flow; it moves in so-called Rossby waves.
4. Changes in the amplitude of the Rossby waves, often disrupting the vortex and thereby causing *blocking* situation.
5. Changes in the position of the center of the vortex or even formation of multi-centered vortices.

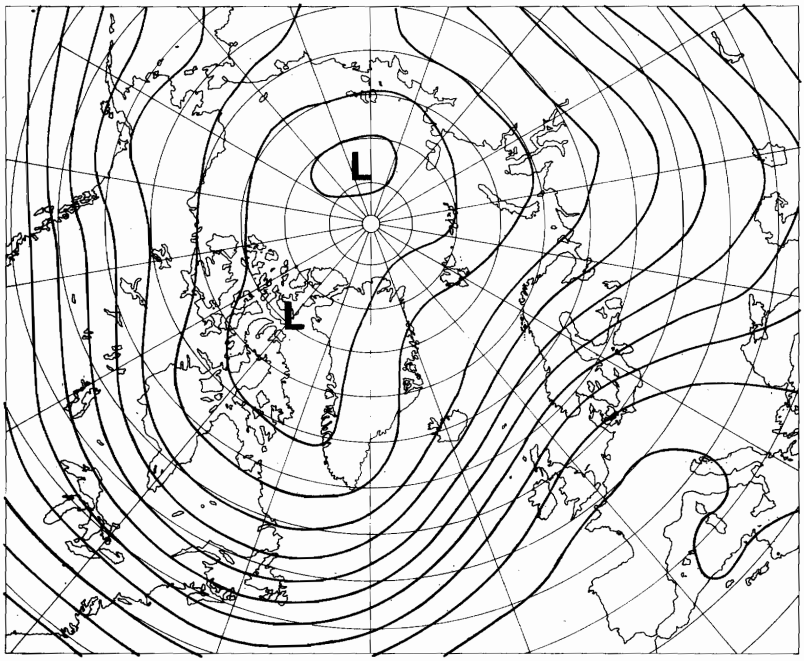


Fig. 3a. Average height of the 500 mb pressure level for January 1989. An example of strong circulation. (From: Deutcher Wetterdienst.)

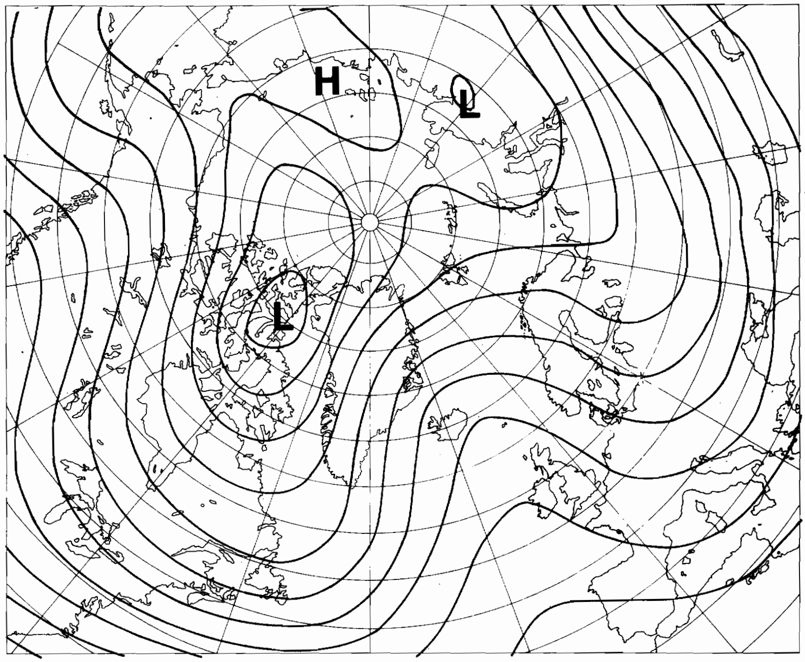


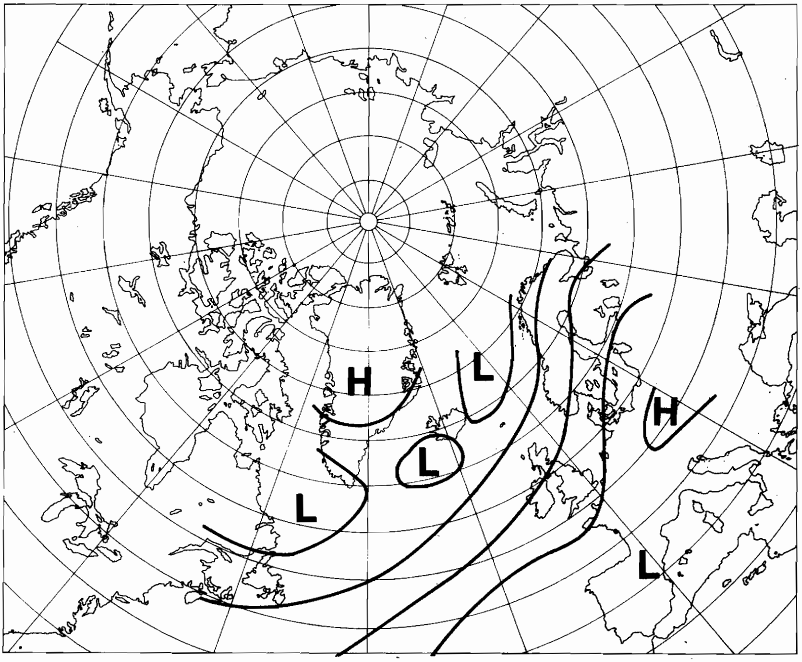
Fig. 3b. Average height of the 500 mb pressure level for January 1987. An example of weak circulation. (From: Deutscher Wetterdienst.)

The next figure shows two examples of contour maps of the average height of the 500 mb pressure level. The first one, Fig. 3a, shows a strong circulation during the month of January 1989, the second one, Fig 3b., shows a weak circulation during the month of January 1987. When these two patterns are compared, the main difference is in the strength of the circulation and in its wave forms. The strong circulation is characterized by regularity and symmetry, with the polar low extending to the West of Greenland. The trough is then symmetric over the pole to Siberia. A strong south-westerly wind is across the North-Atlantic over to the British Isles and Scandinavia.

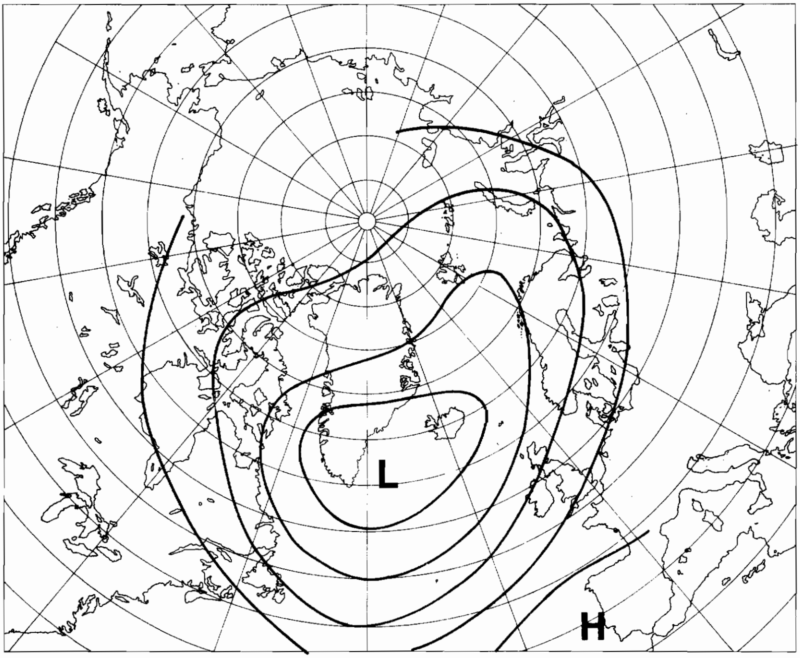
The weak circulation is characterized by an irregularity, a large amplitude of the Rossby waves and a high wave number. Three low-centres are prevailing with a high-pressure ridge in the North-Atlantic which restrains the westerlies, called blocking situation.

Changes in the circumpolar vortex are always taking place. Often, the system changes configuration from weak to strong in a few weeks. Furthermore, seasonal changes take place with considerably stronger circulation in the wintertime. Long term variations are also taking place and cause both climatic variations and climatic change, if a longer time horizon is considered.

In light of this, it is interesting to study the circulation pattern of the past. This has been done by the climatologist H.H. Lamb among others. He has, based on past measurement, reconstructed pressure maps back into the ages and maps of average sea level pressure have been published all the way back to 1750 (Lamb and Johnson 1966).



(a) For the period 1790-1829.



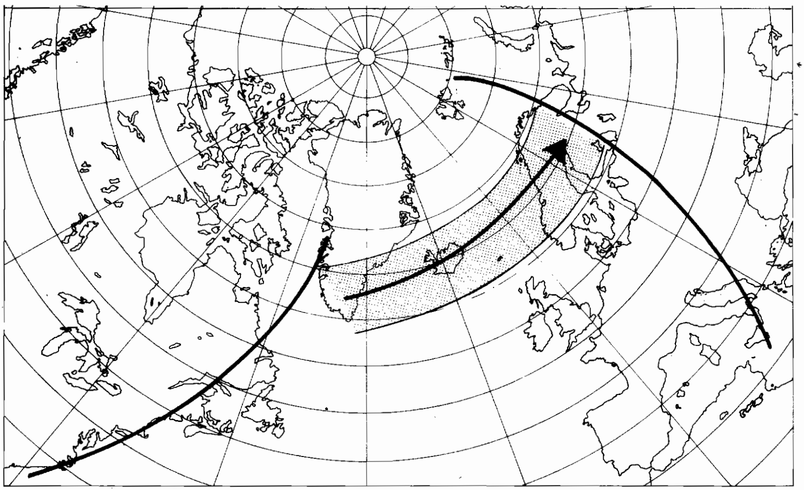
(b) For the period 1900-1939.

Fig. 4. Average mean sea level pressure in January. Isobars at 5 mb intervals. (From: Lamb (1977).)

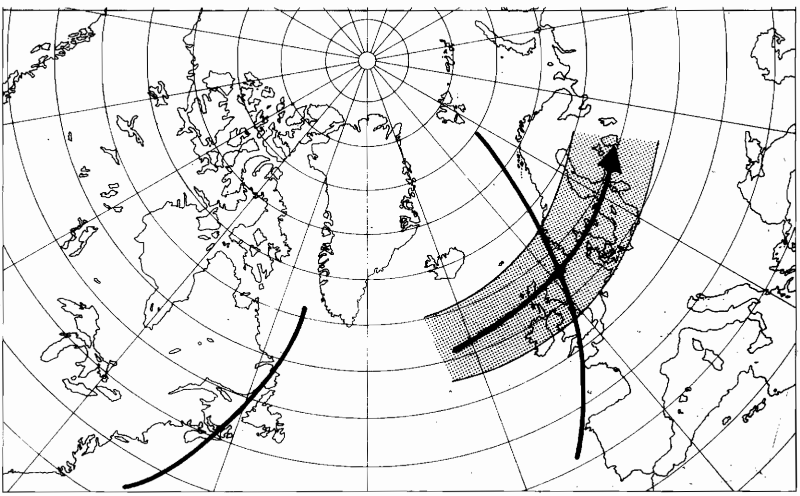
On Fig. 4., two of Lamb's maps are shown (Lamb 1977). One is the average sea level pressure of January for the period 1790-1829, but during that period, Western-Europe experienced cold weather. During the same period, sea ice was very extensive in Icelandic waters.

The other shows a comparable map for the extremely warm period of 1900-1939, again for Western-Europe. The fundamental difference in the two maps in the strength of the circulation, the weak one corresponding to the cold epoch and the strong one to the warm epoch.

Lamb goes even further in his attempt to reconstruct the past climate. On the basis of various data he reconstructs the path of the cyclones over the North-Atlantic, for some epochs of the middle Ages (Lamb 1977).



(a) Positions probably prevailing A.D. 1000-99.



(b) Positions probably prevailing A.D. 1550-99.

Fig. 5. Summer depression tracks and positions of throughs in the upper westerlies. (From Lamb (1977).)

On Fig. 5a., a probable most prevailing track of the cyclones is shown for the period 1000-1099 along with a likely position of the main troughs in the upper westerlies' circulation. The track is just North of Iceland and the westerlies have a strong southerly component due to the position of the trough South-West of Greenland. This caused a warm epoch in Western-Europe during the settlement of Iceland.

On Fig 5b., a similar map is shown for the period 1550-1599. The track is now South of Iceland and the westerlies are directly from the West. This caused a cold epoch in Western-Europe, often called the Little Ice age.

3. HYDROLOGICAL VARIABILITY

A long term variability in hydrological processes like runoff has a considerable bearing upon both climatic variability and upon the variability of the hydrological systems themselves. In many of the largest drainage areas in Iceland this system related variability is of prime importance. What distinquishes these watersheds from typical drainage areas are mainly two hydrological (geophysical) phenomena; first, watersheds with large, but responsive (i.e. high transmissivity) groundwater systems contributing an essential portion of the runoff; secondly, watersheds with glaciated areas contributing an essential portion of the runoff by meltwater drainage. A third type of watersheds are those with large groundwater systems fed directly by glacial meltwater. All these phenomena impose an additional variability on the hydrological system with other characteristics than in the more common cases.

A large ground water system accumulates deviations from mean values, so in addition to filtering out a short time variability, it might aggravate long term deviations caused by e.g. climatic variability. Similarly, the glaciers will generate their own variability in runoff through their mass balance changes, which are forced by climatic variations.

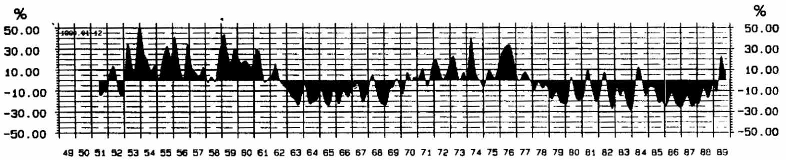


Fig. 6. Hvítá; Kljáfoss, West-Iceland. Deviation from mean discharge (smoothed).

The examples chosen to demonstrate a long term variability of hydrological processes are discharge series of three Icelandic rivers. The deviation from the mean discharge of the river Hvítá (West Iceland) is shown in Fig. 6. The drainage area is 1686 km^2 with 365 km^2 covered by glaciers. The drainage area is covered to a large extent with post-glacial lavas. The main characteristics of the river flow are the high base flow component and the regular variations with time. In the beginning of the measured series, there are a few dry years. Around 1952 a transition to a higher runoff is observed which continues for the next 8-9 years. Around 1961 a period with less runoff sets in, which culminates with both cold and dry years from 1965-1967. Extensive sea-ice was prevailing around Iceland during this period, reaching its peak during 1968, when a good part of the Icelandic coast was blocked by ice well into the month of June. Around 1969 the runoff increases again with wet but cold years, culminating in a very high runoff during 1976, which was both wet and warm. Around 1978 years again turn colder and drier. This period ends in 1988 with warmer and wetter years. This period was broken by both a warm and wet year in 1984.

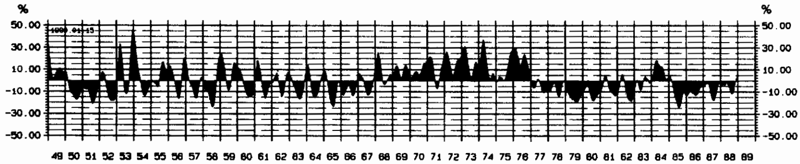


Fig. 7. Brúará; Dynjandi, South-Iceland. Deviation from mean discharge (smoothed).

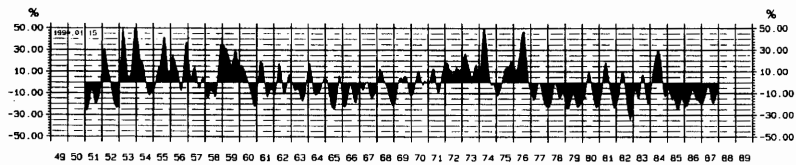


Fig. 8. Ölfusá; Selfoss, South-Iceland. Deviation from mean discharge (smoothed).

In Fig. 7., and Fig. 8., examples of the rivers Brúará and Ölfusá, (South Iceland), are shown. The drainage area of Brúará is about 670 km^2, largely covered by postglacial lavaflows. The drainage area of Ölfusá is about 6100 km^2 of which 690 km^2 are covered with glaciers. The drainage basin is rather complex, nevertheless, considerable areas are covered with postglacial lavas. The main characteristics of the riverflow are quite similar to that of Hvítá.

4. GENERAL CIRCULATION AND RUNOFF

The relationship between the meteorological and hydrological spheres is the focal point of a large part of hydrological research. This relationship depends greatly upon the scales of space and time governing the hydrological system under study. For small scales, traditional measurements of precipitation and temperature are often sufficient for adequate modelling of the system, but when scales get larger the discrete character of the meteorological measurements becomes more apparent as well as the inhomogeneity of the hydrological characteristics. Larger scales, therefore, call for distributed modelling which again calls for generation of distributed meteorological information. For regional scale, with sparse information, transformation of point measurements into distributed variables will often become inaccurate, since it relies upon adequate definiton of the three dimensional character of the meteorological variables as well as their development with time.

Remote sensing of both the meteorological and the hydrological systems is a promising way of investigating these problems. It is also interesting to investigate the possibilities of using a different type of meteorological measurements having now in mind our knowledge of the general circulation of the atmosphere.

The character of the upper atmosphere circulation above Iceland has been studied by Jónsson (1990a, 1990b). Time series of the strength of the upper westerlies in the troposphere around Iceland have been calculated, based on countour maps of the average monthly elevation of the 500 mb pressure level, as well as maps of the average thickness of the airmass between the 1000 mb and 500 mb pressure levels.

In an attempt to investigate the relation of the atmospheric circulation and runoff, time series of the strength of the westerly and southerly component of the average wind vector in the 500 mb pressure level were used. The time series were correlated with the discharge of river Hvítá (West-Iceland), showing a quite significant correlation for the southerly component, but less so for the westerly component.

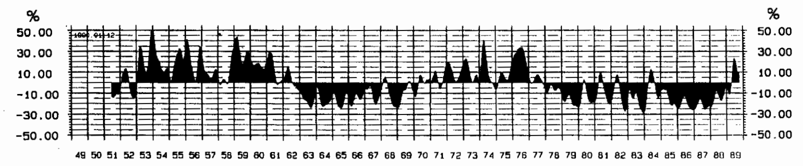


Fig. 9a. Hvítá; Kljáfoss, West-Iceland. Deviation from mean discharge (smoothed).

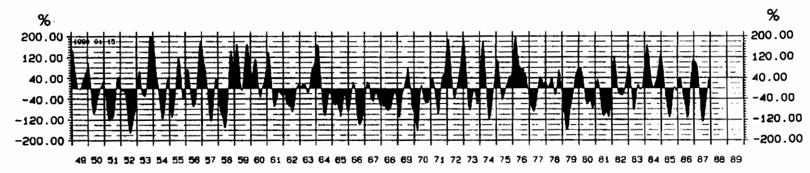


Fig. 9b. Southerly wind component at the 500 mb pressure level. Deviation from mean value (smoothed).

By comparing the two series, shown on Fig. 9a. and Fig. 9b. the relationship is visually observable. Periods of strong southerly winds are related to periods of high runoff. The same is true for periods of weak southerly winds or rather strong northerly wind which coincide with periods of low runoff. Individual years stand out, e.g. 1950-1951 which were very dry in the Southern part of Iceland. The years of 1953, 1959, 1976 and 1984 were all warm and wet, with corresponding increase in runoff. The year 1964 is rather peculiar due to its clear deviation from the pattern. The explanation of this is that the winter of 1963-64 was exceptionally warm due to persistent southerly winds resulting in very low winter accumulation. The summer of 1964 was, however, rather cold, expecially away from the coast. This resulted in abnormally little glacial melting during that summer.

An experiment was also done with measurements of wind strength, wind direction and air temperature, at the Reykjavík airport. These measurements are carried out every three hours. For each observation the wind strength and temperature was multiplied together, given that the temperature was higher than 0°C, and the wind strength more than 10 knots, otherwise the value was set equal to zero. Two series of daily values were then created, one was the sum of the eight daily numbers found above, where the wind direction was in the interval 90°-270°, i.e. from the South. The other one was found in the same way, but for wind direction in the interval 270°-90°, or from the North. The objective here was to find an indication of the advection of warmth by excluding cold air, as well as winds due to e.g. diurnal variation, thereby constructing series which were likely to have significant relations with runoff. The correlation of the southerly advection with the discharge of Hvítá river was significant.

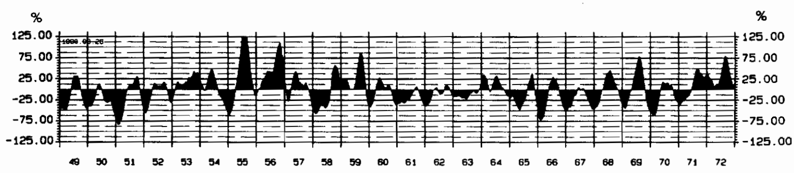


Fig. 10a. Southerly warm advection in Reykjavík. Deviation from mean value (smoothed).

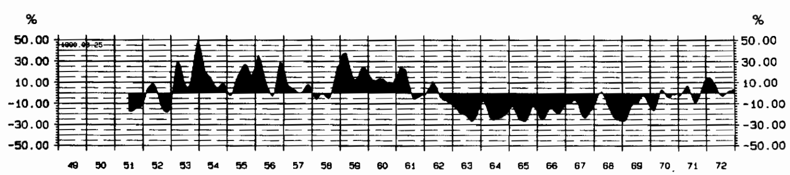


Fig. 10b. Hvítá; Kljáfoss, West-Iceland. Deviation from mean discharge (smoothed).

As shown on Fig. 10a. and Fig. 10b. this relationship is quite similar to the one discussed before.

5. CONCLUSIONS

Long term variability of discharge of a few Icelandic rivers was studied and its relation with general circulation of the atmosphere above Iceland was investigated. Significant relationships were found, and it is hoped that further study will be of aid in improving our understanding of the relationship between the meteorological and hydrological spheres. Concrete results in the form of better tools and models are certainly needed.

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