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SENSITIVITY OF ICELANDIC AGRICULTURE TO CLIMATIC VARIATIONS

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Abstract. Haymaking and grazing in summer and winter are fundamental to Icelandic agriculture. This paper shows that the growth of grass depends very much on the climate, particularly the temperature, and that winter temperatures are especially important. The climate of Iceland is highly variable, and the long-term variations are great in comparison with most other European weather regions. This may be attributed partly to the role of the sea ice, which lags behind the variations in atmospheric temperature. From observations in this century it is possible to compute the potential livestock in the country as a function of temperature, and this computation is tested with historical data. A possible response to climatic variations, by varying the use of fertilizer to counteract the impact of cold preceding winters, is discussed. The paper also discusses the growth of barley and forests, which is barely possible in the cold climate and reacts strongly to climatic variations and changes.

1. Climate and Agriculture in Iceland

Farming in Iceland is highly vulnerable to climatic (long-term) changes and (short-term) variations. Temperature variability is great, particularly over the long term. This may be explained partly by the proximity of the east Greenland polar ice and its secular variations. The impact of temperature on grass growth will be analyzed in this paper, as well as its effect on winter fodder for livestock. This gives an estimate of the potential livestock in the country for a given area of improved grassland. The estimate will then be tested historically. The weight of lambs in the autumn will be shown to depend on the temperature. The possibilities of barley ripening will be discussed, as well as the growth of birch and Norwegian spruce. Sea ice will be shown to be a good indicator of Icelandic climate, and its correlation with mortality due to starvation in past centuries will be analyzed. Hay yields in the spring can be forecast by correlation of yield with winter temperature, and it will be shown how the forecasts can be used to recommend variable application of fertilizers by farmers as a safeguard against low yields.

1.1. Agricultural Products

Cattle and sheep products represented about 80% of the value of agricultural production in Iceland in 1974. This proportion was probably more than 90% before 1900. The number of sheep was about 750,000 during the winter of 1981–82; cattle numbered 65,000 and horses 54,000 in the same period. Icelandic agriculture is therefore heavily dependent on grazing and haymaking. The growth of grass is sensitive to winter and summer temperatures. Moreover, supplies of hay in the autumn need to be greater for colder winters because grazing in winter and spring can be seriously affected by snow and low

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temperature. This was particularly the case until recently, but even in recent decades many farmers have relied considerably on winter grazing for their horses. In some regions summer grazing is a limiting factor for the number of livestock, particularly in unfavorable years.

Potatoes are the main garden products. The harvest is quite variable, but in the best years it is sufficient to meet home demand. Some attempts have been made to cultivate fast-growing strains of barley and they have been fairly successful in the regions having the mildest climate. With respect to forestry, the Icelandic birch is thought to have survived the last Ice Age, but its growth is quite slow. Trials with some coniferous trees are promising in certain areas.

Although the growing of garden products, barley, and forests is not very important economically in Iceland, their particular sensitivity to climate suggests that they are a suitable subject for studies of climate impact.

1.2. The Climate

Iceland is located at the shifting frontier between the *taiga* and *tundra*. When the climate is cold the taiga region in the lowland contracts. In warmer periods the taiga gains territory, northwards in the lowland and upwards in the mountains. The agricultural frontier is, as we shall see, equally sensitive to climatic variations.

Figure 1 shows the annual mean temperature from 1846 to 1982 at the Stykkisholmur climatological station on the west coast of Iceland. There is a strong interannual variation, together with pronounced long-term changes, e.g. shortly after 1920. For comparison, Table I shows some characteristics of temperature climate at three stations: Stykkisholmur (65° N), Edinburgh (56° N), and Berlin (52° N).

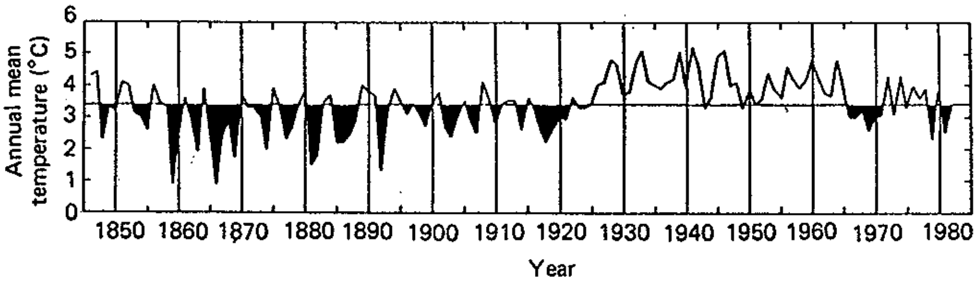

Fig. 1. Annual mean temperature at Stykkisholmur, 1846–1982. Values below the average are shaded.

TABLE I: Thermal Characteristics at Contrasting Climatological Stations in Europe.

	Stykkisholmur	Edinburgh	Berlin
Mean annual temperature, 1851–1950 (°C)	3.3	8.5	9.2
Standard deviation of *annual* temperature	0.88	0.54	0.76
Standard deviation of *decadal* temperature	0.54	0.17	0.24
Temperature difference between 1901–50 and 1851–1900	0.74	0.21	0.14

As examples of a
the years 1873–1922
temperature normals
1931–60 is the norm
presented in Table II.

TABLE II: Stykkisholmu
Period (1873–1922) and

Month:	1	2
1873–1922	–2.0	–2.5
1931–60	–0.8	–0.9

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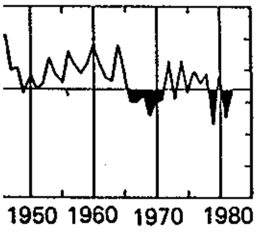


Values below the aver-

tations in Europe.

Edinburgh	Berlin
8.5	9.2
0.54	0.76
0.17	0.24
0.21	0.14

As examples of a cold and of a mild climatic period in Iceland, we can take the years 1873–1922 and 1931–60, respectively. For the earlier 50-year period, temperature normals have been computed for many Icelandic stations, while 1931–60 is the normal period now in use. The figures for Stykkisholmur are presented in Table II.

TABLE II: Stykkisholmur: Monthly and Annual Mean Temperatures (°C) for the Cool Period (1873–1922) and the Mild Period (1931–60).

Month:	1	2	3	4	5	6	7	8	9	10	11	12	Year
1873–1922	−2.0	−2.5	−2.1	0.5	4.3	8.1	9.9	9.2	7.2	3.7	0.6	−1.5	3.0
1931–60	−0.8	−0.9	0.2	1.8	5.7	8.7	10.4	10.0	7.9	4.5	2.3	0.5	4.2

1.3. The Role of the Sea Ice

The sea ice off the east coast of Greenland is an important clue to climate and its variations in Iceland. Figure 2 illustrates the extent of this ice at the end of May over the period 1966–75. When the ice is at its maximum extent, the North Atlantic can be frozen half the way from Greenland to Norway, with Iceland resembling an icy peninsula extending from the Greenland ice cap. There is a marked feedback effect between the ice and the climate. Cooling will extend the ice but, once formed, the ice will also cool the air, particularly when winds blow from the north. The northern part of Iceland is more affected by these variations, both because of the proximity of the ice and because the föhn will modify the cooling effect of northerly winds in south Iceland. This may be seen in Figure 3, which is based on available lowland observations. Furthermore, the ice has a high persistence compared with atmospheric temperature, thus increasing the probability of two or more severe years in succession. This tendency may be noted in the Stykkisholmur graph, Figure 1. For the same reason, cold winters (when livestock requires more fodder than usual) tend to follow cool summers, with limited haymaking.

2. Climate and Grass Growth

Grass for haymaking and grazing is the main crop in Icelandic farming. The author has attempted to assess the impact of climatic variations upon grass cultivation in Iceland for the period 1901–75, using statistics on temperature, fertilizers, and hay yield per hectare of cultivated grassland (Bergthorsson, 1982). Even if availability of soil water may in some cases affect the yield, it is reasonable to assume temperature to be the main limiting factor for grass growth in the country. This assumption will subsequently be tested.

A somewhat surprising conclusion is that cold winters are more effective than cold summers in restricting the growth of grass. Among the possible reasons for this may be the winter killing of grasses, partly as a result of direct killing by severe cold. A less direct effect may be the prolonged snow cover in cold winters, frequently melting during brief thaws and then refreezing. Moreover, severe winters can leave the soil frozen, delaying growth, and sometimes killing the grass because of water lying on impermeable frozen soil in the spring. On the other hand, winter warmth seems to be favorable only to a certain degree,

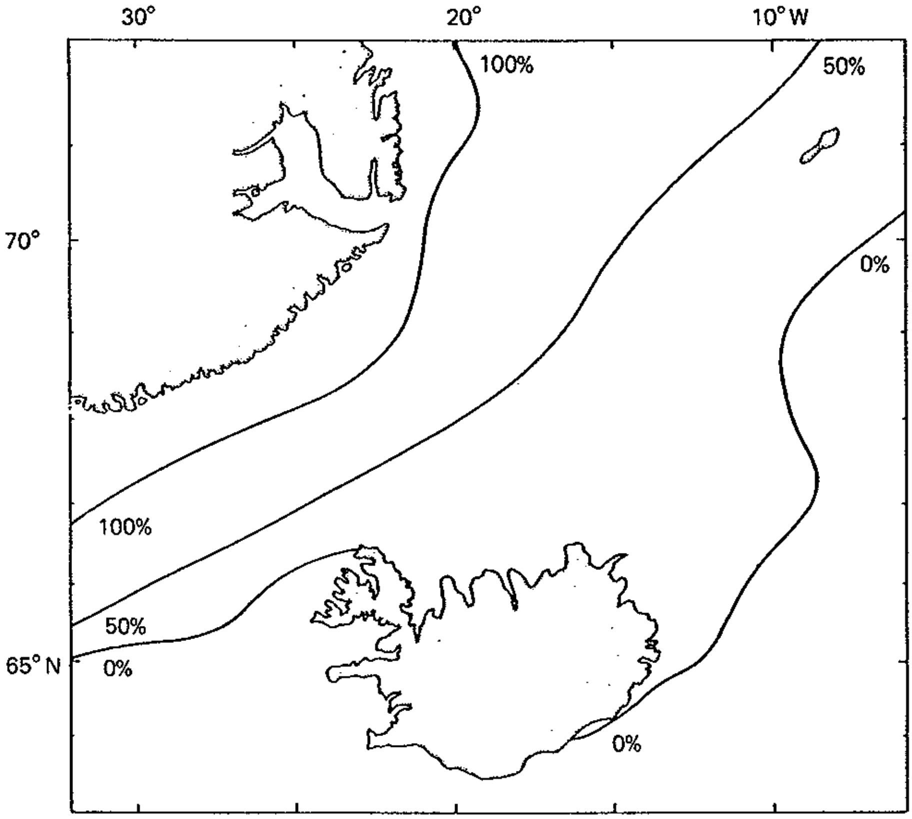


Fig. 2. Percentage frequency of occurrence of all known ice covering at least one-tenth of total sea area at the end of May over the period 1966–75 (based on ice charts from the Icelandic and the British Meteorological Offices).

possibly because very warm winters can induce an untimely start of grass growth.

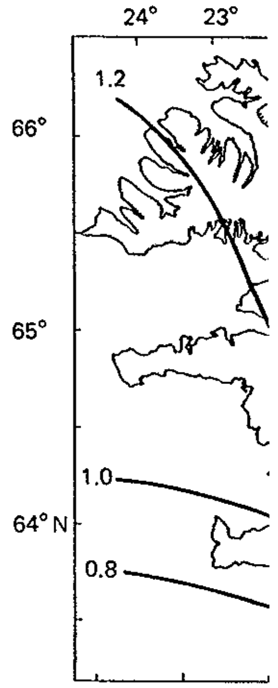
While winter temperature is important for grass growth, summer temperature also affects the hay yield. It will be shown that the average temperature for the period from October 1 to September 30 is a good indicator of the annual hay yield. However, in the assessment of the impact of temperature on hay yield, the great increase in the use of commercial fertilizers after 1920 is a disturbing factor. Fertilizer will therefore have to be included in the regression equation for hay yield.

2.1. *A Model of Grass Growth*

To express the annual hay yield the following model has been found useful:

$$Y = (0.169+0.2814S-0.02S^2)(1,820+28.06N-0.051N^2)\ . \tag{1}$$

The yield Y is here given in kilograms per hectare, S is the average temperature for the period from October 1 to September 30, and N is the total amount of



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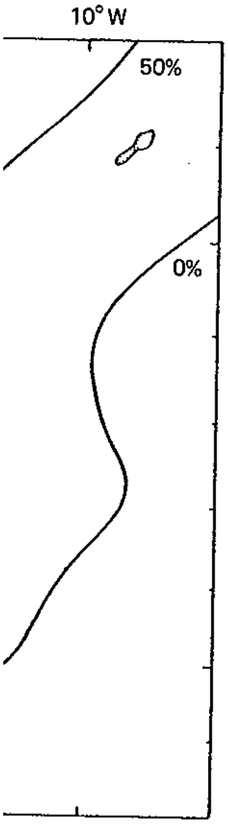

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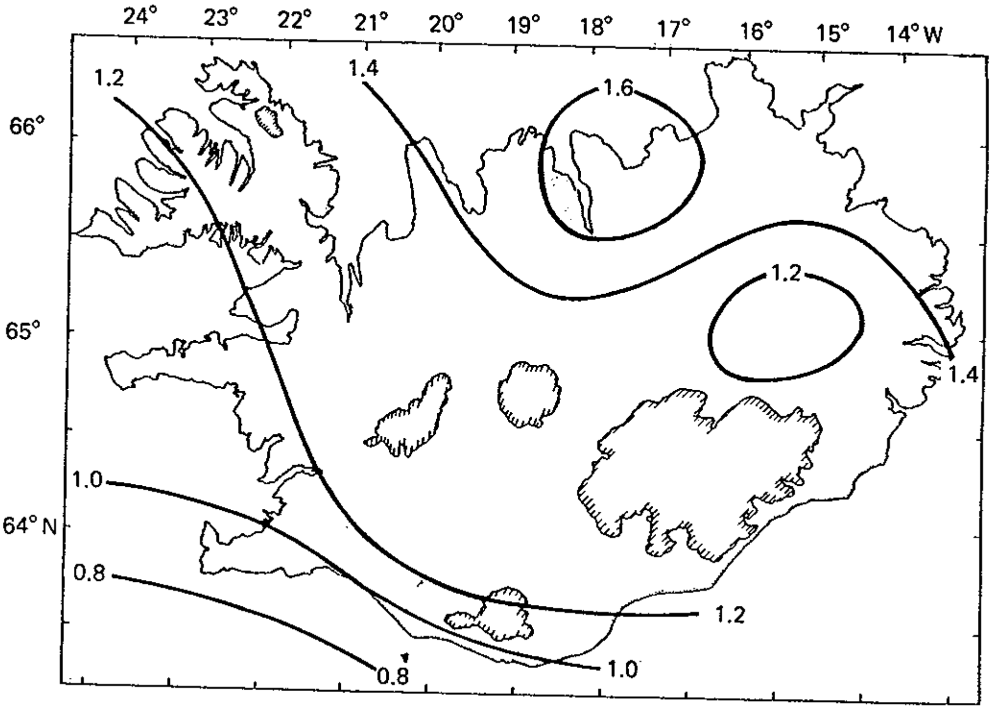

Fig. 3. Isolines of warming (°C) from the period 1873–1922 to 1931–60.

nitrogen fertilizer in kilograms per hectare, including manure. It is assumed that nitrogen is the main limiting nutrient. The temperature data are taken from one station only, Stykkisholmur.

This model enables us to distinguish the impact of fertilizer from that of temperature. Figure 4 depicts the annual hay yield corrected for the effects of fertilizer. The yield, expressed as a percentage of the mean yield in 1931–60, is plotted against Stykkisholmur temperatures. The lowest yield, in 1918, is only half the average for 1931–60, while the greatest yield is about 120% of this average. The curve is fitted to the observations according to the model. In this case we assume applications of fertilizer to be constant. However, before the first use of commercial fertilizer in about 1920, applications of nutrients were not constant, since the available manure was proportional to the hay eaten by the animals during the winter. This tended to amplify the effect of climatic variations and changes. Table III shows estimated temperature impact on the hay yield in relative figures, depending on whether the total amount of fertilizer per hectare is constant or whether only the available manure is used. The yield has been indexed to 100 for an annual temperature of 3.2 °C.

3. Climate and Winter Fodder

Not only hay yield is affected by low temperatures: winter and spring grazing will also be more difficult because of snow, ice, and bad weather. In this connection it should be noted that in Iceland there is an unusual autocorrelation in

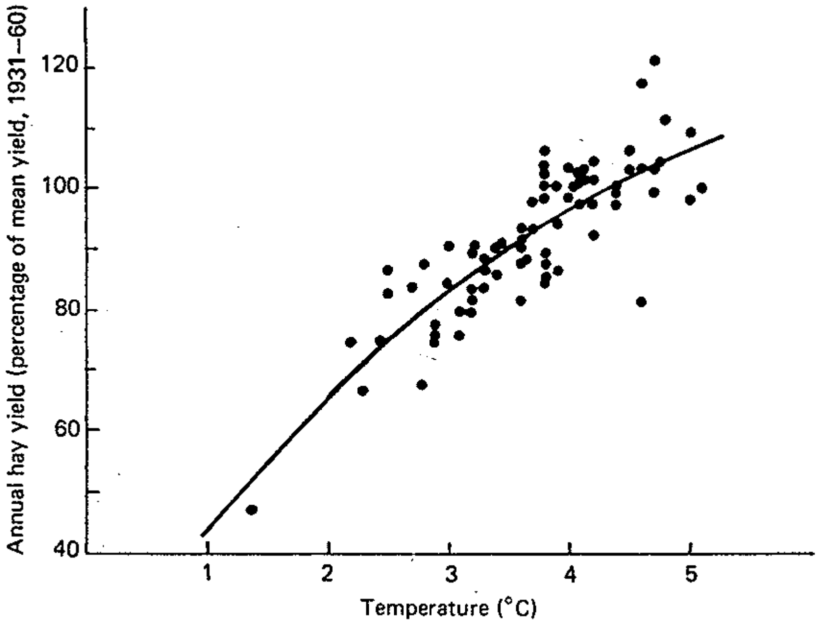

Fig. 4. Hay yield in Iceland, 1901–75, as a function of the October–April temperature in Stykkisholmur. The yield is corrected for the variable amount of fertilizer used in the period.

TABLE III: Hay Yield and Temperature.

Annual temperature (°C)	2.2	3.2	4.2
Hay yield using manure only	73	100	124
Hay yield using constant fertilizer	80	100	116

temperature of seasons and years, so that a severe winter is more likely when the preceding seasons have been cold. This may be partly due to the damping effect of the sea, and in particular of sea ice.

Phenological observations of hay consumption and temperature in the period 1941–49 enable us to estimate the required hay consumption as a linear function of winter temperature at Stykkisholmur, as shown in Figure 5. Since winter temperature is correlated with annual temperature in the long run, we can relate variations in fodder supply to annual temperature (Table IV).

Less information on this subject is available for recent years. It is, however, likely that the effect of temperature on the winter fodder for sheep is now less important than it was in 1941–49, because winter grazing of sheep has been reduced considerably.

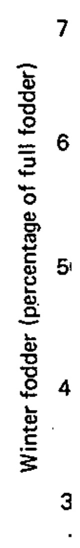

Fig. 5. Winter fodder
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TABLE IV: Winter Fodde

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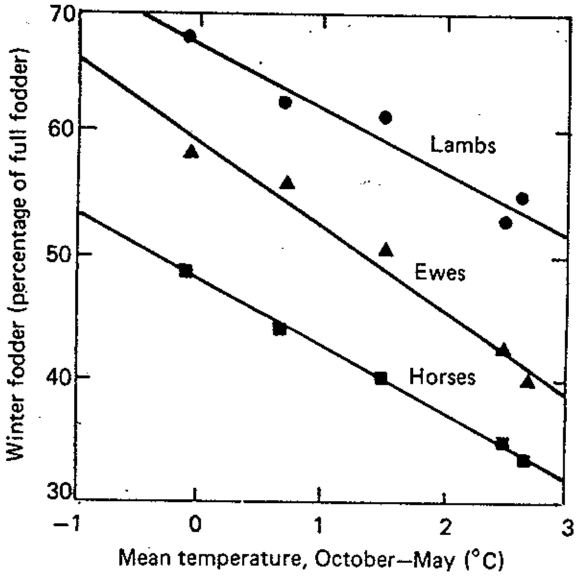

Fig. 5. Winter fodder of lambs, ewes, and horses in the years 1941–42, 1942–43, 1945–46, 1947–48, and 1948–49, as a function of mean temperature in October–May.

TABLE IV: Winter Fodder and Temperature.

Annual temperature (°C)	2.2	3.2	4.2
Winter fodder of sheep	112	100	88
Winter fodder of horses	112	100	88
Winter fodder of cattle	104	100	96

3.1. Winter Fodder and Carrying Capacity

The above considerations indicate that climatic variations affect available winter fodder and its consumption and thus influence the carrying capacity of cultivated grassland. It should be possible to compute from this relationship the potential livestock capacity of the country as a function of the climate.

We assume conditions representative of the nineteenth century in Iceland, that is, that only manure is used as fertilizer. It is assumed that the cultivated grassland area is constant, and that the hay from the cultivated areas is all given to dairy cattle. Haymaking on uncultivated, unfertilized land was extensive at that time, and hay was used for sheep and horses, as well as for non-dairy cattle. The consumption of hay is assumed to vary with the climate, as shown in Table IV.

The result of this computation is shown in Table V, which gives the livestock numbers in relative figures. The results are almost identical for sheep, horses, and cattle: *A temperature deviation of 1°C from the 1901–30 normal (3.2°C) will change the potential livestock carried by cultivated grassland in Iceland by some 30%.*

TABLE V: Potential Livestock on Cultivated (Improved) Grassland and Temperature.

Annual temperature (°C)	2.2	3.2	4.2
Sheep	71	100	132
Horses	71	100	132
Cattle	71	100	131

4. Climate and Actual Number of Livestock

As a test of the computation above we have investigated the actual relationship between climate and the amount of livestock in the period 1846–1900. To account for the cumulative climatic effect over consecutive years, a weighted mean of the preceding annual temperatures was used. The weighting functions found to be suitable were 1.0 for the immediately preceding year and (5/7), $(5/7)^2$, $(5/7)^3$, etc. for the progressively earlier years. The amount of livestock is given in 'ewe-values', based on relative hay consumption by sheep, cattle, and horses (1:20:2.5). The outcome of this regression is shown in Figure 6. It is practically the same as the estimate: A temperature deviation of 1 °C from the 1901–30 normal (3.2 °C) would change the livestock number by 29%.

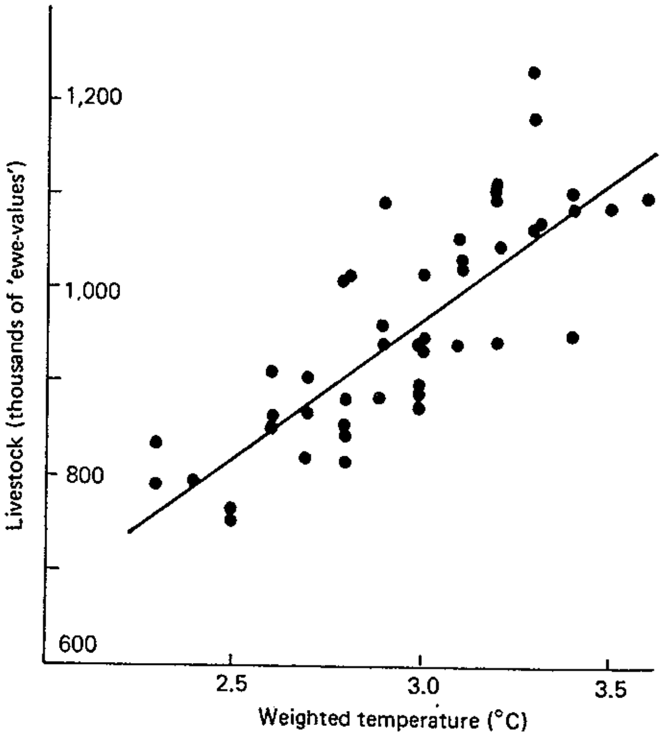

Fig. 6. Livestock in Iceland as a function of weighted temperature of the preceding years, for the period 1846–1900.

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A corresponding investigation for the period 1962–82 indicates only a slightly reduced dependence of stock number on climate: 27% per degree Celsius deviating from 3.2 °C.

5. Climate and Grazing Capacity for Sheep

Apart from the cultivated grasslands, the extensive rangelands are important for summer grazing, particularly for sheep (Dyrmundsson, 1979). We shall now attempt to correlate the average carcass weight of the lambs in autumn with the following variables:

(1) density of sheep in the range lands;
(2) computed grass growth index according to the temperature at Stykkisholmur, as discussed above, assuming that no fertilizer is used;
(3) farming practices.

Since 1940 the total number of sheep has been quite variable, ranging from 400,000 to 900,000. Because of a certain lung disease that arrived from abroad before 1940, all the sheep in many regions were replaced by a new stock from unaffected areas, mainly in the years around 1950. This led to a marked short-term decrease in stock numbers and at the same time a significant increase in carcass weight.

The annual temperature in Stykkisholmur (October 1 to September 30) has been shown to be a good indicator of grass growth, and consequently it is reasonable to expect that it will affect the carrying capacity of the rangelands. However, sheep-farming practices have changed greatly, though gradually, resulting in increasing carcass weight, *ceteris paribus*. In the last term of the following regression equation we have attempted to express this increase by a linear function of time since 1940:

$$W = 9.35 - 0.003F + 0.032G + 0.066A\,, \qquad (2)$$

where W is the national average annual carcass weight (kg), F is the number of winter-fed sheep in the country (in thousands), G is the computed grass growth index as given by Y in Equation (1), and A is the year after 1900 (A = 75 denotes 1975).

According to Equation (2), a lowering of the grass growth index by 0.1 will have the same impact on carcass weight as an increase in the number of sheep in the country by some 105,000, which is equivalent to approximately 15% of the stock. This implies that when it is cold the carrying capacity of the rangelands will be decreased in the summer, even if sufficient winter fodder could be supplied.

5.1. *Grazing Experiments*

The carrying capacity of the rangelands can be tested experimentally as well. Table VI shows the average carcass weight for the years 1977–79 in Audkuluheidi in north Iceland as a function of the stocking rate of the sheep (Gudmundsson and Arnalds, 1980). A moderate stocking rate is here given the index 100. This result is in good agreement with the sheep numbers given in the regression Equation (2).

TABLE VI: Carcass Weight and Grazing Capacity.

Stocking rate of sheep	Light	Moderate	Heavy
Stocking rate index	42	100	162
Carcass weight, deviation (kg)	1.09	0	−1.65

6. Climate and Growth of Barley

Barley, one of the hardiest cereals, is very close to its growing limits in Iceland so that a relatively slight warming or cooling significantly affects its viability. Observations in Samsstadir in south Iceland indicate that a precondition for the ripening of a fast-growing variety of barley (Dönner) is that the growing degree-days from sowing to harvest, with the base 3 °C, should be at least 850 (Bergthorsson, 1969). Anomalous precipitation during the vegetative period will raise this required temperature sum by 30 for every 100 mm exceeding 200 mm in the vegetative period. According to Norwegian experience (K. Vik, private communication) this required temperature sum may be lowered by 30 for every degree of latitude further north, for barley requiring long hours of daylight. This enables us to compute the probability of barley ripening at different stations, knowing the temperature, precipitation, and latitude. According to this assessment, at only one station in Iceland (Reykjavik) would barley have ripened in 60% of the years during the cold period, 1873–1922. In the mild period, 1931–60, 21 of 48 stations should have had ripened barley in 60% of the summers.

7. Climate and Forests

To assess the climatic conditions of forest cultivation in Iceland it is possible to make use of the studies of the Norwegian forester Elias Mork (1968). Mork investigated the relationship between the daily afternoon temperature and the daily height increment of Norwegian spruce. Using this relationship as a basis, he was able to define 'growth units'. One unit corresponds to 1% of the annual height increment of the Norwegian spruce. The relationship is not a linear one, as may be seen from Table VII.

TABLE VII: Mork's Growth Units as a Function of Temperature.

Temperature of the warmest 6 hours	8.1	13.5	17.0	19.4	21.2	22.8
Growth units	1.0	2.0	3.0	4.0	5.0	6.0

Since the temperature of the warmest 6 hours of the day is not readily available from published records, the author suggests the use of the average of (1) the daily maximum temperature, and (2) the daily mean temperature. Calling this average temperature t, we can express the daily growth units empirically using the following relation in the interval 2–20 °C (see Appendix 1):

$$G = (t - 1.6)/(7.4 - 0.215t)\,. \tag{3}$$

If we use the monthly mean of the temperature t, we have only to multiply the resulting growth units by the days of the month to obtain the monthly sum of growth units. This relation is based on observations published by Mork for a mountain region north of Oslo, near the tree line.

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The annual impact of temperature can then be obtained as the sum of the monthly growth units during the summer. Mork found that a minimum annual sum of growth units is required in the long run for species like birch or Norwegian spruce to establish forests in the Norwegian mountains. The minima for the period 1931–60 are, according to Equation (3) for the period 1931–60:

for birch	267 growth units
for Norwegian spruce	300 growth units

They are 45 units higher than Mork's figures, since all months in spring, summer, and autumn are used in the computation, not only the vegetative period. By applying these criteria to 28 Icelandic weather stations, it is possible to identify which stations will permit culture of birch or Norwegian spruce in our two different (cold and mild) periods (Table VIII). All the 28 stations are situated within the inhabited area of the country.

TABLE VIII: Stations Permitting Cultivation of Birch and Norwegian Spruce.

Period	Number of stations	
	Birch	Norwegian spruce
1873–1922	10	4
1931–60	21	13

This variability in growth potential bears comparison with the pollen record, which indicates that the coverage of birch in Iceland has fluctuated markedly during the 10,000 years after the Ice Age, even before human settlement 1,100 years ago.

Comparison with conditions in Iceland gives on the whole a good confirmation of the Norwegian experience. For example, at Hallormsstadur in the eastern part of Iceland, where Norwegian spruce forest should reach a limit of 140 m above sea level and the birch line should be at 225 m, there is good agreement with the actual limit of tree growth.

8. Sea Ice and Living Conditions in Historical Times

Figure 7 shows the relationship between decadal sea ice prevalence and temperature in Iceland for the period 1851–1980, prevalence being measured in months per decade. The ice data of this period may be divided into two distinct classes, before and after 1920. There is little doubt that much more thorough observations are the reason for the recording of relatively heavier ice after 1920. In that year the Icelandic Meteorological Office started compiling the ice data, while before 1920 there were no regular ice observations organized by any Icelandic institution. The main source concerning ice before 1920 is Thoroddsen's ice annals (Thoroddsen, 1916–17), based on historical information available to him. Historical ice data compiled by Thoroddsen also exist for the period before 1850, but he only attempted to represent them graphically after 1780, because before that time the information was less complete. This lack of data must, however, not be interpreted as a sign of mild climate.

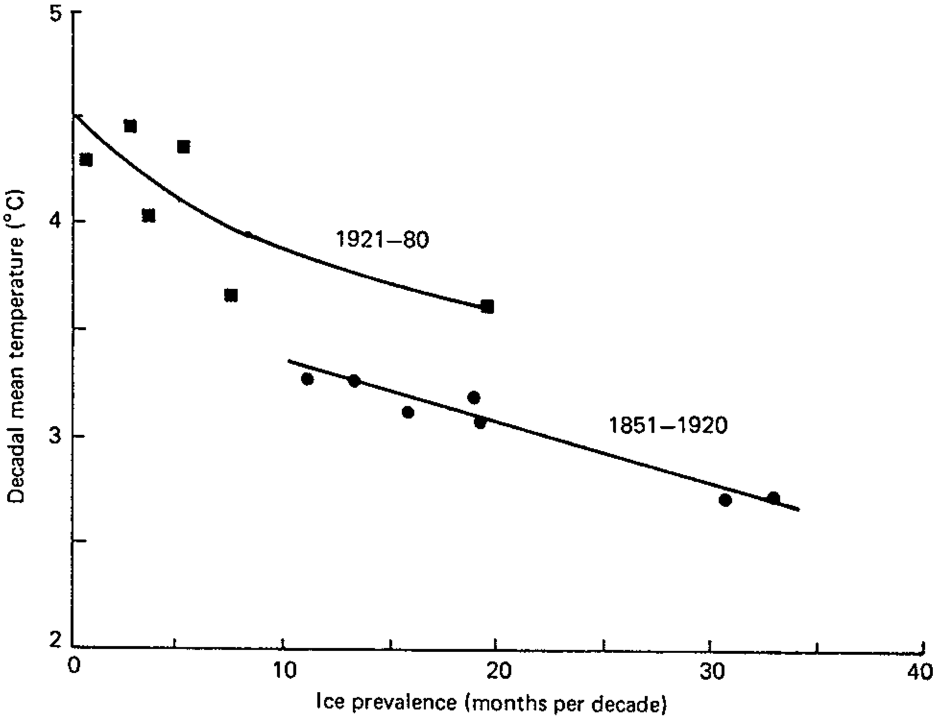

Fig. 7. Decadal mean temperature in Iceland as a function of sea ice prevalence. The relative increase of ice after 1920 is here considered to reflect more thorough observations.

To reconstruct the decadal temperature before 1846, Bergthorsson (1969) used indirect information on mild and severe years to fill in the Thoroddsen ice data for the period 1591–1780. More recently, Ogilvie (1981) unearthed a considerable number of historical sources, mainly for the eighteenth century. She computed two historical indices for the period 1601–1780. One is an index of ice prevalence, using direct ice data only, while the thermal index is based on the general weather information. There is some correlation between the two indices, but the ice index in the seventeenth century is lower than would be expected from the contemporary thermal index.

Bergthorsson's ice index of the seventeenth century compares well with Ogilvie's thermal index for the same century, suggesting that Bergthorsson's interpolation of the ice data is reasonable. That conclusion is furthermore supported by Koch's (1945) estimate of the ice in the seventeenth and eighteenth centuries, showing approximately the same relation with Ogilvie's thermal index in both centuries. Therefore, it is the present author's conclusion that in spite of some material being missing in his index of the ice since 1590, it can still serve as a reasonable estimate.

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9. Sea Ice and Starv

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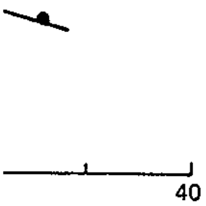

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9. Sea Ice and Starvation in Iceland

We have a fairly reliable record on years of mortality from starvation in Iceland for the last centuries (Thoroddsen, 1916–17). Judging from the strong relationship between ice and temperature and the relationship between temperature and amount of livestock, it is reasonable that starvation will be connected with the weighted means of sea ice prevalence in the years *preceding* famine. The weighting of the previous ice prevalence is: in the preceding year 1.0, the second to last year 5/7, the year before that $(5/7)^2$, and so on. Table IX compares the frequency of starvation with the weighted mean of ice prevalence. This seems to confirm rather strongly the impact of climatic variations on living conditions in Iceland in former times.

TABLE IX: Starvation as a Function of Previous Ice Prevalence in the Period 1591–1846.

Class	Weighted mean of ice prevalence (months)	Number of years	Years of starvation	
			Number in the class	Percentage of all years in the class
1	0–1	26	0	0
2	1–2	87	4	5
3	2–4	131	25	19
4	more than 4	11	6	55

10. Practical Application: Forecasts of Hay Yields

One of the aims of assessing the impact of climate on agriculture is to attempt improvements in farm management. One example will be discussed briefly here: the variable application of fertilizer to counteract the winter effect upon hay yield. The fertilizing of grassland in Iceland usually occurs in May. By then we are able to estimate the effect that winter temperatures will have on hay yield, as already discussed. For a winter temperature lower than 1 °C this impact can be expressed by

$$Y = (0.883+0.117W)(1{,}820+28.06N-0.051N^2), \qquad (4)$$

where Y is the hay yield (kg/ha), W is the mean temperature from October 1 to April 30 in Stykkisholmur, and N is the amount of nitrogen fertilizer (kg/ha).

Figure 8 gives the annual hay yield for 1901–75 as a function of the yield predicted by this regression equation. In spite of some scattering it is evident that by considering a period of several years it is possible to obtain a fairly constant yield, even in a long period of unfavorable years as experienced in the nineteenth century (Figure 1). This can be accomplished by using a variable amount of fertilizer according to the climate. To test this hypothesis, an experiment has been conducted for seven years at Hvanneyri in west Iceland. Keeping the amount of fertilizer constant at 100 kg N/ha, the resulting hay yield can be expressed as a function of the winter temperature, the yield being denoted in kg/ha (dry matter):

$$Y = 5{,}680+690W. \qquad (5)$$

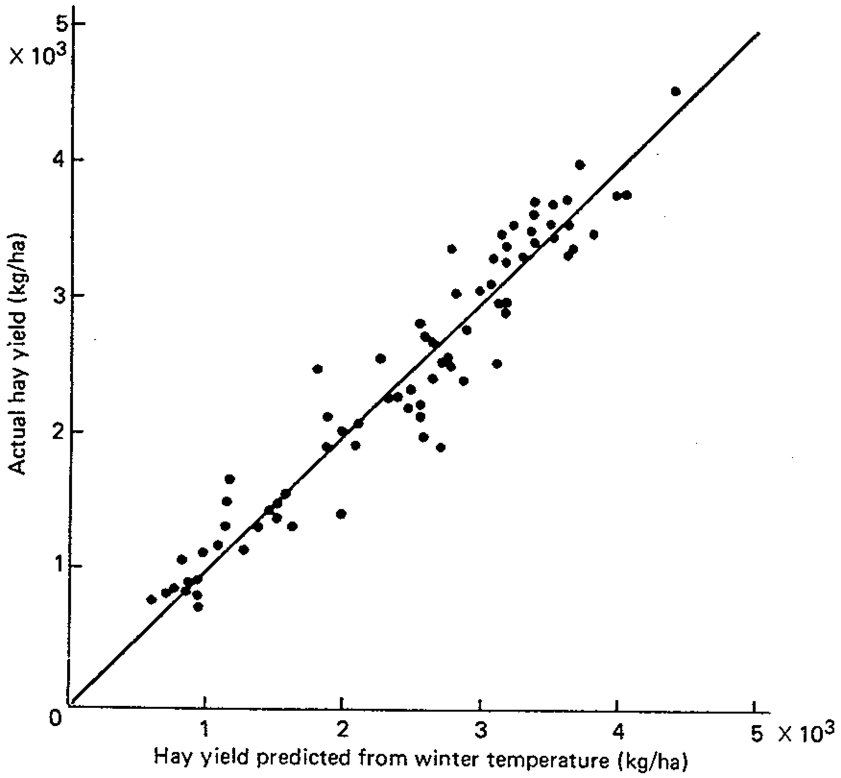


Fig. 8. Hay yield in Iceland compared with the yield computed from the amount of fertilizer and the October–April temperature in Stykkisholmur in the preceding winter and spring, during the period 1901–75.

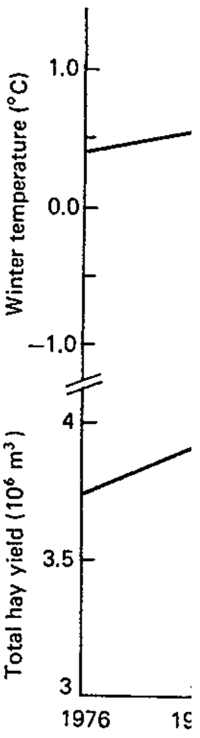
As is usual in trials of this kind, the yield is considerably higher than that obtained on ordinary hay fields, but the relative impact of the winter temperature is in good agreement with Equation (4). When the amount of fertilizer was varied to obtain constant yield, the following regression equation was obtained:

$$Y = 5{,}440 + 30W. \tag{6}$$

In this way the impact of the winter temperature could be practically eliminated, as intended, using an average application of 99kg N/ha.

Finally, we give a test of Equation (4), for the period 1976–83, as shown in Figure 9. Graph A gives the Stykkisholmur winter temperature, and B represents the total hay yield in the country, in millions of cubic meters. In these years the grassland area and the amount of fertilizer used were fairly constant.

It is important that in favorable years the fertilizer should be not so excessive that an additional amount in colder years cannot give the desired increase in yield. This limited use of fertilizer in good years is relatively easy in Iceland, because most of the farmers are able to expand their cultivated grassland by improving the rangelands. This method should enable the farmers to keep their livestock without reduction during single or consecutive severe years.



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11. Conclusions

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Fig. 9. A test of the relationship between winter temperature and hay yield depicted in Figure 8, for a different period. A, October–April temperature in Stykkisholmur; B, hay yield in Iceland.

11. Conclusions

Farming in Iceland is highly sensitive to climatic variations. Long-term changes in temperature are great, partly because of the variable extent of the polar ice off east Greenland. Winter temperature is especially important for the livestock, affecting both hay consumption in the winter and grass growth in the following summer. A model has been derived that relates grass growth to the annual temperature for the period from October 1 to September 30. In addition, phenological observations have been used to relate consumption of winter fodder to temperature. From these relationships it is possible to compute the potential livestock in the country as a function of the long-term temperature. Furthermore, it has been shown that the annual temperature affects the carcass weight of lambs in autumn, and experiments with barley show that relatively slight temperature variations significantly affect its viability. Finally, this study of the effect of temperature variations suggests a method of mitigating climate impacts by a variable application of annual fertilizer.

Appendix 1 Air Temperature and the Growth of Grass and Cereals

Temperature sums have been frequently used as an indicator of growth. Originally, the freezing point was used as a threshold or base temperature, but in most cases it has turned out that a higher threshold temperature is more appropriate, depending on climate and the type of vegetation involved (Table X). We can conclude that the higher the average temperature of the vegetative period, the higher is the appropriate threshold temperature.

TABLE X: Average Temperature and Threshold Temperature for the Vegetative Period of Common Cereals and Grass.[a]

	Average temp. (°C)	Threshold temp. (°C)
European part of the U.S.S.R. (Budyko, 1974)	(15–20)	10
British Isles (Smith, 1975)	(12–15)	5.6–6.1
Iceland (Bergthorsson, 1965)	(10)	3
Northern Ireland, grass in winter (Keatinge *et al.*, 1979)	>0	0

[a] Figures in brackets are the estimates of the author.

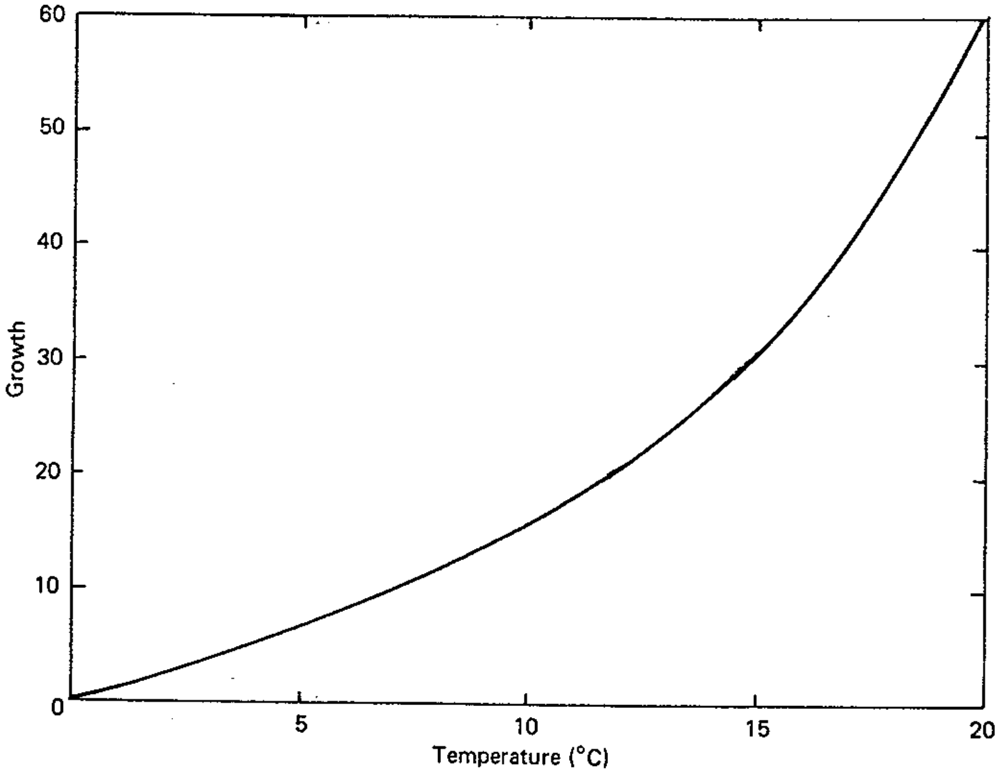

Fig. 10. A graph of growth index G as a function of the mean daily temperature T: $G=T/(1-T/30)$. This function is intended for the computation of temperature sums, avoiding the use of the variable regional threshold temperatures.

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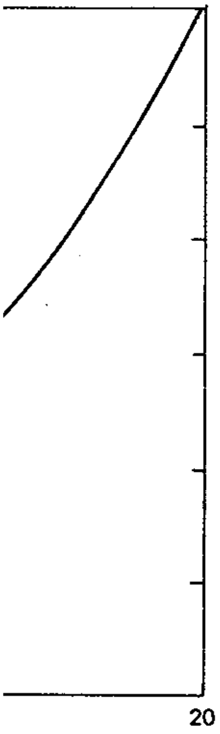

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Calling the average temperature T and the threshold temperature T_g, we can put for the interval 0–20 °C:

$$T_g = T^2/30\,. \tag{7}$$

Assuming that there exists a common growth function for all four regions in Table X, depending on temperature, it follows from the idea of temperature sums that its *derivative* will at any point be, for the interval defined,

$$\mathrm{d}G/\mathrm{d}T = G/(T - T^2/30)\,. \tag{8}$$

Integrating this differential equation, we find:

$$G = T/(1-T/30)\,. \tag{9}$$

This is a kind of daily temperature, approaching the temperature itself when it is close to 0 °C. In all the four climatic regions in Table X, the sums of this function are approximately proportional to the regional temperature sums. This growth function may have to be modified if, instead of the mean daily air temperature, we use another measure of temperature, such as the temperature of the growing points of vegetation, the average of the daily maximum and mean temperatures, etc. The growth function (9) is shown graphically in Figure 10. As Table X indicates, it should not be used for temperatures higher than 20 °C or lower than 0 °C.

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