

## Temperature time series from Icelandic coastal stations

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### ABSTRACT

As a response to growing mariculture in Iceland during the 1980s, the Marine Research Institute initiated a project in 1986 for monitoring the sea temperature at selected locations along the coast. The longest of these records, from seven stations along the west, north and east coast of Iceland, are discussed for the period 1987-1996. The time series contain several gaps, mainly due to battery failure, causing problems in the analysis. The mean for each calendar month at each location was calculated, as well as the deviations of the monthly mean temperature. The years 1987, the latter part of 1990, 1991, 1994 and 1996 were relatively warm, while the remainder of the period was relatively cold. The longer term variations seem to be coherent at all sites. The data can be used for evaluating the temperature conditions at a potential mariculture location and there is probably sufficient data material available for a first evaluation of sites anywhere in Iceland. However, more accurate evaluation would require further measurements at each proposed site. It is therefore suggested that the project should now focus on long term monitoring of the marine climate.

*Keywords: Iceland, temperature, coastal, time series, aquaculture, climate.*

### INTRODUCTION

The temperature along the coast of Iceland will be discussed here and it is therefore appropriate to begin with a short description of the water masses and currents that influence the sea around Iceland. Iceland lies on the intersection between the Mid-Atlantic Ridge and the Greenland-Scotland Ridge. These ridges have profound influence on the waters around Iceland. Not only do they prevent the exchange of water below the thresholds but they also direct the major currents. A schematic view of the surface circu-

lation is shown in Figure 1 together with the location of the sites discussed. From the south, warm and saline Atlantic Water flows towards Iceland with the North Atlantic Current and at the south and west coasts this water mass dominates. West of the Reykjanes Ridge the Irminger Current carries Atlantic Water along the west coast. A small and variable part of this water flows towards the North Icelandic shelf, continues eastward off the north coast and on its way along the shelf gradually loses its characteristics. Along the shelf and slope off Greenland,

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*Dedicated to Professor Umsteinn Stefánsson in honour of his contributions to oceanography and education.*

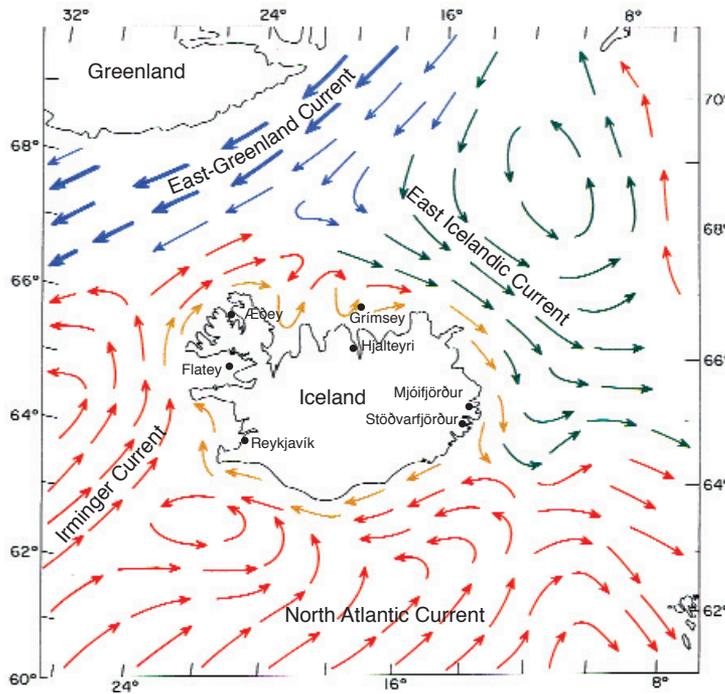


Figure 1. A map showing schematically the surface circulation in the ocean around Iceland. Red: relatively warm and saline Atlantic Water. Blue: Cold and low salinity Polar Water. Green: Arctic Water. Yellow: Icelandic Coastal Water. (From Stefánsson and Ólafsson 1991). The positions of temperature measurements for the present study are also shown.

cold, low salinity Polar Water originating from the Arctic Ocean is carried by the East Greenland Current towards the Denmark Strait. Part of this water enters the Iceland Sea, where it is mixed with Atlantic Water and through cooling of this mixture an arctic water mass is created that subsequently flows within the East Icelandic Current along the continental slope north and east of Iceland and then along the northern flank of the Iceland Faroe Ridge. The amount of Polar Water that is advected to the North Icelandic shelf area is variable and greatly affects the temperature conditions in the area. The east coast is mainly affected by the relatively cold waters of the East Icelandic Current. Along the coast, freshwater runoff creates a coastal water mass, especially during spring and summer, that circulates in a clockwise manner around the country.

The tides around Iceland vary from place to place. The highest tidal elevations occur on the west coast and in shallow areas there can be strong currents. Along the north and east coast the tidal elevations are small and the tidal currents on the North Icelandic shelf are weak. Off the east coast however the tidal currents are quite strong, especially off the southern part (Stefánsson 1981).

One of the first things Unnsteinn Stefánsson did, when starting oceanographic research in Iceland, was to install continuously recording thermometers in cargo ships sailing regular routes along the coasts of Iceland. This sampling started in 1949 and continued until 1966 (Stefánsson 1969). He realized that the long term monitoring of oceanographic conditions was important, not only as an indicator of climate change but also from an ecological point of view (Stefánsson 1970).

This was the first attempt to continuously monitor environmental parameters of Icelandic waters. In 1960 and 1961 weekly measurements of temperature and salinity of the surface layer were initiated by Unnsteinn Stefánsson at four stations on the coast (*i.e.* Reykjavík, Látrar on the southern Vestfirðir peninsula, Grímsey north of Iceland and Vestmannaeyjar south of Iceland (Stefánsson 1970). These measurements were continued until 1969.

By comparing the growth in different areas around Iceland, it was shown by Jónsson (1969) that the growth of cod is greatly dependent on temperature. This has also been shown in laboratory studies (Björnsson 1997) and in general the growth of ectothermic marine organisms depends *i.a.* on the temperature. The temperature regime is therefore of crucial importance for the ecological system in the ocean. Consequently, the

temperature is important when evaluating a location for aquaculture. Furthermore, it is also of interest to know the probability of extreme temperatures, because too high temperature can increase the risk of disease (Björnsson 1997) and very low temperatures can increase fish mortality as was the case in February 1988 in fish farming in Hvalfjörður in southwestern Iceland (Anon. 1988).

With this in mind it was decided in 1986 to start measurements of sea surface temperature at several locations along the Icelandic coast. The purpose of these measurements was twofold. First, mariculture had started in many coastal areas by then and data on local environmental conditions was generally scarce and, second, for the purpose of obtaining continuous records of the marine climate at key positions.

Only the longest records that have been gathered during the period 1987-1996 will be discussed here. Shorter records from other locations have been briefly discussed by Kristmannsson (1989, 1991).

## DATA

The locations discussed here are shown in Figure 1. The measurements were made in harbours, 1-2 m below spring tide sea level in an exposed position. The temperature was recorded every 2 hours using thermometers of the MS-110SH type produced by Hugrún. The accuracy of the instruments is given by the manufacturer as  $\pm 0.1^{\circ}\text{C}$ . The thermometers were changed every 3-4 months which is the normal lifetime of the batteries used. However, there are several gaps in the records causing problems in the analysis. The batteries sometimes failed, resulting in gaps of up to 3 months in some records, and shorter gaps are either due to battery failure or other reasons such as damage to the installation. The temporal coverage is shown in Figure 4.

Daily means of temperature were calculated from the records and these constitute the basic data set used in this work.

A data base containing this material is being developed and will be made available to the public.

## RESULTS

### *Monthly mean temperature*

#### *The annual pattern*

The monthly mean temperature at each site was calculated from the basic data set. Then the mean for each calendar month for all available years was calculated, together with the corresponding standard deviation, which is thus a measure of the inter-annual variability. The results of these calculations are shown in Figure 2.

The lowest monthly mean temperature (Fig. 2) was at all locations reached in February or March, and in April it was somewhat higher in all cases. Stefánsson (1970) observed that the minimum monthly mean temperature occurred later north of Iceland (i.e. in the beginning of April at Grímsey) than in Reykjavík. He attributed this to the presence of sea ice at the north coast of Iceland where its melting delayed the normal solar heating of the surface layer. The period 1960-1969, studied by Stefánsson, included the so-called ice years in North Icelandic waters. The present study does not include such anomalous ice conditions to the same extent, and this is probably the reason why there does not seem to be much difference between locations in the timing of the temperature minimum in the data set. The minimum of the monthly mean temperature is very similar at all stations, highest in Reykjavík  $1.8^{\circ}\text{C}$  and lowest in Æðey  $0.2^{\circ}\text{C}$ .

The monthly mean temperature maximum is reached in August at all stations except for Stöðvarfjörður, where the temperature is slightly higher in September. There is much greater range of the maximum than of the minimum temperature. It is highest in Reykjavík,  $11.3^{\circ}\text{C}$ , and lowest at Stöðvarfjörður,  $6.7^{\circ}\text{C}$ . The reason for the greater range of the monthly maximum temperature is that during the cooling period there is more mixing and the heat is distributed over a thicker layer than during the heating season and the mixing thus acts as a buffer on the temperature variation.

Similarly, there is a large variation in the difference between the monthly mean maximum and minimum temperature at the stations. The variation is largest in Reykjavík,  $9.5^{\circ}\text{C}$ , while in Stöðvarfjörður it is only  $6^{\circ}\text{C}$ . The variation is also quite small in Mjóifjörður and at Grímsey.

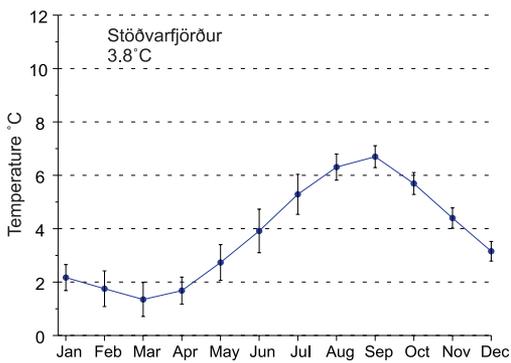
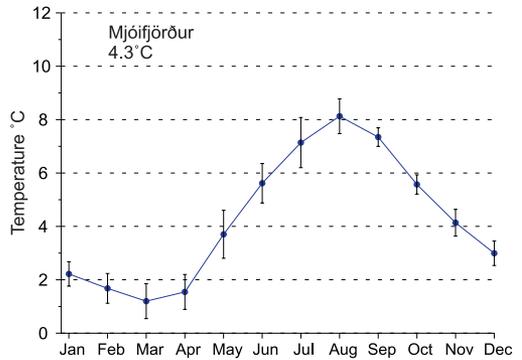
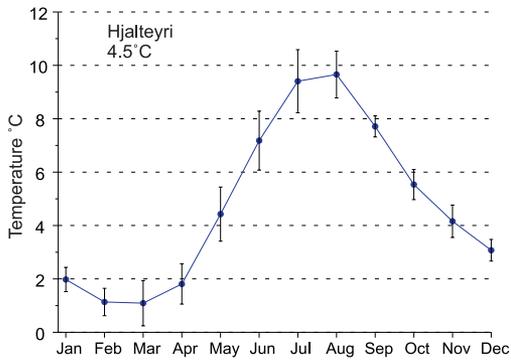
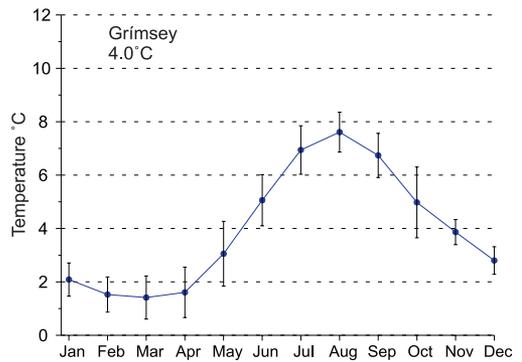
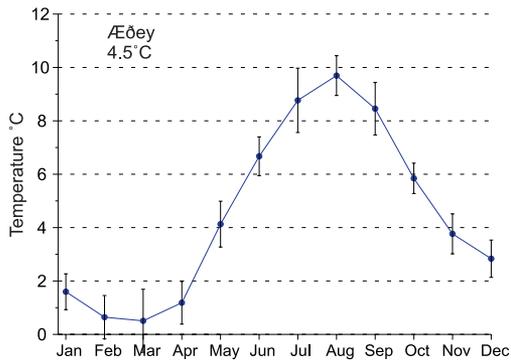
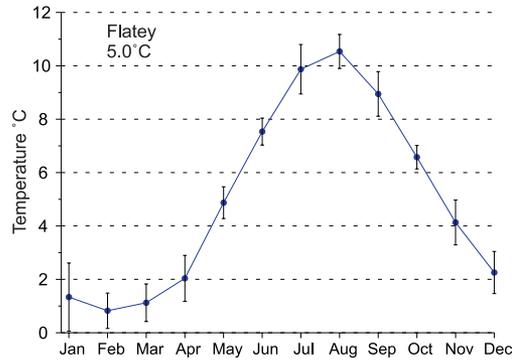
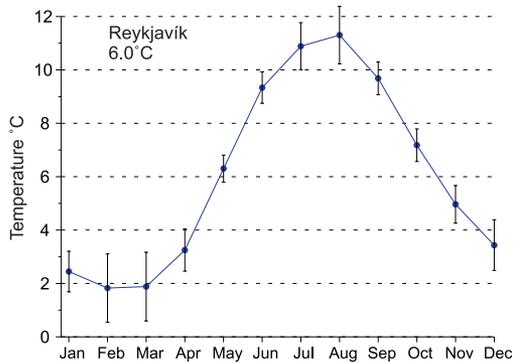


Figure 2. The mean temperature for each calendar month at all the stations for all available years. The error bars represent one standard deviation. The average temperature for each curve is also shown.

Stöðvarfjörður seems to be anomalous in many respects. The annual range is small, with low temperatures in summer, but in winter the mean is similar to that at the other locations. The minimum is reached in March followed by a very gradual heating and the maximum temperature occurs in September. For all months the monthly mean temperature has a small standard deviation. This pattern is probably caused by vigorous tidal mixing which limits stratification and keeps the water in the fjord mixed. Furthermore, the fjord is short and the waters within it are well mixed with the shelf water outside, thus further reducing all variation.

The average temperature has been computed for the curves shown in Figure 2. It is highest in Reykjavík, 6°C, and then generally decreases as one proceeds clockwise around the coast being lowest in Stöðvarfjörður, only 3.8°C.

#### *The 1991 pattern.*

In order to show variations within one year, the year 1991 was chosen since it has the best data coverage (Fig. 3). The only missing data are 3 days in April at Grímsey and 15 days in February at Hjalteyri. The error bars indicate the variability within each month. This was a relatively warm year at all stations. In winter, the temperature rarely fell below 2°C, but it stayed quite cold in April. The standard deviation is generally largest during spring, when a surface layer is developing and gradually becoming less dense and thus more isolated from the colder water below. Noteworthy is the small standard deviation at Stöðvarfjörður and also the small seasonal variation due to the strong mixing mentioned before.

#### *Deviations of monthly means*

In order to evaluate individual monthly mean temperatures for different years, the deviation for each month from the mean calendar month has been calculated (Fig. 4). The year 1987 was relatively warm, especially during spring. Then there was a cold period until autumn 1990 when a warming started which lasted until spring 1992. This period, especially the year 1991, was the warmest during the 10 years under study. The high temperature was observed at all stations, but was most persistent at the north and east coast.

The period from the latter half of 1992 until 1996 was rather cold but variable. The spring of

1995 was extremely cold, and at Grímsey the warming of the surface layer did not start until late April. This is in accordance with Stefánsson's findings that, during the cold years 1965-1969, the minimum temperature at Grímsey was not observed until the middle of April (Stefánsson 1970). During spring 1995, exceptional conditions were observed in the area north of Iceland with polar and arctic water from the north, with low salinity and temperature, dominating the whole area (Anon. 1995). However, this cooling seems not to be confined to the area north of Iceland but was observed at all locations discussed here.

In 1996 there was a change to warmer conditions, except for the last couple of months.

There is a general agreement between the anomalies at all stations, although there can be differences for individual months. This indicates that large scale and long term changes are coherent over the whole area.

#### *Annual temperature cycle in 1993*

There is one anomalous episode, which is exceptional for the whole data set, occurring in the autumn of 1993 off the north coast when the temperature at Grímsey fell by about 6°C within 6 weeks, from the beginning of September until mid-October (Fig. 5). During the same period the temperature at Hjalteyri fell by 7°C, thereof by 4°C within 10 days in the middle of September. After that, temperatures returned back to normal in the beginning of November. This event was caused by advection of large amounts of Polar Water from the East Greenland Current onto the North Icelandic shelf which were then advected with the North Icelandic Irminger Current eastwards. Some minor effects of this anomaly are probably seen in Mjóifjörður where there is a small minimum in temperature in the beginning of November. In Stöðvarfjörður it was, however, not detectable. The time difference between the minimum at Grímsey and in Mjóifjörður is about 30 days, which would then indicate the travel time for the disturbance between these locations. This would imply a speed of about 15 cm/s which is not unrealistic. The mean monthly temperature at Grímsey is shown in Figure 5 for comparison. Evidently 1993, especially the summer and autumn period, was rather cold.

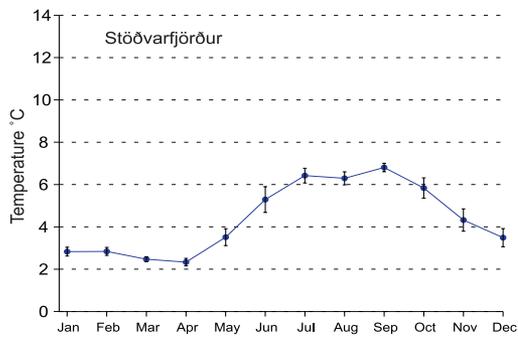
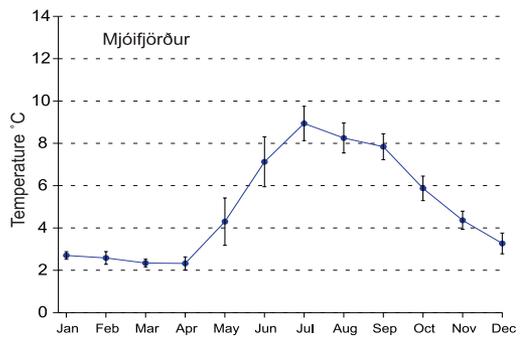
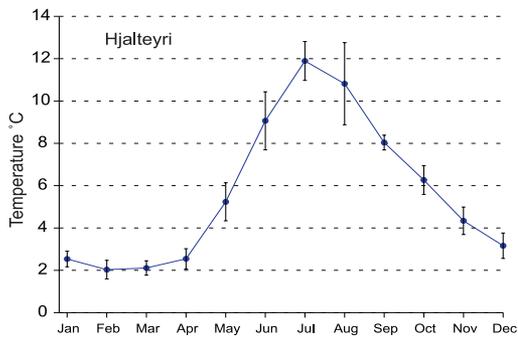
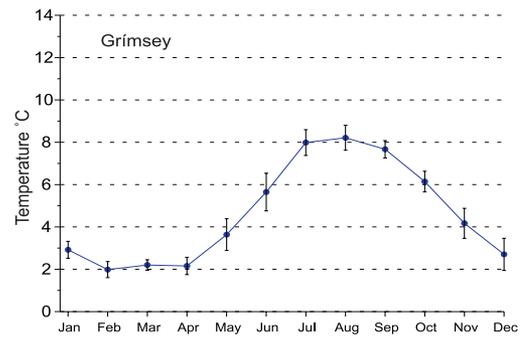
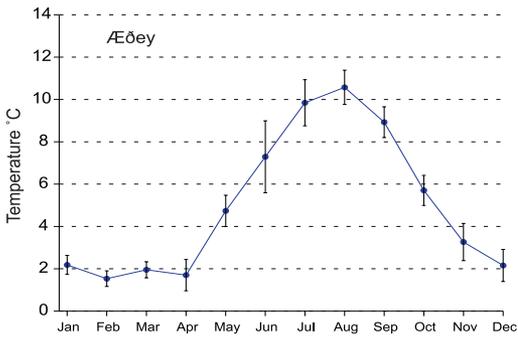
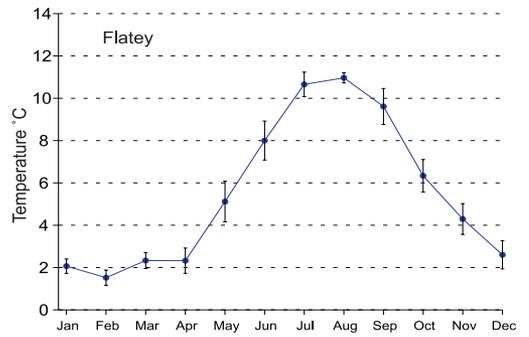
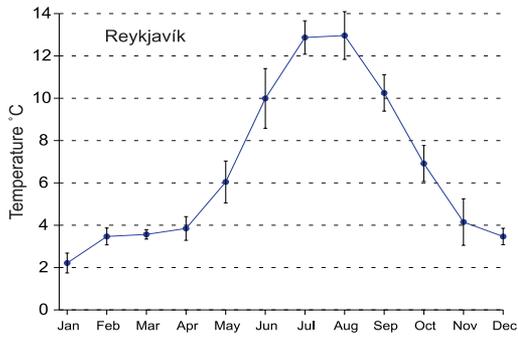


Figure 3. The mean temperature for each month and all stations for 1991. The error bars represent one standard deviation.

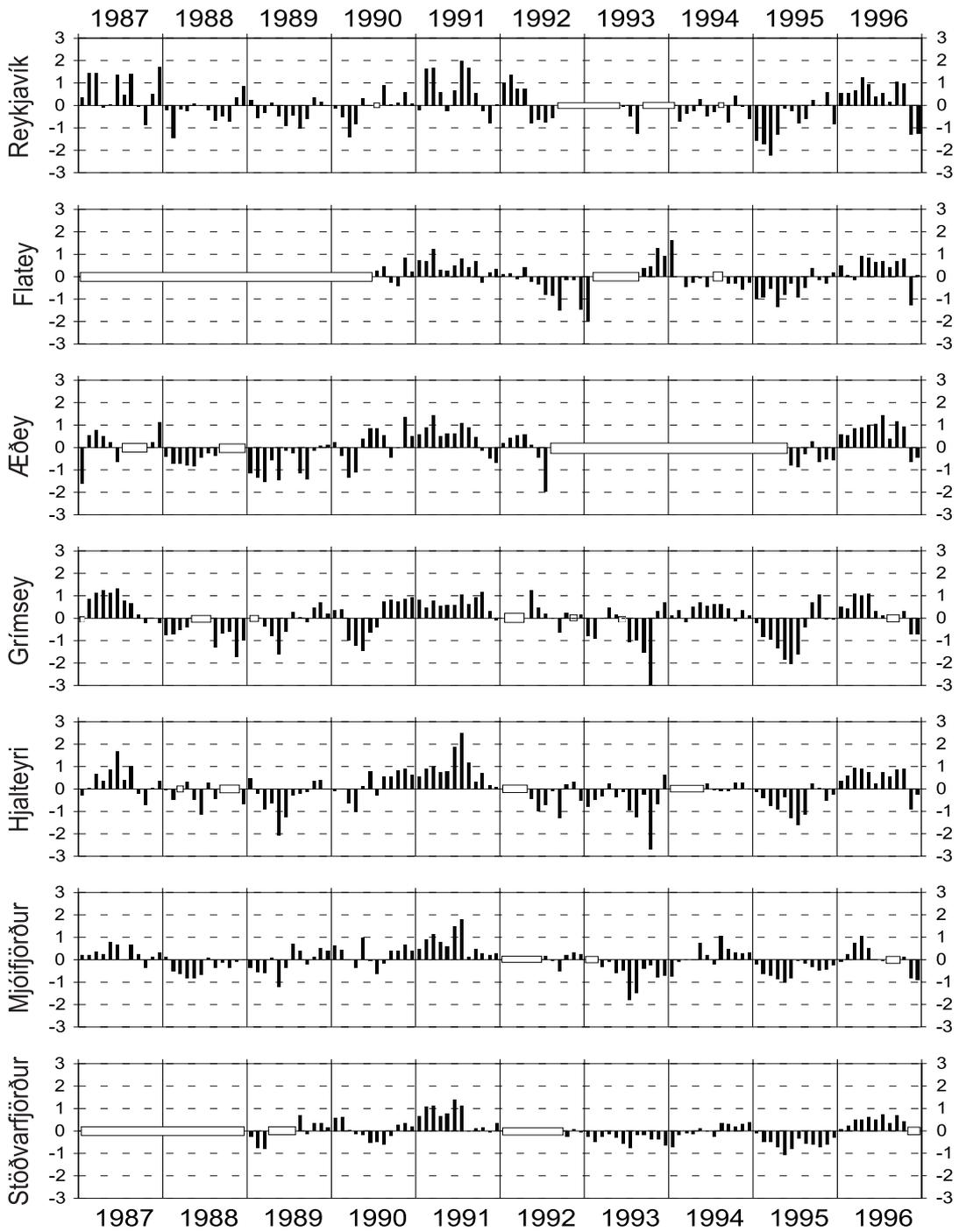


Figure 4. Temperature deviations ( $^{\circ}\text{C}$ ) at all stations from the calendar month mean for the period 1987-1996. The white boxes indicate missing data.

Figure 5 also illustrates the variations in the daily mean temperature. During winter, the temperatures at Grímsey and Hjalteyri are very similar. This is due to the vigorous mixing due to cooling and energy input from the wind. In spring, the heating of the surface layer is much more rapid at Hjalteyri because it is a sheltered area inside a long fjord. During spring, the stratification develops faster at Hjalteyri because of less turbulence and also because the fresh water runoff from land helps speed up the process. It is seen that at Hjalteyri the variations are much greater than at Grímsey. This occurs because the surface layer at Hjalteyri is thinner than at Grímsey, the energy is not spread over as much water and therefore the effect on the temperature change is greater. This also has the effect that temperature during summer is much higher at Hjalteyri than at Grímsey.

#### Mariculture aspects

Temperature is crucial when evaluating a location for aquaculture since the growth of the cultured

species depends on temperature and it is important to know what growth conditions to expect at a given location. In this respect it is also of interest to know the probability of extreme temperatures since too high temperature can increase the risk of diseases (Björnsson 1997). Furthermore, very low temperatures can increase fish mortality as mentioned previously (Anon. 1988).

In order to assess the suitability of a site for mariculture the average number of days in a year when the temperature lies within  $\pm 0.5^\circ\text{C}$  of an integer degree is shown in Figure 6. Only years with adequate data coverage, i.e. years when gaps in the data set were so small that they could be replaced by linear interpolation between points, have been used. The years used for each station are listed in Figure 6. Temperatures below  $-0.5^\circ\text{C}$  were only observed at Aðey and Flatey during the available years. The most common low temperature interval is between  $1.5$  and  $2.5^\circ\text{C}$ , representing the months in late winter when the temperature, as we have previously seen, shows relatively small variations.

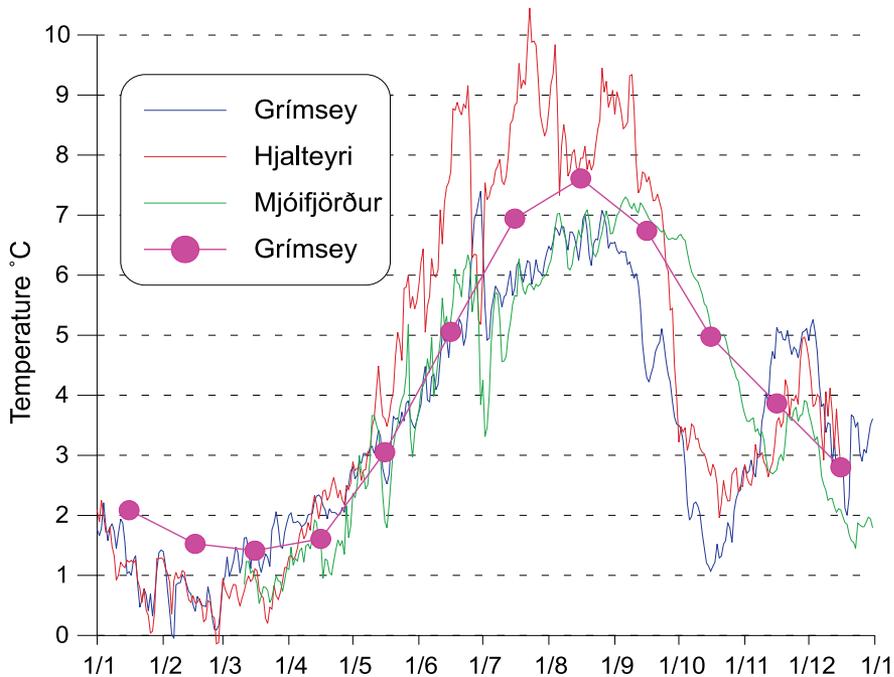


Figure 5. The daily mean temperature at Grímsey, Hjalteyri and Mjóifjörður in 1993. The monthly mean temperature at Grímsey is shown as dots.

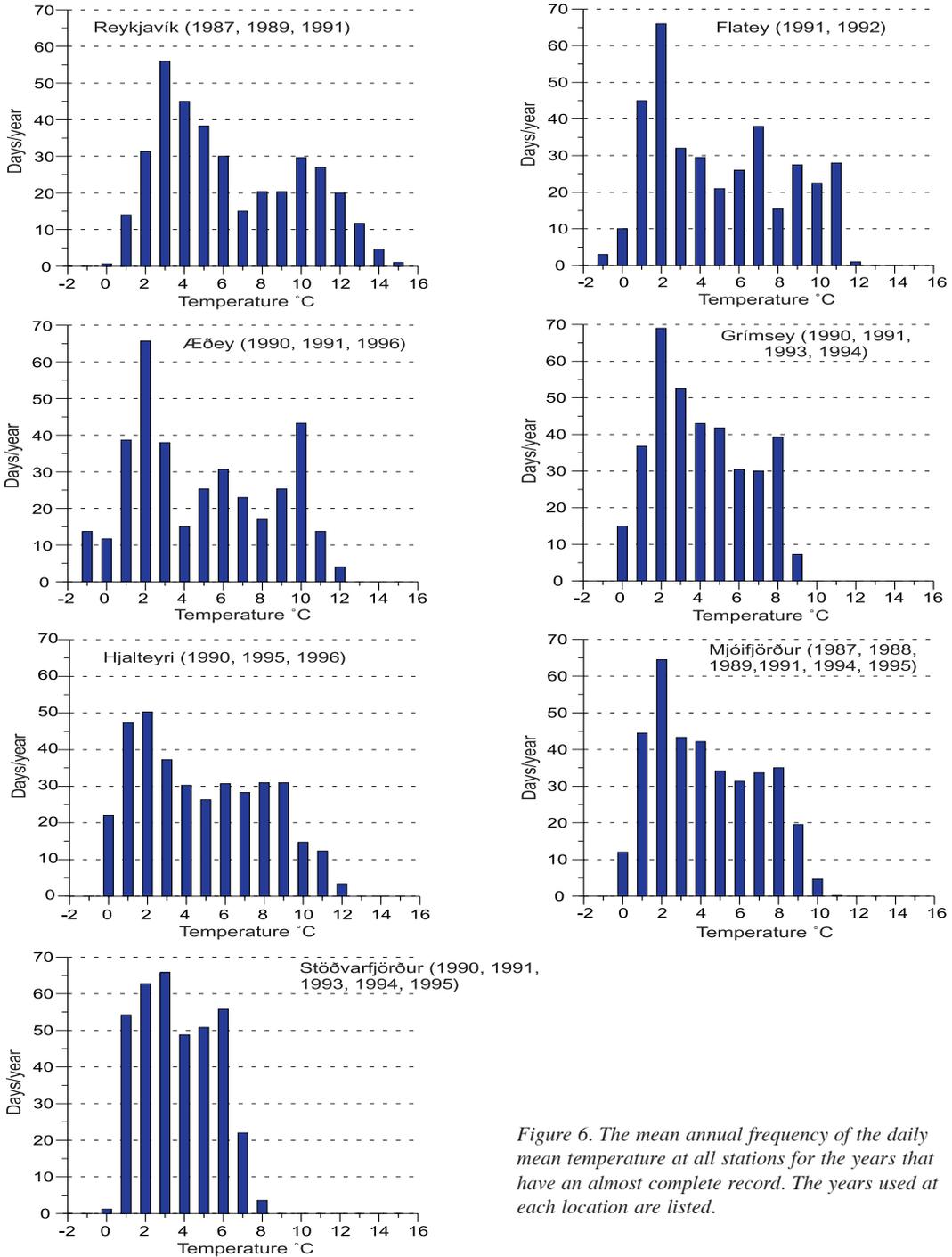


Figure 6. The mean annual frequency of the daily mean temperature at all stations for the years that have an almost complete record. The years used at each location are listed.

## DISCUSSION

When this project was started, aquaculture had begun in many coastal areas where the local environmental conditions were poorly known. The purpose of the measurements presented here was to provide data suitable for evaluating sites for mariculture and to continuously monitor the marine climate at key positions. As far as the mariculture aspect of these measurements is concerned, there is probably sufficient data available for a first evaluation of sites. However, more accurate evaluation would require further measurements at each proposed site.

It is now most important to concentrate on the long term monitoring aspect of these measurements. There are several ways to improve this. There is probably no reason to increase the number of stations, since the anomalies (Fig. 4) show that the large scale and long term variations seem to be coherent over large areas. However, because no stations from the south coast are included, there is a gap in spatial coverage. Stefánsson (1970) included a record from Vestmannaeyjar off the south coast. This island group is embedded in Atlantic Water, and the data from there showed a somewhat different behaviour from the other stations included in Stefánsson's study. It is therefore important to establish a monitoring site there.

A further step would be to make the measurements available in near real-time, thus increasing the value of the measurements and to make it possible to react sooner if unusual conditions develop. It should also be considered to include salinity measurements, since such recording instruments are now commercially available. This might be implemented at strategic locations, such as Grímsey and Vestmannaeyjar which seem to be ideal for monitoring the water mass conditions on the North Icelandic shelf, and in the Atlantic Water south of Iceland, respectively.

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