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M. J. DUNBAR AND DENIS H. THOMSON

WITH 6 FIGURES IN THE TEXT

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Abstract

Climatic variations affecting the West Greenland marine region since the 16th century are reviewed in association with historical records of the Atlantic salmon (*Salmo salar* L.) in that area. There is evidence that the salmon, which are very abundant at present during their sea-life in West Greenland waters, were also present in some numbers in the years around 1600 and 1810. In all three periods the marine climate was cooling, following a warming phase. A possible hydrographic mechanism for this effect is suggested in the alternation of a strong zonal (west-east) climatic system over the North Atlantic region, giving warmer conditions in West Greenland, and periods of weakening of this zonal system and the appearance of anomaly easterly winds in South Greenland. The latter cause East Greenland Current water and Irminger Current water to increase in transport in the formation of the West Greenland Current, and are associated with a southward movement of the Iceland Low and a reduction in pressure gradient between the Iceland Low and the Azores High.

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Introduction

The West Greenland fishery for the Atlantic Salmon (*Salmo salar* L.) is of recent vintage. HORSTED (1971) describes it as having increased considerably in 1964. It began to develop in the late 1950's (PYEFINCH, 1972) and the appearance of the salmon in noticeable number was recorded first at the end of the 1920's. Salmon were reported to be fairly common in the early 1950's, according to information collected from Faroese and Spanish cod-fishermen (HORSTED, *pers. comm.*). Since it has been claimed (LANK, 1972) and denied (DUNBAR, 1975) that the salmon was first found in the West Greenland area by the crews of United States nuclear submarines, we quote here a passage from JENSEN's (1939) now classic paper on climatic change and its faunistic effects:

"The salmon (*Salmo salar*) was previously only known and only in small numbers at two places, namely, Kapisigdlit in Godthaab Fjord and Amerdlok Fjord near Holsteinsborg. But towards the end of the twenties the observation was made, that in the autumn (October and November) a migration of large salmon takes place in the Sukkertoppen district, though not very near the coast. Later, especially in 1935 and 1936, the salmon occurred in numbers from October and on into December at several places in the Sukkertoppen district, at the dwelling place Ikerasak and in fjords round about as also at the outpost Napassok and the dwelling place Agpamiut. In the autumn of 1935 about 200 of this stately fish were caught at Ikerasak. In September 1936 a number of salmon were caught at Lichtenau, in 1935 in October several salmon were noticed at Fiskenæsset, and in September 1938 a salmon was caught in the Tasermiut Fjord."

There is no doubt that the West Greenland Current is now an important sea-life area of the Atlantic salmon from the rivers of Canada, Ireland, Scotland and Norway. Pelagic salmon fisheries opened up at the same time off the Norwegian coast and in the vicinity of the Faroe Islands, and it may now be said that the mystery of the whereabouts of the salmon at sea is now no longer a mystery. This appears to have left the impression among fishery biologists and the public alike that the salmon have always visited the West Greenland region in numbers, and that their presence there has only recently been discovered. This view has been questioned (DUNBAR, 1972, 1973) on several grounds: The

salmon swim very close to the surface and are taken in surface drift nets. The West Greenland waters have been fished and hunted for some four centuries. Whalers sailed up the West Greenland coast regularly during the 19th century and well into the 20th, and the Greenlanders themselves, though using mainly the inshore waters, know what is going on further to seaward. The "Tjalfe" Expeditions of 1908 and 1909, Dr. A. S. JENSEN in charge, worked in Southwest Greenland specifically with the purpose of exploring for possible fisheries to develop, and these investigations have continued to the present time. It is thus quite unreasonable to believe that, had the salmon been in those waters during such a long period of time, they could have escaped attention and exploitation long ago.[1]

It is also unreasonable to suppose that the climatic warming that occurred from about 1915 to 1940, which drastically altered the whole of the marine fauna of West Greenland and made it possible to establish cod and halibut fisheries there, should not also have involved the salmon. The clear inference, therefore, is that the sea-life area of the salmon in the Northwest Atlantic shifted from an uncertain region, perhaps in the Irminger Current water southwest of Iceland, in response to the recent climatic change. The present paper will show reason to suppose that this has occurred, and that the Atlantic Salmon were abundant during at least two periods in the past, about the years 1600 and 1810, when the climate was in a cooling phase following a brief warming phase, the condition of the climatic cycle in West Greenland, and indeed globally, at the present time.

The climatic cycle

According to present accepted accounts (e.g. FAIRBRIDGE, 1972) the melting of the last glacial ice sheets to their approximate present extents occupied the time between about 14,000 years to 6000 B.P. The date of the "climatic optimum", or warmest time, varied with latitude. In Africa it occurred about 12,500 B.P., in Arctic Canada about 6000 years B.P. (see, e.g. HATTERSLEY-SMITH, 1972). After the climatic optimum there has been general cooling. The treeline in the north has retreated south some 500 km, there has been a decrease of air temperature of 2.5°C in mid-latitudes, and an increasing aridity in the tropics (FAIRBRIDGE, 1972). This general cooling has been interrupted by warm periods. There was a secondary climatic optimum which lasted from the

[1]) This view may be questioned on the grounds that the salmon in fact avoid detection from the decks of ships, and that their presence is detected only by the use of the drift nets at present used in the fishery. Nevertheless, four centuries is a long time for such an oversight.

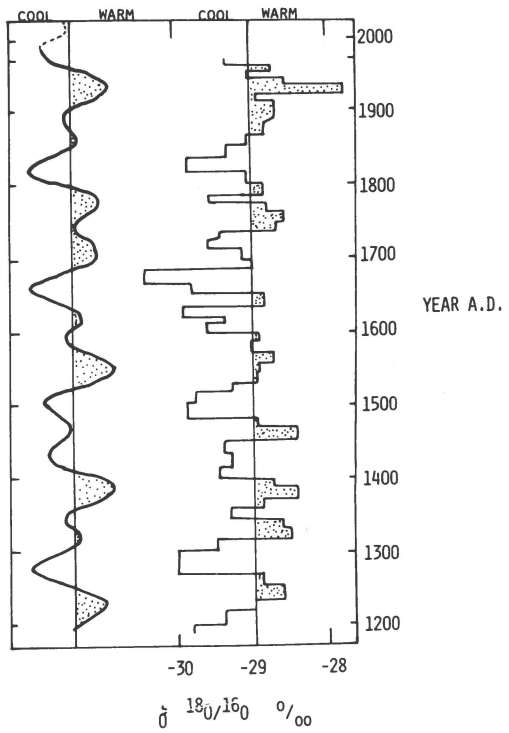

Fig. 1. Right: The deviation of $^{16}O/^{18}O$ in dated layers from the Camp Century ice core from standard water. Low values indicate warm periods. Left: The results of harmonic analysis of the $^{16}O/^{18}O$ ratio projected into the next century. (From JOHNSON et al., 1969).

6th to the 12th centuries, during which the polar sea ice retreated, vineyards extended up to 500 miles further north than at present and the North Atlantic surface water was warmer (LAMB, 1963). The most recent warming occurred in the 20th century, described below.

The interval between these two warmer periods is known as the "little ice age". Its duration varied with latitude, but it is generally placed from 1430 to 1850. It was marked by general cooling, advance of glaciers, and expansion of the Arctic pack-ice, and there were short periods of warming within it.

Superimposed on these long term changes are variations of shorter period. The glacial-interglacial oscillation, according to several authorities, will probably be maintained as long as the geographic poles are approximately in their present positions; a view put forward first, or implied, by EWING & DONN (1956) and developed in later papers (e.g., DONN & EWING, 1966). The present climatic position is that the climate is cooling on the glacial-interglacial scale, warm but cooling on the 20th

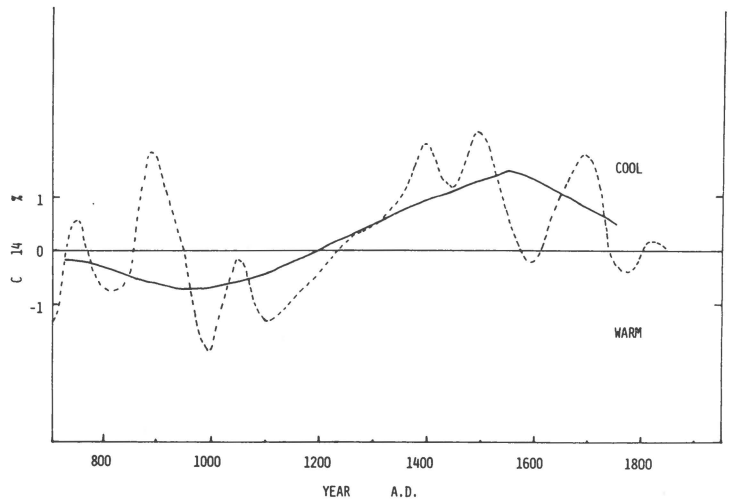

Fig. 2. Variations of C^{14} in the atmosphere plotted as a % of 1859 values.
– – – – – variations plotted every 50 yrs. (From WILLIS et al., 1960).
———— 200 year means of C^{14} variation. (From BRAY, 1966).

century scale; and there is also some evidence that the cooling trend of the past 40 years has been reversed locally in the past five years (LAUZIER, 1972 and others), on evidence, *inter alia*, from the Gulf of St. Lawrence and the eastern Canadian seaboard. The warming trend in West Greenland reached its peak between 1936 and 1940 (DUNBAR, 1946; LAUZIER, 1972), and the salmon appeared there in large numbers well after the peak, in the late 1950's, when the cooling process was well advanced.

The record of climate in previous centuries comes from historical records and from various techniques of temperature measurement and dating, such as pollen analysis, foraminifera in sea sediments, and the use of oxygen, carbon, and other isotopes. The details of the method do not concern us here. The relevant papers are: WILLIS et al., 1960; BRAY, 1966; DANSGAARD et al., 1969; JOHNSON et al., 1969, and the patterns of climatic change that have come out of these studies are summarised in Figs. 1, 2, and 3.

The records elicited by the use of different methods are in good agreement, and it is apparent that there have been, within the past five centuries (which is as far back as the records of salmon in West Greenland go) three main periods in which the climate has been in a cooling phase, excluding the smaller variations, namely in the mid-20th century, the period about 1800, and in the early 17th century, or about 1600. It remains to compare this climatic record with what can be extracted from the historical record of the presence or absence of Atlantic salmon in the waters along the West Greenland coast.

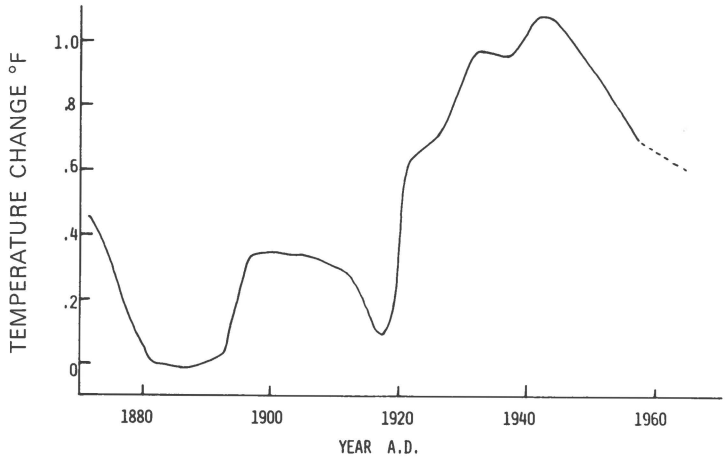

Fig. 3. Change in northern hemisphere air temperatures relative to the 1880–84 pentade, plotted as 5 year means in °F. The data are from a large number of uniformly distributed stations from 0–80°N. (From MITCHELL, 1961).

The Salmon in West Greenland

We meet at once a linguistic problem. The word "salmon" is frequently used among English-speaking Northerners to denote the Arctic char (*Salvelinus alpinus*), and the same applies to the Danish "Laks". The precise vernacular terms are "salmon" for *Salmo salar* and "char" for *Salvelinus alpinus*, and respectively in Danish, "Skællaks" and Lakseørred" or "Fjeldørred". In Greenlandic Eskimo there is no such confusion; char is "Ekraluk", or "Eqaluk", and the word for the Atlantic salmon is "Kapisilik", and the Greenlanders do not confuse the two, either linguistically or biologically. Unfortunately the records are in English and Danish, not in Greenlandic. Nevertheless a search of the literature has produced some interesting results.

The first reference to fluctuations in Atlantic salmon abundance in West Greenland waters is to be found in PENNANT (1784), a highly reputable zoological author. He refers to the "Fauna Groenlandica" of FABRICIUS (1780) throughout his work, and in the case of the salmon specifically identifies it as *Salmo salar*. The entry reads: "The salmon, No. 143" (FABRICIUS's number—which is in fact misquoted by PENNANT; it should be No. 123) "is extremely scarce at present, yet in DAVIS' time, was among the presents made to him by savages; and BAFFIN saw most amazing schools of these fish in "Cockin's Sound" on this western coast in Lat. 65°20′N". PENNANT does not confuse the salmon with the char, which he also records.

All sources agree that the salmon was very scarce in Greenland in the 18th century. FABRICIUS (1780) records it as rare. CRANZ (1782), after mentioning the abundance of the "Lachs-forellen" (char), common in the streams, writes: "A few of the common salmon ("Lachse oder Salme") are found in a few places, but they fall greatly short of those of Norway and other countries in size and abundance". HANS EGEDE (1763), after discussing the beauty and abundance of the "small salmon" (char) comments that "the species of large salmon is found in a few places in the country".

PENNANT's mention of DAVIS and BAFFIN refers to the late 16th and early 17th centuries, and there are others from the same period. FROBISHER visited West Greenland in 1576, and records that the natives "came aboard his ship and brought him salmon and raw flesh and fish" (BEST, 1758). From this bare statement it is not safe to identify his "salmon" as *S. salar*. JOHN DAVIS in 1586 (MARKHAM, 1880) was brought skins, cod, capelin and "salmon peale" by the natives. "Salmon peale" is defined as salmon of the first season or grilse, by WRIGHT (1903). WILLUGHBY (1686), a work which we have seen only in the original Latin, has it: "At D. WILLUGHBY in Pisce *Salmon-Peal* dicto, quem Salmonem juvenem esse conjicio ...". In MARTYN's (1785) "New Dictionary of Natural History", we find: "Salmon Peel — an appellation given to a fish very common in some of the Welsh rivers, agreeing in the colour of its flesh, and perhaps also in kind, with the Salmon"; in fact, a salmon. HOUGHTON (1879) tells us that "the term grilse or Salmon-peal denotes a fish on its first return from the sea". Although the term was apparently used somewhat loosely by countrymen and fishermen, to mean sometimes the young of the "bull trout" (sea trout), it appears to have been used by serious authors to refer to the salmon only. In contemporary Newfoundland, incidentally, "salmon peel" denotes young salmon before they go to sea for the first time: parr, or smolt.

It should be pointed out that in fact salmon and char are not easily confused: The much larger and easily detachable scales of the salmon, and the lack of the conspicuous white leading edges on the fins, typical of the genus *Salvelinus*, are the obvious external characters, and no man of experience, zoologist or not, would confuse the two genera.

JAMES HALL was in West Greenland in 1605; in describing the country, he wrote: "Moreover in the rivers we found sundry sorts of fishes, as seals, whales, salmons with other sorts of fishes in great abundance" (HALL, 1625). From the description of these "rivers" it is clear that he is using the term to mean "fjords", a common usage at the time (Godthåbsfjord, for instance, was until quite recently named "Baal's River", or "Ball's River" on Admiralty charts. MARKHAM (1880) refers to

DAVIS travelling two miles up a "river" which was two leagues at its narrowest).

BAFFIN (1625a) has the following passage in a description of a voyage made with JAMES HALL in 1612 to West Greenland, describing fishing from kayaks:

> "In these Boates they catch the most part of their food, being Seales and Salmons, Morses, and other kinds of fishes. Some they kill with their Darts, and other some with Angles, having a line made of small shivers of Whales Finnes, and a Hooke of some fishes bones; with which Line and Hookes, we also caught very much fish".

This is a description of sea fishing, not river fishing. Char are not normally caught in salt water except very close to shore, being fished in streams by the building of wiers or the use of the fish-spear.

In August of 1616 BAFFIN was at anchor in "Cockin's Sound", Latitude 65°45'N (BAFFIN, 1625b), now called Søndre Isortoq. He writes: ". . . on the first of August, six of the Inhabitants in their canoes, brought us Salmon Peale, and such like"; and "In this Sound we saw such Scales (shoals) of Salmon swimming to and fro, that it is much to be admired . . ."

All these records of the 15th to 16th century period refer to salmon seen and caught in full salt water, where the char, during their short seasonal sea-life, are seldom seen and seldom caught.

Following the general scarcity of salmon in West Greenland during the 18th century, its presence in the 19th century appears to have been variable, to judge from the available literature. There is very good evidence for the presence of both Atlantic cod and Atlantic halibut in West Greenland waters as far north as Disko island in the years between 1807 and about 1825, so that the association of Atlantic salmon with them would not be surprising, on analogy with the 20th century. JENSEN (1950) documents the abundance of cod during that period, and quotes GIESECKE (1878), among others. GIESECKE travelled in West Greenland for eight years, 1806 to 1813, on geological reconnaissance, and kept good notes on animals and plants in an extensive diary. Unfortunately he uses the same German word "Lachs" for both salmon and char, and does not give Latin (systematic) names for them; yet he must have seen both species, for he describes the "excellent salmon" in the river at Kapisigdlit (Godthåbsfjord), where *Salmo salar* is still found today. Nevertheless there is little doubt that he refers to salmon at several points in his diary, in the sea and in association with Atlantic halibut, cod, and seals. Such observations could not refer to char, which do not go far from shore in their brief visit to salt water and are not caught, as the salmon are, in drift nets offshore.

The relevant passages from GIESECKE (1878) are the following: 1807, Diskofjord: "Dorsche, Helleflynder, Lachse und Kabliaue trifft man an mehreren Stellen". 1808. Ataneq fjord (Egedesminde District): "Ein thätiger Europäer würde hier sowohl mit Eisgarnfange also auch mit Kabliaue- und Lachsfang vieles erwerben können...". 1806, Tunugdliarfik fjord (Julianehåb District): "Nepiseten (*Cyclopterus lumpus*), Dorsche und Lachse sind ebenfalls häufig". 1808, Tasiusarssuk (Lachsebugt) (Holsteinsborg District): "In dieser Bucht giebt es viele Lachse". 1808, Tasiusak (in Godthåbsfjord): "In derselben ist guter Angmagsak- und Lachsfang". Angmagsak is the capelin, caught only in full salt water. All these records in GIESECKE, in fact, refer to fjord water, and hence to salmon rather than char.

DEWHURST (1834) wrote that "the common salmon is occasionally met with on the coast of Greenland." After that early 19th century period, *Salmo salar* appears to have become scarce again, as in the 18th century. RINK, writing in 1857, recorded the salmon as scarce. In 1891 PACKARD wrote of the Labrador coast: "At Hopedale the salmon is quite rare and not common north of this point. It seems to be a rare species in Greenland".

It is clear, then, that the Atlantic salmon has not always been abundant off the West Greenland coast. The historical evidence presented here can be summed up as follows:

1576–1586:	Salmon probably present
1605–1625:	Salmon probably abundant
18th century:	Salmon scarce
1806–1812:	Salmon present, perhaps abundant
1820–1850:	Salmon scarce
1890–1928:	Salmon scarce
1928–1931:	Salmon observed in increasing numbers
1935–1958:	Salmon becoming more common
1958-present:	Salmon very abundant.

Salmon migration and changing oceanographic conditions

There remains the problem of the manner in which the salmon respond to marine climatic change, and the environmental signals to which the salmon respond in their migration. In the fluctuations of North Atlantic climate, the positions of the Iceland low pressure area and the subtropical Azores high pressure area, and the intensity of the pressure gradient between them, are decisive. During the recent cooling one of the

Fig. 4. Number of days per year, with a westerly type circulation over the British Isles plotted as 19 year means. (From DICKSON & LAMB, 1972; LAMB, 1973)

important changes has been the shift from the predominantly zonal (west-east) circulation involving strong westerlies, which marked the warm period, to a circulation with more meridional (north-south) movement. The zonal circulation, for instance, was accompanied by strong westerly circulation over the British Isles. Fig. 4, from DICKSON & LAMB (1972) and LAMB (1973) shows that the westerly winds were weakening during the cooling period following the West Greenland warm peak in the mid 1930's. At the same time the North Atlantic pressure gradient (Iceland-Azores), which was high in the early 1920's, declined, with a temporary upswing in the late 1940's, to the 1960's (Fig. 5, from World Weather Records, RODEWALD, 1947, 1972). During periods of high gradient, the subtropical (Azores) high remained at a fairly constant latitude, but the Iceland low was pushed northward, also shown in Fig. 5 for the month of January. The subpolar (Iceland) low moves northward with intensification of the westerlies and southward with their diminution (DICKSON & LAMB, 1972). The mean latitude of 55.5°N for the years 1961–1973 is the lowest on record.

It should be emphasized that we are dealing here with global effects; there are always local variations and temporary reversals. The global nature of the processes is well shown by the fact that the southward movement of the westerly wind belts during decline in the North Atlantic pressure gradient allows expansion of the polar vortex and is accompanied by a southward shift of the principal zones. Troughs in the belt of the westerlies travel farther south, giving the Mediterranean and the Middle East a wetter climate. The tropical belt of meridional circulation contracts and the monsoons do not extend so far north, giving North Africa a drier climate (WINSTANLEY, 1973). The years from

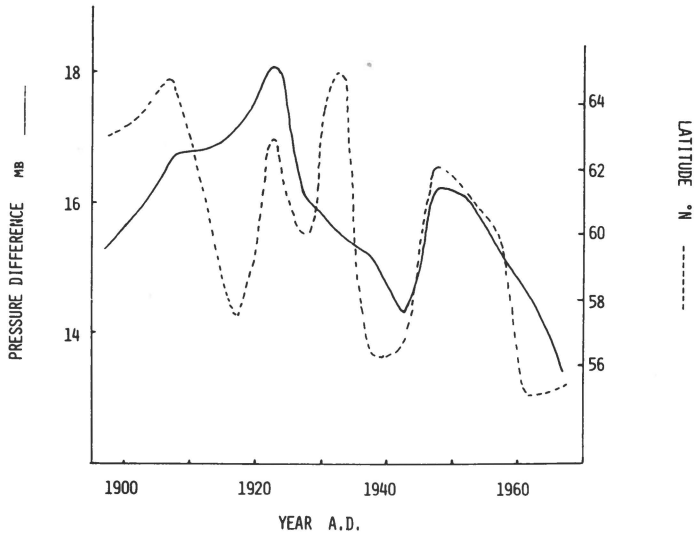

Fig. 5. North Atlantic pressure gradient. The difference in surface pressure between Iceland and the Azores in mb plotted as 5 yr means. (From World Weather Records, RODEWALD, 1967; RODEWALD, 1972). Solid line. Latitude of the Icelandic low in January plotted as a 5 yr means. (From LAMB & JOHNSON, 1966, recent values from Deutscher Wetterdienst charts of mean monthly pressure). Dotted line.

1950 to 1970 have shown a great decrease in zonal, westerly type circulation (Figs. 4 and 5), northern hemisphere air temperature (Fig. 3), and North African rainfall (WINSTANLEY, 1973). How far this change will proceed is impossible to determine on present data. Based on data from the Greenland Ice cap JOHNSON et al. (1969) expect the present cooling trend to continue for one or two decades, with subsequent amelioration reaching a maximum in about 40 to 50 years. WINSTANLAY (1973) does not except a change for another 60 years.

The oceanic response to changes in atmospheric circulation involves changes in current velocity and transport, surfaces and subsurfaces temperatures and salinity, and the distribution of ice. When there is a strong zonal atmospheric circulation the Atlantic oceanic gyre shrinks in size and increases in velocity (MARTIN, 1972). The western boundary current (Gulf Stream proper) is found farther from shore, causing a decrease in sea level on the eastern seabord (KUTALO, 1972). With the weakening of the westerly zonal pattern of circulation, the Atlantic gyre is reduced in velocity, the gyre as a whole expands, and the boundary current moves closer to the shore. These effects hold for both secular and seasonal changes; there is a three-month time lapse in the response of the hydrospheric circulation, so that the response to the maximum wind stress, which occurs in winter, has its marine maximum in the early spring. But this seasonal, or annual, effect, does not concern us here.

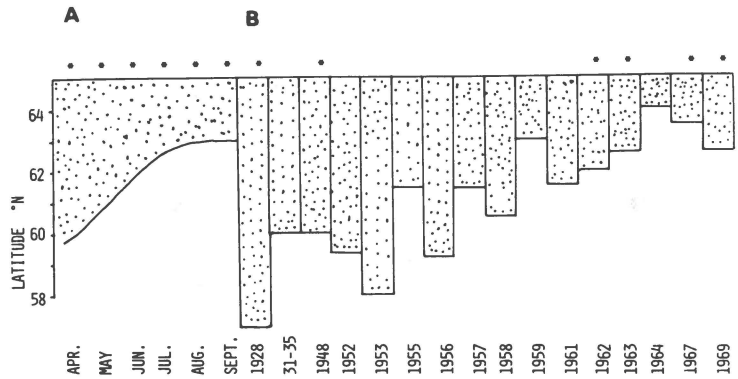

Fig. 6. Latitude of the northernmost point of the Labrador Sea trough, the point at which the West Greenland Current begins to turn westward. a) Seasonal variation from April to September 1962 and 1963; b) Variation in July from 1928 to 1969. (From SMITH, SOULE & MOSBY, 1937; LEE, 1968; ALEKSEEV et al., 1972; HERMANN, 1953, 56, 58, 59a, 59b, 61, 63, 66). Where noted, • the latitude was taken from charts of dynamic topography. Others were determined from the distribution of surface temperatures.

WEYL (1968) has suggested another mechanism by which circulation is slowed down during periods of weak zonal circulation. Weak wind fields will cause reduced evaporation, leading to a reduction in surface salinity. In the Caribbean, for instance, surface salinity will be reduced by a reduction of water vapour flux across the Isthmus of Panama. WEYL (1968) shows a reduction of more than 10 $^0/_0$ in the transport of water vapour from the Caribbean to the Pacific. This Caribbean water of reduced salinity eventually finds its way to the Labrador, Greenland and Norwegian Seas, where because of lower density, the formation of bottom water will be retarded, reducing thermohaline circulation.

The effects in West Greenland waters of these global atmospheric changes are not yet clear, but may be something like the following: During periods of strong zonal westerly circulation the Iceland low is in its highest latitude and westerly winds prevail in the south Greenland region, retarding and suppressing the entry of both Irminger Sea (Atlantic) and East Greenland Current (polar) water into the West Greenland region. The warming of the West Greenland Current, which accompanies the strong zonal atmospheric flow, is caused by the increased participation in it of the Labrador Sea (Atlantic) water, which is dominant in the West Greenland Current north of Ivigtut in the southwest of Greenland (DUNBAR, 1951). During periods of weak zonal circulation the Iceland low is in lower latitudes and easterly "anomaly" winds appear in the south Greenland area, including Kap Farvel (RODEWALD, 1967, 1972). The flow of both Irminger Sea water and East Greenland water to the west round Kap Farvel is increased (ALEKSEEV et al., 1972; SOULE

et al., 1950; MOYNIHAN & ANDERSON, 1969). The total effect is the cooling of the West Greenland Current, and a shift northward of the Labrador Sea gyre into Davis Strait. Fig. 6 shows the northward progression of the Labrador Sea trough, the point at which the West Greenland Current begins to turn westward, between the years 1928 and 1969. During the period of the appearance of the salmon in abundance, the gyre has been moving steadily northward.

The responses of the salmon to these changes are unknown. It is reasonable to speculate that the salmon, if their former sea-life region was in the Irmiger Current region southwest of Iceland, as was suggested by MENZIES (1949), are simply carried up toward Davis Strait by the increase in the West Greenland transport. The same might apply in the case that the former sea-life region was in the Greenland Sea, a possibility that is suggested by the fact that the salmon appear in abundance in West Greenland waters as those waters grow cooler, not warmer as in the case of the Atlantic cod. But on these possibilities adequate evidence is lacking, nor do we know wath environmental signals guide the salmon migration. It is proposed here, however, that the northward expansion of the Labrador Sea gyre into Davis Strait, and the intensification of the West Greenland Current, are involved in the process of the change in the distribution of the salmon. And at the ultimate (as opposed to the proximate) level of evolutionary events, there is food for thought in the fact that the salmon, in moving into West Greenland waters as the climate is cooling and the Atlantic cod are moving out, profit by the availability of food organisms abandoned by the cod.

Whatever the precise nature of the salmon response, or of the ecological signals to which they are attuned, it is clear that the grilse (one-year sea-life stock) respond differently from the older fish (two-year sea-life stock or "salmon" proper in the fishermens' jargon). No grilse have been taken in the Greenland waters. It is also interesting that although Canadian, Scottish and Irish salmon are common in the Greenland catch, salmon from Norway and Iceland are scarce. Such differences within the Atlantic salmon stocks constitute a question quite separate from the thesis proposed here, and have not yet been explained.

It is also possible to argue that the appearance of salmon in large numbers in West Greenland and in Southeast Greenland could be attributed to fluctuations in the total North Atlantic stock, or to fluctations in the grilse "salmon" ratio, or to unknown changes in the freshwater phase of the life cycle, rather than to climatic change. We have no information on these points; but the strongest argument for climatic control, as mentioned earlier in this paper, is that it is extremely unlikely that the salmon, alone among the species in the ecosystems concerned, should have been unaffected by climatic change.

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