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On Some Temperature Trends in Iceland, Northern Europe, and Northeastern USA Associated with Prolonged Periods of Severe and Light Ice off Iceland

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by

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A. ABSTRACT

The character of the ice off Iceland by decade was compared with the contemporary, preceding, and subsequent temperatures of Iceland, northern Europe (north of 55°N) and northeastern United States (New Haven, Connecticut).

The decades of severe ice were accompanied by below normal and the decades of light ice, mostly by above normal temperatures, respectively.

The temperature anomaly at Stykkisholm and Archangel in the decade subsequent to a decade of severe ice conditions tends to be negative and in a decade subsequent to a decade of light ice, positive. Further, the temperature anomaly is greater at Archangel but is smaller at Iceland in the decade subsequent than in the decade contemporary with extreme ice.

It is suggested that the tendency for the temperature anomaly at Stykkisholm and Archangel to retain its character in the decade subsequent to a decade with extreme ice conditions is due to persistence and that the intensification at Archangel of the effects of severe and light ice, respectively, off Iceland is due to a diluting of the North Atlantic warm water headed towards the Barents Sea, etc. by the East Icelandic Polar Current.

No consistent relation between the ice and the preceding temperatures for any of the areas was found.

B. PREFACE

Evidence from numerous investigations in the past two decades, or perhaps longer, points decisively to a marked rise in the temperature over wide areas and to a smaller but no less significant rise in the temperature of the northern North Atlantic ocean. Little, if anything, has been said about the possible causes of this rise and whether the relatively high temperatures may continue and for how long.

While a fully successful attack on this problem may not be possible until such time as we possess more adequate data, we can attempt to formulate the broad character of the problem for the North Atlantic and adjacent regions, for which a considerable body of data has recently been published, and to obtain indications of certain trends in the air and water circulation that could be checked with more comprehensive data as they become available.

The comparatively long-air temperature series from the northern North Atlantic and "adjacent" areas cannot, it appears, serve effectively as a basis for measuring the changes in the circulation in that general area. On the other hand, the character of the ice off Iceland, which has been reliably observed for a long period and which reflects in some measure both the changes in the limits of the Arctic ice mass and in the southward transport of polar water, may, in conjunction with the available temperature series, permit an analysis of a major element in the fluctuations in the circulation of the northern North Atlantic and, accordingly, will form the subject of the present investigation.

C. INTRODUCTION

The marked variations from year to year in the limits of the Arctic ice mass, which in some years may amount to several hundred thousand square kilometers, as well as in the southward transport of polar waters[1/] are presumably an important factor in the circulation of both the air and water masses of the North Polar and adjacent regions. The effects of these variations may be secondary but nevertheless sufficient, especially following prolonged periods of either severe or light ice and a great or small influx of polar water, to weaken or intensify existing trends in the circulation. As a result, warm periods may be relatively cooler than might be expected were it not for severe ice conditions prevailing or warmer if little or no ice is at present.

In addition, conditions in the sea change more slowly than in the air (persistence). These in turn are due to the greater stability in the movements of large water masses and the greater heat capacity of water as compared with the air. The oceans, therefore, may be expected to affect the air masses above them following prolonged periods of severe or light ice conditions. Conversely, it might be possible to extrapolate weather conditions in an area for a long series of years for which ice records are available, but for which there are no records of weather conditions.

1/ No data are available for the variations in the southward transport of polar water, which, according to Zubov's (1945) estimates for the East Greenland Polar Currents between Spitzbergen and Greenland (at 81°N), amounts to 80,000 km^3. It may be assumed from the fact that there was little or no ice off Iceland from 1919 to 1940 that the volume of polar water reaching Iceland during that period was very much less than in the period from 1865 to 1874, when Iceland was almost completely surrounded by ice for months at a time.

D. EARLIER INVESTIGATIONS

Wiese (1924) Brooks and Quennell (1928), Scherhag (1937) and others, report a possible interrelation between the ice in the Arctic and certain features of the weather in that and adjacent areas. For example, they suggest that when ice and cold Arctic water extend farther south than normal, the boundary of the polar and warm North Atlantic water is likewise displaced southward. As a result, the North Atlantic storm tracks, which are closely associated with this boundary, also take a more southerly course. The precipitation in areas affected by these storms changes as well. The various steps in the relationships outlined above are not well defined, partly due to a lack of data and partly due to the complexity of the problems involved. However, a correlation between the southerly limits of ice in the Greenland Sea between April and July and precipitation over northwestern Europe between October and December is evident on studying records over a period of nearly 60 years (Schell, 1947).

In general, investigations noted above were based on ice and weather data beginning in the 1880's or later, with the exception of that of Meinardus (1906), who used ice observations from Iceland dating from the early 1800's and on the temperature and precipitation data for Europe previously published by Brückner (1890). A long series of annual estimates of ice off Iceland recently compiled by Lauge Koch (1945) adds nearly forty years to the records previously compiled by Meinardus. These together with the long series of meteorological data now available permits a reexamination of the possible relationships between the long-period ice trends off Iceland and the meteorological conditions in that and adjacent areas.

E. METHODS

The present study is limited to an examination of a comparatively long series of annual temperature observations from Iceland, northern Europe and the northeastern United States and the ice off Iceland. The data have been averaged by decades, because the smoothing of values for longer time intervals tends to give results showing broad correlations between air temperatures and ice rather than reflecting the fluctuations which appear in averaging observations over shorter periods of say a season, a month, or a week. Obviously, some periods of shorter duration of severe ice will be combined with some of light ice and, hence, certain relationships may be obscured. Broad trends, however, may be detected.

The use of annual mean temperatures rather than temperatures for the ice season alone may be criticized. Nevertheless there is considerable justification for this procedure, when one considers the persistence of given water conditions for longer periods than indicated by the presence of ice. Thus, although the ice season off Iceland lasts only for a period of several months (i.e., from late winter or early spring to late spring or early summer), the flow of cold polar water which likewise affects air temperatures, does not necessarily commence with the appearance of the ice or cease with its disappearance. Hence, in the absence of more information on the fluctuations in volume of the various water masses, it is actually impossible to determine the precise effect of the ice conditions alone.

F. DATA

Because significant temperature data (see below) for one of the more important areas is not available prior to 1831, the present study is based on data accumulated since that time. Thus, data for eleven decades

(1831-1940) and one incomplete one (1941-48/9) are considered here.

1. Ice

The oldest record of Arctic ice is from Iceland. It is generally agreed that these observations were carefully made and that they give a fairly accurate idea of actual ice conditions because of its importance in the lives of the inhabitants of Iceland and southwest Greenland. The severity of the ice season off Iceland is usually recorded as the number of days or weeks the ice was observed off the coast and by its relative abundance. This has been tabulated, as already mentioned, by Meinardus (1906) and more recently by Koch (1945) from observations of Thoroddsen (1884) and from records in the "Isforholdene i de Arktiske Have," published by the Danish Meteorological Institute. Koch (1945) also included the extent of the ice surrounding the island. In general, the longer the ice is observed off Kap Horn on the northwest coast, the heavier it is and the farther it spreads eastward along the north coast, thence southward along the east coast and westward along the south coast.

For discussion of the causes of the ice situation off Iceland, the reader is referred to the literature. It should be noted, however, that prolonged periods of severe ice conditions off Iceland, such as those considered here, can, it is believed, occur only when the Arctic ice pack is well developed and a large quantity of ice is carried via the East Icelandic Current to the vicinity of Iceland.

The Icelandic ice data presented here (Table I) consists of annual estimates taken from Koch's graph (1945, Fig. 103). These figures over a period of years show the number of weeks with ice multiplied by the number of areas where the ice was observed along the Icelandic shores. The mean annual values are given for each decade from 1831 in Table II. A comparison of the latter with those of Meinardus (1906) up to 1900 are

Table I. Estimates of Annual Ice Severity off Iceland Given by the Number of Weeks Multiplied by the Number of Areas with Ice Around Iceland Each Year During 1831-1940 (after Lauge Koch, 1945).

Year	Ice Severity	Year	Ice Severity	Year	Ice Severity	Year	Ice Severity	Year	Ice Severity
1831	5	1853	6	1875	0	1897	3	1919	1
2	1	4	6	6	60	8	3	1920	0
3	0	5	95	7	2	9	2	1	2
4	24	6	15	8	60	1900	0	2	0
5	207	7	36	9	3	1	2	3	1
6	0	8	35	1880	9	2	138	4	1
7	137	9	96	1	160	3	9	5	0
8	4	1860	64	2	113	4	0	6	0
9	5	1	0	3	15	5	2	7	0
1840	184	2	6	4	0	6	3	8	1
1	0	3	32	5	6	7	15	9	7
2	0	4	0	6	60	8	2	1930	0
3	2	5	17	7	89	9	0	1	0
4	0	6	174	8	251	1910	0	2	6
5	0	7	96	9	0	1	94	3	0
6	0	8	40	1890	0	2	0	4	0
7	0	9	125	1	49	3	0	5	0
8	3	1870	107	2	131	4	26	6	0
9	0	1	10	3	0	5	47	7	0
1850	4	2	20	4	0	6	2	8	12
1	0	3	7	5	38	7	3	9	0
2	0	4	94	6	83	8	34	1940	0

Table II. Estimated Mean Annual Ice Severity Off Iceland by Decade Shown by the Number of Weeks with Ice Multiplied by the Number of Areas with Ice Around Iceland: 1831-1940 (after Lauge Koch, 1945).

Decade	Ice Units*	Type
1831 - 40	<u>56.7</u>	<u>Severe</u>
- 50	<u>0.9</u>	<u>Light</u>
- 60	35.3	Moderate
- 70	<u>59.7</u>	<u>Severe</u>
- 80	26.5	Moderate
- 90	<u>69.4</u>	<u>Severe</u>
- 00	30.9	Moderate
1901 - 10	17.1	Moderate
- 20	20.7	Moderate
- 30	<u>1.2</u>	<u>Light</u>
- 40	<u>1.8</u>	<u>Light</u>
Average	29.1	

* See Table I

remarkably alike except for those of the first decade (1831-1840). According to Meinardus this period was one of moderate ice, but according to Koch's analysis of Thoroddsen's data, it was a severe one. The latter, I believe, is more accurate because he included the extent of the ice surrounding the island. Accordingly, in this report, that decade (1831-1840) is considered to have been one of severe ice.

Fortunately, the series just described contain three decades (1841-1850, 1921-1930, 1931-1940), which are characterized by little or no ice and three others (1831-1840, 1861-1870, 1881-1890) in which severe ice conditions (Table II) prevailed. In addition to these there is also a decade with light ice (1841-1850) following one of severe ice and two successive decades with light ice conditions (1921-1930, 1931-1940). Thus, the data afford a wide range of ice conditions for analysis.

2. Temperature

Annual temperature records for various localities in the Arctic or sub-Arctic are available as far back as 1846 in Iceland (Stykkisholm), as 1840 in Norway (Vardo) and as 1831 for Archangel.2/ Uninterrupted

2/ Following the completion of this report it was discovered that the temperature record at Archangel actually started in 1814 rather than in 1831, as listed in the Köppen-Geiger Handbuch der Klimatologie (1939). However, since the ice severity for the decade 1821-1830 was not extreme and since extreme ice conditions will be mainly dealt with here, the earlier temperatures have not been incorporated in this report.

temperature series from other stations in northern Europe (north of 55°N) go back even further (i.e., Stockholm, to 1757; Edinburgh, to 1764; Copenhagen, to 1798; Leningrad, to 1806). In North America, on the other hand, New Haven, Connecticut (41°18'N) is the most northern station with a record extending as far back as 1780. The mean annual temperatures for each decade at Iceland (Stykkisholm), Vardo3/, Archangel, etc. are tabulated

3/ Because there appears to be some doubt as to whether the early observations from Vardo (see below) are representative, the data for this station prior to 1868 should be treated with reservation.

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as mean annual deviations (Table III).

3. Localities Considered for Study

Since any long period variations which show a correlation between ice off Iceland and temperatures in that and adjacent areas should be more obvious at stations within or near the Arctic, the situation is first examined at Stykkisholm (Iceland) and then compared with the record from Archangel followed by that for Vardo (Norway) and other localities in northern Europe and the United States.

The location of Archangel on the White Sea, suggests that the temperature there is perhaps correlated with ice conditions in the Barents Sea. Unfortunately, ice data for the Barents Sea are not available prior to 1895. We may assume, however, that the mean decadal character of the ice off Iceland (Table II) is indicative in general of ice conditions for the same periods in the Barents Sea.4/ The long period changes appear

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4/ Beginning with 1895 the general ice pattern in the Barents Sea was generally severe until 1918. From then on to 1939 (last consecutive year available), it was light, or much the same as ice conditions off Iceland for the same periods. During the severe ice period (1895-1918) the mean annual temperature at Archangel and Stykkisholm were, respectively 0.15°C and 4.02°C, as compared with 1.53°C and 4.92°C respectively during the light ice period (1919-1939) which would corroborate the interdependence of the two areas for longer period variations in ice.

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similar in the two areas. Thus, the ice retreated northward in the 20's and 30's from both Iceland and the Barents Sea (as well as from the intervening area). Hence, comparison of the Archangel temperature with ice conditions off Iceland appears permissible.

At Vardo on the north coast of Norway, one might expect to find a

Table III. Mean Annual Temperature Deviation from Long-Term Average at Stykkisholm, Vardo and Archangel and the Severity of Ice off Iceland, by Decade, during 1831-1940.

Decade	Ice Severity (see Table 2)	Stykkisholm °C Δ	Archangel °C Δ	Vardo °C Δ
1831-40	Severe	-	-.47°	-
-50	Light	.43*	.35	(-.20)
-60	Moderate	-.22	.18	(-.16)
-70	Severe	-.58	-.36	(-.42)
-80	Moderate	-.13	-.71	-.25
-90	Severe	-.53	-.30	-.17
-1900	Moderate	-.12	-.68	-.29
-10	Moderate	-.12	.01	-.03
-20	Moderate	-.20	-.11	.00
-30	Light	.65	.65	.53
-40	Light	1.09	1.41	.97

* 1846-50. ( ) Approximate value. ° 1832 lacking.

relation between the temperature there and ice off Iceland similar to that at Archangel. On the other hand, although it is farther north than either Archangel or Stykkisholm, Vardo appears not as affected by northerly winds as the other two (Shaw, 1936). Consequently, it might also be expected to show a somewhat different relation to the ice off Iceland and in the Barents Sea.

The relationship between the general character of the ice off Iceland and the mean decadal temperature at Stykkisholm, Archangel and to a lesser extent at Vardo, is part of a more extensive system involving the circulation of the North Atlantic as a whole, the areas which border it, and possibly other regions as well (Wiese, 1924; Schell, 1940). Thus, the drift of ice from the Arctic, whether in a series of pulsations (Koch, 1945) or as less regular and more gradual outflows, as generally believed, is closely related to the flow of warm North Atlantic water. This, in turn, is dependent on the strength of the trade winds.

Unfortunately, there are no long series of data from the ocean areas in question. Therefore, in order to show a relation between ice in the North Atlantic - Arctic and the circulation of that general area, it is necessary to use the comparatively long temperature records for areas bordering on the North Atlantic (i.e., northern Europe and the northeastern part of the United States). The temperatures of these areas are noticeably influenced by the continental air masses. Nevertheless, if one could find a correlation between ice conditions off Iceland and temperatures at these localities, it would support earlier, more limited evidence that variations in the ice of the North Atlantic and Arctic are related to changes in the circulation over very large areas rather than over local ones.

G. ICE CONDITIONS AND TEMPERATURES, 1831-1940

Ice conditions (a) existing at the same decade, (b) in the preceding decade, or (c) in the subsequent one have been compared with air temperatures in the analysis of data (Tables III and IV) for the several localities under consideration here.

1. Stykkisholm

(a) Comparison with ice conditions in the same period. -- For each of three decades with light ice (1841-1850, 1921-1930, 1931-1940), the mean annual temperature at Stykkisholm for the same period was above average (0.43°C[5], 0.65°C, 1.09°C, respectively), the highest positive deviation occurring for the decade 1931-1940 (Table III). On the contrary, for two decades with severe ice (1861-1870, 1881-1890), negative temperature deviations (- 0.58°C, - 0.53°C) prevailed at Stykkisholm. These are likewise the lowest on record.

(b) Comparison with ice conditions of the previous decade. -- The decades (1871-1880, 1891-1900) with temperature deviations (- 0.13°C, - 0.12°C) somewhat below average, follow decades (1861-70, 1881-90) with severe ice but a third (1841-1850) had a temperature deviation (0.43°C) above average following a decade (1831-40) with severe ice. However, the latter (1841-50) was a period with little ice. It is significant that though the temperature deviation for the decade as a whole was in all probability positive, it is equally probable that it was markedly less than for other decades with light ice (1921-30, 1931-40) which followed periods of moderate or light ice (Table III). Thus, the latter (1931-1940),

[5] Based on 1846-1850 only. However, the entire period of light ice from 1841 to 1854 was implied by Thoroddsen (Meinardus, 1906, p. 155) to have been rather mild in Iceland. According to evidence cited by Jenson (1939) the 1840's must have been quite mild also off the southwest coast of Greenland.

Table IV. Mean Annual Temperature Deviation from Long-Term Average in Northern Europe (Bergen, Edinburgh, Oslo, Stockholm, Helsinki, Copenhagen, Leningrad, Moscow) and Northeastern USA (New Haven, Connecticut) by Decade and the Severity of Ice off Iceland during 1831-1940.

Decade	Ice Severity	Bergen °C Δ	Edinb. °C Δ	Oslo °C Δ	Stock. °C Δ	Copen. °C Δ	Hels. °C Δ	Lenin. °C Δ	Moscow °C Δ	Northern Europe °C Δ	Northeastern USA (New Haven, Conn) °C Δ
1831-40	<u>Severe</u>	-.05	-.27	-.51	-.43	-.53	-.31	-.84	-.35	-.41	-.83
-50	<u>Light</u>	-.02	.01	-.60	-.25	-.39	-.29	-.24	-.20	-.25	-.04
-60	Moderate	-.02	-.02	-.36	.11	-.28	-.25	-.02	-.15*	-.12	-.48
-70	<u>Severe</u>	-.16	-.17	-.38	-.57	-.33	-.64	-.47	-.66	-.42	-.33
-80	Moderate	-.19	-.28	-.29	-.42	-.25	-.42	-.53	-.41	-.35	.35
-90	<u>Severe</u>	-.14	-.26	.00	-.12	-.19	-.02	.07	-.05	-.09	-.41
-00	Moderate	-.15	.23	.19	.23	.18	-.05	-.11	-.13	.05	-.06
1901-10	Moderate	-.01	-.07	.30	.02	.06	.19	.24	.21	.12	-.05
-20	Moderate	.00	.09	.41	.22	.40	.26	.29	.19	.23	.38
-30	<u>Light</u>	.09	.10	.20	.16	.28	.34	.33	.38	.24	.59
-40	<u>Light</u>	.65	.59	1.09	1.03	.93	1.24	1.14	1.17	.98	.86

* Based on 9 years only.

following a decade with light ice conditions, had the largest positive temperature deviation (1.09°C). The decade (1851-1860), on the other hand, which also followed one with light ice, had a small negative temperature deviation (- 0.22°C). This on closer examination appears to have been due to two extremely cold years (1859 and 1860). Thus, for the first eight years (1851-1858) the mean temperature deviation is slightly positive (0.11°C).

(c) Comparison with ice conditions in a subsequent decade. -- Two decades (1861-70, 1881-90) with extreme negative deviations in temperature at Stykkisholm were each followed by moderate, not severe, ice conditions off Iceland (Table III). On the other hand, following decades with a marked positive temperature deviation (1841-50; 1921-30; 1931-40), the ice conditions were moderate in two decades (1851-60; 1941-50[6/]) and

6/ According to preliminary reports, see pp. 33-34.

light in the other (1931-40).

From the foregoing, it is obvious (1) that temperatures at Stykkisholm reflect ice conditions off Iceland for the same period. Furthermore, (2) it appears that after a decade of severe ice off Iceland, the next decade in the general area of Iceland has temperatures below the average unless it be one with little ice. Similarly, in a decade following one with light ice, the temperature is above average.[7/]

7/ The character of the ice during 1941-1950 is available for the first eight years, only in terms, "close to normal," "above" and "below." This and other considerations made it desirable to treat the results for this period separately. Hence, for the temperatures above average following the light-ice decade of 1931-1940, see p. 27.

(3) Finally, as might be expected, no relationship between the air temperatures of Iceland and ice conditions which occur there at a later date

was found, because as mentioned above, the ice off Iceland is chiefly carried down from the north and is not of local origin.

2. Archangel

(a) Comparison with ice conditions in the same period. -- The temperature deviations for Archangel are positive (0.35°C, 0.65°C, and 1.41°C) for three decades (1841-50, 1921-30, 1931-40) with light ice. The highest temperature occurred in the third which followed a decade with light ice (Table III). As at Stykkisholm, on the other hand, the temperature at Archangel for the two decades (1861-70, 1881-90) with severe ice as well as for the first decade (1831-40) was below average, deviations being - 0.47°C, - 0.36°C and - 0.30°C, respectively. These deviations are, however, smaller than those at Stykkisholm. This is the more significant because the standard deviation, σ, of the mean annual temperature at Archangel, ± 1.22°C (1831-1940) is appreciably greater than at Stykkisholm, ± 0.94°C (1846-1940).

(b) Comparison with ice conditions of the previous decade. -- Two decades (1871-80, 1891-1900) following decades (1861-70, 1881-90) of severe ice off Iceland, had temperatures (- 0.71°C and - 0.68°C) below average but a third (1841-50) which was free of ice, following one (1831-40) of severe ice had a small positive deviation (0.35°C). The positive temperature deviation for this decade, however, is much less than those for two other decades with light ice (Table III). Hence, one may assume that had this period (1841-1850) not been almost entirely free of ice, the temperature would likewise have been below average. One decade (1851-1860), on the other hand, following one (1841-1850) of light ice had a slight positive temperature deviation (0.18°C), but another (1931-1940)[8]

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[8] For a discussion of temperatures following the decade 1931-1940, see p. 35.

had a greater one (1.41°C); the largest such value recorded (Table III). This in part was probably due to the absence of ice during the period 1931-40.

(c) Comparison with ice conditions in a subsequent decade. — The three coldest decades at Archangel (1831-40, 1871-80, 1891-1900) were followed by one (1841-50) of light ice, by one (1881-90) of severe ice and by one (1901-10) of moderate ice. Likewise, no consistent relation can be traced between decades with relatively high temperatures at Archangel and ice in subsequent periods off Iceland. Thus, two decades (1841-50, 1931-40)[9] were followed by moderate ice, and a third (1921-30) by light ice.

[9] According to preliminary reports (pp. 33-34).

In short, ice conditions off Iceland are related to temperatures at Archangel for the same period or in the next decade in about the same way as at Stykkisholm, but there is no apparent relationship between temperatures there and ice conditions off Iceland in the next decade.

3. Vardo

(a) Comparison with ice conditions in the same period. -- The Vardo temperature deviations for decades of severe ice (1861-70, 1881-90) are - 0.42°C and - 0.17°C, respectively. Similarly, for three decades with light ice (1841-50, 1921-30, 1931-40), the deviations were - 0.20°C, 0.53°C, 0.97°C, respectively (Table III). Thus, only the temperature of the decade (1841-50) does not reflect the ice conditions. Since some of the early Vardo observations are apparently merely approximations it appears that the Vardo values are relatively consistent with the ice for the general area off Iceland and presumably the Barents Sea.

(b) Comparison with ice conditions of the previous decade. -- Omitting the early Vardo observations, the temperature deviations for the decades (1871-80 and 1891-1900) are both negative (- 0.25°C and - 0.29°C, respectively). Both periods followed decades of severe ice. On the contrary, the deviation in the decade (1931-40)[10] which followed a light-ice decade, was positive (0.93°C). The large deviation in all probability was due to light ice conditions during that period.

[10] For the positive temperature deviation following the light-ice decade (1931-40) see p. 35.

(c) Comparison with ice conditions in a subsequent decade. -- Following the two decades (1861-70 and 1891-1900) with the lowest temperatures at Vardo, ice was moderate. On the contrary, following the two with the highest temperatures (1921-30, 1931-40), the ice was light in one (1931-40) and moderate in the other (1941-50).[11]

[11] According to preliminary accounts (pp. 33-34).

From the above it appears that the temperatures at Vardo as at Archangel show no consistent relationships to the ice conditions off Iceland the subsequent decade, as was to be expected.

4. Northern Europe (exclusive of Archangel and Vardo) and Northeastern United States (New Haven, Connecticut)

(a) Comparison with ice conditions in the same period. -- Three decades of severe ice were accompanied by negative temperature deviations in northern Europe, but only the first two (1831-40, 1861-70) had values markedly below the average (- 0.41°C and - 0.42°C, respectively) (Table IV). In contrast, two of the three decades (1921-30, 1931-40) of light ice had temperatures above average. For the latter the positive deviation was very marked (0.98°C).

At New Haven, Connecticut, the temperature deviations (Table IV) were appreciably below the average (- 0.83°C, - 0.33°C, - 0.41°C, respectively) during each of three decades with severe ice and markedly above the average (0.59°C, 1.18°C) during two light-ice decades (1921-30, 1931-40) but not during a third (1841-50) (- 0.04°C).

(b) <u>Comparison with ice conditions in the previous decade.</u> — The temperature deviation of northern Europe following two decades (1831-40, 1861-70) of severe ice were both negative (- 0.25°C, - 0.35°C) but it was somewhat positive (0.05°C) during a decade (1891-1900) after one (1881-90) of severe ice (Table IV). Following one decade (1841-50) of light ice there was one with a negative temperature deviation (- 0.12°C) but another (1921-30) was followed by one with a positive temperature deviation (0.98°C).[12/]

12/ For the positive temperature deviations following the light-ice decade (1931-40) see p. 35.

Likewise, no consistent relation appears between the temperature of New Haven and the ice of the period preceding it. Thus, for the decades (1841-50, 1891-1900) which followed decades of severe ice, the temperature correlations (Table IV) were negative (- 0.04°C and - 0.06°C, respectively), but for a third (1871-80), it was positive (0.35°C). Similarly, one decade (1841-50) of light ice was followed by a negative deviation (- 0.48°C) at New Haven, but a second (1921-30) by a positive deviation (0.86°C).

(c) <u>Comparison with ice conditions in a subsequent decade.</u> -- For northern Europe, a cold decade (1831-40) was followed by light ice off Iceland, a second (1861-70) by moderate ice there and a third somewhat less cold decade (1871-80) by severe ice (Table IV). Similarly, at New Haven, Connecticut, a cold decade (1831-40) was followed by light ice, a second (1851-60) by severe ice, and a third (1881-90) which was somewhat less cold by moderate ice. Again, the warmest decade (1931-40) of all both in northern Europe and at New Haven, is apparently followed by one with moderate ice (pp. 33-34).

From the comparisons presented above, it appears that temperatures along the northwestern and northeastern borders of the North Atlantic are to some extent related to variations in the ice conditions occurring at the same time off Iceland. One might also expect an ice-temperature correlation between a given temperature trend and ice conditions at some subsequent time, because of the time which must elapse before changes in the circulation of the North Atlantic produce any obvious effects on ice conditions to the north. However, this does not appear to be true since the mean temperature for one decade in northern Europe and the northeastern United States appears to have no consistent relationship with the ice of the next. This was actually to be anticipated because the temperature variations of these land masses are markedly determined by the air masses over these continents, especially in winter with the development of the Siberian and North American Highs, rather than by the waters off their shores.

The absence of a consistent relation for northern Europe, other than at Archangel and Vardo, between decadal ice conditions off Iceland and the mean decadal temperatures in the next decade does not imply that such a relationship does not exist for shorter time intervals. Thus, following severe ice conditions between April and July in the Greenland Sea, the mean North Atlantic cyclonic track (Wiese, 1924), the pressure distribution over northwestern Europe (Brooks and Quennell, 1928), and precipitation over the same area (Schell, 1947) in subsequent months all appear to vary with severe- and light-ice conditions.

H. PROBABLE CIRCULATION PATTERNS ASSOCIATED WITH PROLONGED PERIODS OF SEVERE AND LIGHT ICE OFF ICELAND AND THEIR ORIGIN

From the fact that 10-yearly means of ice extremes off Iceland appear to be related to the mean temperature of the corresponding decades in Iceland, Archangel, Vardo and to some extent in northern Europe and the northeastern United States (i.e., New Haven, Connecticut), it appears that the circulation of the North Atlantic and to some extent also that of the adjacent areas of Europe and North America is associated with variations in the ice of the North Atlantic - Arctic.

With severe ice conditions off Iceland and a greater flow of water from the Arctic Ocean, more cold water can be expected to flow out with the East Iceland Current to mingle with the warm North Atlantic water moving northeastward as the Norwegian Current to the Barents Sea and northward to Spitzbergen (Fig. 1[13/]). Coincident with a decrease in the flow of warm water into the Arctic, less warm air would be transported northeastward. Conversely, with little ice off Iceland and presumably a weaker outflow of polar water from the north, the northward flow of warm North Atlantic water will have less cold water mixed with it and more warm air would move into the Arctic. With severe ice conditions in the North Atlantic - Arctic, farther south, either a southward displacement[14/] of the warm North Atlantic water mass (LeDanois, 1934) or a contraction of the warm North Atlantic cell, presumably due to the strengthening of the trade wind circulation (Iselin, 1940), results in a southward

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13/ Information obtained since the publication of Nansen's paper, confirms the basic picture drawn by him (Kiilerich, 1945).

14/ The word "displacement" seems to the writer a better term for LeDanois' "transgression" in describing the horizontal swayings of the large mass of warm North Atlantic water.


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displacement of the Arctic convergence zone and in a reduced flow of warm water northeastward into the Arctic.

The extent of the ice, the strength of the water and air circulation, and the steepness of the south-north temperature gradients are all interrelated, but it is improbable that they ever reach their maxima at the same time. Thus, the steepest south-north temperature gradient probably does not coincide with the increased circulation, nor the latter with the farthest retreat poleward of the ice.[15] This is partly due to the resistance

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15/ Because the wind is an important factor in the distribution of ice, the view is sometimes held that severe ice off Iceland or in that general area is associated with an increased circulation (Meinardus, 1906; Wüst, 1941). However, Defant (1924) obtained negative correlation coefficients between the ice off Iceland and the mean annual pressure falls between 30°N and 65°N over the North Atlantic and northern Europe to the Northern Atlantic along approximately 70°N. This indicates that an abundance of ice off Iceland tends to be associated with smaller south to north and east to west pressure falls or with a decreased circulation. Substantially, the same results were obtained for the Barents and Greenland Seas by Wiese (1924).

One possible reason for the fact that an abundance of ice off Iceland appears to be associated with a decreased rather than an increased circulation is that severe ice can only occur there if the ice to the north is plentiful. Also the steepening of the south to north and east to west pressure gradients over the North Atlantic and the corresponding increase in the circulation is generally associated with a northward displacement of the Icelandic Low (Eriksson, 1943). Thus, that region is influenced by more southerly winds. This shift would tend to drive the ice away that is carried to Iceland by the off-shoots of the East Greenland Polar Current or directly from the Greenland sea itself.

Meinardus' (1906) conclusion that severe ice off Iceland over long periods of time is associated with an increased circulation is based on a comparison of the smoothed five-year means of the mean annual Copenhagen to Stykkisholm pressure fall and the mean fifteen-year ice values off Iceland centered about the middle five-year period corresponding to the current five-year period. However, his results are in part due to a fortuitous combination of data. Thus, the largest positive deviation (0.96 mm.) in the Copenhagen-Stykkisholm pressure fall (i.e., increased circulation) for the period of severe ice (centered about 1861-1865), but the pressure deviation corresponding to an equally severe ice period (centered about 1886-1890) is only 0.04 mm. In addition, the deviation for a very mild ice period (centered about 1846-1850), which would be expected to show a marked negative deviation, was actually shown by him to be slightly positive (0.07 mm.).

Not only the ice off Iceland but also that of the Arctic as a whole shows an increase in the circulation correlated with a decrease rather than an increase in the ice. Thus, the increase in circulation in recent decades in the northern North Atlantic, the northern North Pacific and the Arctic Ocean was accompanied by a marked shrinkage of the Arctic pack both in area and thickness. The first result of an increased circulation is for more ice and polar water to be carried out of the Arctic. With a continuation of this flow more warm air and water enters the Arctic from the south. As a result, the ice will melt and the Arctic ice pack will shrink.

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to change (inertia) of the ice and the oceanic circulation, partly because some critical limit must be attained before an obvious reversal in trend can occur, and partly because of the interaction of the atmospheric circulation of the North Atlantic with that of other areas. Some time must elapse, therefore, before an increased transport of warm air, for example, can effect a decrease in the southward extension of the ice.

As suggested earlier (Schell, 1940), a given set of ice conditions with its corresponding circulation and temperature gradient, when fully established, tends to promote conditions that work against the initial state. If undisturbed, these will eventually lead to the opposite state. Thus, an increase in the northward transport of warm water and air and a poleward retreat of the ice is caused by a steeper south-north temperature gradient. In time this process will produce a less steep gradient with decreased circulation. Partly because of the momentum of the circulation and partly because of conditions elsewhere, the decrease to be expected by the return of the normal south-north gradient may sometimes be greater than normal. The transport of warm water and air to the north will then decrease below normal, and the ice will subsequently advance southward beyond its normal limits.

On the other hand, with the retreat poleward of the ice, there will be a fall in pressure to the north. This increases the circulation, but the weakened south-north temperature gradient, caused by the increased transport of warm water and air northward, results in a decreased circulation. The apparent contradiction resulting from these two tendencies (Simpson, 1927) can be reconciled, however, if we assume that the more or less simultaneous trends toward an increased and decreased circulation are not in balance (Brooks, 1928). Consequently, these swings in the North Atlantic circulation are, as often observed, irregular both in phase and amplitude.

Were the circulation self-contained, these irregular swings would soon die out. However, this is not the case, and means that they are in part determined by non-atmospheric factors of a terrestrial or extra-terrestrial origin. It is reasonable to assume that with the sun as the primary cause of the equator-to-pole temperature gradient, changes in its radiation whether directly or indirectly could cause the irregular shifts in circulation. However, an increase in solar radiation does not necessarily accentuate the general south-north temperature gradient of the surface layer. The effect caused by a change in the sun's activity is such as one might expect when superimposed on the particular phase in the circulation of a particular region.[16]

16/ The scheme for the circulation fluctuations described above is in partial agreement with Ångstrom's (1939) views that large temperature differences between equator and poles presumably result from a reduced circulation. According to him, however, a change in the temperature gradient cannot affect the circulation, as it is determined by changes in the stratosphere alone. Ångstrom believes that the atmosphere is stirred by traveling depressions controlled from the stratosphere.

This appears improbable because the bulk of the air lies within the first few kilometers of the atmosphere and because the oceans are the primary source of the atmosphere's moisture as well as stabilizers of the circulation, by reason of their great heat storage. It is reasonable to suppose that the changes in the lower layers of the atmosphere though initially due to changes in the sun are more significant in effecting the irregular swings in circulation than the changes in the stratosphere as suggested by Ångstrom (1939) and others.

I. EFFECT OF ICE OFF ICELAND ON THE SUBSEQUENT TEMPERATURE AT ARCHANGEL

From the examination of the mean decadal character of the ice and corresponding temperature deviations, it appears that following severe ice, the temperature deviations at Stykkisholm and Archangel tend to be negative and following light ice, positive. This might be expected from the distribution of currents and winds in the northern North Atlantic (Fig. 1), because following severe ice off Iceland, more cold water than usual presumably enters the warm North Atlantic water and thence flows into the Barents Sea after it rounds the North Cape. This suggests that at Archangel we may expect an accentuation of the local persistence effect due to either severe or light ice conditions off Iceland the decade before. Hence, the temperature deviation at Archangel will be greater than at Stykkisholm where it depends only on the local persistence of such conditions. If this is true, it is to be expected that the temperature deviation at Archangel will be greater following these periods of extreme ice conditions, than it was during such periods.

Thus, for the two decades (1871-80; 1891-00) each following one with severe ice, both followed by moderate ice, the negative temperature deviation in each (Table V) was (1) greater at Archangel than at Stykkisholm (- 0.58°C vs. - 0.13°C and - 0.68°C vs. - 0.12°C, respectively) and (2) greater in the succeeding decade than during the one (- 0.58°C vs. - 0.36°C and - 0.68°C vs. - 0.30°C, respectively) of the severe ice.

For a decade (1831-40) of severe ice followed by one with light ice with a positive temperature deviation (presumably in response to the light ice regime), the positive deviation was smaller at Archangel than at Stykkisholm (0.35°C vs. 0.43°C). This suggests that cold water and ice at Iceland the previous decade may have affected conditions at Archangel the succeeding one (1841-50).

Table V. Differences in Temperature Deviations Between Archangel and Stykkisholm for Decades Following Severe and Light Ice, Respectively, off Iceland: 1831-1949

Decade Contemporary	Decade Following	Ice Character		Archangel °C	Stykkisholm °C	Difference °C
1831-40		Severe		-.47	-	
	1841-50		Light	.35	.43	-.08
1861-70		Severe		-.36	-.58	
	1871-80		Moderate	-.58	-.13	-.45
1881-90		Severe		-.30	-.53	
	1891-00		Moderate	-.68	-.12	-.56
1841-50		Light		.35	.43	
	1851-60		Moderate	.18	-.22	.40
1921-30		Light		.65	.65	
	1931-40		Light	1.41	1.09	.32
1931-40		Light		1.41	1.09	
	1941-9		"Moderate"	2.3*	1.10	

* 1949 only.

For the decades with light ice one (1851-60) following another with light ice (1841-50) showed a positive temperature deviation at Archangel as compared with a negative one at Stykkisholm (0.18°C vs. - 0.22°C). The Archangel temperature, however, was not higher than that for the previous decade.[17] The temperature deviation at Archangel for 1931-40, following

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[17] The circulation associated with the light ice decade (1841-50) was probably not as intense as during the recent light-ice period (1919-1940) when all of northern Europe as well as northeastern United States had the highest temperatures on record. This may explain the rather small positive temperature deviation at Archangel the next decade (1851-60) and negative deviation at Stykkisholm. (For the first eight years (1851-58) it was positive, averaging 0.11°C).

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a light-ice decade (1921-30) was somewhat greater than at Stykkisholm even allowing for Archangel's larger standard deviation, σ, (1.41°C vs. 1.09°C) and was also greater than for the previous decade (1.41°C vs. 0.65°C). It is not possible to make any definite conclusions about the effect of light ice off Iceland for 1931-40 on the Archangel temperature in the years 1941-50, because only one year (1949) of the Archangel record is available. Furthermore, the decade (1931-40) itself was one of little ice. The Archangel deviation that year was positive and one of the largest (2.3°C) on record.

On the whole, following severe and light ice respectively, off Iceland, the temperature at Archangel is more extreme than at Stykkisholm since it not only reflects conditions off Iceland but also seems accentuated by the E. Icelandic Current diluting the warm North Atlantic water entering the Barents Sea.

J. ICE AND TEMPERATURE TRENDS AFTER: 1941-1950

The light ice off Iceland during the last two decades (1921-40) raises the question as to whether the mean temperature during the present one (1941-50) in the general vicinity of Iceland, Vardo and Archangel will prove to be above average and also as to whether the positive deviation at Archangel will be greater than at Stykkisholm as suggested above. Actually, since there were two consecutive decades with light ice we might expect to find especially large positive temperature deviations at Stykkisholm for 1941-50 provided the ice trend during this decade has not reversed itself.

Rough estimates of the ice conditions off Iceland for the period 1941-48 (U. S. Coast Guard Bull. 1947; Danske Meteorologiske Institut 1941, 1946; author's correspondence) indicate the following:

1941	"close to normal"
1942	"below normal"
1943	"somewhat above normal"
1944	"much above normal"
1945	"close to normal"
1946	"close to normal"
1947	"somewhat less than normal"
1948	"close to normal"

or, taking the eight years together (no data later than 1948 were available) the ice off Iceland for 1941-8 may be considered as "close to normal."

Hence, since the ice was not severe enough to counteract a trend toward temperatures above normal caused by the presence of little ice in the two preceding decades, we may assume that the mean temperature for 1941-8 was above average at Stykkisholm, at Archangel and perhaps also Vardo.

Observations at Stykkisholm indicate that the mean annual temperature for the period 1941-8 corresponding to generally normal ice conditions off Iceland, was 1.30°C above average and for the period 1941-9, 1.15°C, compared with 1.09°C in the preceding decade (1931-40). The mean annual temperature at Archangel for the year 1949 was one of the highest on record. At Vardo[18] the average temperature deviation based on seven

18/ The station was destroyed in August 1944 and did not open again until June 1945. Comparison with neighboring stations, however, indicated that the annual temperature in 1944 and 1945 was slightly above normal.

years (1941-3, 1946-9) was 0.33°C.[19]

19/ The mean 1941-9 annual temperature deviation at Edinburgh, was 0.55°C, at Bergen 0.54°C, at Oslo 0.90°C, at Stockholm 0.70°C, at Helsinki 0.64°C, at Copenhagen 0.75°C, and at New haven, Connecticut 1.34°C (Table VI).

Comparing the ice off Iceland for this period (1941-8) with that of the preceding 22 years (Table I), it appears that in the 8-year period (1941-8) the ice was on the whole "close to normal" and in at least one year, "above normal." On the other hand, the ice was "below normal" each year for the period 1919-40. Fourteen years had no ice at all. The trend, therefore, for very little ice may not have reversed itself, but, at least, it was temporarily ceased.

If the general atmospheric circulation is self-contained (see pp. 20-22), any prolonged rise in the temperature in high latitudes will weaken the general atmospheric south-north temperature gradient. As a result, the transport of warm air poleward will soon decrease and conditions favoring an increase in the polar ice-cap and a greater flow of ice into the East Greenland Polar Current and also towards Iceland will occur once more (Schell, 1940).

We may, therefore, anticipate from the relationship described above and from the evidence for the period 1941-8, suggesting that the years with light ice have ceased, that everything else being constant the trend toward high temperatures in the general vicinity of Iceland, Vardo and Archangel is not likely to continue long in its present intensity. The change at Archangel, however, would be expected to occur later than at Stykkisholm.

Table VI. Mean Annual and Decadal Temperatures at Archangel, Bergen, Copenhagen, Edinburgh, Helsinki, Leningrad, Moscow, New Haven (Conn.), Oslo, Stockholm, Stykkisholm, and Vardo, during 1831-1949 (except as noted).

Year	Archangel °C	Bergen °C	Copenhagen °C	Edinburgh °F 40+	Helsinki °C	Leningrad °C	Moscow °C	New Haven °F 40+	Oslo °C	Stockholm °C	Stykkisholm °C	Vardo °C
1831	0.7	8.0*	8.3	8.1	4.1	3.5	4.2	9.2	5.7	5.4	-	-
2	-	8.1*	8.0	7.7	4.7	3.3	3.5	7.7	5.9	5.6	-	-
3	0.2	7.6*	7.7	7.2	4.6	3.9	5.0	8.3	5.6	5.8	-	-
4	-0.4	8.5*	9.0	8.7	4.5	3.3	4.4	8.9	6.3	6.8	-	-
5	-0.7	7.2	7.7	6.8	3.8	3.4	3.4	6.6	5.8	5.6	-	-
6	0.6	6.4	7.1	5.7	4.0	4.0	5.2	5.2	4.7	5.0	-	-
7	0.0	6.6	6.8	5.7	4.2	3.4	3.9	6.4	4.9	4.8	-	-
8	-0.7	5.8	5.3	4.7	2.5	2.1	3.0	8.2	3.5	3.9	-	-
9	0.6	6.9	6.3	6.4	3.8	2.7	3.6	9.2	4.7	5.3	-	-
1840	-0.8	6.6	5.1	6.7	2.9	2.1	2.5	9.0	5.0	5.3	-	-
1	1.4	6.9	6.8	6.6	4.4	4.7	4.8	9.5	4.6	5.6	-	1.2
2	0.5	8.2	8.1	8.0	4.8	4.2	3.5	9.9	6.7	6.4	-	1.1
3	0.9	7.4	7.7	7.6	4.5	4.7	4.9	7.4	5.6	5.8	-	0.7
4	0.4	6.4	6.5	6.8	2.4	2.7	3.4	10.2	4.0	4.1	-	0.5
5	-0.3	6.9	6.3	6.2	3.5	2.9	3.3	10.2	4.6	5.0	-	0.6
6	1.0	8.7	8.6	9.6	4.4	3.8	4.0	10.1	6.5	6.5	6.0	1.3
7	1.3	7.4	7.3	7.4	4.3	4.0	4.6	9.4	5.2	5.5	5.5	1.3
8	1.5	7.0	7.5	7.0	4.3	4.2	4.9	9.2	4.7	5.9	3.2	0.6
9	0.6	6.5	6.9	6.5	3.2	2.9	3.1	8.3	4.5	5.1	4.2	0.5
1850	0.3	6.6	7.0	7.1	3.5	3.6	3.7	8.8	4.8	5.4	4.0	-0.5
1	1.9	7.0	7.5	7.1	4.4	4.7	4.6	9.0	5.3	6.0	4.7	1.2
2	-0.5	8.1	8.1	8.6	3.3	2.9	3.5	8.8	5.4	6.1	4.6	-0.1
3	2.0	7.1	6.8	6.9	4.2	4.2	4.2	9.6	5.2	5.6	4.3	1.9
4	1.2	7.3	7.4	8.6	4.6	4.5	4.6	9.3	6.1	6.5	3.8	1.3
5	-0.6	6.2	6.0	6.3	3.1	3.2	4.0	9.0	4.1	4.9	3.4	0.1
6	-1.7	6.5	6.8	8.1	2.1	2.2	3.5	7.0	4.1	4.7	4.9	-1.6
7	-1.0	8.3	8.3	9.5	4.3	4.4	4.6	7.5	6.3	6.7	4.2	0.4
8	2.0	7.7	7.7	6.8	4.9	4.8	4.6	8.3	6.6	7.0	4.2	2.3
9	2.5	7.6	8.4	6.1	5.1	5.2	-	8.0	6.5	6.5	1.8	1.4

* Interpolated from neighboring stations.

Year	Archangel °C	Bergen °C	Copenhagen °C	Edinburgh °F 40+	Helsinki °C	Leningrad °C	Moscow °C	New Haven °F 40+	Oslo °C	Stockholm °C	Stykkisholm °C	Vardo °C
1860	0.1	6.2	6.8	4.3	3.7	3.8	3.1	8.6	4.0	4.9	3.4	0.8
1	-0.5	7.8	7.5	6.5	4.0	3.7	3.1	10.1	5.6	5.5	4.6	1.8
2	-2.1	7.4	7.1	6.2	2.0	1.2	1.2	9.5	4.6	3.7	3.7	-0.3
3	2.8	7.6	8.5	7.4	5.6	5.8	5.2	10.0	6.7	6.7	2.7	1.9
4	0.2	6.7	6.5	5.7	3.4	3.6	3.5	9.9	4.3	4.5	4.8	0.6
5	-0.1	7.0	7.3	6.8	3.2	3.6	3.2	9.3	5.1	5.4	3.2	-0.1
6	-0.3	7.3	7.8	6.9	4.1	4.4	4.7	8.0	5.7	5.3	1.8	0.2
7	-1.9	6.3	6.1	6.9	1.4	1.5	2.6	8.0	4.1	3.2	3.3	-1.2
8	0.8	7.6	8.4	8.8	4.2	3.8	4.0	7.0	6.5	6.4	3.5	0.8
9	2.6	6.4	7.6	7.2	4.6	4.9	5.4	7.0	6.0	5.6	3.1	1.2
1870	-1.0	6.5	6.5	7.2	3.3	2.9	2.7	9.0	4.8	5.0	5.0	0.2
1	-1.0	6.6	6.0	6.7	2.1	2.2	3.2	8.0	4.2	3.7	4.6	-0.1
2	0.0	8.2	8.7	7.0	5.5	4.9	5.0	8.0	6.6	6.9	4.5	0.5
3	-1.0	7.6	8.0	7.0	4.9	4.0	4.4	7.9	6.3	6.4	3.8	0.6
4	1.1	7.2	7.9	7.1	4.7	4.3	4.6	9.3	6.3	6.0	2.8	1.1
5	-1.6	6.8	7.0	7.6	1.8	1.4	1.3	8.3	4.7	4.3	4.8	0.3
6	-0.5	6.7	7.3	7.2	3.0	2.9	3.6	10.8	5.1	4.9	4.1	0.8
7	-0.4	6.4	7.0	6.5	3.2	2.9	3.3	12.5	4.1	4.7	3.2	0.4
8	1.5	7.0	8.3	7.4	5.1	4.8	5.1	12.7	6.3	6.2	3.4	1.7
9	-0.7	6.4	6.3	3.8	3.9	3.7	3.5	10.8	4.8	4.8	4.3	1.3
1880	-0.4	7.4	7.6	7.3	3.8	3.7	4.1	11.7	5.9	5.7	4.7	0.2
1	-0.4	6.0	6.5	5.8	2.5	2.9	3.3	9.9	4.3	4.1	2.4	-1.1
2	0.0	7.8	8.4	7.2	5.2	5.1	5.5	8.8	6.4	6.7	2.6	0.8
3	1.4	7.4	7.7	7.0	4.3	4.2	4.4	7.6	5.9	6.0	4.3	1.7
4	-0.9	7.9	8.2	7.7	4.3	3.6	3.5	8.9	6.2	5.9	4.5	0.8
5	-0.6	6.4	7.3	6.3	4.1	4.2	4.1	7.4	5.3	5.2	2.9	0.2
6	0.9	6.7	7.6	6.2	4.6	4.6	4.3	8.3	5.5	6.1	2.9	0.9
7	0.5	6.9	7.3	6.8	4.9	4.8	5.1	8.7	6.2	6.1	3.2	1.2
8	-1.7	6.4	6.4	6.0	2.3	2.0	2.7	7.2	4.5	4.1	3.8	-0.4
9	1.3	7.7	7.6	7.4	4.5	4.2	3.7	10.2	6.8	5.9	4.9	1.7
1890	0.6	7.6	7.7	7.6	5.3	5.2	5.1	9.3	6.1	6.5	4.7	1.8
1	-0.7	7.5	7.5	7.1	4.6	4.1	4.4	10.0	5.8	6.2	4.6	0.4
2	-0.8	6.1	7.2	5.6	3.0	2.8	3.8	8.6	5.2	5.2	2.3	-0.1
3	-2.1	7.1	7.3	8.9	2.6	2.3	2.9	7.6	5.4	5.0	4.1	-0.7
4	1.1	7.9	8.3	7.8	5.5	4.8	4.4	9.7	6.7	7.0	4.9	1.4
5	-0.1	6.4	7.3	6.7	4.1	3.7	4.0	8.9	5.2	5.7	4.5	0.7
6	0.5	7.5	8.4	8.2	5.2	4.6	3.8	8.9	6.5	6.7	3.9	1.2
7	0.7	7.2	8.0	7.5	4.9	4.8	5.1	9.5	6.3	6.4	4.2	1.8
8	0.6	7.3	8.2	9.2	4.7	4.7	4.6	10.3	6.2	6.5	4.0	1.7
9	-1.4	7.0	8.4	8.0	3.6	3.6	4.2	9.2	6.2	5.7	3.5	0.0

Year	Archangel °C	Bergen °C	Copenhagen °C	Edinburgh °F 40 +	Helsinki °C	Leningrad °C	Moscow °C	New Haven °F 40 +	Oslo °C	Stockholm °C	Stykkisholm °C	Vardo °C
1900	-0.5	6.7	7.8	7.7	3.5	3.6	3.7	10.7	5.6	5.7	4.3	0.0
1	0.0	7.6	7.9	7.9	4.8	4.6	5.2	8.7	6.3	6.5	4.8	1.1
2	-2.6	6.5	6.6	6.4	2.5	2.1	3.2	9.4	4.7	4.2	3.7	-0.8
3	1.5	7.2	7.9	6.9	5.4	5.3	5.9	9.2	6.1	6.4	3.3	0.8
4	0.3	7.0	7.8	7.0	3.7	3.8	3.8	6.7	5.8	5.3	3.9	1.1
5	1.8	7.2	7.7	7.6	4.8	4.9	5.1	8.8	6.3	6.5	4.3	1.2
6	1.2	7.5	8.5	7.5	5.4	5.3	5.6	10.4	6.9	6.5	3.7	[illegible]
7	-0.3	7.0	7.5	6.8	3.4	3.1	2.8	8.3	5.7	5.4	3.4	[illegible]
8	0.0	7.7	7.8	7.9	4.1	3.7	2.8	10.9	6.4	5.6	5.1	1.2
9	0.9	6.6	6.9	6.4	4.2	4.1	4.3	10.1	5.3	5.0	4.5	1.0
1910	1.4	7.8	8.6	6.9	5.8	5.6	5.6	10.3	6.7	6.6	3.6	1.0
1	0.4	7.7	8.9	8.3	4.9	4.3	4.0	10.5	7.2	6.7	4.3	1.3
2	-1.1	7.6	7.6	7.3	4.2	3.8	3.6	9.9	5.9	5.7	4.5	-0.4
3	0.6	7.8	8.6	8.0	5.2	5.3	5.3	12.3	6.9	6.6	4.4	1.4
4	0.5	8.0	9.0	8.8	5.4	5.3	5.0	9.4	7.3	7.2	3.4	1.5
5	-1.0	6.0	7.2	6.6	2.5	2.7	4.1	11.1	4.7	4.5	4.5	0.4
6	1.1	7.3	8.0	7.2	4.2	4.5	4.5	9.4	6.2	5.7	4.2	0.6
7	-0.3	6.4	7.5	6.4	3.9	3.4	3.9	7.9	5.1	5.2	3.4	-0.3
8	-0.5	7.5	8.1	7.7	4.6	4.0	4.5	9.8	6.3	6.1	3.0	1.0
9	0.1	6.1	7.3	6.1	4.0	3.7	3.7	10.9	5.3	5.4	3.9	1.0
1920	3.2	7.8	8.4	7.9	5.9	6.0	5.5	9.3	6.4	6.9	3.9	2.8
1	1.8	7.3	8.8	9.2	5.0	4.5	5.1	11.9	6.9	6.8	3.8	1.9
2	1.9	6.4	6.9	6.5	3.8	3.9	4.8	10.8	5.4	5.1	4.7	2.2
3	1.0	6.4	7.2	6.8	3.9	3.6	4.5	9.6	5.2	5.1	4.3	1.7
4	1.3	7.5	7.3	7.4	5.0	4.6	4.3	9.3	5.8	5.8	4.3	1.7
5	1.3	7.8	8.5	7.2	4.9	5.2	6.2	10.6	6.2	6.3	4.3	1.4
6	0.3	8.0	8.5	8.2	3.7	3.6	3.9	8.4	6.0	5.8	5.0	0.5
7	0.7	7.0	7.9	7.2	4.4	4.0	4.1	10.7	5.2	5.8	5.2	0.9
8	1.0	7.1	7.9	7.4	4.4	4.4	4.1	10.9	5.5	5.5	5.9	1.4
9	0.0	7.0	7.5	7.3	4.2	3.9	3.8	10.6	5.8	5.7	5.7	1.0
1930	1.3	8.6	8.9	7.3	6.3	5.7	5.2	11.5	7.2	7.5	4.8	1.9
1	1.7	6.9	7.6	7.1	3.9	4.0	4.1	12.8	5.5	5.2	4.9	1.4
2	2.4	7.8	8.9	8.2	5.4	5.6	6.0	11.8	6.9	6.7	5.5	1.4
3	0.2	8.5	8.6	9.5	4.7	4.0	3.4	11.1	6.9	6.4	6.0	1.5
4	2.7	8.7	9.9	9.3	7.0	6.5	6.1	9.8	7.9	8.2	5.0	2.5
5	1.8	7.6	8.8	7.9	5.6	5.0	5.4	10.2	7.0	7.0	4.8	1.8
6	2.6	8.2	8.6	7.9	6.1	6.0	6.3	10.4	6.9	7.1	4.9	1.8
7	2.9	8.0	8.6	7.7	5.9	5.9	6.0	11.6	6.9	7.3	5.0	2.8
8	2.9	8.2	9.5	9.3	6.9	6.4	6.9	11.8	7.8	8.1	5.3	3.2
9	1.1	8.1	8.8	8.7	5.7	5.0	5.5	10.9	6.9	7.2	6.2	1.6

Year	Archangel °C	Bergen °C	Copenhagen °C	Edinburgh °F 40+	Helsinki °C	Leningrad °C	Moscow °C	New Haven °F 40+	Oslo °C	Stockholm °C	Stykkisholm °C	Vardo °C
1940	-0.1	6.7	6.6	7.7	3.4	3.1	4.2	8.8	5.4	4.9	4.8	1.0
1		7.0	7.0	6.9	2.5			11.6	5.1	4.8	6.4	0.0
2		6.6	6.5	7.5	2.8			10.9	5.1	4.5	5.4	0.3
3		8.2	9.2	8.9	6.4			10.7	7.5	7.8	4.2	2.1
4		7.7	8.7	8.0	5.9			11.9	7.0	7.1	4.9	-
5		8.3	9.2	9.6	4.8			11.7	7.4	7.0	6.1	-
6		8.0	8.3	8.0	5.0			12.3	6.9	6.7	6.2	1.7
7		7.4	8.0	7.3	4.1			11.5	5.6	6.2	5.0	1.3
8		8.2	9.1	8.4	5.6			11.2	6.9	7.1	5.2	1.7
9	2.7∞	8.4	9.7	9.7	6.6			14.2	8.1	8.0	4.3	1.7

<u>Ten Year Means</u>

Year	Archangel	Bergen	Copenhagen	Edinburgh	Helsinki	Leningrad	Moscow	New Haven	Oslo	Stockholm	Stykkisholm	Vardo
1831-40	-0.06°	7.17	7.13	6.77	3.91	3.17	3.87	7.87	5.21	5.35	-	-
-50	.76	7.20	7.27	7.28	3.93	3.77	4.02	9.30	5.12	5.53	4.58+	.73
-60	.59	7.20	7.38	7.23	3.97	3.99	4.07*°	8.51	5.36	5.89	3.93	.77
-70	.05	7.06	7.33	6.96	3.58	3.54	3.56	8.78	5.34	5.21	3.57	.51
-80	-0.30	7.03	7.41	6.76	3.80	3.48	3.81	10.00	5.43	5.36	4.02	.68
-90	.11	7.08	7.47	6.80	4.20	4.08	4.17	8.63	5.72	5.66	3.62	.76
1900-00	-0.27	7.07	7.84	7.67	4.17	3.90	4.09	9.26	5.91	6.01	4.03	.64
-10	.42	7.21	7.72	7.13	4.41	4.25	4.43	9.28	6.02	5.80	4.03	.90
-20	.30	7.22	8.06	7.43	4.48	4.30	4.41	10.05	6.13	6.00	3.95	.93
-30	1.06	7.31	7.94	7.45	4.56	4.34	4.60	10.43	5.92	5.94	4.80	1.46
-40	1.82	7.87	8.59	8.33	5.46	5.15	5.39	10.92	6.81	6.81	5.24	1.90
-49		7.76	8.41	8.26	4.86			11.78	6.62	6.58	5.30	1.26*+

<u>Mean</u>

Year	Archangel	Bergen	Copenhagen	Edinburgh	Helsinki	Leningrad	Moscow	New Haven	Oslo	Stockholm	Stykkisholm	Vardo
1831-1940	0.41°	7.22	7.66	7.26	4.22	4.01	4.22*°	9.37	5.72	5.78	4.15++	.93**

° Except 1832 ∞ Approximately *° Except 1859 +Mean: 1846-50
++Mean: 1846-1940 ** Mean: 1841-1940 *+Mean: 1941-43, 1946-49

K. SUMMARY

1. We have assumed that due to the interaction between air and the oceans the trend of ice off Iceland and that general vicinity must be closely related to the circulation in the northern North Atlantic and adjacent areas. In addition, because of the persistence of the ice and the polar water associated with it, a relationship was also assumed between ice and the circulation trends for the next decade in the area of the ice and general vicinity.

2. In this investigation, only the air temperatures of Iceland, northern Europe, and the northeastern United States (1831-1949) were compared with ice conditions off Iceland. A consideration of direct measures of air and water circulation to be derived from ocean currents, pressure distribution, winds, etc. is planned for the future. The analysis was also limited to prolonged periods of severe and light ice conditions, to permit the relationships between ice and temperature to become more obvious than is possible in comparing "close to normal" conditions. Under the latter circumstances, fluctuations in the temperature can occur in either direction[20] because of the quasi-stable character of the circulation.

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[20] Actually, at Stykkisholm, which unlike Archangel, appears to be uncomplicated by an accentuation of effects caused by a transport of water from the West, the temperature deviation also corresponded to the ice character for the moderate ice decades.

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3. Comparison of the mean decadal ice extremes with mean temperatures for the same decades at Stykkisholm, Archangel and Vardo indicate a definite relationship between the two for the same period (Table III). Thus, three decades with severe ice off Iceland (1831-40, 1861-70, 1881-90), were accompanied by temperatures below average at Archangel. At Stykkisholm and Vardo, where no data are available for a decade with severe ice

(1831-40), temperatures were below average in the other two decades in question. Similarly, three decades with light ice (1841-50, 1921-30, 1931-40) were accompanied by temperatures above average except at Vardo in the one decade (1841-50), (see below). Comparison of the mean decadal temperature of northern Europe, exclusive of Archangel and Vardo, and of the northeastern United States with the ice off Iceland indicates that the circulation over these areas is to a marked degree part of the same process that determines ice conditions off Iceland (Table IV).

4. Furthermore, the temperatures of Iceland, Archangel, and perhaps also Vardo[21] are seemingly related to the ice conditions of the previous

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[21] From the fact that Vardo lies between Iceland and Archangel and appears more exposed to the influence of the warm North Atlantic water flowing around the North Cape than Archangel, we might have expected better agreement between the Vardo temperatures and the ice conditions of the previous decade than was actually obtained. We have already noted the possibility that some of the Vardo observations during the early period of that station's operation are only approximate. It is also possible in view of Vardo lying to the west of Archangel that the effect of different ice extremes off Iceland on Vardo's temperature occurs earlier there than at Archangel and for that reason the relation of the Vardo temperature with the ice may not have been as clear in the decadal comparison.

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decade. This apparently means that the effects of ice and cold water persist for a considerable period locally. Thus, lower than average temperatures usually follow decades with heavy ice and higher temperatures, decades with light ice. In addition, these are strengthened at Archangel by cold water carried southeastward from Iceland and mixed with the northeastward flowing warm North Atlantic water. Hence, at Stykkisholm the extreme deviations occur during periods of extreme ice conditions (Table III), but at Archangel, the extreme deviations occur in the decade following one of extreme ice conditions.

5. No consistent relationship was indicated between the ice off

Iceland and the temperature of Iceland, Archangel, Vardo, etc. during the preceding decade.

6. The reversal in trend from practically no ice at all during the period from 1919 to 1940 toward normal conditions for the period 1941-8 suggests that the trend toward comparatively high temperatures in the general areas of Iceland, Vardo and Archangel may not continue much longer. The change at Archangel would, however, occur later than at Stykkisholm.

L. APPENDIX

1. Influence of City Development on the Temperature

In connection with the increase of the temperature in recent decades at stations considered here, the question arises as to what extent the rise at stations in cities has been due to the growth of the city itself. A recent comparison (Liljequist, 1943) of the mean December-March temperature in Stockholm and with a station "2.5 km. north of the observatory of Stockholm and about 1.5 km. outside Stockholm proper" for the period 1882-1940 shows that the observatory values have always been slightly higher, but there has been no consistent increase in the temperature difference between the two locations. Similarly a comparison of the annual temperatures in Copenhagen with those of a neighboring village for the period 1861-1935, indicates that the effect of upbuilding is only about 0.15°C (Lysgaard, 1937). Essentially the same conclusions have been drawn for other areas, such as the United States (Kincer, 1933, 1946), and the East Indies (de Boer and Euwe, 1949). From these reports we may safely conclude that by far the major portion of the marked rise in temperatures in recent decades at Oslo, Leningrad, Moscow, etc. was due to the same causes that produced the rise at Stykkisholm where the question of city upbuilding does not arise.

2. Temperature Data

The data were taken for the most part from World Weather Records by H. H. Clayton (Editor) (1927, 1934, 1947) and the Handbuch der Klimatologie by W. Köppen and R. Geiger (1939). The use here of temperature observations over the long period 1831 to 1940 or later, made it desirable to examine the data carefully to make sure that the data were comparable. In many cases the site of the stations had changed. Accordingly certain corrections have been necessary for some of the published series.

Archangel

The mean annual values for 1831-1930 except for the years 1832, 1833 and 1921, are available in the Köppen-Geiger (1939) Handbuch d. Klimatologie (Section N_2) tabulated as deviations from the mean 0.2°C. The values for 1881-1915 were 0.1°C too high and those for 1922-1930, 0.2°C to correct them to the 24-hr. mean.

The data for 1921 was found in Reseau Mondial and an approximate value for 1833 was derived from the figures for the 10-month period March-December and the long-term average for January and February. The new mean derived from the 109-year series, 1831-1940 (less 1832) is 0.41°C. The mean annual value for 1949 was derived from figures in Die Mitteleurop Grosswetterl. Deutsch. Wetterdienst, U. S. Zone, Bad Kissingen.

Leningrad

The values given as deviations from a mean of 3.9°C for 1831 to 1920 were taken from the Köppen-Geiger (1939) Handbuch d. Klimatologie and those for 1921-1940 from World Weather Records (Clayton, Ed., 1927, 1934, 1937). The annual values for 1921-1930 were reduced by 0.1° to correct them to 24-hr. means. The 1831-1940 mean is 4.01°C.

Moscow

The temperature values given as deviations from a mean of 3.5°C at the Konstantin Institute (55°36'N, 37°40'E), for 1831 to 1930 (except 1859) were taken from the Köppen-Geiger (1939) Handbuch. The values for 1916-1930 represent temperatures from another station, the Agricultural Institute (55°50'N, 37°33'E), where the mean annual temperature was found to be 0.7°C lower. Thus, the values from 1916 to 1930 had to be increased by 0.7°C. However, since those for 1921-1930 were not corrected to 24-hr. means, only 0.6°C was added to the values for that period. Furthermore, the March 1930 temperature was incorrectly given as $- 12.2^{\circ}$ instead of $- 1.2^{\circ}$ (in both the Handbuch and the World Weather Records), the net rise for that year was actually only $+ 1.5^{\circ}C$.

Finally, the values for 1931-1940 (World Weather Records, Volume III) had to be increased by $0.7^{\circ}C$ to make them comparable with the corrected series for 1831-1930. The new mean derived from the 109-year series (1831-1940, omitting 1859) is $4.22^{\circ}C$.

Stykkisholm

Mean annual temperatures for the period, 1846-1930, were taken from World Weather Records (Clayton, Ed., 1927, 1934, 1937) and for subsequent years were obtained through correspondence. The values are based on observations made at 2 p.m. except for the period January 1869 to May 1873 when the observation was taken at noon. The latter have been adjusted to conform with the 2 p.m. reading by adding $0.4^{\circ}C$, one exception (1873). For the five months of that year only $0.2^{\circ}C$ was added. The mean based on the 95-year period, 1846-1940 is $4.15^{\circ}C$.

Bergen and Oslo

The mean annual temperatures up to 1940 were taken from World Weather Records (Clayton, Ed., 1927, 1934, 1937) and for subsequent years, from official publications and by correspondence. The Oslo station was moved to a new site (Blindern) in May 1937, and the records taken there have been reduced to make them comparable with the series from the old site by adding $0.9^{\circ}C$ to the annual figure. The Bergen and Oslo means for the period 1831-1940 are $7.22^{\circ}C$ and $5.72^{\circ}C$, respectively.

Vardo

The data for the period from 1867 to 1933 are from Table II (p. 33), those from 1840 to 1866 from Tables Ia and Ib (p. 3?) of Birkeland's (1934) paper, and those after 1933 from official publications and from personal correspondence. The figures for the period from 1867 to 1875 in Table Ib (Skancke's series) do not differ in a uniform way from those for the same period in Table II. Thus, some of the values for 1856 to 1866 as well as those for some of the earlier years must be regarded as approximations only. The mean value for the 100-year period 1841-1940 is 0.93°C.

Stockholm

The data given as deviations from the mean 5.7°C until 1925 were taken from the Köppen-Geiger (1939) Handbuch der Klimatologie and after that from official publications and by personal correspondence. The 1831-1940 mean is 5.78°C.

Copenhagen

The information up to 1940 is from World Weather Records (Clayton, Ed., 1927, 1934, 1937) and for subsequent years by correspondence. The 1831-1940 mean is 7.66°C.

Edinburgh

The mean annual values from 1831 to 1863 are taken from a paper by Brunt (1925), from 1864 to 1940, from World Weather Records (Clayton, Ed., 1927, 1934, 1937) and from 1941 on, through personal correspondence. Because of a recent change in the site of the station, 0.6°F was added to the annual figure to make the values after 1930 comparable with the earlier series with 1931. The mean value for the 110-year period 1831-1940 is 47.26°F.

New Haven, Connecticut

The data up to 1940 are taken from World Weather Records (Clayton, Ed., 1927, 1934, 1937) and subsequently through personal correspondence.

After June 30, 1943, temperatures have been taken at airport station. To reduce the data taken there to a comparable basis with that of the old site, 1.9°F has been added. For 1943, however, to adjust for the first six months, at the old site only 1.0°F was added. The mean value for the 110-year period of 1831-1940 is 49.37°F. The value for the year 1897 was erroneously given as 48.7°F instead of 49.5°F.

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